Sugar Beet

Edited by

A. Philip Draycott

Formerly of Broom's Barn Research Station,
Bury St Edmunds, Suffolk,
UK

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Editorial Offices:
Blackwell Publishing Ltd, 9600 Garsington Road, Oxford OX4 2DQ, UK
Tel: +44 (0)1865 776868
Blackwell Publishing Professional, 2121 State Avenue, Ames, Iowa 50014–8300, USA
Tel: +1 515 292 0140
Blackwell Publishing Asia, 550 Swanston Street, Carlton, Victoria 3053, Australia
Tel: +61 (0)3 8359 1011

First published 2006 by Blackwell Publishing Ltd

ISBN-10: 1-4051-1911-X
ISBN-13: 978-1-4051-1911-5

Library of Congress Cataloging-in-Publication Data
Sugar beet / edited by A. Philip Draycott.
p. cm.
Includes bibliographical references and index.
ISBN-13: 978-1-4051-1911-5 (alk. paper)
ISBN-10: 1-4051-1911-X (alk. paper)
1. Sugar beet. I. Draycott, A. Philip (Arthur Philip)
SB221.S88 2005
633.6'3--dc22
2005013771

A catalogue record for this title is available from the British Library

Set in 10.5/12 pt Ehrhardt
by Sparks, Oxford – www.sparks.co.uk
Printed and bound in India by Replika Press PVT Ltd, Harayana

Cover pictures provided by A. Kockelmann, M. Cariolle, I. Håkansson, E. Ober and P. Draycott.

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Foreword

It was a great pleasure when Broom's Barn was approached to produce a new book on sugar beet as part of Blackwell's World Agriculture Series. Now the task is complete I am delighted at the opportunity to write a few words by way of introduction. Considering the crop is widely grown and researched so thoroughly, surprisingly few books are devoted to it. Appearance of this account of the current state of our knowledge is indeed a remarkable event.

The Editor has cast his net wide to ensure each topic is covered by some of the leading world authorities in their respective fields. That sugar beet is internationally grown and researched is reflected in the countries contributing – France, Germany, Spain, Sweden, the Netherlands, UK and USA. It is a matter of pride for me that so many are either Broom's Barn colleagues, or choose to collaborate significantly with us.

Sugar beet growers and processors worldwide, like us researchers, are fortunate to have two international bodies looking after our interests. In Europe we have the Institut International de Recherches Betteravières (IIRB) and in USA the American Society of Sugar Beet Technologists (ASSBT), bringing together scientists regularly, and through publications, engendering good collaborative work. We thank both organizations for their help, which make production of a book like this so much easier.

Similarly, in many individual countries sugar beet research and development is encouraged, for example in the UK by British Beet Research Organisation (BBRO). It is they, as representatives of growers and British Sugar, whose far-sighted funding policy has enabled production of this book. Whatever the outcome of current European Union sugar regime reform, throughout the world there will be increasing need for the industry to become more competitive – raising yields, reducing costs and minimizing environmental impact. This book will help greatly in meeting challenges that lie ahead.

Recent changes and improvements are dealt with throughout every chapter and these will lead on to further progress. In practice there have been rapidly increasing yields, not least as a result of genetic improvement. Major reductions in agrochemical inputs, with environmentally benign products being introduced and steady advances in mechanization, particularly in harvesting, have all had a large effect in many countries.

In research terms, a major emphasis has been on seeking to broaden the crop's genetic base through introducing molecular biological approaches and genetic resistance to important diseases. Introduction of varieties with partial resistance to *Beet necrotic yellow vein virus* (BNYVV), the virus responsible for rhizomania, has been a major success. However, improvement to yield or drought tolerance are currently too difficult for such techniques to be applied and classical breeding remains supreme. A major missed opportunity has been the inability, in the present political climate, to introduce genetically modified glyphosate-tolerant beet. As the need for greater competitiveness begins to bite, this will be bitterly regretted by the industry.

The editor and authors are to be congratulated on bringing so much up-to-date information together in one place. *Sugar Beet* will serve the industry, practitioners and researchers alike, for the next one or two decades, as an important part of its knowledge base and a springboard for further progress.

John Pidgeon
Director, Broom's Barn Research Station
March, 2005

Preface

Sugar became a staple food over the past two centuries and average annual consumption per head is now about 20 kg. Worldwide demand continues to rise and approaches 140 Mt per year. This comes from only two plants – cane and beet. To meet increasing needs, all aspects of how to produce these crops efficiently have been widely researched and work continues rapidly in all countries where they are grown.

Researchers publish results in scientific papers, spread through national and international journals. Thus much of the latest information is not readily available to the people involved with the crops. It is therefore necessary periodically to review research and assemble results in an accessible form.

Glyn James has done just that in his excellent up-to-date account of the cane crop. This appeared in 2004 as one of Blackwell's new titles: *Sugarcane*. I am very pleased to attempt the same with this book about sugar beet.

In fact I began drafting a general sugar beet crop book whilst working at Broom's Barn under Raymond Hull with him as co-author. My colleagues, David Cooke and Keith Scott, subsequently published a book as a multi-author, edited volume for Chapman and Hall in 1993 entitled *The Sugar Beet Crop – Science into Practice*. This was a huge achievement, welcomed by all sides of the industry, because it was the first time all facets of the crop were gathered together in English in one volume. It rapidly became the standard work for all students, researchers, growers and processors throughout the world.

With the retirement of David Cooke and the sad and premature death of Keith Scott it has fallen to my lot to take over editorship. When invited by Blackwell Publishing to produce a companion volume for *Sugarcane* it was a challenge difficult to resist – now an earlier ambition fulfilled!

My first job was to assemble a team of 32 international authorities to cover each subject. Not easy because there are so many good scientists researching sugar beet. Without exception everyone invited accepted willingly. Ten contributed to the earlier book and 22 new scientists were recruited.

Every topic has been brought up to date, drawing on over 2500 references from the world literature. Of these more than a third appeared since 1990. Also new is addition of colour, particularly useful when identifying pests, diseases and nutrient deficiencies of sugar beet.

A. Philip Draycott
April 2005

Acknowledgements

Past and present colleagues at Broom's Barn have been a constant source of inspiration and encouragement, particularly John Pidgeon. Ralph Beckers at IIRB, Thomas Schwartz at ASSBT and John MacLeod at BBRO have all taken a keen interest in production of the book throughout.

It was a relief to be able to call on numerous colleagues to read and advise on chapters outside my own field of knowledge. For this I especially thank Donald Christenson, Gunter Diener, Keith Jaggard, John Pidgeon and Richard Powell.

I and my co-authors thank the writers assembled by Cooke and Scott for the thorough and extensive groundwork they did some 15 years ago. Their efforts made production of the present book so much easier for us. We note the generosity of E. Bornscheuer, J. Duffus, K. Meyerholz, E. Ruppel, E. Schweizer, R. Winner and K. Wunderlich. We thank H. Ahlfeld of *Licht's World Sugar Yearbook* for information and R. Sams of University of California for nutrient deficiency photographs. G Colbeck and G. Pattrick provided pictures, and M. Chester produced the world map of sugar beet growing areas.

I have been grateful from the outset for help from the team at Blackwell's, notably N. Balmforth as commissioning editor and his editorial assistant, Laura Price. Many people have aided me in production of the text, tables, figures and plates, particularly I. Pettitt, C. Clark and T. Stevens at Broom's Barn, and colleagues at Syngenta AB, Landskrona, Sweden.

Most thanks of all go to my secretary, Mrs Judy Robertson, who has done outstanding work typing several drafts of the text, assembling tables and figures, and checking all 2500 references. I and all the authors are indebted for her meticulous attention to every detail.

A. Philip Draycott
April 2005

Chapter 1

Introduction

A. Philip Draycott

Most of the food for the world comes from some 150 plant species cultivated as crops. Sugar (the common name for sucrose) is obtained from only two crops, cane and beet. Cane sugar has been produced in large quantities in tropical regions for many centuries and continues to dominate the world supply of sugar. In contrast, sugar beet is a relatively new crop, appearing in temperate regions in the nineteenth century and spreading widely only in the twentieth century. Sugar beet is now grown in some 50 countries and provides about a quarter of the 140 Mt sugar currently used each year. James (2004) has reviewed sugar cane and this book attempts to do the same for the beet crop.

As a result of its sweetening, energy giving and preserving properties, sugar is a major component of a wide range of foods and drinks. Despite concerns about its effects on health and competition from other sugars (e.g. isoglucose from cereals and fructose from maize) and from artificial sweeteners (e.g. saccharin, aspartame and cyclamate) the need for sugar continues to rise rapidly. Thus world consumption of sugar from cane plus beet has increased fivefold in the past 60 years and there is no sign of a slackening in this rising demand.

Many countries set up beet sugar industries in the twentieth century to ensure a constant supply in times of political uncertainty or war. Sugar beet then became an important cash crop on many farms throughout the world and national sugar industries once established are jealously guarded by growers, processors and political lobbyists. At the time of writing, attempts are being made once again to move to a freer trade in world agricultural products, which may have far-reaching effects on area of sugar beet grown.

ORIGINS OF CROP

What we know as sugar beet was first grown at least 2000 years ago as a garden vegetable. The sugar beet currently grown is far removed from the garden plant. The vegetable was probably selected from various *Beta* species growing round the shores of the Mediterranean. It was widely used for culinary purposes throughout Europe from the Middle Ages onwards.

During this period, bee honey was prized for its sweetness, being the only such sugary food readily available. Limited quantities of cane sugar were imported into Europe for the tables of the rich and the rest made do with fruits and vegetable juices for sweetening. Any plant whose juice was sweet was therefore highly valued.

Beet was grown on a field scale first in the seventeenth century but only as fodder for cattle. A range of different types of *Beta vulgaris* was grown for this purpose, some for its storage root, some for its leaf and always in a variety of colours. Of common, spring-sown crops, all beet types have the important characteristic of being able to store one of the largest amounts of dry matter wherever grown in the world. It was from a white root type of Silesian beet with high sugar concentration that sugar beet was bred early in the eighteenth century. A detailed history of the crop and its development is in Chapter 2.

PRODUCTION

Several German chemists discovered how to extract sugar from beet roots and showed that the crystals were the same as those derived from cane. Various attempts were made to industrialize the process in primitive factories in the late eighteenth century, coupled with field-scale cultivation of the crop. None was very successful.

By the beginning of the nineteenth century cane sugar had become an important world commodity, being imported by many European countries from their colonies. This trade was then severely interrupted by the Napoleonic wars, which led to a reawakening of interest in sugar from beet. Over the past 200 years, after many false starts, the sugar beet industry became firmly established worldwide, as described in Chapter 2.

CROP IMPROVEMENT

Plant breeding has contributed most to improvements in the productivity of the plant and hence the crop. Sugar concentration has been increased from some 12% of the fresh root to current values of 20%. Improvements in yield and chemical properties of the root by plant breeding continue to increase the amount of white sugar extracted at the processing factories. In addition, resistance and/or tolerance to pests and diseases aid in the production of this crop. Perhaps the biggest breakthrough by plant breeders was the introduction of monogermity allowing 'sowing to a stand', described in Chapters 3, 4 and 5.

Alongside these improvements from selection, yield and quality have been greatly influenced by progress in plant nutrition and soil management. During the twentieth century, research in every country where the crop is grown has gone on apace (Gebhard *et al.*, 2003). The work detailed in Chapters 6, 8 and 9 recounts how research has focused on ensuring that the crop is grown in optimum soil conditions with sufficient macro- and micronutrients and water to perform to the limits imposed by the climate in each locality (Draycott & Christenson, 2003).

Equally important in many areas were the plant protection measures that ensured the establishment and healthy growth of the crop. Pesticides, applied as seed treatments, fumigants, granules or sprays, have had, and will continue to have a major role, but other methods, particularly the development of pest- and disease-resistant varieties, are likely to become increasingly important. Curly top resistance saved the sugar beet crop in the western USA in the 1930s, and the rapid progress which has been made in producing rhizomania-resistant varieties may well have prevented the crop from having to be abandoned in many parts of the world in the 1990s. More details are in Chapters 11, 12 and 13.

Throughout western Europe and North America, most sugar beet root crops are now produced from good quality monogerm seeds (often pelleted and with a germination of over 95%), sown at wide spacings (usually in the spring but, in warmer climates, in the autumn to over-winter) into well-prepared seedbeds, protected from a range of weeds, pests and diseases. The beet roots are harvested mechanically, stored (Chapter 15) and processed in large factories. For example in the European Union about 130 factories have a total daily capacity of 1.4 Mt, or an average of about 10 000 t/day (Graff, 2003).

WHERE GROWN

Once established in Europe, with field production and processing methods proven, sugar beet was taken to other regions of the world (Fig. 1.1). Processing factories have been built in areas favourable to the crop in the Americas, Asia and North Africa. In 2000, nearly 7 Mha of sugar beet were grown worldwide and Table 1.1 lists the countries with a sugar beet industry together with production in 2003–2004.

Despite this spread throughout the world, sugar beet is essentially a crop grown in temperate regions. Most is grown at latitudes between 30 and 60ºN, as a summer crop in maritime, prairie, semi-continental and some semi-arid and arid climates and as a winter and/or summer crop in Mediterranean and other semi-arid and arid conditions (Draycott, 1972). The crop is now grown with supplemental irrigation in regions where low rainfall previously limited its production; this is described in Chapter 10.

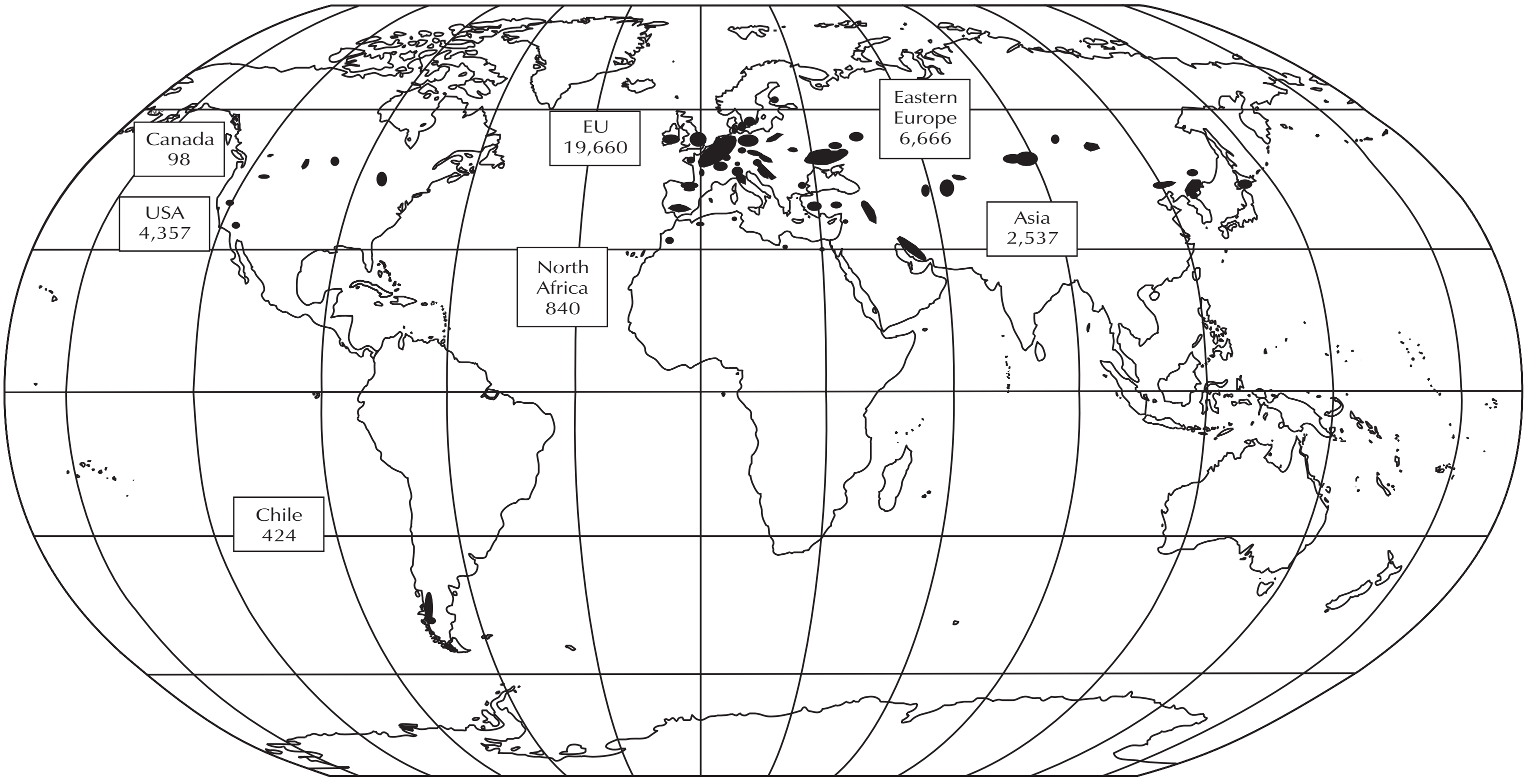


Fig. 1.1 Approximate world distribution of sugar beet growing areas (after Cooke & Scott, 1993) and sugar produced, 1000 t.

Table 1.1 Countries growing sugar beet and sugar produced in 2003–2004 (after Licht, 2004).

	1000 t
Austria	420
Belgium	1 117
Czech Republic	559
Denmark	535
Finland	148
France	4 313
Germany	4 079
Greece	223
Hungary	296
Ireland	243
Italy	978
Netherlands	1 167
Poland	2 126
Portugal	77
Slovakia	179
Spain	992
Sweden	452
UK	1484
Other European Union	272
European Union	**19 660**
Moldovia	87
Romania	76
Russia	2 098
Serbia	227
Switzerland	201
Turkey	1 883
Ukraine	1 690
Other Europe	404
Europe	**26 326**
Egypt	435
Morocco	405
Africa	**840**
Canada	98
USA	4 357
North and Central America	**4 455**
Chile	424
South America	**424**
China	638
Iran	745
Japan	858
Pakistan	27
Syria	105
Other Asia	164
Asia	**2 537**
World	**34 582**

Besides being widely spread geographically, the crop is produced successfully on a range of soil types. On a textural classification, the crop is found on virtually all types – clays, silts, sands and organic soils. Production may be limited on soils with excessive wetness in spring and autumn. Delayed sowing or difficulties in harvest can limit its production on soils with a very high clay content. In many areas this may be overcome through the use of artificial drainage, such as mole drains, tile drains and other methods. Generally the crop is grown on fairly level land to aid mechanical field operations. Where soils are deep and in a good physical state, sugar beet thrives almost everywhere if the climate allows.

An essential aspect of all soils where the crop is grown is pH, which must be near the neutral point. Problems in this respect are easily rectified (Chapter 9). When this criterion is met and if the nutrients detailed herein are available, with good husbandry the crop will produce sugar commensurate with the limits set by the climate (Scott & Jaggard, 1993). See also Chapters 3 and 7.

SUGAR CONSUMPTION

Humans have probably always had a sweet tooth and sugar industries in cane and beet producing countries aim to profit from satisfying this desire for sweetness. Worldwide average annual consumption per head of population is now over 20 kg (Table 1.2). Where cost per kg is small compared with total disposable income (Europe and the USA) intake per head has stabilized just below 40 kg. In contrast in poorer areas (Africa, Asia) consumption is only 16 kg per head.

Table 1.2 Sugar consumption per head of population from cane plus beet (after Licht, 2004).

	kg/annum
Europe	40
North and Central America	37
South America	46
Africa	16
Asia	16
Oceania	48
World	23

ECONOMICS AND POLITICS

The majority of the world's sugar is now produced and sold within the protection of preferential international agriculture and trade agreements. This leaves a small proportion to be sold on the world market, where prices fluctuate greatly but, except during rare periods of shortage (e.g. 1974–1975 and 1980–1981), are well below guaranteed prices.

The European Union, which produces more than half the world's beet sugar, still operates a sugar regime that sets national tonnage quotas for home-grown white sugar whilst permitting a limited amount of preferential imports (mainly into the UK as raw sugars from cane grown in African, Caribbean and Pacific countries of the Commonwealth). The sugar regime was intended to link community-wide production with consumption, but in fact results in a large surplus of white sugar to be sold on the world market. Some radical changes to these European Union structures are under discussion at the time of writing (early 2005).

In the USA, the beet sugar industry has had to survive for 30 years without the degree of protection it enjoys in other areas. The Sugar Act, which for 40 years had ensured stable prices for both growers and consumers, was not renewed in 1974, and since then prices have been subject to fluctuations in line with those on the world market. In the last 20 years, the USA crop has accounted for only 11% of total world beet sugar production and an increasing proportion of the USA caloric sweetener market is replaced by corn syrups. Many USA farmers have switched to alternative crops of higher value, and the only places where there has been any expansion in beet growing are Michigan in the mid-1980s and the low-input areas such as Red River Valley of North Dakota and Minnesota.

The extent and distribution of the world's sugar beet crop is, therefore, to a large extent determined politically, and over the next few years, attempts to liberalize trade in world agricultural products (e.g. through the World Trade Organization [WTO] and General Agreement on Tariffs and Trade [GATT] negotiations) may have far-reaching effects on national sugar industries. However, the very existence of those industries has depended upon the ability of agricultural scientists of many disciplines to breed varieties, and develop systems of cultivating, harvesting and processing the crop, which enable it to be grown economically in a range of climatic and soil conditions.

Monogerm varieties enabled seeds to be sown at wide spacings, ending the requirement for the labour-intensive work of thinning and singling. New selective herbicides of the 1980s eliminated the need for hand weeding in many crops (see Chapter 14). With the introduction of mechanical harvesters, first in the USA and then in Europe, the crop no longer had to be harvested by hand. These developments meant that, in the UK for example, average labour requirements declined from about 300 man-hours/ha in 1954 to 50 man-hours/ha in the late 1970s, and as little as 20 man-hours/ha in some crops now. This reduction in labour was greater than that associated with any other agricultural crop over the same period; without it the sugar beet crop would not have survived the changing agricultural conditions of western Europe and the USA during the last 40 years.

WORLD PRODUCTION OF SUGAR FROM BEET AND CANE

Total production of sugar now approaches 140 Mt, having risen from 30 Mt over the course of the last 60 years (Fig. 1.2). It now increases at about 2 Mt per year, and during the last decade increased steadily at 1.9% per year. Sugar made from the two crops strives to satisfy world demand for sweet food, despite increasing production of syrups from other crops and of artificial sweeteners. A small proportion of sugar produced from cane and beet is fermented to alcohol and this is likely to rise as use of biofuels increases worldwide.

In 1900 beet and cane each provided about half the sugar produced and increases in each rose in parallel during the early part of the twentieth century. During the second half of the century to the present day, sugar from cane rose rapidly whereas from beet it has risen more slowly (Fig. 1.2) and currently shows signs of decreasing. Between 1950 and 2000 the proportion of sugar produced from cane changed from about two-thirds to three-quarters of world sugar production. These changes

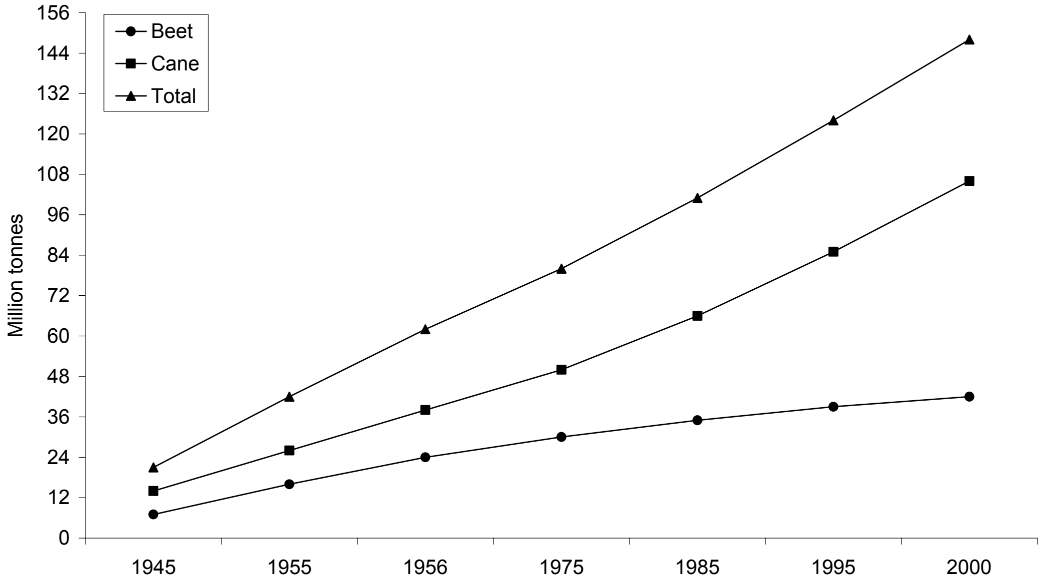


Fig. 1.2 World sugar production from cane and beet, 1940–2000.

are due to complex social, political and economic pressures, which will inevitably continue to beset the sugar industry in the new century.

Europe is the major producer of sugar from sugar beet, accounting for about 75% of the total beet sugar produced (Table 1.3). The USA and Asia make up 19% of the production with South America and Africa accounting for the remainder.

A comparison of sugar beet production between Europe and the USA is given in Table 1.4. Within Europe there are large variations in production due to climate, soil and many aspects of growing the crop, discussed in later pages. In the USA shorter growing seasons and less certain moisture supplies contribute to the lower yields in the Great Lakes, Upper Midwest and Great Plains. In the Far West (Idaho and California), a longer season and irrigation contribute to the higher yields. Yield of both roots and sugar is high in the Imperial Valley of California and growers there hold the world record for sugar beet production, averages exceeding 90 and 12 t/ha of roots and sugar respectively, and individual farms sometimes producing over 150 and 18 t/ha roots and sugar.

Table 1.3 Annual world sugar production from beet by continent.

	Mt	%
Europe	26	75
Africa	1	3
America		
North	4	11
South	1	3
Asia	3	8
Total	35	

SUGAR BEET PERFORMANCE

As mentioned earlier, conventional plant breeding and variety testing in many countries have gradually produced the highly efficient sugar beet grown today. This yields more weight per unit area and is of much better processing quality than its primitive ancestors (see Chapter 16). Annual improvements through selecting from the best continues to increase productivity and probably contributes

Table 1.4 Comparison of area in sugar beet production, amount of beet processed, amount of sugar produced, and yield of beet and sugar for Europe, the European Union and the USA (from Haley & Suarez, 2004; Licht, 2004).

	Area (Mha)	Beet processed (Mt)	Sugar produced (Mt)	Beet yield (t/ha)	Sugar yield (t/ha)
Europe	4.4	173	26	40	6
Included above European Union	2.2	120	20	55	9
USA	0.55	27.7	4.36	50.8	8

most to the dramatic change seen for more than 70 years (Fig. 1.3). With novel methods of plant breeding researched during the past 20 years, perhaps even greater advances will be made. At the time of writing, however, sugar production from genetically modified beet is banned in most if not all countries.

Pidgeon *et al.* (2001) have recently sounded a warning over a likely slowing of the future rate of rise in yield per unit area. Their analysis suggests that national average production in the most efficient countries (France and the UK are quoted) is now some 80% of estimated potential yield, as set by climate, soil and variety. They imply that nutrition must be near optimal (or possibly still excessive in the case of some nutrients) in these countries but suggest that there is a long way to go to optimize factors affecting growth of the crop (including nutrition) in other parts of the world.

FUTURE

Research workers everywhere are attempting to improve the economics and sustainability of beet growing, minimize any threat posed to the environment and find other sources of income from the crop. Improved profitability has always been a major research objective, and this book contains numerous examples of attempts to increase yields, decrease inputs, and minimize root impurities and dirt tares. The environmental acceptability of the

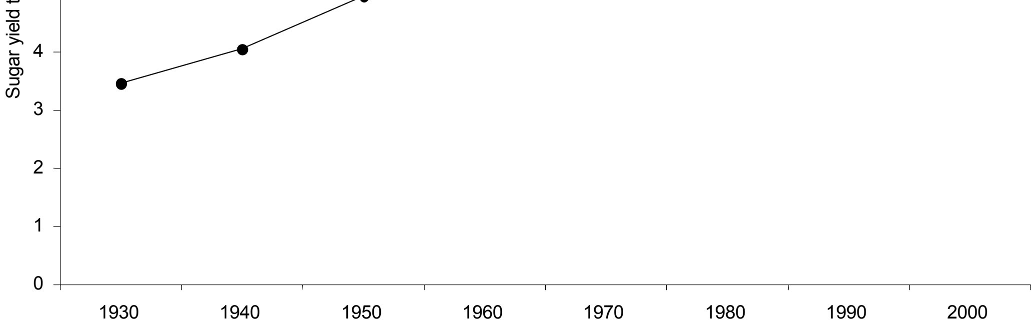


Fig. 1.3 Average improvement in sugar beet performance in the UK and USA, 1930–2000.

crop is aided by the fact that it is a most effective scavenger of nitrogen fertilizer, leaving little in soil at harvest to then move into groundwater. Work on resistant varieties, biological control and pesticide seed treatments will all help to reduce or dispense completely with use of pesticide sprays. By-products of the crop (tops, insoluble root material and molasses) are extensively used as animal feeds (and, to a small degree, in human dietary fibre), in contrast with sugar cane, where the principal by-product (bagasse) is used as a fuel in the factory (see Chapter 17).

Many attempts have been made to find new uses for sugar – most notably in production of ethanol to be used either as a fuel or as a feed-stock for the chemical industry. Although this process, using cane and beet sugar, is now a well-established industry, it is usually uneconomic in developed countries at present energy costs. However, sugar is currently used in the manufacture of a range of potentially high-volume products (e.g. polyurethane foams) and high-value, low-volume products (e.g. high intensity sweeteners, vitamins and antibiotics). The search for new markets will continue.

Finally, the developments in genetic engineering, already being exploited to improve beet quality and transfer resistance to herbicides, pests and diseases, could result in sugar beet plants that will be used in manufacture of products such as biodegradable plastics or modified carbohydrates.

SUMMARY

On a world scale sugar beet is an important source of sugar and the crop occupies nearly 7 Mha each year. Whilst complex political and social tensions exist among nations there will be a need for sugar production from sugar beet. The Napoleonic wars enhanced the establishment of the sugar beet industry in Europe because availability of cane sugar was restricted. Such a situation could occur again and explains why many other countries have set up their own sugar beet industries.

Wherever sugar beet is grown in the world, climate and soil are the two major determinants of success. Diseases, weeds and pests can usually be overcome and the following chapters show how this can be achieved. A maximum economic yield of quality roots is essential to grower and processor. More importantly, the crop should be sustainable and have a minimum impact on the environment, and much recent research on this topic is reviewed.

REFERENCES

Cooke, D.A. & Scott, R.K. (1993) *The Sugar Beet Crop*. Chapman and Hall, London.

Draycott, A.P. (1972) *Sugar Beet Nutrition*. Applied Science Publishers Limited, London.

Draycott, A.P. & Christenson, D.R. (2003) *Nutrients for Sugar Beet Production: Soil–Plant Relationships*. CABI Publishing, Wallingford.

Gebhard, H-J., Beckers, R. & Märländer, B. (2003) Sugar beet research and development. *IIRB/ASSBT Proceedings*. pp. 23–34.

Graff, R. (2003) Sugar beet growing in Europe. *IIRB/ASSBT Proceedings*. pp. 1–22.

Haley, S. & Suarez, N.R. (2004) Sugar and sweeteners outlook (September). *Economic Research Service, United States Department of Agriculture*, Washington, DC.

James, G. (2004) *Sugarcane*. Blackwell Science Limited, Oxford.

Licht, F.O. (2004) *World Sugar and Sweetener Yearbook 2005: World Sugar Statistics*. F.O. Licht, GmbH, Agra Informa Limited, Tunbridge Wells.

Pidgeon, J.D., Werker, A.R., Jaggard, K.W., Richter, G.M., Lister, D.H. & Jones, P.D. (2001) Climatic impact on the productivity of sugar beet in Europe, 1961–1995. *Agriculture and Forest Meteorology* **109**, 27–37.

Scott, R.K. & Jaggard, K.W. (1993) Crop physiology and agronomy. In: Cooke, D.A. & Scott, R.K. (eds) *The Sugar Beet Crop*. Chapman and Hall, London, pp. 179–237.

Chapter 2

Development of Sugar Beet

Sally A. Francis

INTRODUCTION

Sugar beet is the most important of several crops, including spinach beet, Swiss chard, garden beet (beetroot) and fodder beet, within *Beta vulgaris* ssp. *vulgaris* (Plate 1a–e) (Gill & Vear, 1980). It was selected from high sugar-content fodder beets at the end of the eighteenth century, and the first commercial processing 'campaign' was in 1802. Extraction of sugar from beet was one of the major agricultural developments of nineteenth century northern Europe. Experimental work in Germany laid the foundations of the beet sugar industry and the Napoleonic Wars gave the initial stimulus to its further development as an alternative to cane sugar, especially in France. With various technical developments, and with favourable government policies, the beet sugar industry has expanded and the crop is cultivated and processed in Europe, North and South America, Asia and Africa.

In this chapter, the history of the sugar beet crop and the global beet sugar industry is detailed and prospects for the industry's development are outlined.

EARLY DOMESTICATION OF BEET CROPS

Wild sea beet (*B. vulgaris* ssp. *maritima*, or *B. maritima*) (Plate 2), the probable ancestor of cultivated beets, is a straggly, halophytic perennial that grows on sea walls, shingle, and sand dunes around the coasts of the UK, mainland Europe including the Mediterranean, and North Africa. It is a wind-pollinated, mainly out-breeding species with hermaphrodite flowers. Flowering is induced by exposure to a period of low temperatures (vernalization), which causes stem elongation ('bolting'). The seed develops inside fused corky fruits (colloquially called 'seed' or 'multigerm seed') adapted for sea-borne distribution. On germination, each multigerm seed produces a tightly packed cluster of seedlings.

Initially, the leaves of sea beet were probably gathered from the wild and eaten as a spinach-like vegetable, which still occasionally happens in Britain today (Mabey, 1996). However, by ancient historical times, different varieties of beet were deliberately cultivated around the shores of the Mediterranean as a garden vegetable. They were grown mainly for their leaves, and probably resembled what we would describe today as spinach beet or Swiss chard. In both the Greek and, later, the Roman civilizations, they were highly valued supplements to the diet.

The earliest Greek name for beet is *teutlon.* A fancied resemblance between the fanged root systems of early beet plants and the tentacles of a squid has prompted the suggestion that this word and the word for squid (*teuthis*) are etymologically connected (Ford-Lloyd & Williams, 1975); this can, however, be regarded only as imaginative speculation. Many of the names for beet in other ancient languages (e.g. *selg* in Arabic and *silg* in Nabataean) are apparently derived from the Greek word *sicula,* which Theophrastos (372–287 BC) used to mean beet from Sicily. The word survived until recently as the specific or subspecific epithet in *Beta cicla* or *B. vulgaris* ssp. *cicla.* An old Assyrian text refers to beet as *silga,* when describing its cultivation around 800 BC in the gardens of the Babylonian kings (Lippmann, 1925; Deerr, 1949; 1950).

The first references to beet, which can be dated accurately, occur in two comedies, *The Acharneans* and *Peace*, written by the Greek poet Aristophanes and performed in Athens around 420 BC. Theophrastos described beet as a garden plant that could be used in many ways, and already distinguished between dark-coloured and pale-coloured forms. After the second century BC, beet was mentioned several times in Roman literature, now, however, under the name *Beta*. The origin of this apparently Greek name is uncertain, but it probably spread from Sicily, an old Greek colony, and gradually entered the spoken and then the written Latin language. Under its new name, beet was mentioned by numerous Roman writers, firstly Cato (about 200 BC) and later Cicero, Varro, Columella and Pliny, the latter two being mainly interested in botany. Medical notes concerning beet were given in the *Materia Medica* of the military physician Dioscorides (written between AD 50 and 70). More detailed accounts of beet in ancient times are given by Lippmann (1929) and Ford-Lloyd and Williams (1975).

Fig. 2.1 Beet plant (here illustrated in its reproductive stage with seed-bearing shoot) as it was cultivated in gardens and as a fodder crop at the end of the sixteenth century in many parts of France. In this variety the upper part of the root is already of considerable thickness, and the base of the stunted shoot has red pigmentation (after Dalechamps, 1587).

References from the Middle Ages, when beet passed from areas dominated by the Romans into the cultural circles of northern Europe, do not always differentiate clearly between roots of *Brassica* and *Beta* plants, so it is difficult to be certain where beet was known or grown regularly. In a 'Regulation Concerning Landed Property' (*Capitulare de Villis*) issued by Charlemagne in about 812, however, *Beta* was included as a plant which should be cultivated in the gardens of the imperial estates. It is probable that beet varieties which had both edible leaves and an enlarged, sweet-tasting root were grown in France and Spain, often in monasteries but also, on a small scale, by peasant farmers. By the end of the fifteenth century the plant was probably grown all over Europe, and, in 1420, the first mention of its use in England appeared (Deerr, 1949; 1950).

The first detailed descriptions of different forms of beet were given in 1538 by Caesalpinus in his book *De Plantis*. He recognized four varieties, one of them red-coloured. The latter probably arose from red-veined individuals of wild sea beet, which can still be found growing today (Mabey, 1996). In Britain, red 'Roman beets' with thickened midribs were introduced in the sixteenth century (Gerard, 1597). Around the same period, 'Burgundian beets' (the precursors of today's table beet or red beet), with a sweet taste and red flesh, were quite common in France (Fig. 2.1). In 1600, the French agronomist Olivier de Serres reported vividly in his *Theatre d'Agriculture*: 'A kind of parsnip which has arrived recently from Italy is the beetroot. It has a deep red root and rather thick leaves and all is good to eat when prepared in the kitchen. The root is counted among choice foods, and the juice which it yields on cooking is like a sugar syrup and very beautiful to look on for its vermilion colour.'

At that time any plant that tasted sweet was highly valued. Honey was not available to everyone and cane sugar, which had to be imported from the

Orient and later from the West Indies, was prohibitively expensive (Lippmann, 1929; Deerr, 1949; 1950; Baxa & Bruhns, 1967). As a rule, therefore, the majority of people had to be satisfied with the juice of fruit, berries or carrots, or the leaves and seeds of herbs like sweet cicely (*Myrrhis odorata* L. Scop.) (Brown, 1995) to add a sweet taste to food.

It was not until the seventeenth century that beet was cultivated regularly in the field, making it a relatively recent crop in the history of European agriculture. It is thought that this practice began in Spain, and was introduced into Germany by the Mennonites in *c.* 1700 when they came to the Palatinate from the Netherlands (Sneep *et al.*, 1979). The tops and roots of various forms of field-grown beet were used mainly as cattle fodder in France and Germany. In the cooler regions of central Europe, some varieties with white flesh were cultivated mainly for storage and use as fodder during the long winter. By the middle of the eighteenth century, varieties of this kind, the ancestors of sugar beet, were grown in Germany, mainly on the fertile loess soils around Magdeburg and Halberstadt, and in Silesia.

The development of beet into an industrial crop grown for sugar production did not start until the second half of the eighteenth century. The distinction in names between the thick-rooted forage beet (*Runkelrübe*) and the sugar beet (*Zuckerrübe*) cultivated for sugar production occurred around 1830.

DEVELOPMENT OF SUGAR BEET FROM FODDER BEET

Discovery of sugar in roots of beet

The first milestone in the history of the modern sugar beet industry was a remarkable discovery by chemist Andreas Sigismund Marggraf, an eminent scientist and president of the Physical Class of the Berlin Academy of Science. He demonstrated that sweet-tasting crystals obtained from beet juice were identical to cane sugar. In order to confirm his findings, he observed microscopic crystallization of beet sugar, a method that he pioneered in analytical chemistry. The sugar content of the roots of the red and white forms of beet that he investigated was, however, very low and the amount of crystallized sugar he obtained by alcoholic extraction from the macerated root was only around 1.6% of the roots' fresh weight. In 1747, Marggraf reported the results of his investigations to the Prussian Academy of Science. Two years later this report was translated from the original Latin and published in French in the Proceedings of the Academy (Marggraf, 1749). Although Marggraf later repeated his experiments, and in 1761 even gave some small loaves of refined sugar to the king, the public did not pay much attention to his discovery. The very low sugar content of the beet roots dissuaded him from thinking seriously about extracting sugar on a large scale and he devoted himself to other fields of research.

Re-examination of beets for sugar production

Marggraf's student Franz Carl Achard (Fig. 2.2), now universally recognized as the 'father of the beet sugar industry', investigated the beet crop in more detail and opened the way to industrial sugar production from the roots. In 1776, Achard, at the age of 23, became a member of the Berlin Academy of Science. He was a versatile individual whose interests included mineralogy, botany and major constituents of plants (Speter, 1938). Despite many other obligations, not least as a teaching professor, he did not let Marggraf's findings sink into oblivion. Around 1784, he started growing plants such as corn, Swiss chard and forage beet in his private garden at Kaulsdorf, a village near Berlin, to determine which would be most suited for sugar production. After testing many forms of *Beta*, he found that roots with white skin, white flesh and a conical shape were richest in sugar and of 'pure, sweet juice'. This form, selected by him from beets grown for fodder by farmers around Magdeburg and later propagated in Silesia, became known by the name 'White Silesian beet'. It would seem that this early work was supported by a grant from Frederick the Great of Prussia, which ultimately allowed Achard to plant around 25 ha of

Fig. 2.2 Franz Carl Achard (1753–1821), scientist and chemist. Achard was the first person to select beet plants successfully for sugar production and is considered to be the founder of the beet sugar industry.

beet (MAF, 1931). In these early studies, Achard's main problem was the great variability that existed from beet to beet, not only in morphology but also in sugar content. These differences were apparent even between plants grown from seed of the same origin and at the same site.

The death of his patron in 1786 threatened to end Achard's experiments, and it was not until 1799 that he felt justified in publishing his results (Achard, 1799). The same year, Achard presented Frederick William III of Prussia with some samples of beet sugar (MAF, 1931) and appealed to him for support for further experiments on large-scale beet sugar production. A neutral committee was appointed by the Prussian government to evaluate his methods and proposals. The findings of the committee were generally favourable and, in 1801, the king approved an award to further Achard's work.

First beet sugar factory

Achard's award allowed him to buy an estate at Cunern in Lower Silesia and to construct the world's first beet sugar factory in 1801. Cultivation of beet for processing started in the same year and around 250 t were used in the first experimental campaign, beginning in early spring 1802. The roots had been harvested the previous year and the delay was caused by unexpected difficulties in completing the factory equipment. The amount of extracted raw sugar (4% of the roots' fresh weight) was lower than Achard had hoped, probably because the beet had been stored for too long between harvest and processing. The campaign demonstrated, however, that large quantities of sugar could be extracted from beet (Achard, 1803), and the Prussian government, as well as the public, started to take considerable interest. It was clear that there was a realistic possibility of producing domestic sugar, thereby limiting the import of expensive raw sugar from the British colonies.

In England, the first reports of Achard's success were not received with unqualified delight. The cane sugar producers and trading firms became aware of the possibility of dangerous competition from the continent, not least because, in contrast to cane, white sugar could be produced directly from beet without separate refining. Achard claimed that, shortly after his first publication, representatives of cane sugar refineries offered him considerable sums of money to recant his findings. He refused to do so (Deerr, 1949; 1950).

After only a few years of commercial sugar production Achard suffered a great misfortune. His small factory, erected with so much personal involvement, burned down completely in 1807. His financial resources were stretched in reconstructing the building (Fig. 2.3) and from then on he was in constant economic difficulties trying to replace machinery and carrying out makeshift repairs. However, his methods and ideas had already been successfully adopted by others.

Fig. 2.3 Achard's sugar production building at Cunern (Silesia), photographed in 1912. The first beet sugar factory was erected on this site in 1801, but it burned down in 1807. This new edifice, rebuilt in the same year and also equipped with a small distillery, was again used as an experimental factory and then later as a school of beet sugar production. The building was finally destroyed by military action at the end of the World War II. Achard's grave is located not far from here (original photograph: Zuckermuseum, Berlin).

Achard's legacy

In 1802, a second sugar factory near Tula in Russia produced small quantities of sugar from beet using Achard's methods. The scientific work of Lowitz, who, in 1799, had produced an appreciable quantity of beet sugar, was instrumental in establishing further factories in Russia. In 1805, a progressive farmer and friend of Achard, Moritz Baron von Koppy, built another beet sugar factory on his farm at Krayn, near Cunern. It was designed in accordance with plans (Fig. 2.4) and advice from Achard, but was considerably larger than Achard's Cunern factory. Koppy, who harvested about 500 t of beet each year for processing, demonstrated that growing beet for sugar production offered considerable benefits in a diversified farming system. It was potentially a high value crop with by-products such as tops, beet pulp and molasses, which could be used as cattle feed (Koppy, 1810). Koppy's factory at Krayn offered striking proof to Achard that a courageous farmer with an interest in processing techniques could successfully make use of his invention, not only for the profit of the farmer himself, but also to the advantage of the national economy.

In 1809, Achard published his main work on growing and processing beet for sugar production: *Die europäische Zuckerfabrikation aus Runkelrüben* (Achard, 1809). In this comprehensive book he assimilated all of his and Koppy's experiences in selecting, cultivating and processing beet for sugar production and making the best use of the by-products. He was able to show that soil type, growing conditions and cultivation methods could influence sugar content and the level of unwanted non-sugars. He discussed the advantages and disadvantages of different methods of growing plants, in particular comparing sowing the seed in rows with transplanting young plants that had been raised in seedling beds (Fig. 2.5), a method now used for sugar beet crops in Japan. He even expressed the hope that, in the future, 'a way or a machine' could be invented to prepare beet seed that was not multigerm and would therefore produce only one plant per seed on germination. This would enable the time-consuming work of manually singling the clusters of beet seedlings to be

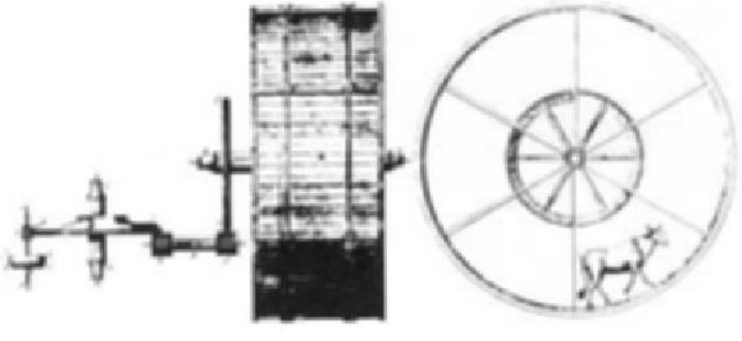


Fig. 2.4 Detail from plans for the Krayn beet sugar factory. The ox-treadwheel provided the power source for cutting beet roots (after Achard).

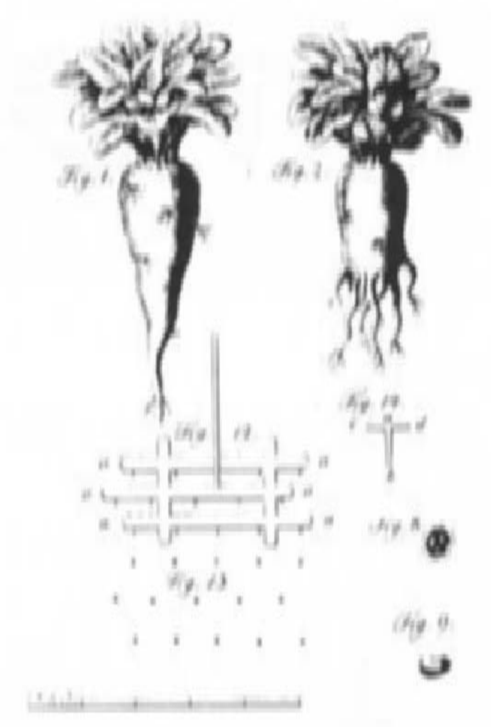


Fig. 2.5 Observations made by Achard on the growth of beets (left): grown from seed sown *in situ*; (right): grown from a transplanted seedling raised in a seedbed; (below): a 'pin board' for making small holes of equal depth in the soil, into each of which a single beet seed was placed by hand.

abandoned. He described in detail the methods of processing roots, obtaining alcohol from molasses, and manufacturing vinegar, and substitutes for tobacco (from leaves) and coffee (from dried pulp).

Economic difficulties on Achard's estate at Cunern meant that his factory remained an experimental plant with only a small capacity. In 1810, with the approval of Frederick William III, whose provinces at that time were still occupied by Napoleon's troops, Achard established a school of beet sugar production. For a few years, students from different countries came to Cunern to receive instruction from the Prussian professor. With the end of the continental blockade, however, there was no further need for this establishment, and in 1814 Achard's school was officially closed. He died in 1821.

ESTABLISHMENT OF A GLOBAL BEET SUGAR INDUSTRY

Europe

Soon after Achard's first reports, his new ideas about the possibilities of sugar production spread quickly across the borders of Prussia. However, it was the interest shown by the French, and primarily by Napoleon I, which catalysed the development of a flourishing beet sugar industry in Europe. In the decades around 1800 cane sugar held a central position in the world economy, which it never assumed before or since. The Napoleonic Wars, starting then, illustrated this quite clearly. In essence they represented a struggle between two different economic systems. The first was based on Great Britain's colonial trade, steady export into countries on the continent and naval supremacy. The second consisted of Napoleon's continental system, which emerged from his plan for the economic development of the continent of Europe, with France as the central region of technical progress. In 1806, with the intention of destroying British export trade lines, Napoleon banned all imports of British goods into Europe. Britain responded by trying to cut France off from her colonies. These measures quickly took effect and the price of sugar increased enormously. West Indian cane sugar disappeared almost completely from the shelves of European shops from 1806, and a replacement was vitally necessary.

In Paris in 1809, a French commission headed by the chemist Deyeux tested and confirmed the results of Achard's experiments. Deyeux presented two loaves of beet sugar, products of his own experimental work, to the Institut National. One of these was passed in January 1811 to Napoleon by his Minister of the Interior, Montalivet (Fig. 2.6). Later that year Napoleon, still sovereign of the major part of Europe, published his famous first decree for the introduction of beet sugar production in France and countries under French administration. According to this decree 32 000 ha of beet were to be sown, but there was a shortage of seed and only around 7000 ha were sown that year. The new sugar plant, however, was now known all over the continent (Fig. 2.7).

Fig. 2.6 The French Minister of the Interior dedicates sugar manufactured from beet to the Emperor Napoleon (etching after a drawing of Monnet).

Fig. 2.7 The nurse encourages the baby holding a beet to 'Suck, my darling, suck! Your father says it is sugar!' Simultaneously Napoleon presses juice from the beet into his coffee (French cartoon *c.* 1811).

At that time most people had a long-standing aversion to the import of cane sugar. Europeans knew that growing sugar cane in the plantations of the West Indies had become possible only because of the exploitation of the slaves brought from Africa. The Slave Rebellion on the 'sugar island' of Santo Domingo (Haiti) in 1791, when the sugar factories were totally destroyed, was a terrifying example of the consequences of slavery, and many people in Europe hoped that it would now be possible to produce sugar on a large scale from a European crop.

Within a very short period during 1811, more than 40 small beet sugar factories were established, mostly in northern France (where two beet sugar manufacturers were already working before the continental blockade), but also in Germany, Austria, Russia and even in Denmark. In January 1812, Napoleon published a second edict declaring that 100 000 ha of beet should be sown within the French Empire, and that many further factories should be erected. Licences were given for 334 factories, although no more than half of them actually started sugar production.

In 1813, however, this short, flourishing era of beet sugar production in Europe ended. The European nations shook off Napoleon's yoke. The continental blockade was removed and English cane sugar again appeared on the European market. Beet sugar was no longer competitive and all beet sugar factories in Germany and Austria were closed down.

France was the only country that did not give up all hope of maintaining this young branch of rural industry. Much of the credit for maintaining and further developing sugar production from beet must go to the French manufacturer Crespel-Dellisse, at Arras. He improved techniques of sugar extraction by the use of new machines (steam engines, presses and juice pumps), mostly imported from England. Other interested manufacturers followed his example. Between 1820 and 1839, the number of beet sugar factories in France slowly increased again, encouraged by a duty on imported cane sugar. This trend was accelerated by publications from de Dombasle (1820) and Dubrunfaut (1825), which described advances in sugar processing. Initially, batch-based methods, involving extracting the beet juice in presses, were commonplace. However, the continuous diffusion process was subsequently developed into working technology by Julius Robert in around 1860. So, while the basic discoveries were made in Germany, the practical development of the beet sugar industry on the European continent in the early nineteenth century took place in France, not least as a result of French government industrial policy.

It was not until the 1830s that beet sugar factories were again built in Germany. These made use of the improved methods of sugar extraction that had been developed in France. The UK's first beet sugar factory opened in Ulting, near Maldon in Essex, in 1832, but was very short-lived (MAF, 1931). In Austria-Hungary the beet sugar industry began to flourish in the late 1840s, mainly in Bohemia and Moravia. By 1856, no less than 108 beet sugar factories were operating, resulting in the closure of many cane sugar refineries. No cane sugar was imported into Austria after 1862.

In Russia there was always great interest in growing beet, and small sugar factories were built all over the country, mainly in the Ukraine. In 1840, about 350 sugar-producing establishments existed, but around a third of these were very primitive. By 1870 about 180 relatively large and well-equipped factories were operating, and by 1889, 250 000 t of beet sugar were produced annually in Russia.

Eventually, all these countries decided to tax cane sugar imports in order to support domestic sugar production. They introduced various forms of bonuses and protectionist import duties. This led to new sugar factories being opened, more beet sugar being produced and the state income from import duties declining. As a result, some governments (e.g. France in 1837, Prussia in 1841) decided to impose taxes on domestic beet sugar. In Germany the excise duty was calculated on the weight of beets processed. Initially, this imposed a heavy financial burden on the factories; however, it also provided the impetus for increasing the industry's efficiency. Factories insisted on the sowing of high-yielding beet cultivars and good crop husbandry. Ways of increasing sugar extraction rates during processing were sought and developed. Elsewhere in mainland Europe, taxes were levied on the stated processing capacities of factories. This led to an increase in throughput (MAF, 1931). All these developments increased yields and, as a result, production of beet sugar in France, Germany and Austria in the second half of the nineteenth century began to outstrip consumption. The economic battle between the cane sugar industry of the warmer countries and the beet sugar industry in northern Europe now became more intense.

During the second half of the nineteenth century, the example of the four 'big' beet sugar producers (France, Germany, Austria and Russia) was followed by seven more European countries (Belgium, the Netherlands, Denmark, Sweden, Italy, Spain and Switzerland) which all started to produce beet sugar on a large scale (Deerr, 1949; 1950; Baxa & Bruhns, 1967). In some of these countries, small beet sugar factories had operated in the early nineteenth century, but they had been of no economic importance. The first large beet sugar factory in Sweden was founded in 1853 (Kuuse, 1983), in the Netherlands in 1858, in Denmark and Italy in 1872 and in Switzerland in 1891. Beet sugar production in Spain did not become important until 1898, after the loss of Spain's last colonies in Asia and America. In Ireland a single factory was built in 1850 at Mount Mellick, County Laois (MAF, 1931), but production was discontinued until 1925, when sugar beet growing was reintroduced (Foy, 1976).

A second attempt was made to establish the industry in Britain with the construction of a factory in Lavenham (Suffolk) (Fig. 2.8) in 1868 by the London cane sugar refiner, James Duncan. The factory processed up to 400 t of beet per week (de Man, 1870), presumably only partially, as the factory's products were sent to Duncan's London refinery to be purified into white sugar. The Lavenham factory closed in 1871 because of problems with the supply of beet and with effluent disposal (MAF, 1931). It reopened in 1885 under new management whose aim was to clarify and refine the beet juice with strontia (a mineral that forms addition compounds with sugar and can be used as an alternative to lime in sugar processing (Flood, 1963)) but again failed and was closed down shortly afterwards (Francis, 2002). The writer de Man called for the establishment of a sustainable long-term beet industry in Britain, putting forward agricultural, economic,

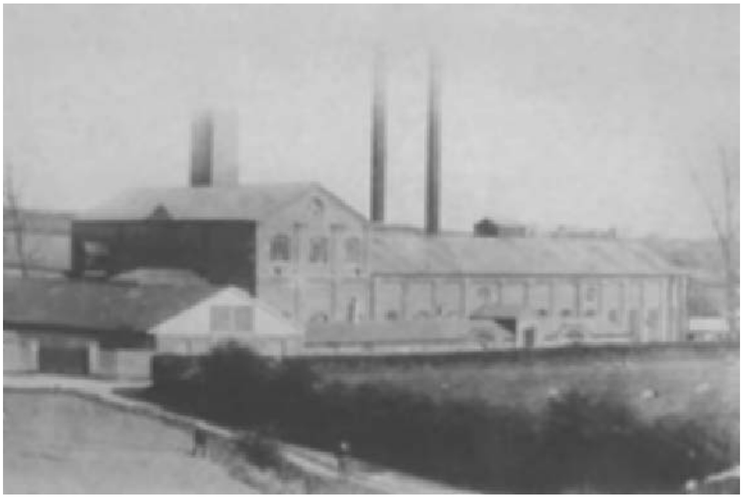


Fig. 2.8 The beet sugar factory at Lavenham (Suffolk, UK) built in 1868 by the London cane sugar refiner, James Duncan. This factory represented the second attempt to establish the industry in the UK. It closed in 1871 as it was not commercially viable, re-opened in 1885 under new management but again failed. The building was destroyed by fire in 1905. © Lavenham Exhibition and Museum Trust.

social and moral arguments (de Man, 1870). One key benefit he identified was the increase in rural jobs the beet sugar industry could create, which would 'take away from the younger class of people the dangerous inducement of flocking to large towns for employment, where they often contract immoral habits'. Beet cultivation trials continued sporadically, but it was not until 1912 that another beet factory was built in Britain.

In France, which until 1875 was the largest beet sugar producer in Europe, beet cultivation began to stagnate near the turn of the twentieth century. Repeated sugar slumps (e.g. in 1840 and 1875) and the demand of the crop for the more fertile soils caused beet production to be concentrated around the factories. In 1834, beet was grown in 55 departments, but by the end of the century it was mainly grown around large refineries in Cambresis, Artois, Picardie and, especially, the Paris region.

The success of growing beet for sugar production in the nineteenth century was due to the application of scientific research, and the industrialization and increasing efficiency of beet processing. By the turn of the century more of the world's sugar was produced from beet than from cane, and there were fears that cane sugar production would soon be totally abandoned. In 1901, at an international conference in London, a general agreement was reached that, worldwide, no national bounties would be paid for beet sugar production, and that import taxes on cane sugar would cease. This ensured that cane sugar again became competitive and, by 1914, it accounted for half of the world's sugar consumption.

In the early years of the twentieth century there were several abortive attempts to re-establish beet sugar production in Britain. They all failed owing to a lack of interest by investors, in spite of the fact that several demonstrations of successful beet cultivation were made in various trials. There seemed to be no future for the industry (MAF, 1931; 1953). British interest in cane sugar from the West Indian colonies was the major obstacle; however, Dutch capital was used to build a factory at Cantley in Norfolk in 1912. The following year a government grant was issued and Dutch casual labourers were billeted on East Anglian farms to cultivate the crop (MAF, 1931). A heavy financial loss was made and Cantley factory closed after four campaigns.

However, World War I demonstrated the value of a supply of sugar that was not dependent on the freedom of the sea routes, and proposals to found a domestic sugar industry were finally supported by the British government. The Cantley factory reopened in 1920, and in 1921 a second factory near Newark in Nottinghamshire was built. Government intervention, in the form of a remission of excise duty and in 1925 a 10-year period of subsidy, resulted in a rapid development of the industry and, by 1928, five companies operated a total of 18 sugar factories. Between 1923 and 1930 sugar production increased from 13 000 (from two factories) to 420 000 t (from 18 factories).

In 1935, the beet sugar subsidy was reviewed and it looked as if the industry might come to an end (Francis, 2002). The findings of the majority group of the enquiry committee (the so-called 'Greene Tribunal report') recommended the withdrawal of all subsidies. The 'Lloyd minority report' however, highlighted the advantages of the beet sugar industry to the UK: (a) it was important in reducing the reliability on sugar imports; (b) beet had a pivotal role in farmers' rotations since it was a cash crop and gave better capital turnover than other roots, e.g. swedes and turnips, where indirect profit was made only after the sale of fattened animals; (c) it gave stability to the whole farming system because it was grown on contract; and (d) it was 'an educative example of an intensive, scientific, planned agriculture' (MAF, 1935). A Home Sugar Beet Defence Committee was organized by growers to fight against the withdrawal of the subsidy. More than 8000 people gathered at one of the committee's meetings in Bury St Edmunds (Fig. 2.9) and were addressed by the mayor who said that if the industry came to an end, 'grass would grow in the town's streets' (Francis, 2002). The government opted for the Lloyd minority report's recommendations and the industry was re-organized in 1936. The various companies amalgamated to form what is now British Sugar plc, and a body (now known as the British Beet Research Organisation) was established to administer funds paid jointly by growers and British Sugar for research into ways of increasing the efficiency of beet cultivation and communicating the findings to growers (Francis, 2002).

The countries in Europe (and worldwide) where beet is grown, and the tonnages of sugar they produce are detailed in Chapter 1, Table 1.1.

North and South America

The history of beet sugar production in the USA can be traced back to 1838 when two Americans, Edward Church and David Lee Child, who had lived for some time in Paris, built a beet sugar factory at Northampton, Massachusetts (Ware, 1880; Harris, 1919). This factory, however, made only 1300 pounds of sugar in its first campaign and it closed down in 1841.

Similar initiatives were undertaken in vain at other locations. An outstanding example was the attempt in 1852 by the leaders of the Mormon Church to establish the industry in Utah. A missionary, John Taylor, had studied the sugar beet industry in France and, on his return to Utah, he formed the Deseret Manufacturing Company. Processing equipment, together with 1200 pounds of seed were purchased and shipped to New Orleans from where they were transported by barges up

Fig. 2.9 Growers from eastern England protesting at Bury St Edmunds against government proposals to remove the state subsidy from the beet sugar industry, 1935. Had the subsidy been removed, the industry would probably have become extinct causing severe rural unemployment in the many beet growing areas of Britain. © *British Sugar Beet Review*.

the Mississippi and Missouri rivers and then, in an expedition of heroic proportions, by wagons drawn by teams of oxen across deserts and mountain ranges to Provo, Utah where it had been planned to build the factory. Unfortunately the technical skills of the collaborators in this venture did not match their enthusiasm and when the factory, which was eventually built in Salt Lake City, was put into operation in 1855 it failed to produce any crystallized sugar (Arrington, 1966).

It was not until many years later in California that sugar beet cultivation was introduced successfully. In 1870, Dyer built a sugar factory at Alvarado, at a cost of $125 000 and with a daily capacity of 50 t of roots. Dyer, a courageous businessman, can be considered as the founder of the beet sugar industry in America. During the first 4 years his factory produced 250, 400, 560 and 750 t of sugar respectively. Production then had to be stopped for some time due to inadequate machinery but, after the acquisition of new equipment, the enterprise restarted in 1880 and continued to expand, now directed by Dyer's son Edward. The plant at Alvarado became the first successful beet sugar factory in the USA and operated, with some breaks, until 1967.

Only a few miles away at Watsonville, another factory was founded in 1888 by Spreckels, which also worked profitably for many years. Factories were soon built in Nebraska, in Utah and other states. Although in 1896 there were still only a total of six factories, the following year government policy changes, aimed at protecting the domestic sugar industry, gave rise to rapid expansion (MAF, 1931); by 1900, 79 000 t of sugar was produced from 34 factories (McGinnis, 1982).

In the first half of the twentieth century sugar beet growing in the USA expanded steadily (Browne, 1937). American trade policy was aimed at protecting the small domestic sugar industry and in 1934 the Jones-Costigan Amendment was enacted which taxed imported sugar whilst controlling and limiting domestic production (Cottrell, 1952; Anon., 1959; Souder, 1971); this Sugar Act remained until 1974.

In the 1950s, sugar beet was cultivated over about 360 000 ha in 22 states, mainly on irrigated land. The centres of beet production were, as now, located in California, the Intermountain area, the Great Plains to the east of the Rocky Mountains (from Montana down to Texas), the Red River Valley (North Dakota and Minnesota) and the Great Lakes area (Michigan and Ohio).

In Canada, sugar beet growing started in 1881 in the Province of Quebec, but without continuing success, and at the beginning of the twentieth century several sugar companies introduced beet growing into Ontario.

In South America, sugar beet cultivation was established in Uruguay and Chile.

Asia and Africa

Sugar beet was first grown in Japan around 1880 when a small factory was erected in Hokkaido and continuous cultivation of beet started around 1920. Since the middle of the 1920s beet has also been grown in Turkey. In some other Asian countries (e.g. Pakistan, Syria, China, Iran and Iraq) sugar beet was established as a field crop after World War II. Beet sugar production was also started in some regions of northern Africa, first in Egypt and Algeria and later in Morocco and Tunisia.

Worldwide statistical data on sugar production are published in F.O. Licht's World Sugar Statistics (annually); further information can be found in Deerr (1949; 1950) and FAO statistics (1961).

TECHNICAL DEVELOPMENT OF SUGAR BEET

Plant breeding and genetics

Achard's selection and seed production work continued after his death on the estate of the Barons von Koppy, father and son, in Krayn, Silesia. The beet seed produced there, derived from Achard's plant material, was used especially in France and Belgium during the first decades of the nineteenth century. This 'White Silesian beet' was the ancestor of all current sugar beet cultivars. In Paris, the plant breeder P.A. de Vilmorin already had expertise in forage beet seed production and in about 1810, began to propagate sugar beet seed, obtaining the original source from Silesia. The essential step towards systematic sugar beet breeding was taken by his son, the well-known plant breeder Louis de Vilmorin. After preliminary investigations he postulated that a beet root with a high density would normally also have a high sugar content. In about 1850 he started to use salt or sugar solutions of different concentrations to measure the specific gravity of roots, and thereby give an indication of their sugar content (Vilmorin, 1850). In about 1852 he modified his method and determined the specific gravity of the beet juice by the 'silver ingot method', described later by Vilmorin (1923) and McFarlane (1971).

These methods laid the foundation for the individual selection of single beet roots and the progeny system of breeding. Superior mother roots were chosen from existing varieties and their progenies evaluated. Through the use of this breeding system and new laboratory techniques, the Vilmorins made rapid progress in sugar beet quality improvement. The 'Vilmorin beet' very soon secured a leading position in several beet growing countries, which was retained for many years. Meanwhile in Germany, the beet grower and sugar manufacturer Knauer, at Grobers near Halle, was the first to produce a new beet variety ('Imperial') that was homogeneous in appearance and also possessed a relatively high sugar content (11–13%). The breeder Matthias Rabbethge, in Kleinwanzleben near Magdeburg, who, since 1859, had followed the principle of individual selection of mother beets, became especially successful. Others followed his example. Their rate of progress was accelerated by using the polarimeter which had already been introduced into the sugar industry by Ventzke (1842) for analysing different kinds of juice, and into beet breeding (around 1853) by Vilmorin. In three decades, from 1850 to 1880, the progeny system of breeding raised the sugar content of beet to 18–20% (and sugar extraction rates in the factories increased correspondingly).

Around 1870, breeding aims started to diverge. On the one hand, breeders continued to develop varieties with high sugar (*Zucker*) content (Z-type); these varieties however had a limited yield potential. On the other hand, new varieties were propagated with root yield (*Ertrag*) above average (E-type) but which, as a rule, had lower sugar contents. Between those two types, breeders produced intermediate varieties, the so-called 'normal' beet (N-type). This formal differentiation into 'types' was first introduced, around 1880, by the seed firm Rabbethge und Giesecke (Kleinwanzleben). It was adopted by other breeders and remained in use until recent times.

In the twentieth century new standards for higher resistance to certain sugar beet diseases were set. One example of breeders' success, accomplished in the USA between the two world wars, was the development of curly-top-resistant varieties, described by Coons *et al.* (1955) and McFarlane (1971). Successful breeding for disease resistance has also allowed the continued cultivation of sugar beet in areas infested with rhizomania. Wild relatives of *B. vulgaris* have yielded novel disease resistance genes (e.g. $Hs1^{pro-1}$ from *B. procumbens*, which confers resistance to beet cyst nematode) and work continues to evaluate wild *Beta* germplasm for new genes to augment those already available in breeding lines (Francis & Luterbacher, 2003).

The way that plant breeding has most radically changed the sugar beet crop is through the introduction of monogerm seed. This seed produces single seedlings on germination and has therefore removed the time-consuming task of 'singling' the crop (Fig. 2.10). The search for sugar beet plants that bore genetic monogerm seed started in the first decade of the twentieth century (Townsend & Rittue, 1905). Success, however, was not achieved until the 1930s, when Savitsky and Bordonos found a monogerm plant at the Sugar Beet Institute in Kiev. In 1947, Savitsky, after emigrating to the USA, continued his research and during an intensive examination of seed crops in 1948 found five monogerm individuals among 300 000 plants in a field in Oregon. It was mainly owing to his subsequent work that monogerm sugar beet varieties suited for agricultural production (Savitsky, 1950) became available to growers in the USA from around 1957 and to growers in western Europe from the mid-1960s.

The improvement of the first genetic monogerm varieties to a level of performance comparable with the old multigerm varieties took place unexpectedly quickly. This was in part due to another important breakthrough in plant breeding: the detec-

Fig. 2.10 Farm workers in Britain, 'chopping-out' and 'singling' in a beet field, *c.* 1931. The aim of this time-consuming work was to remove unwanted seedlings to leave single plants that could grow to maturity the correct distance apart. It was required because multigerm beet seed then used produced clusters of seedlings on germination. © DEFRA/The Stationery Office.

tion of beet plants that exhibited 'cytoplasmic male sterility' (CMS) by the American breeder Owen (1942). Since CMS plants cannot produce viable pollen, they cannot self-pollinate and so only bear hybrid seed. This was an important step for beet breeding in general because it allowed totally controlled crosses to be made and also the beneficial effects of heterosis could at last be harnessed.

The more recent history of breeding and genetics in beet has seen many exciting new discoveries, made using molecular biology techniques. The first detailed genetic map of sugar beet was constructed in the early 1990s (Pillen *et al.*, 1992) and it laid the foundations for many other mapping projects, the cloning of beet disease resistance genes (Cai *et al.*, 1997), and the introduction of marker-assisted sugar beet breeding. The latter technique has dramatically increased the throughput of breeding programmes and it allows positive selection for marked genes, e.g. *Rz*1 for rhizomania resistance, in large numbers of seedling plants without recourse to field trials during the earliest stages of a breeding programme (Francis & Luterbacher, 2003).

Genetic modification (GM) has been achieved in sugar beet using several different target genes to create different GM beet lines and cultivars. In one example, the rhizomania virus coat protein gene has been transformed into an experimental line for coat-protein-mediated disease resistance; this results in a lower virus titre (Mannerlöf *et al.*, 1996). In another line, carbohydrate metabolism has been altered so that, rather than accumulating sucrose, the roots produce fructan ('fructan beet'; Sevenier *et al.*, 1998). Herbicide tolerance (HT) has also been engineered into sugar beet (e.g. to glyphosate; Mannerlöf *et al.*, 1997). In western Europe and elsewhere, GM crops have attracted a bad press and are highly controversial, especially those that are tolerant to herbicides (Fig. 2.11) Further comments are made on GM HT beet later in this chapter and in Chapters 4 and 14.

Fig. 2.11 A cartoon depicting genetically modified herbicide-tolerant beet that appeared in the British agricultural magazine *Farmers Weekly* in June 1995. Public perception of genetically modified crops, including sugar beet, has generally been negative and genetically modified beet is not currently grown commercially in Britain. © *Farmers Weekly*.

Agronomy and plant protection

Several agricultural developments have contributed to the continuing improvement in sugar beet yields. The introduction of guano and mineral fertilizers (Chile saltpetre, potassium, phosphate) helped to increase yields on less fertile soils, and the special nutritional requirements of the crop became the object of systematic research. In 1882, at Bernburg in Germany, an experimental station supported by the beet sugar industry was founded to investigate the mineral fertilization of sugar beet. The first director of this station was Hellriegel, the discoverer of nitrogen fixation by legumes. Since the 1980s, research has allowed the reduction of fertilizer inputs whilst maintaining high yields. In the UK for example, nitrogen applications have fallen by 33% (DEFRA, 2002).

Another problem that was energetically tackled and finally solved was the chemical control of weeds in the beet crop. Following an extensive research programme, the first 'selective' herbicide, propham (IPe), was offered to beet growers in the USA around 1950. It killed mainly grass weeds without doing significant harm to the young beet plants. This product was soon followed by others that were even less damaging to the crop and could be sprayed against broadleaf weeds, even after the beet seedlings had emerged. Some of the most important beet herbicides (and the years when they were first announced in the literature) have been: di-allate (Avadex; 1959); chloridazon (Pyramin; 1962); phenmedipham (Betanal; 1967); ethofumesate (Nortron or Tramat; 1969); and metamitron (Goltix; 1975). The development of GM HT cultivars offers another means of chemical weed control.

Protecting the crop against pests and diseases has also been a priority. In the nineteenth century, farmers had already learned that the yield of sugar beet decreased steadily when beet crops were grown repeatedly in narrow rotations. Schacht (1859) showed that this damage was caused by beet cyst nematode, a parasite that has been a limiting factor in beet production until the present day. Pioneering research on this pest and its biological control by catch crops was done by Kühn (1880) who, in 1891, founded an experimental station for nematode control at Halle, the first research station of its kind in the world. By the end of the century farmers had already learnt to adapt sugar beet growing to prevent excessive damage from this soil pest by widening rotations.

Other pests and diseases, which went unrecognized in the early years of the beet sugar industry, became an increasing threat as beet production intensified. The most important of these were Cercospora leaf spot and some virus diseases such as curly top, virus yellows, and recently, rhizomania. They still present a threat to crop yields, but the use of pesticides and the development of disease-resistant varieties have helped to keep them, at least partially, under control. After 1950, efficient insecticides became available to control the major arthropod pests of beet, such as various seedling pests, virus-transmitting aphids (western Europe), the curly-top-transmitting leafhopper (USA) and other leaf-eating insects. These insecticides soon helped to stabilize beet production in almost all countries where the crop was grown. Effective fungicides have been developed to protect against losses caused by diseases like powdery mildew and rust. In the UK in recent years, new pesticide application technology and related research has led to a 60% reduction in the level of pesticides applied to the crop, including a 95% reduction in insecticide use (DEFRA, 2002).

Crop mechanization

Cultivation and harvesting of sugar beet during the crop's early history was highly labour intensive: after germination, the seedlings had to be 'chopped-out' to approximately the correct distance apart; the clusters of remaining seedlings had to be 'singled' to leave one individual (Fig. 2.10); the crop was hand-hoed and weeded; it was lifted from the ground by digging up with forks and soil was knocked off the roots by striking them together; the tops were cut off by hand with a 'beet knife' (Fig. 2.12); and finally the roots were hand-loaded onto carts. At the beginning of the twentieth century, it still required more than 1000 hours of hand labour to grow and harvest each hectare of sugar beet.

Fig. 2.12 'Topping' sugar beet by hand with beet knives in Britain, *c*. 1931. © DEFRA/The Stationery Office.

In around 1835 the first drill designed for sowing sugar beet was invented (Horsky, 1851) (Fig. 2.13) which, in some respects, was very similar to the modern precision drills, developed 100 years later. Before monogerm seed was introduced, trials were made with drills that sowed 'bunches' of multigerm seed at the correct final spacing (MAF, 1931) to avoid chopping-out. However, these proved disappointing. Seed quality at the time meant that there were enough failures to adversely affect the final population of beet plants, and unlike hand singling and chopping-out, no compensation could be made for missing plants. Various implements were invented for thinning ('gapping') the crop; these were mainly types of hoes used perpendicularly to the rows, again to obviate the need to chop-out (MAF, 1931). The next development was mechanically processed beet seed (precision seed), produced by splitting and rubbing natural multigerm seed. This procedure was developed in Halle, Germany, shortly before World War II (Knolle, 1940). Somewhat later, in California, Bainer produced segmented 'decorticated' beet seed by a slightly different method (Bainer, 1942).

Drills were further improved and seeds were pelleted to make their shape more uniform and

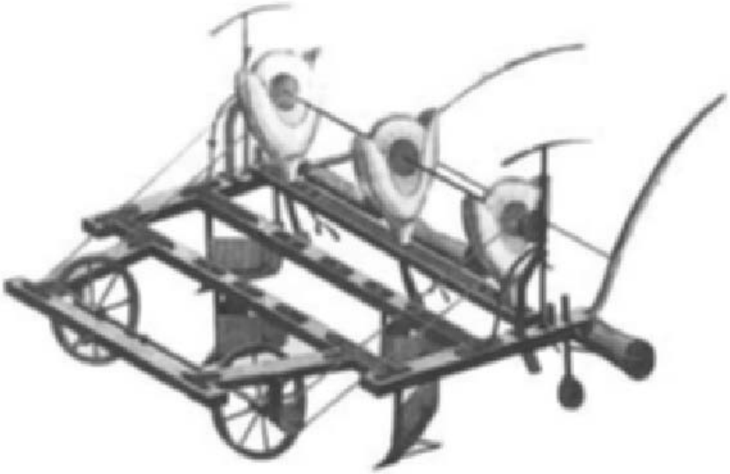


Fig. 2.13 The first precision-drill for sowing sugar beet by placing single seeds into the ground, a three-row machine, constructed by Horsky in 1834 (Horsky, 1851).

allow more precise sowing. Farmers in western European countries were the first to experiment with ‘sowing to a final stand’, in regions where a high field emergence could be expected. The use of newly available genetic monogerm seed from around the 1960s made the handwork of singling and chopping-out unnecessary.

Weed control by hand-hoeing was superseded by the development of horse-drawn beet hoes. However, the disadvantages caused by using horses in narrow beet rows stimulated research into tractor hoeing in Britain, beginning in the late 1920s and early 1930s (MAF, 1931).

To aid harvesting beet, horse-drawn ploughs with their mould-boards removed were used to loosen the soil around the rows, which made pulling the roots out easier. Later, special horse-drawn lifters were developed (Fig. 2.14); however, some designs caused problems by soiling the tops, making them unusable for fodder, and churning up the soil, which made carting off the fields difficult (MAF, 1931).

The first steps towards constructing harvesting machines that could lift and top beets were taken before World War I. It is no surprise that the first harvesters were built in the USA where hand labour was especially expensive and difficult to obtain (Walker, 1942). These machines used either ‘machine topping’ or ‘ground topping’ systems. In regions such as California, where beet was grown under artificial irrigation and on heavy soils, the ‘machine topping’ system had obvious advantages, particularly the better separation of soil and clods from the harvested roots. In about 1930, the Scott-Viner harvester represented one of the first practical machines of this type. Some years later Blackwelder of Rio Vista, California, constructed another type of machine, which for many years became the most favoured single-operation harvester in the West. By means of spikes on the rim of a large

Fig. 2.14 Two designs of horse-drawn implements used during beet harvesting in the UK, *c.* 1931, (a) for loosening the soil around the plants to make pulling out the roots easier, and (b) for lifting sugar beet roots directly from the soil. © DEFRA/The Stationery Office.

Fig. 2.15 Marbeet one-row sugar beet harvester in California (*c.* 1942); sugar beet plants are lifted before topping.

iron wheel, the beets were lifted from the ground and then separated from the tops, which were returned to the field (Fig. 2.15). About 35 single-row machines and 50 two-row machines of this type were already in use in the USA in 1943–1944. In most regions, however, farmers preferred 'ground topping' systems, where machines topped the beet in the ground and subsequently lifted the roots. The trend towards harvest mechanization was accelerated by the active support of some sugar companies, e.g. Spreckels, which hired harvesters to the growers or to contractors equipped with suitable tractors.

After World War II, about 25 different types of beet harvesters were produced in the USA by Blackwelder, John Deere, International Harvester and others. By 1945, 99% of the Californian crop was entirely handled by machinery. By 1949, about half of the beet crop in the USA was mechanically harvested, and by 1952 almost 100%.

In western Europe, technical progress towards harvest mechanization was considerably delayed by the war. In the mid-1950s, however, European engineers invented a wide variety of harvesting machinery. In Germany and Denmark, where most of the sugar beet crops were grown on smaller farms, the trend was towards a single-row harvester, operated by one person. Conversely, in France and Belgium farmers were more interested in multi-row machines, which performed individual stages of the harvesting operation: topping; lifting and accumulating the roots in windrows; and loading. Both techniques, as well as other intermediate ones, reflected farming systems, farm size, and the availability of hand labour and tractors in different countries and regions. Currently the largest harvesters are self-propelled nine-row machines.

FUTURE DEVELOPMENTS

Several issues will influence the beet sugar industry in the future. The revolution in molecular genetics since the mid-1980s will allow greater characterization and understanding of gene function, which will ultimately enable advances in conventional breeding. Novel disease resistance, and other desirable genes will be identified in *Beta* germplasm screening studies, and introgressed into breeding lines and finally into commercial cultivars (Francis & Luterbacher, 2003). Such advances could result in truly low-input, high yielding, pesticide-free sugar beet cultivation. This would be beneficial both to the environment and, depending on the seed price, to growers' incomes.

The issue of GM beet will no doubt continue to be controversial, both from the human health standpoint and over the effects of GMs on the environment. Highly refined sugar is an extremely pure substance that contains neither protein nor DNA, and therefore does not contain the transgenes that have elicited so many alarming health scares (Klein *et al.*, 1998). Herbicide tolerant GM beet (HT beet) is often assumed to have detrimental effects on the environment; however, under certain management regimes non-competitive weeds can remain between the rows of young beets until later in the season (Dewar *et al.*, 2003), or it can allow retention of autumn weeds (May *et al.*, 2004), either of which could have positive environmental outcomes. HT beet may also present a way of controlling weed beets in the crop, and it has economic advantages over conventional sugar beet that could become important if sugar prices decrease (Pidgeon *et al.*, 2004). If it does become more publicly acceptable, GM technology may present ways of tackling previously insoluble problems, e.g. resistance to diseases for which there are no known sugar beet resistance genes, possibly by allowing the transfer of genes from related, but sexually incompatible, *Beta* species. GM techniques, coupled with molecular marker-assisted selection may also allow the transfer of desirable genes into elite germplasm more quickly than would be the case with traditional breeding methods (see also Chapter 4).

Public concern over various issues has led to some demand for organically produced commodities, including sugar. Only a small area of organic sugar beet is currently grown in the world. The crop's main problem is weed control, and another consideration is that it must be segregated and passed through the factory before conventional beets arrive for processing. If the organic beet area increases, it is inevitable that pest and disease problems will be more severe than those encountered at present and new ways of dealing with them will need to be developed. In Europe, the very small market for organic sugar is currently satisfied by cane sugar imports.

Climate change will undoubtedly impact on the sugar beet crop. Changing patterns in precipitation and increasing temperatures may mean that severe water deficits will occur in some beet growing countries (Pidgeon *et al.*, 2001; Jones *et al.*, 2003). The search is already being made for genetic sources of drought tolerance (Ober & Luterbacher, 2002; Ober *et al.*, 2004), with promising initial results. However, where drought is most acute, beet cultivation may eventually be abandoned altogether for economic reasons if the cost of irrigation cannot be recouped. Conversely, new areas may become more suitable for beet cultivation by amelioration of their, at present, unfavourable climates. This could lead to increased yields at higher latitudes. Sugar beet may also expand into areas in the tropics formerly the preserve of sugar cane. In such locations beet has several advantages over cane: it needs 30–70% less water; it has a shorter growing season, which would allow the cultivation of a cash crop afterwards; and it can grow in degraded alkaline or saline soils (Chatin *et al.*, 2004). To this end, India's first beet processing factory is due to open in 2004 and further development work is currently being carried out in Sudan, Pakistan and Kenya (Chatin *et al.*, 2004). The distribution of sugar beet pests and diseases is expected to change in the future because of global warming; those species formerly confined to lower latitudes will advance to higher latitudes. Disease severity might increase if winters are not cold enough to effectively reduce levels of inoculum and pest populations. Finally, if, as predicted, winters in northern European countries become wetter and warmer, higher yielding autumn-sown beet crops may be a possibility. These crops would have their own pest and disease problems due to a 'green bridge' effect with year-round growing of sugar beet. Bolting resistance would also need to be increased in autumn-sown crops to prevent them prematurely running to seed because of vernalization over the winter period.

Perhaps one of the most fundamental changes on the horizon is that a large proportion of beet may not be grown for sugar at all, but will be destined for bioethanol production. In this case, it may be possible to disregard the traditional breeding objectives of high sucrose and low impurity content, and instead select only for high levels of fermentable sugars (Doney & Theurer, 1984). In addition the crowns of beet plants, not currently used in sugar refining for food use, could be utilized to increase the level of sugar for fermentation.

Several crops have been considered as valuable renewable resources offering alternatives to fossil fuels, either as biodiesel or bioethanol. In the group of crops under investigation for liquid biofuel production, sugar beet stands out as the highest yielding one, giving around 5.6 t/ha of bioethanol (Leroudier, 2002). As well as processing the whole roots for fermentation, sugar beet pulp, a residue of sugar refining, can be used as the substrate for ethanologenic recombinant bacteria in ethanol production (Sutton & Doran Peterson, 2001). Bioethanol, which can be mixed with petrol at a 5% incorporation level without engine modifications, would help reduce greenhouse gas emissions as required by the Kyoto Protocol, increase fuel security, and create rural employment. Fledgling beet bioethanol industries are already developing in Europe and the USA. Bioethanol can also be reacted with isobutene to give the alternative fuel ethyl tertiary butyl ether (ETBE).

Political decisions will continue to affect the sugar beet industry, as they have always done. In March 2001, the European Union announced its 'Everything But Arms' initiative that plans duty-free access to imports of all products, including sugar, from the world's 49 least-developed countries with no quantitative restrictions. There is to be a gradual reduction of the duty on sugar to July 2009. It is expected that the EBA initiative will cause a reduction in the European Union's sugar beet area. However, the sugar beet crop offers so many advantages in the areas where it is grown that it is unlikely to be abandoned. It is an effective break crop that reduces pest problems and fertilizer requirements for subsequent cereal crops. It is a rare example of a large-scale spring-sown crop, which means that the cereal stubbles that precede it can be left unploughed throughout the winter providing an invaluable food source for wild life. Its open canopy makes ideal cover for ground-nesting birds, including endangered species such as stone curlews (DEFRA, 2002). Sugar beet is the 'corner stone crop' that has provided high levels of income for farmers and undoubtedly contributed to the maintenance of the rural economies where it is grown.

It is interesting to speculate what Herr Professor Achard would think today if he could see the modern-day industry that he was so instrumental in starting. Would he have imagined that a global industry could be developed using a crop completely unknown to the world only 200 years ago?

REFERENCES

Achard, F.C. (1799) *Ausführliche Beschreibung der Methode, nach welcher bei der Kultur der Runkelrübe verfahren werden muß.* C.S. Spener, Berlin (reprinted: Akademie-Verlag, Berlin, 1984).

Achard, F.C. (1803) *Anleitung zum Anbau der zur Zuckerfabrikation anwendbaren Runkelrüben und zur vortheilhaften Gewinnung des Zuckers aus denselben.* Wilhelm Korn, Breslau (German translation reprinted, 1907, in Ostwald's Klassiker der exakten Wissenschaften No. 159, Engelmann, Leipzig, pp. 14–67).

Achard, F.C. (1809) *Die europäische Zuckerfabrikation aus Runkelrüben, in Verbindung mit der Bereitung des Brandweins, des Rums, des Essigs und eines Coffee-Surrogats aus ihren Abfällen.* J.C. Hinrichs, Leipzig (reprinted: Verlag Bartens, Berlin, 1985).

Anon. (1959) *The Beet Sugar Story.* United States Beet Sugar Association, Washington, DC.

Arrington, L.J. (1966) *Beet Sugar in the West.* University of Washington Press, Seattle.

Bainer, R. (1942) Seed segmenting devices. *Proceedings of the American Society of Sugar Beet Technologists* 3, pp. 216–219.

Baxa, J. & Bruhns, G. (1967) *Zucker im Leben der Völker.* Verlag Bartens, Berlin.

Brown, D. (1995) *The Royal Horticultural Society Encyclopedia of Herbs and their Uses.* Dorling Kindersley, London.

Browne, C.A. (1937) *The Centenary of the Beet Sugar Industry in the United States,* 6th edn. pp. 46–51.

Cai, D., Kleine, M., Kifle, S., Harloff, H-J., Sandal, N.N., Marcker, K.A., Klein-Lankhorst, R., Salentijn, E.M.J., Lange, W., Stiekema, W.J., Wyss, U., Grundler, F.M.W. & Jung, C. (1997) Positional cloning of a gene for nematode resistance in sugar beet. *Science* **275**, 832–834.

Chatin, P., Gokhale, D., Nilsson, S. & Chitnis, A. (2004) Sugar beet growing in tropical areas: a new opportunity for growers and the sugar industry. *International Sugar Journal* **106** (1266), 329.

Coons, G.H., Owen, F.V. & Stewart, D. (1955) Improvement of the sugar beet in the United States. *Advances in Agronomy* **8**, 89–135.

Cottrell, R.H. (ed.) (1952) *Beet-sugar Economics.* Caxton Printers, Caldwell, ID.

Dalechamps, J. (1587) *Historia Generalis Plantarum.* Lugduni.

Deerr, N. (1949) *The History of Sugar*, Vol. 1. Chapman and Hall, London.

Deerr, N. (1950) *The History of Sugar*, Vol. 2. Chapman and Hall, London.

DEFRA (2002) *Sugar Beet and the Environment in the UK.* Department of the Environment, Food and Rural Affairs, London.

Dewar, A.M., May, M.J., Woiwood, I.P., Haylock, L.A., Champion, G.T., Garner, B.H., Sands, R.J.N., Qi, A.M. & Pidgeon, J.D. (2003) A novel approach to the use of genetically modified herbicide tolerant crops for environmental benefit. *Proceedings of the Royal Society of London (Series B)* 270 (1513), pp. 335–340.

de Dombasle, M. (1820) *Faits et Observations sur la Fabrication du Sucre de Betteraves*. Huzard, Paris.

Doney, D.L. & Theurer, J.C. (1984) Potential of breeding for ethanol fuel in sugarbeet. *Crop Science* **24**, 255–257.

Dubrunfaut, P.A. (1825) *L'Art de Fabriquer le Sucre de Betteraves*. Paris.

FAO (1961) *The World Sugar Economy in Figures 1880–1959*. Food andAgriculture Orginization, Rome.

Flood, W.E. (1963) *The Origins of Chemical Names*. Oldbourne Book Co. Ltd, London.

Ford-Lloyd, B.V. & Williams, J.T. (1975) A revision of *Beta* section *Vulgares* (Chenopodiaceae), with new light on the origin of cultivated beets. *Botany Journal of the Linnaean Society* **71**, 89–102.

Foy, M. (1976) *The Sugar Industry in Ireland*. Irish Sugar plc, Dublin.

Francis, S. (2002) 200 years of sugar beet. *British Sugar Beet Review* **70** (3), 32–35.

Francis, S.A. & Luterbacher, M.C. (2003) Indentification and exploitation of novel disease resistance genes in sugar beet. *Pest Management Science* **59**, 225–230.

Gerard, J. (1597) *The Herball or Generall Historie of Plantes*. (reprinted: Studio Editions Ltd, London, 1985).

Gill, N.T. & Vear, K.C. (1980) *Agricultural Botany. 1. Dicotyledonous Crops*, 3rd edn. Duckworth, London.

Harris, F.S. (1919) *The Sugar-beet in America*. Macmillan, New York.

Horsky, F. (1851) *Die vervollkommnete Drillkultur der Feldfrüchte, besonders der Kartoffel und Zuckerrüben aut Erdkämme*. André, Prague.

Jones, P.D., Lister, D.H., Jaggard, K.W. & Pidgeon, J.D. (2003) Future climate impact on the productivity of sugar beet (*Beta vulgaris* L.) in Europe. *Climatic Change* **58**, 93–108.

Klein, J., Altenbuchner, J. & Mattes, R. (1998) Nucleic acid and protein elimination during the sugar manufacturing process of conventional and transgenic sugar beets. *Journal of Biotechnology* **60** (3), 145–153.

Knolle, W. (1940) Erleichterte Rübenpflege durch einkeimigen Samen. *Deutsche Zuckerindustrie* **65**, 611–612.

von Koppy, M. (1810) *Die Runkelrüben-Zucker-Fabrikation in ökonomischer und staatswirtschaftlicher Hinsicht*. Korn, Breslau and Leipzig.

Kühn, J. (1880) Bericht über Versuche zur Rübenmüdigkeit des Bodens und Erforschung der Nematoden (II). *Zeitschrift des Vereins für die Rübenzucker Industrie* **30**, 154–200.

Kuuse, J. (1983) *The Swedish Sugar Company Cardo, 1907–1982*. Cardo, Malmö.

Leroudier, J-P. (2002) Perspectives for the development of bioethanol in the European Union. *Zuckerindustrie* **127** (8), 614–616.

Licht, F.O. (annually) *World Sugar Statistics*. F.O. Licht, Magdeburg and Ratzeburg.

von Lippmann, E.O. (1925) *Geschichte der Rübe (Beta) als Kulturpflanze*. Verlag Springer, Berlin.

von Lippmann, E.O. (1929) *Geschichte des Zuckers*, 2nd edn. Verlag Springer, Berlin (reprinted with annex (1934): Sändig, Niederwalluf, 1970).

Mabey, R. (1996) *Flora Britannica*. Sinclair-Stevenson, London.

de Man, E.F. (1870) *The Beet Root Sugar Question*. William Ridgway, London.

Mannerlöf, M., Lennerfors, B.L. & Tenning, P. (1996) Reduced titer of BNYVV in transgenic sugar beets expressing the BNYVV coat protein. *Euphytica* **90** (3), 293–299.

Mannerlöf, M., Tuvesson, S., Steen, P. & Tenning, P. (1997) Transgenic sugar beet tolerant to glyphosate. *Euphytica* **94**, 83–91.

Marggraf, A.S. (1749) Expériences chymiques, faites dans le dessein de tirer un véritable sucre de diverses plantes, qui croissent dans nos contrées. In: *Histoire de l'Académie Royale des Sciences et Belles Lettres*. Berlin, pp. 79–90.

May, M., Champion, G.T., Dewar, A.M. & Pidgeon, J.D. (2004) Management of weeds, weed seed rain and crop yield in GMHT sugar beet for environmental benefits. *Proceedings of the Royal Society of London*.

McFarlane, J.S. (1971) Variety development. In: Johnson, R.T., Alexander, J.T., Rush, G.E. & Hawkes, G.R. (eds) *Advances in Sugarbeet Production: Principles and Practices*. Iowa State University Press, Ames, pp. 401–435.

McGinnis, R.A. (ed.) (1982) *Beet-sugar Technology*, 3rd edn. Beet Sugar Development Foundation, Fort Collins.

MAF (1931) *Report on the Sugar Beet Industry at Home and Abroad*. Ministry of Agriculture and Fisheries, HMSO, London.

MAF (1935) *Report of the UK Sugar Industry Enquiry Committee*. Ministry of Agriculture and Fisheries, HMSO, London.

MAF (1953) *Sugar Beet Cultivation. Bulletin 153*. Ministry of Agriculture and Fisheries, HMSO, London.

Ober, E.S. & Luterbacher, M.C. (2002) Genotypic variation for drought tolerance in *Beta vulgaris*. *Annals of Botany* **89**, 917–924.

Ober, E.S., Clark, C.J.A., Jaggard, K.W. & Pidgeon, J.D. (2004) Progress towards improving the drought tolerance of sugarbeet. *Zuckerindustrie* **129** (2), 101–104.

Owen, F.V. (1942) Inheritance of cross- and self-sterility and self-fertility in *Beta vulgaris*. *Journal of Agricultural Research* **69**, 679–698.

Pidgeon, J.D., Werker, A.R., Jaggard, K.W., Richter, G.M., Lister, D.H. & Jones, P.D. (2001) Climatic impact on the productivity of sugar beet in Europe, 1961–1995. *Agricultural and Forest Meteorology* **109**, 27–37.

Pidgeon, J.D., Dewar, A.M. & May, M.J. (2004) Can GMHT beet contribute to sustainable crop production in Europe? *International Sugar Journal* **106** (1270), 542–547.

Pillen, K., Steinrücken, G., Wricke, G., Herrmann, R.G. & Jung, C. (1992) A linkage map of sugar beet (*Beta vulgaris* L.). *Theoretical and Applied Genetics* **84**, 129–135.

Savitsky, V.F. (1950) Monogerm sugar beets in the United States. *Proceedings of the American Society of Sugar Beet Technologists* 6, pp. 156–159.

Schacht, H. (1859) Über einige Feinde der Rübenfelder. *Zeitschrift des Vereins für die Rübenzuckerindustrie* **9**, 175–179.

Sevenier, R., Hall, R.D., Van der Meer, I.M., Hakkert, H.J.C., Van Tunen, A.J. & Koops, A.J. (1998) High level fructan accumulation in a transgenic sugar beet. *Nature Biotechnology* **16** (9), 843–846.

Sneep, J., Murty, B.R. & Utz, H.F. (1979) Current breeding methods: sugar beet. In: Sneep, J., Hendriksen, A.J.T. & Holbek, O. (eds) *Plant Breeding Perspectives.* Centre for Agricultural Publishing and Documentation, Wageningen, pp. 203–215.

Souder, E. (1971) A history of US sugar policy. *The California Sugar Beet* (Annual Report of the California Beet Growers Association Ltd, Stockton, CA), pp. 18–20, 34–36.

Speter, M. (1938) Bibliographie von Zeitschriften-, Zeitungs-, Bücher-, Broschüren- u. dgl. Veröffentlichungen Franz Carl Achards. *Deutsche Zuckerindustrie* **63**, 69–74, 152–154, 315–318, 407–409, 592–593.

Sutton, M.D. & Doran Peterson, J.B. (2001) Fermentation of sugarbeet pulp for ethanol production using bioengineered *Klebsiella oxytoca* strain P2. *Journal of Sugar Beet Research* **38** (1), 19–34.

Townsend, C.O. & Rittue, E.C. (1905) *Breeding of monogerm beet seed.* Bulletin no. 73, Bureau of Plant Industry of the US Department of Agriculture, Washington.

Ventzke, K. (1842) Über die verschiedenen Zuckerarten und verwandte Verbindungen in Beziehung auf ihr optisches Verhalten und dessen praktische Anwendung. *Journal für Praktische Chemie* **25**, 65–83.

de Vilmorin, L. (1850) Note sur un projet d'expérience ayant pour but d'augmenter la richesse saccharine de la betterave. *Bulletin des Séances de la Société Impériale d'Agriculture*, 2e série 6, 169.

de Vilmorin, J.L. (1923) *L'hérédité chez la betterave cultivée.* Gauthiers-Villars, Paris.

Walker, H.B. (1942) Trends in sugar-beet field machinery development. *Proceedings of the American Society of Sugar Beet Technologists* 3, pp. 242–251.

Ware, L.S. (1880) *The Sugar Beet: Including a History of the Beet Sugar Industry in Europe.* Henry Carey Baird, Philadelphia.

Chapter 3
Plant Structure and Crop Physiology

George F. J. Milford

INTRODUCTION

The sugar beet plant (*Beta vulgaris* ssp. *vulgaris*) is agriculturally important because of its ability to accumulate a large quantity of sugar in its storage root. It is a halophyte belonging to the Chenopodiaceae, which originates from areas around the Mediterranean. The anatomy and development of the vegetative organs and the storage root were fully described by Artschwager (1926; 1930) – the main stages are shown in Fig. 3.1. Bouillene *et al.* (1940) and Van de Sande Bakhuyzen (1949) divided the vegetative development of the plant into several distinct phases: one of shoot growth, one of storage root growth ('tuberization'), and one of sugar storage ('ripening'). It is now generally accepted that the plant's development is less discontinuous than these distinctions would imply. The early growth of the plant is dominated by the development of the leaf canopy but, very early in this phase, the characteristic secondary rings of the mature storage-root are laid down and start to develop. There is, therefore, a more gradual transition between the early-season shoot-dominated growth (which in temperate climates ends in late July or early August) and the later period of storage-root growth and sugar accumulation which can continue until late November if conditions are favourable and the

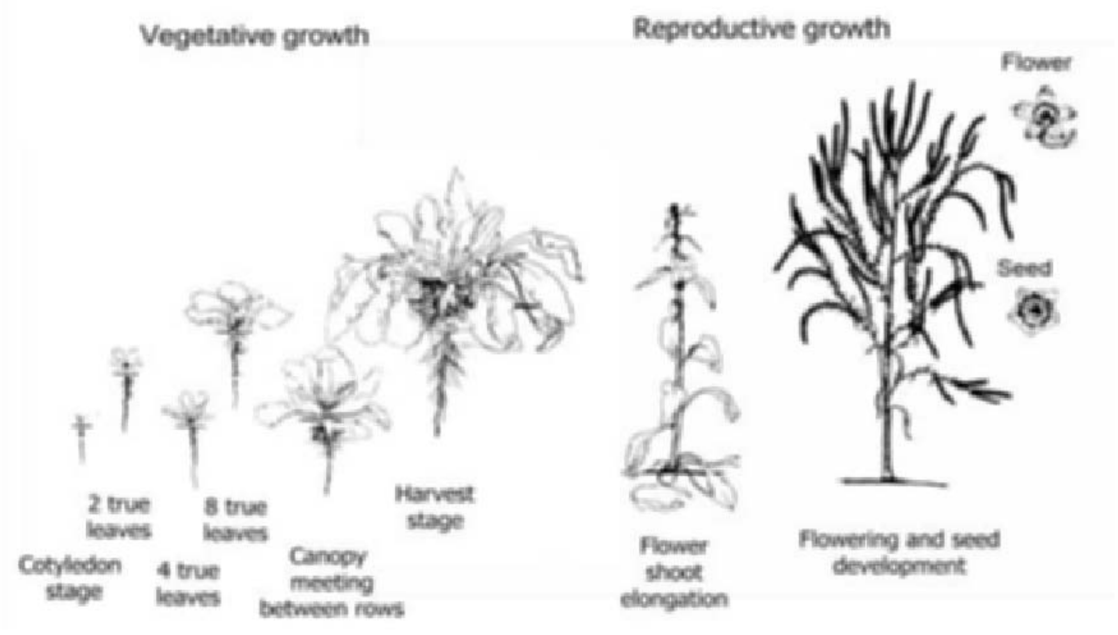


Fig. 3.1 Main features of the vegetative and reproductive growth of the sugar beet plant.

beet are not harvested earlier. There is no stage in the plant's growth when it may, physiologically, be considered to have undergone any 'ripening' process.

Seed germination is epigeal, and seedling establishment leads to the formation of a shoot consisting of a rosette of leaves subtended from a compressed stem in a 5:13 phyllotaxis on erect petioles. In commercial practice, the compressed stem is referred to as the crown; it is distinguished as that part of the beet that lies above the level of the lowest leaf scar. The size of the crown depends very much on the extent of shoot growth and is strongly influenced by genotype, soil type and fertility, seasonal weather and husbandry practices (Milford & Houghton, 1999). The upper part of the storage root itself, is derived from the seedling hypocotyl, and the lower part from the series of secondary cambial rings that are laid down in the root pericycle (Artschwager, 1926). The lower part of the root contains the highest concentration of sugar of about 16–20% on fresh weight and the concentration decreases progressively toward the hypocotyl (about 15%) and the lower (about 13%) and upper (about 7–9%) parts of the crown. The decrease in sugar concentration is accompanied by an increase in concentrations of potassium (K), sodium (Na), α-amino nitrogen (amino N) compounds and invert sugars, all of which interfere with the crystallization of white sugar in the factory (Jaggard *et al.*, 1999; Mahn *et al.*, 2002; see also Chapter 16). The sugar beet plant produces an extensive fibrous root system that, under favourable conditions, is capable of exploiting the soil profile for water and nutrients to 1 m depth by the time the leaf canopy is fully grown and to 1.5 m depth by the autumn (Brown & Biscoe, 1985).

Reproductive development requires a period of cold vernalization to initiate floral development within the shoot's apical meristem, after which the stem elongates as the length of the day increases and branches bearing the flowers are produced. Sugar beet is biennial and vernalized if allowed to over-winter after the first season of vegetative growth, flowering in the following year. However, plants can become vernalized prematurely if the seedling is exposed to cold weather (Wood & Scott, 1974). Partial vernalization can occur if the seed is exposed to cool conditions while still attached to the mother plant (Wood *et al.*, 1979). Premature vernalization causes varieties with a low vernalization requirement to flower and seed ('bolt') in their first year. Modern sugar beet varieties that are suitable for use in temperate climates, where the spring is often cool, have a high vernalization requirement and are largely resistant to bolting. However, many European sugar beet fields became contaminated in the early 1970s with annual types that require no vernalization and have little yield potential. These now constitute a major weed problem in many parts of Europe (Longden & Breay, 1995), discussed in Chapter 14.

Canopy development and dry matter production

Most sugar beet crops are sown in spring in Europe and the beet are lifted at the onset of winter for delivery to factories for sugar extraction. In Mediterranean climates, where the winter is mild and wet, the crops may be sown in autumn and harvested before the onset of the hot dry summer. Most modern crops are grown from monogerm seed, drilled to a stand in rows that are 45–55 cm apart using precision drills, the aim being to achieve uniform stands of at least 80–100 000 plants/ha. Typical modern commercial sugar beet yields are between 50 and 100 t clean beet/ha with sugar concentrations of 17–18% on fresh weight, yielding 8–18 t sugar/ha. The seasonal patterns of production and distribution of dry matter in sugar beet are relatively consistent, with much of the dry matter being in the shoot during early growth and in the storage root at harvest – when the majority of the dry matter is present as sugar (Scott & Jaggard, 1993). However, the exact proportions of the total dry matter that are allocated to the storage root and to stored sugar are influenced considerably by harvest date, genotype, nitrogen fertilizer, plant density, soil type and seasonal weather – especially occurrence of drought at critical stages of crop growth (Bell *et al.*, 1996). These factors can cause the proportion of crop's total dry matter allocated to the storage root to vary from 47 to 77%, and the proportion of sugar in storage-root dry matter from 72 to 78% (Table 3.1).

Table 3.1 Genotypic differences and effects of site, season and agronomic practices on partitioning of total crop dry matter (DM) to the storage root and on the concentrations of sugar in the storage root in fresh (FW) and dry matter (DM).

Factor	Root DM % of total DM	Sugar % of root DM	Sugar % of root FW	Reference
Genotype	47.1–57.9	73.1–76.6	14.1–16.9	Loach (1970)
	63.8–77.3	66.7–69.9	12.2–16.7	Follet *et al*. (1970)
Site/season	53.3–68.5	59.9–75.2	13.6–17.4	Goodman (1963)
	60.9–71.6	72.2–74.7	–	Last & Draycott (1975)
Plant density	60.1–68.4	71.6–75.0	18.2–18.6	Harris (1972)
	63.1–68.0	74.7–75.1	16.0–17.1	Draycott & Webb (1971)
Drought	61.2–63.0	72.4–74.4	18.0–18.9	Harris (1972)
	72.5–77.3	72.8–75.9	16.5–18.6	Brown *et al*. (1987)
Nitrogen fertilizer	58.4–76.0	62.0–70.1	16.4–19.3	Carter & Traveller (1981)
	63.5–75.1	68.4–71.4	16.0–17.7	Follet *et al*. (1970)
	63.1–75.1	74.7–75.7	16.0–17.7	Draycott & Webb (1971)
Potassium fertilizer	66.1–67.7	71.9–72.7	16.8–17.1	Farley & Draycott (1974)
Sodium fertilizer	66.1–69.4	72.0–72.7	16.7–17.1	Farley & Draycott (1974)
Season/genotype	63.0–83.9	72.0–78.0	17.3–18.9	Scott & Jaggard (1993)

Leaf canopies and radiation interception

The crucial relationships between patterns of leaf area development and seasonal radiation receipts that limit yields of spring-sown sugar beet in the UK were recognized over 50 years ago by Watson (1952). He showed, for instance, that daily radiation receipts were at their maximum at 15–25 MJ/m^2/day in mid-June, whereas very few commercial crops had produced sufficient leaf area to intercept it fully before late July or early August. This finding led directly to development of bolting-resistant varieties that could be sown early enough to advance growth of the canopy to intercept more of the seasonal radiation (Campbell & Russell, 1965). The result is that sugar beet is now sown between mid-March and mid-April in the UK compared with mid-May 50 years ago.

The basic physiological principles of interception and conversion of solar radiation that govern production of dry matter and sugar in sugar beet in the UK were more directly formalized by research done at Broom's Barn Research Station in Suffolk in the early 1980s. This work showed that yields of sugar beet crops in the UK were proportional to the amount of solar radiation intercepted by foliage during the growing season (Fig. 3.2; Scott & Jaggard, 1978; Milford *et al*., 1980), Fig. 3.3 demonstrates the physiological basis of the relationship.

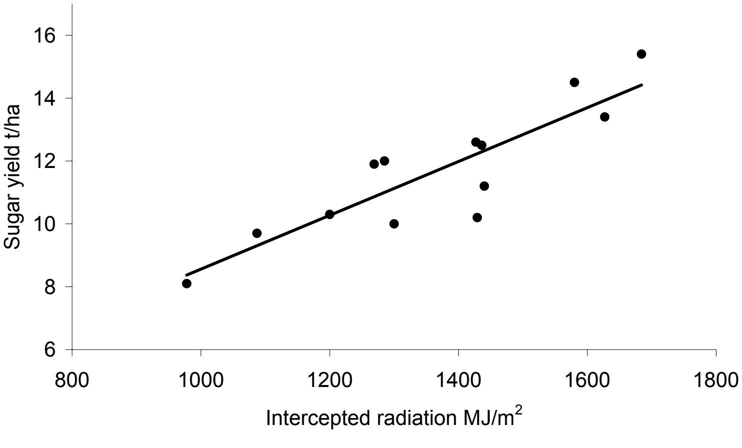


Fig. 3.2 Relationship between sugar yield and the quantities of solar radiation intercepted during the growth of a series of standard, irrigated sugar beet crops grown at Broom's Barn Experimental Station, Suffolk, UK, between 1978 and 1990 (after Scott & Jaggard, 1993).

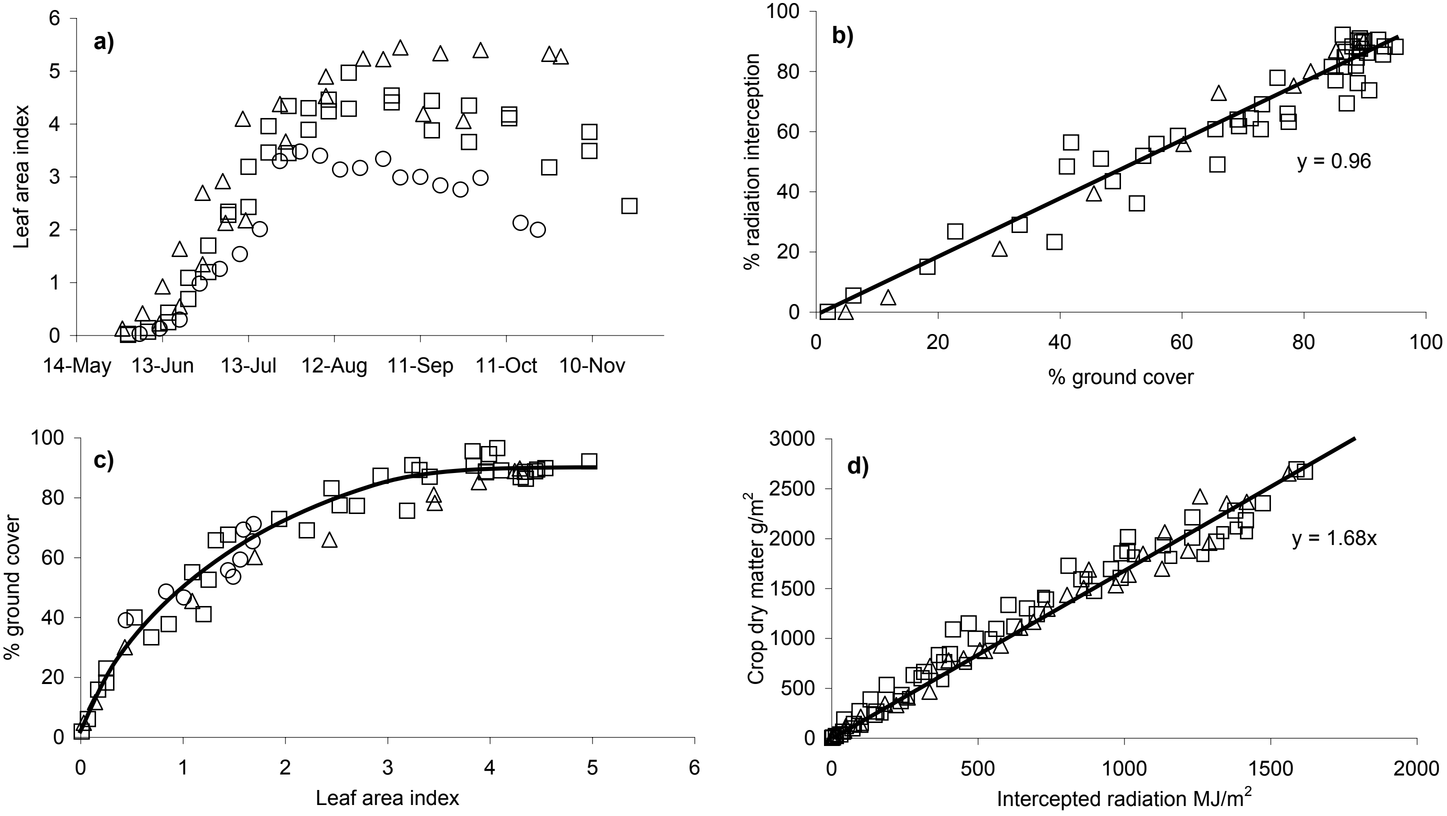


Fig. 3.3 The seasonal patterns of leaf area index (a) and relationships between radiation interception and the percentage of ground covered by the foliage (b), ground cover and leaf area index (c), and the production of dry matter and radiation interception (d) on soils of low (○), average (□) and high nitrogen fertility (△) in the UK.

The seasonal patterns of leaf area index (LAI, the ratio of leaf area to ground area) for a series of crops grown with differing soil nitrogen fertility are shown in Fig. 3.3a. In these, maximum LAI ranged from about 3 with little nitrogen to just over 4 in adequately-fertilized crops, and well over 5 under very fertile conditions. The proportion of incident radiation intercepted by these crops was directly proportional (1:1 ratio) to the percentage of ground covered with leaf (Fig. 3.3b). Ground cover is measured easily with spectral ratio meters, which use red and far-red wavelengths of the radiation spectrum to distinguish between green leaves and soil (Steven *et al.*, 1986). The percentage of ground area covered by leaf increased asymptotically with LAI, and was maximal when LAI was greater than 3, irrespective of site and season (Fig. 3.3c) meaning that light interception was also asymptotically related to LAI. Finally, the total amount of dry matter produced increased linearly with the amount of radiation intercepted during each period of growth and over the season as a whole (Fig. 3.3d).

Thus much of the variation between seasons and locations in dry matter yields of well-fertilized, irrigated, healthy crops can be attributed to differences in energy capture. Irrespective of site and season, different crops produce similar amounts of dry matter per unit of intercepted radiation (i.e. 1.7–2.0 g of dry matter per MJ of total radiation or 3.4–4.0 g dry matter per MJ of photosynthetically active radiation). The main factors likely to decrease these conversion ratios for absorbed energy to dry matter are drought and disease, especially virus yellows (Clover *et al.*, 1999a,b).

Factors affecting expansion of leaf area

Sugar beet crops need to achieve a minimum LAI of 3.0 to maximize interception of incident radiation and, in northern latitudes, this leaf area needs to be produced by mid-July when solar radiation receipt is at or near its seasonal peak. The size and longevity of sugar beet leaf canopies varies greatly with season and location, and is strongly influenced by soil moisture, soil fertility and husbandry practices (Figs 3.3 and 3.4; Watson, 1952; Goodman, 1968). Canopies of commercial crops have been estimated to expand at a rate of 0.5–1.0 units of LAI for each 100°C day units of thermal time that are accumulated after sowing – the actual rate depending upon nitrogen supply and water status of soil (Milford *et al.*, 1985b).

Differences in the rates of expansion of leaf canopies originate in the rates at which individual leaves are produced and expand, their final size, and the rates at which they die. The plant's shoot meristem continues to produce new leaves for as long as it remains in a vegetative state, at a rate that is primarily regulated by temperature. A new leaf appears every 30°C day units of thermal time above 3°C, and this rate is not greatly affected by water or nutrient supply (Milford *et al.*, 1985a). Therefore, differences in the growth rate and final size of leaf canopies are largely due to differences in the growth rate and final size of individual leaves rather than to differences in leaf number (Milford *et al.*, 1985c).

There is a progressive increase in area and weight of the lamina and in the length and weight of the petiole of the successive early leaves that are produced by the plant, but a point is reached beyond which leaves subsequently grow progressively smaller (Bouillene *et al.*, 1940; Clark & Loomis, 1978; Milford *et al.*, 1985b). The increase in size of the early-produced leaves is due to a progressive increase in the number of cells within each leaf, even though this increase in cell number is accompanied by a progressive decrease in the average size of the cells. In terms of cell number, the small later-produced leaves have the same potential for growth as the larger leaves that precede them in the sequence but they remain small because their cells have limited growth (G.F.J. Milford, 1988, unpublished data). The mechanisms that regulate these differential rates of cell division and cell expansion in successive leaves are not fully understood.

The plant's early leaves usually die in the order in which they were produced, and LAI becomes maximal soon after the largest leaf completes its expansion (Milford *et al.*, 1985c). Rapid leaf growth requires adequate supplies of nitrogen, water and warm temperatures, all of which influence the size of the largest leaf and its position in the leaf sequence. This is illustrated by the leaf profiles shown in Fig. 3.4a of the series of sugar beet crops that were grown under different climate and soil

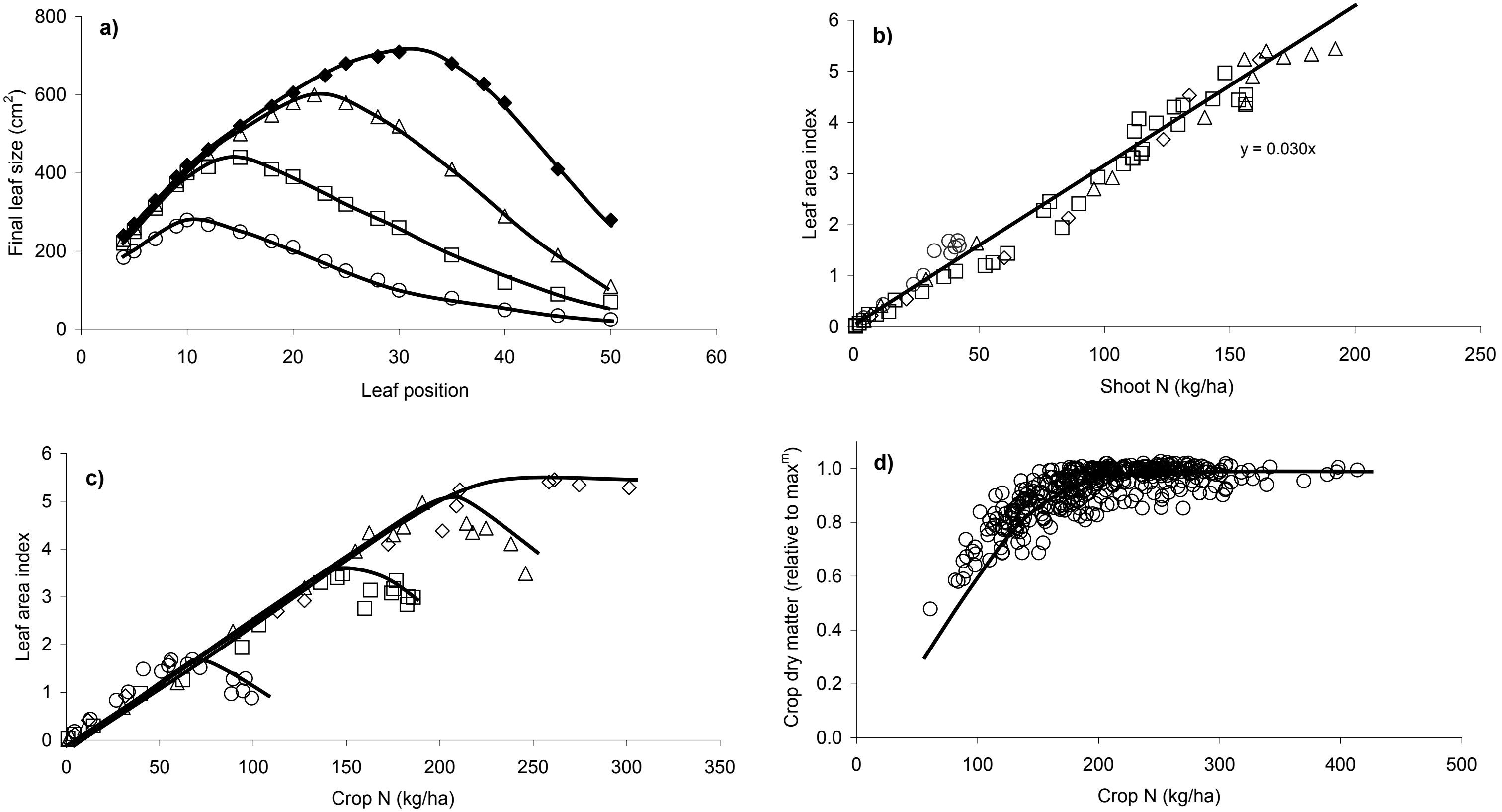


Fig. 3.4 Leaf area profiles of individual leaves (a) and the relationships between leaf area index and shoot nitrogen (b), leaf area index and crop nitrogen (c), and dry matter production and crop nitrogen (d) for sugar beet grown on soils of low (○), average (□) high (△) and very high nitrogen fertility (◇) in the UK, and at low density with irrigation on highly fertile soils and under extremely favourable climatic conditions in California, USA (◆).

fertility conditions in the UK and in California, USA. A lack of nitrogen during early growth restricts leaf growth and causes the largest leaf to be produced much earlier in the sequence than when plants have access to adequate nitrogen and all leaves remain relatively small. Also, as Milford and Riley (1980) showed, early-produced leaves generally grow smaller if temperatures are cool before they unfold from the shoot apex and large if temperatures are warm. Very high nitrogen uptakes encourage leaves to grow very large and the largest leaf to occur much later in the leaf sequence (Jaggard *et al.*, 1981; Milford *et al.*, 1985b). Extremely large leaves and leaf canopies are produced when crops are subjected to ideal growing conditions, such as those grown by Clark and Loomis (1978) at low density and with irrigation under the warm and fertile conditions of California, USA.

Under European conditions, however, the availability of nitrogen in the soil and its uptake by the crop appear to exert the greatest effect on leaf growth. LAI in UK sugar beet crops increased linearly with the amount of nitrogen in the shoot (Fig. 3.4b), and maximum LAI increased linearly with the amount of nitrogen in the crop (Fig. 3.4c). During the linear phase of leaf area expansion the shoot required about 30 kg N/ha to produce one unit of LAI (Fig. 3.4b). Crops also needed a minimum of 100 kg N/ha to produce a leaf canopy sufficient to meet between the rows and fully intercept incident solar radiation (Malnou *et al.*, 2003). Overall, the crops required a total uptake of about 220 kg N/ha for maximum dry matter production (Fig. 3.4d). The relationships between crop nitrogen uptake and the yields of clean beet and sugar are considered later.

The length of the early leaf growth phase and final size of the leaf canopy greatly influence the distribution of dry matter between shoot and storage root. An extension of the leaf growth phase increases the shoot:root ratio at harvest and decreases the proportion of the crop's total dry matter that is present in the storage root as sugar. The effect is particularly noticeable when the uptake of nitrogen from the soil is prolonged, either through late applications of fertilizer or continued mineralization of nitrogen from soil organic matter (Houba, 1973). Much of the site-to-site and year-to-year variation in shoot growth, and the subsequent shifts in dry matter partitioning between shoot and storage root shown by the values in Table 3.1, can be explained by differences in plant population, the availability of water, and the dynamics of nitrogen uptake (Milford *et al.*, 1988).

The physiological concepts outlined have formed the basis of models that simulate the growth of sugar beet crops. These have been used to predict regional and seasonal yields and forecast the effects of drought and predict the effects of climate change (Spitters *et al.*, 1989; Werker *et al.*, 1995; Werker & Jaggard, 1997; 1998; Pidgeon *et al.*, 2001; Richter *et al.*, 2001; Launay & Guérif, 2003). See also Chapter 7.

STORAGE ROOT DEVELOPMENT AND SUGAR ACCUMULATION

Storage root development

The developmental anatomy of the storage root of sugar beet was first described by Artschwager (1926) and more recently by Pocock (in Elliott & Weston, 1993). The storage root is an organ of potentially unlimited growth. Its conspicuous ringed structure in transverse and longitudinal section (Fig. 3.5) is the result of the continued cell production and enlargement from a series of concentric, secondary cambia that originate within the pericycle of the primary taproot. The six to seven cambia that produce the bulk of the harvested storage root are laid down within the pericycle at a very early stage of seedling development – usually by the sixth-leaf stage. Although several more peripheral, secondary cambia subsequently form outside these rings, they contribute little to the overall growth of the storage-root (Artschwager, 1926). The inner six to seven cambial rings develop simultaneously, not sequentially, through the continued production of new cells thus surrounding the adjacent vascular tissues with zones of small-celled parenchyma. As more cells are produced and the older cells expand, these small-celled cambial/vascular zones become separated by wide central zones of large-celled parenchyma (Milford, 1973).

Various attempts have been made to correlate genotypic differences in sugar concentration with

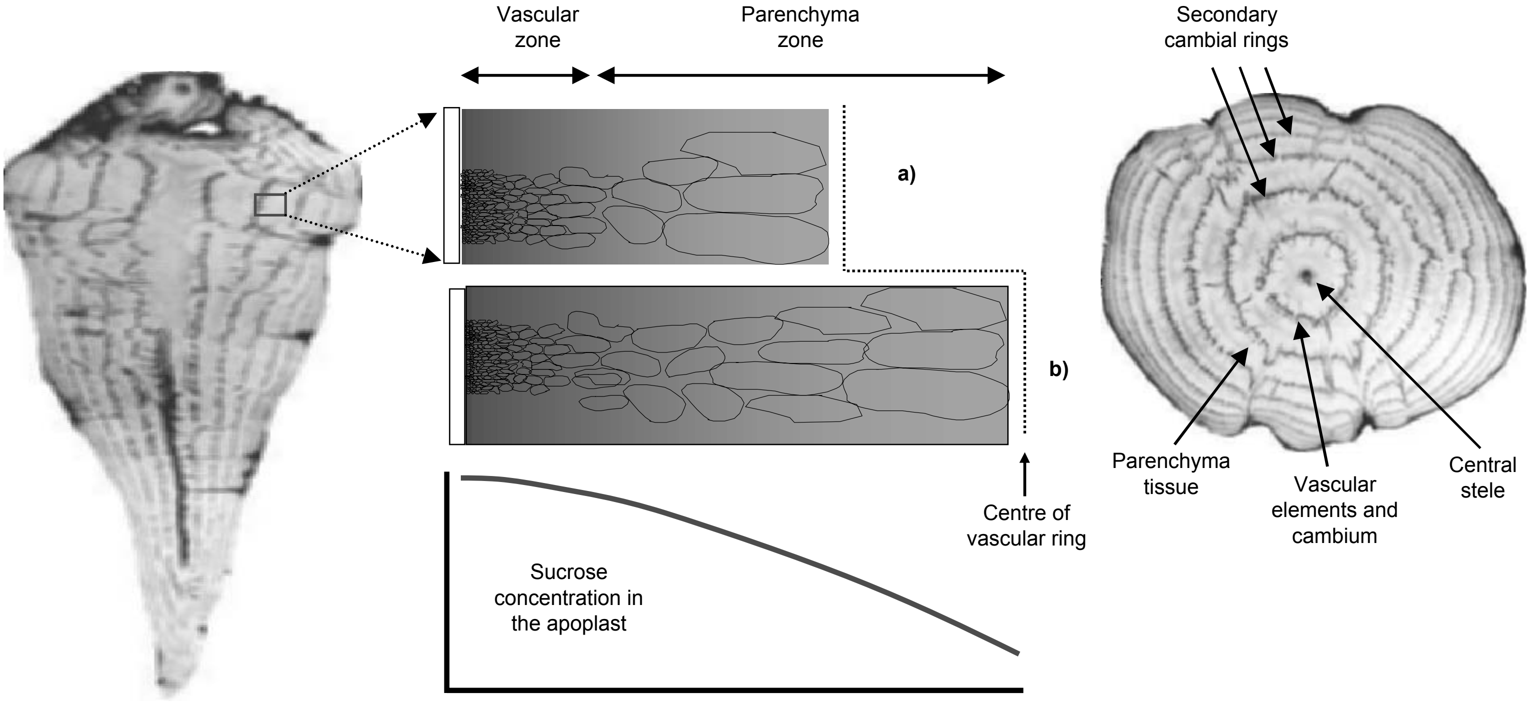


Fig. 3.5 Longitudinal and transverse views of the secondary structure of the sugar beet storage root and a diagram of the sucrose-gradient hypothesis of sugar accumulation in (a) a high sugar concentration beet and (b) a high yield beet (after Wyse, 1979a; Bell *et al.*, 1996).

particular anatomical or morphological characteristics of the storage root, largely with the aim of developing selection criteria for use in plant breeding. For instance, sugar concentrations have been inversely correlated with root yield (Artschwager, 1930) and positively correlated with the density of cambial rings within the radius of the root (Pack, 1927; 1930). Similarly, inverse correlations between root yield and sugar concentration have been shown between varieties and for crops grown with differential amounts of nitrogen. Crops that are well supplied with nitrogen tend to produce larger yields of beet containing a lower concentration of sugar than crops grown with less nitrogen (Draycott & Christenson, 2003). The next section considers the physiological basis of these correlations.

Sugar accumulation

The biochemistry of sugar production in the shoot and the physiology of its transport to the storage root, and the biophysical mechanisms that regulate sugar uptake in storage-root cells are not considered here because they have been comprehensively reviewed elsewhere (Elliott & Weston, 1993; Bell *et al.*, 1996).

Ulrich (1952; 1955) observed that sugar concentration was increased by factors that slowed or restricted overall growth of the plant (such as low night temperature or nitrogen deficiency) and concluded that the sugar accumulated by the storage root was merely the excess assimilate that was not required for the growth of the plant. Subsequent experiments failed to substantiate this. Watson *et al.* (1972) decreased photosynthate supply by shading field crops, Milford and Thorne (1973) did so by lowering light intensities in controlled environments, and Wyse (1980) increased the photosynthate supply in field crops by raising the carbon dioxide concentration of the surrounding air. All of the treatments altered the total amounts of assimilate allocated to the storage roots, and so affected their size. Some increased the fresh-weight concentrations of sugar but only by decreasing beet water content. None of the treatments changed the ratio with which the assimilate entering the storage root was partitioned between sugar and non-sugar dry-matter. The studies clearly showed that mechanisms operated over a wide range of photosynthate supply within the storage root to balance the usage of assimilate between storage root growth and sugar storage.

Milford (1973; 1976) showed that concentration of sugar in beet tissues increased proportionally with the mean volume of the cells of which the tissues were composed – but the relationship was linear only up to a particular size, beyond which, less sugar was accumulated per unit of cell volume. On the other hand, the amounts of water and non-sugar dry matter per cell both increased proportionally with cell volume over the whole size range. Because the surface area of cells increases more slowly than volume, these relationships imply that the cell wall thickens as cells enlarge. The largest cells in the storage root are located in central parenchyma zones that separate adjacent cambial/vascular rings and it has been shown that these cells do, indeed, have lower fresh- and dry-weight concentrations of sugar than the small-celled parenchyma of the vascular zones (Winner & Feyerabend, 1971; Milford, 1976; Doney *et al.*, 1981). Wyse (1979a) proposed the sucrose-gradient hypothesis, illustrated in Fig. 3.5, as a mechanism to explain these findings.

According to this hypothesis, sucrose enters the storage root via the phloem (Giaquinta, 1979), is transported within the apoplast (Richter & Ewald, 1983), and is stored in the vacuoles of the undifferentiated parenchyma cells without being hydrolysed to glucose and fructose prior to transport across cellular membranes. This contrasts with the situation in sugar cane where sucrose is hydrolysed before it is transported into the cell vacuole and then reconstituted (Giaquinta, 1977). Sucrose uptake by sugar-beet storage-root cells remains more or less linear and positively correlated with the concentration outside the cell over the range 0.5–500 mM (Wyse, 1979b). In each of the storage-root's secondary rings, the cambium is embedded within the vascular zone. This means that the small, most recently produced parenchyma cells that lie within the vascular zone have high concentrations of sucrose within their apoplast and hence large uptakes of sucrose. As cells enlarge more sucrose needs to be taken up into their vacuoles to compensate for the increase in vacuole volume. However, enlargement moves cells further from the cambium, causing the diffusion pathway for sucrose from the phloem to lengthen and the concentration of sucrose in the surrounding apoplast to decrease as sucrose is taken up by upstream cells. The result is that both the fresh and dry weight sucrose concentrations of the large-celled tissues of the central parenchyma zone of each ring are consistently smaller than concentrations in the small-celled tissues of the adjacent cambial/vascular zone.

Factors that increase the overall size of the storage root cells, especially that of cells of the central parenchyma zone of each ring, increase root size and the distance between vascular rings, and decrease the overall sugar concentration of the storage root (especially if cell number remains relatively constant). Several factors, e.g. genotype, soil fertility, the availability of water, nitrogen supply and plant population density, have been shown to influence the cell size in the storage-root (Milford & Watson, 1971; Milford, 1973; 1976). Therefore, many of the correlations between root weight, ring density and sugar concentration reported in the literature for different genotypes or for crops grown on different soil types, with different agronomy or with fertilizer inputs can be traced directly back to the changes in storage-root morphology brought about by the effects of those factors on cell growth.

The sugar-gradient hypothesis has a noteworthy implication. This is that differential sugar concentrations develop along the diffusion pathway, especially between the small cells closest to, and the large cells furthest from, the vascular zone (Hayward, 1938; Zamski & Azenhot, 1981). These need to be balanced by other osmotic solutes to maintain the osmotic balance of the tissues. Cressman (1969) showed that the tissues of central parenchyma zones of the storage root do indeed contain higher concentrations of potassium (K) and sodium (Na) than the vascular zones. This is the probable explanation of the negative correlation observed by Alexander (1971) between beet sugar concentration and the concentrations of major processing impurities such as potassium, sodium and amino nitrogen in commercially grown beet. Readers are referred to Bell *et al.* (1996) for a recent, in-depth review of the interactions between sugar and other non-sugar solutes in the osmotic and turgor relations of the developing sugar beet storage root.

NUTRITIONAL PHYSIOLOGY AND BEET QUALITY

This section is devoted to the uptake, distribution and physiological use of nitrogen, potassium and sodium by the sugar beet crop and their roles in beet quality. The main characteristics of high quality beet are large concentrations of sugar and small concentrations of amino nitrogen, potassium and sodium relative to sugar. The quality of delivered beet greatly affects the efficiency and economics of the factory process (Carruthers & Oldfield, 1961; Alexander, 1971; Kubadinow & Hampel, 1975; Devillers, 1983; Harvey & Dutton, 1993), and several formulae and indices have been developed that weight the impurities in beet according to their influence on factory operations and the extractability of white, crystalline sugar (Carruthers & Oldfield, 1961; Wieninger & Kubadinow, 1971; Reinefeld *et al.*, 1974; Buchholz *et al.*, 1995; Huijbregts, 1999). It is important for the stability of factory juices that the concentrations (which are converted to acids during processing) of amino nitrogen is also suitably balanced by the combined concentrations of alkaline cations such as potassium and sodium, but the processes by which the natural alkalinity of the beet is regulated in the growing crop are still poorly understood. There is much genetic variability in many of the beet quality attributes, and a considerable influence of environmental and agronomic factors, especially on the concentrations of amino nitrogen and sodium (Bosemark, 1993). See also Chapter 16.

Nitrogen relations

Beet sugar concentrations are decreased and amino nitrogen concentrations increased when crops take up large quantities of nitrogen from soils that naturally contain much available mineral nitrogen or as a consequence of large inputs of fertilizer or manure (Carter *et al.*, 1976; Draycott & Christenson, 2003). Sugar and amino nitrogen concentrations are also affected by other site-related factors

(Märländer, 1991), such as extremes of weather (e.g. drought during growth or heavy rain immediately before harvest), by plant population density (Campbell, 2002) and by diseases such as virus yellows and rhizomania (Van der Beek & Huijbregts, 1986; Asher, 1993). Consequently, the concentrations of sugar and amino nitrogen in delivered beet are usually negatively correlated (Shore *et al.*, 1982; Palmer & Casburn, 1985). Factory tarehouse measurements of amino nitrogen on delivered beet have been used, with some success, to identify and advise upon the overuse of nitrogen in fertilizers and manures by growers (Dutton & Turner, 1983; Marcussen, 1985).

The work of Pocock *et al.* (1990) on how the sugar beet crop partitions the nitrogen that it takes up to amino nitrogen in the harvested beet has recently been confirmed by data from a more extensive 4-year series of nitrogen-response trials on a wide range of conventionally-fertilized and manured sugar beet crops grown over on different soil types in the UK (Fig. 3.6). These studies confirmed that uptake of nitrogen by the crop increased linearly with the total amount of available mineral nitrogen in the soil (i.e. residual nitrogen from preceding crops, added nitrogen from fertilizers and manures, and nitrogen mineralized from soil organic matter during the growth of the crop; Fig. 3.6a). Maximum yields of sugar were consistently achieved with a crop uptake of about 220 kg N/ha and were decreased when nitrogen uptakes were larger than optimal (Fig. 3.6b), primarily because the excessive nitrogen decreased sugar concentration. The analysis also showed that storage-root nitrogen increased linearly with the total amount of nitrogen taken up by the crop, with more being apportioned to the storage root in heavily manured than conventionally fertilized crops (Fig. 3.6c). Finally, the amount of amino nitrogen in the storage root increased exponentially as the total amount of nitrogen in the storage root increased especially when the crop's uptake of nitrogen exceeded that required for maximum sugar yield. The increase in amino nitrogen was exceptionally large in manured and drought-affected crops (Fig. 3.6d).

Glutamine and asparagine are the main constituents of the amino nitrogen fraction in the storage root (Burba *et al.*, 1984). Amino nitrogen compounds constitute 40% of the total soluble nitrogen in beet, and glycine betaine a further 30% (Mahn *et al.*, 2002). It is generally accepted that the accumulation of amino nitrogen compounds reflects an enlargement of the organic-nitrogen storage pools within the plant when the uptake of nitrogen from the soil exceeds the requirement for growth (Burba *et al.*, 1984). The overall increase in amino nitrogen when crop uptakes exceeded 220 kg N/ha, or growth was curtailed by drought or disease (Fig. 3.6d) is consistent with this interpretation. Some authors consider that glycine betaine acts as an osmotic regulator within the cytoplasm to counteract the large osmotic shifts in the vacuole that occur as a consequence of the accumulation of sugar and other solutes during normal development or as the consequence of drought or salinity (Hansen & Wyse, 1982; Beringer *et al.*, 1986). Others consider glycine betaine to be merely another form in which the plant stores its accumulated nitrogen (Leigh *et al.*, 1995).

Potassium and sodium

Potassium is the main osmoticum in most plant cells and as such plays a major biophysical role in the maintenance of turgor, stomatal control and regulation of plant water content (Hsaio & Läuchli, 1986). Potassium also has biochemical functions in the cytoplasm involving the activation of numerous enzymes (Wyn Jones & Pollard, 1983). In cereals, critical sap concentrations of 120–150 mM have been quoted for the osmoregulatory role of potassium and 50 mM for its biochemical functions (Barraclough & Leigh, 1993).

Commercial sugar beet cultivars (*Beta vulgaris* ssp. *vulgaris*) are halophytes descended from wild forms of *Beta vulgaris* ssp. *maritima* that evolved mechanisms of salt exclusion or toleration to allow them to colonize saline habitats of tidal seashores and coastal marshlands. Consequently, commercial sugar beet have retained the ability to use sodium to regulate osmotic concentration alongside potassium. At one time, it was thought that sodium was completely interchangeable with potassium in sugar beet (Marschner, 1971), but it is now evident that the two differ in some of their physiological roles. Sodium, for instance, is largely restricted to the shoot and is a relatively minor constituent of the storage root; it is largely immobile within the plant

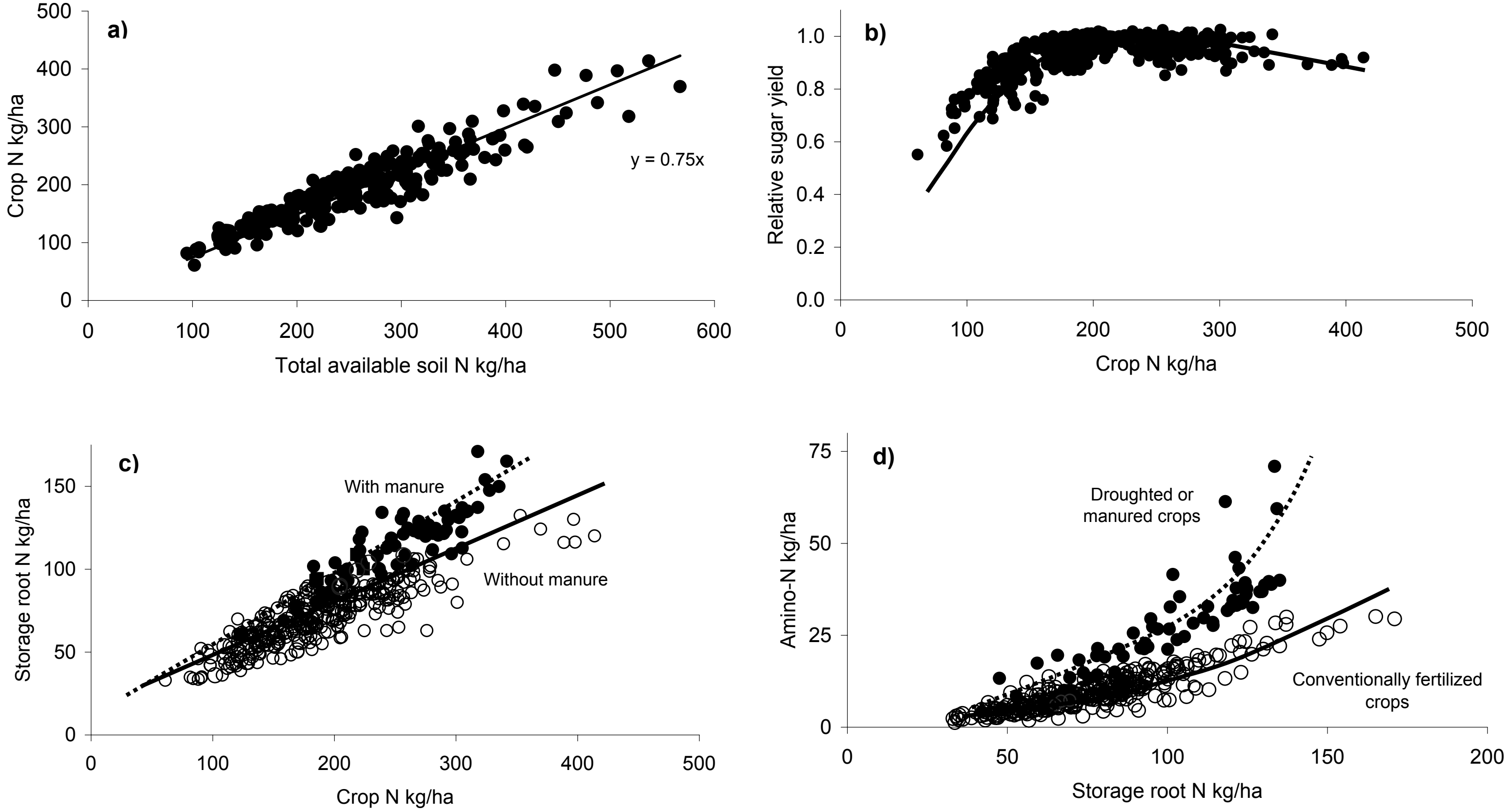


Fig. 3.6 Relationships between crop nitrogen uptake and the total amount of available soil nitrogen during growth (a); the relative yield of sugar and crop nitrogen (b); storage-root nitrogen and crop nitrogen (c) and amino nitrogen and storage-root nitrogen (d) in sugar beet crops grown under a wide range of soil fertility in the UK.

and, unlike potassium and nitrogen, very little is relocated to the storage root as leaves senesce and die (Bürcky *et al.*, 1978; Bürcky & Biscoe, 1983). On the grounds that the primary role of sodium in higher plants is to replace some of the functions of potassium, Subbarao *et al.* (2003) classify sodium as a 'functional' rather than 'essential' element in plant growth.

Many workers have examined the relationships between yield and applied potassium and demonstrated significant agronomic yield interactions between potassium and applied nitrogen (Loué, 1985). In the UK alone, over 600 experiments testing the effects of potassium and sodium fertilizers were done between 1934 and 1974 (Draycott & Durrant, 1976; Durrant *et al.*, 1979). Because such trials needed to be done on many sites differing in soil type to obtain the necessary differences in exchangeable soil potassium, it was difficult to establish definitive relationships between the concentrations of exchangeable potassium in the soil and its uptake by sugar beet, and between soil potassium and yield. Therefore, yield response curves for potassium for different soils have usually been defined in terms of the responses to the amounts of potassium applied as a fertilizer rather than to concentrations present in the soil (Draycott & Durrant, 1976).

Relatively few of these field experiments considered the physiological basis of yield responses to potassium, the interactions between potassium and nitrogen, or the inter-changeability of potassium and sodium. When relationships between yield and plant potassium and sodium were considered, they were largely confined to their dry matter concentrations. Working with cereals, Leigh and Johnston (1983) and Barraclough and Leigh (1993) showed that better physiological insights into critical nutrient concentrations for growth and yield could be obtained by expressing the concentrations of soluble ions, such as potassium and sodium, on the basis of the plant's tissue water rather than its dry matter.

This physiological, tissue-water approach has recently been applied to sugar beet crops to develop ways of using routine factory tarehouse measurements of potassium concentrations in delivered beet to provide feedback on the nutrient status of the fields on which the beet was grown. Jarvis *et al.* (2003) showed that tarehouse measurements of potassium provide an accurate estimate of the amounts of potassium removed in delivered beet that have to be replaced to maintain the long-term fertility of the fields. In other work, two fields at Rothamsted Research (one having a sandy loam, the other a silty clay loam) that contained experimental plots with a wide range of long-established differences in exchangeable soil potassium concentration were used to show that the concentration needed to achieve maximum sugar yield was similar (about 120 mg K/kg soil) on both soil types and varied little between seasons (Fig. 3.7a). Other measurements showed that the critical shoot tissue-water concentration of potassium for maximum yield was 280–300 mmol/kg tissue-water (for simplicity, such concentrations are hereafter referred to as millimolar concentrations, mM). Sodium could partially substitute for potassium when soil potassium was limiting – although when both elements were readily available, the plant used potassium in preference to sodium. The corresponding critical tissue-water concentration of potassium in the storage root for maximum sugar yield was about 40 mM (Fig. 3.7b). It should be remembered that, in the storage root, sugar is the primary osmotic solute and little sodium is present. Because existing tarehouse measurements allow the water content of beet to be estimated indirectly, it has been suggested that it should be possible to develop physiological methods of monitoring the potassium status of growers' crops and soils based on the concentrations of potassium in the tissue-water of the delivered beet (Jarvis *et al.*, 2003).

REPRODUCTIVE DEVELOPMENT

Physiological and agronomic aspects of bolting

Environmental factors that influence the time of flowering are vernalization (exposure to a long period of cold), photoperiod (day length), light quality (spectral composition), and the light quantity (photon flux density). Flowering is also accelerated by nutrient and water stresses and by overcrowding. Light and temperature are perceived by dif-

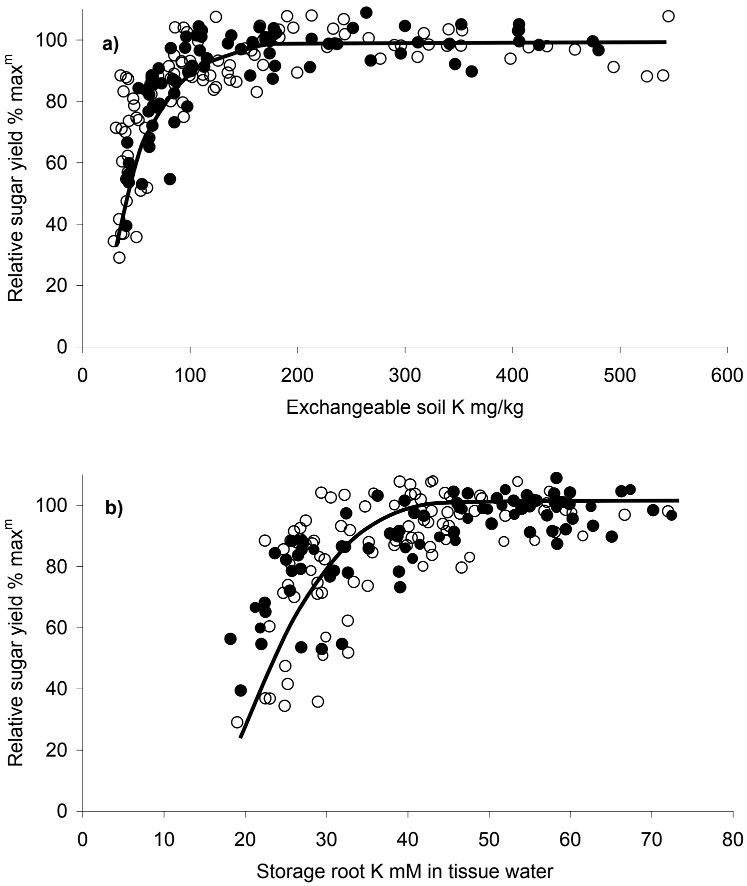


Fig. 3.7 Relationships between the relative yields of sugar and the concentrations of exchangeable potassium in the soil (a) and potassium in beet tissue water (b) for crops grown on plots on sandy (○) and silty clay (●) loam soils in the UK with long-established differences in soil potassium.

ferent parts of the plant – photoperiod and irradiance are perceived mainly by mature leaves, and low temperature vernalization by the shoot apex (Bernier *et al.*, 1993). Vernalization is a reproductive strategy adopted by many species, and bred into many crops to ensure they over-winter in a vegetative state and flower under favourable conditions in spring. Vernalization prepares the plant to flower rather than evoking flowering itself, and there is often a clear temporal separation between the cold treatment and the actual flowering process (Simpson & Dean, 2002).

Cultivated sugar beet varieties are normally biennial and have to be vernalized by exposure to a period of cool temperature for the shoot apex to become floral. Although they can become vernalized under short-day conditions, sugar beet are essentially long-day plants. They require long days to promote stem extension and flowering, i.e. bolting, (Fig. 3.1; Lexander, 1980; 1987). There seems to be no requirement for a period of juvenility before plants are able to respond to vernalizing conditions because germinating seed and young seedlings (Smit, 1983) as well as seeds on the mother plant (Wood *et al.*, 1979) have the potential to respond. Under suitable, non-vernalizing conditions, sugar beet plants can remain vegetative and capable of producing new leaves without stem elongation for several years (Ulrich, 1952). However, if commercial beet crops are sown too early in spring, the seeds and seedlings may receive a sufficient cold stimulus to cause a proportion of the plants to bolt in the first year. These bolters decrease yield (Longden *et al.*, 1975) and produce viable seeds that may result in infestations of 'weed' beet in later years (Hornsey & Arnold, 1979).

Various workers have attempted to define the vernalization requirement of sugar beet. Temperatures within the range 5–10°C seem to be most effective in inducing flowering and plants respond little, if at all, to temperatures colder than 2.5°C (Stout, 1946). Long days increase the efficiency of the cold treatment, and are essential for the extension of the flowering stem and production of flowers (Campbell & Russell, 1965; Bosemark, 1993). To maximise flowering when selecting for bolting resistance, young sugar beet plants are usually subjected to photothermal treatments of 5–8°C temperature within a daily 16-hour light regime for 8–14 weeks – the actual length depending upon the bolting resistance of the material (Bell & Bauer, 1942; Bell, 1946). Vernalization can be reversed, if not too advanced, by exposing plants to temperatures of over 15°C immediately after the cold treatment (Chroboczek, 1934; Smit, 1983).

In early-sown field crops, Wood and Scott (1974) showed that the percentage of bolting plants was positively correlated with the number of days on which minimum air temperatures fell below 7°C during the 4–6 weeks after sowing, and negatively correlated with the number of days on which maximum temperatures exceeded 13°C. This was considered indicative of the effects of cold night temperatures being nullified by high temperatures during the following day. Jaggard *et al.* (1983) showed that the percentage of bolters in UK crops was strongly correlated with the number of days when maximum air temperature was below 12°C during the period from sowing until late summer. Greater account needs to be taken of the devernalizing effects of high summer temperatures under continental conditions than in the UK.

Genetic and molecular control of flowering

During the past decade, there has been much progress in understanding the genetic and molecular processes that control vernalization, flowering and bolting. This has derived largely from the studies on the model *Arabidopsis thaliana* system (see reviews by Bernier *et al.*, 1993; Levy & Dean, 1998; Sheldon *et al.*, 2000; Simpson & Dean, 2002; Sung *et al.*, 2003). Work relating to sugar beet has been reviewed briefly by Roden and Mutasa-Göttgens (2004).

The *B* locus gene that confers an early bolting, annual habit was first described in a commercial sugar beet cultivar (*Beta vulgaris* ssp. *vulgaris*) in the first half of the twentieth century (Munerati, 1931). It was later shown that the dominant *B* allele is abundant in wild beet (*B. vulgaris* ssp. *maritima*) where it causes plants to bolt under long, but not short-day, conditions without the need for vernalization (Abe *et al.*, 1997). Commercial varieties have the recessive *b* allele which confers the requirement for vernalization and results in the biennial growth habit (Owen *et al.*, 1940). In recent years, the outcrossing with wild beet during seed multiplication has inadvertently introduced the *B* allele into commercial varieties resulting in some of them becoming contaminated with early-bolting plants (Shimamoto *et al.*, 1990). This has produced serious 'weed beet' problems for many European beet growers (Hornsey & Arnold, 1979). Interest has centred on the *B* gene because, if cloned, it could be used as a marker to identify heterozygous individuals capable of transmitting the bolting habit to progeny in breeding programmes. It is possibly of greater interest to the breeder if, through the transcriptional control of the *B* gene with inducible promoters, the flowering process could be manipulated to shorten the breeding process whilst still allowing commercial progeny to exhibit the non-bolting phenotype. Alternatively, molecular anti-sense technologies could be used to completely suppress the bolting gene in commercial varieties to open the way for autumn sowing and capitalize on the higher yield potential offered by a longer growing season (Jaggard & Werker, 1999; El Mezawy *et al.*, 2002).

Much of our current understanding of the vernalization process comes from work on natural variants or induced mutants of *Arabidopsis thaliana*. In these, the requirement for vernalization is conferred by a single gene, *frigida* (*FRI*), which interacts with a *flowering time control* gene (*FCA*) to promote the accumulation of messenger RNA for a floral inhibitor from the *flowering locus C (FLC)*. Vernalization results in a quantitative reduction in *FLC* mRNA by, perhaps, decreasing the level of methylation of the *FRI* gene (Sheldon *et al.*, 2000). The reduction in *FLC* mRNA correlates with the time of flowering (Simpson & Dean, 2002). There are similarities between these *Arabidopsis* vernalization genes and the *B* gene in sugar beet, but no homologies have yet been demonstrated at the chromosomal and molecular levels (Roden & Mutasa-Göttgens, 2004).

It is well known that applied gibberellic acids (GAs) promote stem elongation and flower formation in many rosette plants grown under unfavourable conditions for flowering (Zeevart, 1983; Bagnall, 1992). Long days and vernalization, which promote bolting and flowering in rosette plants, have been shown to remove specific blocks in the GA biosynthetic pathway (Metzger, 1987). It has not yet been resolved whether GAs act primarily to control stem elongation and have only a secondary role in the actual production of flowers, or whether they control both processes independently (Bernier *et al.*, 1993). However, recent work has shown that gibberellin hormones do have an important role in controlling responses to vernalization in sugar beet, and that reducing sensitivity to gibberellin can provide an acceptable level of bolting resistance (Roden & Mutasa-Göttgens, 2004).

SUMMARY

This chapter summarizes current knowledge of the developmental and physiological processes that govern the responses of sugar beet crops, in terms of both the yield and beet quality, to soil fertility, climatic factors, agronomic practices and husbandry inputs. It is intended to provide a background for later chapters that deal, in more detail, with aspects of the crop's agronomy, nutrition and quality. No attempt has been made to discuss the physiology of the crop's water relations here because these are better considered in the chapter dealing with crop responses to drought and irrigation (Chapter 10).

The broad physiological principles that govern growth and nutrient uptake of sugar beet are now well established. The main emphasis for the few physiologists still actively researching the sugar beet plant now seem to be centred on the molecular improvement of crop responses to drought in the face of impending climate change, and in unravelling the molecular bases of pest and disease resistance, vernalization and flowering. These are essentially long-term objectives. In the short term, it is imperative to fully utilize our current physiological understanding of productivity, nutrition and quality to ensure that the maximum yield of high quality beet is delivered to factories at least cost to maintain the competitiveness of the sugar beet industry and ensure that it can take full advantage of future molecular technologies.

REFERENCES

Abe, J., Guan, G.P. & Shimamoto, Y. (1997) A gene complex for annual habit in sugar beet (*Beta vulgaris* L.). *Euphytica* **94**, 129–135.

Alexander, J.T. (1971) Factors affecting quality. In: Johnson, R.T., Alexander, J.T., Rush, G.E. & Hawkes, G.R. (eds) *Advances in Sugarbeet Production: Principles and Practices.* Iowa State University Press, Ames, pp. 371–380.

Artschwager, E. (1926) Anatomy of the vegetative organs of the sugar beet. *Journal of Agricultural Research* **33**, 143–176.

Artschwager, E. (1930) A study of the structure of sugar beets in relation to sugar content and type. *Journal of Agricultural Research* **40**, 876–915.

Asher, M.J.C. (1993) Rhizomania. In: Cooke, D.A. & Scott, R.K. (eds) *The Sugar Beet Crop: Science into Practice.* Chapman and Hall, London, pp. 311–346.

Bagnall, D.J. (1992) Control of flowering in *Arabidopsis thaliana* by light, vernalization and gibberellins. *Australian Journal of Plant Physiology* **19**, 401–409.

Barraclough, P.B. & Leigh, R.A. (1993) Critical plant K concentrations for growth and problems in the diagnosis of nutrient deficiencies by plant analysis. *Plant and Soil* **155/156**, 219–222.

Bell, C.J., Milford, G.F.J. & Leigh, R.A. (1996) Sugar beet. In: Zamski, E. & Schaffer, A.A. (eds) *Photoassimilate Distribution in Plants and Crops: Source-Sink Relationships.* Marcel Dekker Inc., New York, pp. 691–707.

Bell, G.D.H. (1946) Induced bolting and anthesis in sugar beet and the effect of selection of physiological types. *Journal of Agricultural Science, Cambridge* **36**, 167–183.

Bell, G.D.H. & Bauer, A.B. (1942) Experiments on growing sugar beet under continuous illumination. *Journal of Agricultural Science, Cambridge* **32**, 112–141.

Beringer, H., Koch, K. & Lindhauer, M.G. (1986) Sucrose accumulation and osmotic potentials in sugar beet at increasing levels of potassium nutrition. *Journal of the Science of Food and Agriculture* **37**, 211–218.

Bernier, G., Havelange, A., Houssa, C., Petitjean, A. & Lejeune, P. (1993) Physiological signals that induce flowering. *Plant Cell* **5**, 1147–1155.

Bosemark, N.O. (1993) Genetics and breeding. In: Cooke, D.A. & Scott, R.K. (eds) *The Sugar Beet Crop: Science into*

Practice. Chapman and Hall, London, pp. 67–119.

Bouillene, R., Kronacher, P-G. & de Roubaix, J. (1940) Étapes morphologiques et chimique dans le cycle végétatif da la betterave sucrière. *Publications Institut Belge pour l'Amélioration de la Betterave* **8**, 87–166.

Brown, K.F. & Biscoe, P.V. (1985) Fibrous root growth and water use of sugar beet. *Journal of Agricultural Science, Cambridge* **105**, 679–691.

Brown, K.F., Messem, A.B., Dunham, R.J. & Biscoe, P.V. (1987) Effect of drought on growth and water use of sugar beet. *Journal of Agricultural Science, Cambridge* **109**, 421–435.

Buchholz, K., Märländer, B., Puke, H., Glattkowski, H. & Thielecke, K. (1995) Neubewertung des technischen Wertes von Zuckerrüben. *Zuckerindustrie* **120**, 113–121.

Burba, M., Nitzschke, U. & Ritterbusch, R. (1984) Die N-Assimilation der Pflanze unter besonderer Berücksichtigung der Zuckerrübe (*Beta vulgaris* L.). *Zuckerindustrie* **109**, 613–627.

Bürcky, K. & Biscoe, P.V. (1983) Stickstoffe im rubenblatt und N-tranlokation aus alterden blättern. *IIRB Symposium 'Nitrogen and Sugar Beet'*. Brussels, pp. 63–75.

Bürcky, K., Beiss, U., Winner, C., Drath, L. & Schiweck, H. (1978) Versuche zur Bedeutung des Nährstuffangebotes für die Qualität der Zuckerübe. 2. Sticstoff und Kalium. *Zuckerindustrie* **103**, 190–200.

Campbell, G.K.G. & Russell, G.E. (1965) Breeding sugar beet. *Report of the Plant Breeding Institute for 1963–1964*, pp. 6–32.

Campbell, L.G. (2002) Sugar beet quality improvement. In: Basra, A.S. & Randhawa, L.S. (eds) *Quality Improvement in Field Crops*. The Haworth Press Inc., Binghamton, NY, pp. 395–413.

Carruthers, A. & Oldfield, J.F.T. (1961) Methods for the assessment of beet quality. *International Sugar Journal* **63**, 72–74.

Carter, J.N. & Traveller, D.J. (1981) Effect of time and amount of nitrogen uptake on sugarbeet growth and yield. *Agronomy Journal* **73**, 665–671.

Carter, J.N., Westermann, D.T. & Jensen, M.E. (1976) Sugarbeet yield and quality as affected by nitrogen level. *Agronomy Journal* **68**, 49–55.

Chroboczek, E. (1934) A study of some ecological factors influencing seed stalk development in beets (*Beta vulgaris* L.). *Cornell University Agricultural Experimental Station, Memoir* 154.

Clark, A.E. & Loomis, R.S. (1978) Dynamics of leaf growth and development in sugar beet. *Journal of the American Society of Sugar Beet Technologists* **20**, 97–113.

Clover, C.R.G., Azam-Ali, S.N., Jaggard, K.W. & Smith, H.G. (1999a) The effects of beet yellows virus on the growth and physiology of sugar beet (*Beta vulgari*s). *Plant Pathology* **48**, 129–138.

Clover, C.R.G., Smith, H.G., Azam-Ali, S.N. & Jaggard, K.W. (1999b) The effects of drought on sugar beet growth in isolation and in combination with beet yellows virus infection. *Journal of Agricultural Science, Cambridge* **133**, 251–261.

Cressman, R.M. (1969) Physiological studies on sugarbeets. *USDA Review of Sugarbeet Research for 1969*, pp. E44–50.

Devillers, P. (1983) Role des composes azotés dans la fabrication industrielle du sucre de betteraves. *IIRB Symposium 'Nitrogen and Sugar Beet'*. Brussels, pp. 1–11.

Doney, D.L., Wyse, R.E. & Theurer, J.C. (1981) The relationship between cell size, yield and sucrose concentration of the sugarbeet root. *Canadian Journal of Plant Science* **61**, 447–453.

Draycott, A.P. & Christenson, D.R. (2003) *Nutrients for Sugar Beet Production: Soil-Plant Relationships*. CABI Publishing, Wallingford.

Draycott, A.P. & Durrant, M.J. (1976) Response of sugar beet to potassium and sodium, particularly in relation to soils containing little exchangeable potassium. *Journal of Agricultural Science, Cambridge* **87**, 105–112.

Draycott, A.P. & Webb, D.J. (1971) Effects of nitrogen fertilizer, plant population and irrigation on sugar beet. *Journal of Agricultural Science, Cambridge* **76**, 261–267.

Durrant, M.J., Draycott, A.P. & Boyd, D.A. (1979) The response of sugar beet to potassium and sodium fertilizers. *Journal of Agricultural Science, Cambridge* **83**, 427–434.

Dutton, J.V. & Turner, F. (1983) Correcting excessive use of nitrogen – beet amino-N measurements. *British Sugar Beet Review* **51** (2), 12–17.

Elliott, M.C. & Weston, G.D. (1993) Biology and physiology of the sugar beet plant. In: Cooke, D.A. & Scott, R.K. (eds) *The Sugar Beet Crop: Science into Practice*. Chapman and Hall, London, pp. 37–66.

El Mezawy, A., Dreyer, F., Jacobs, G. & Jung, C. (2002) High resolution mapping of the bolting gene *B* of sugar beet. *Theoretical and Applied Genetics* **105**, 100–105.

Farley, R.F. & Draycott, A.P. (1974) Growth and yield of sugar beet in relation to potassium and sodium supply. *Journal of Science of Food and Agriculture* **26**, 385–392.

Follett, R.F., Schmel, W.R. & Viets, F.G. (1970) Seasonal leaf area, dry weight and sucrose accumulation by sugar beets. *Journal of the American Society of Sugar Beet Technologists* **16**, 245–252.

Giaquinta, R.T. (1977) Sucrose hydrolysis in relation to phloem translocation in *Beta vulgari*s. *Plant Physiology* **60**, 339–343.

Giaquinta, R.T. (1979) Sucrose translocation and storage in the sugar beet. *Plant Physiology* **63**, 828–832.

Goodman, P.J. (1963) Some effects of different soils on composition and growth of sugar beet. *Journal of Science of Food and Agriculture* **3**, 196–203.

Goodman, P.J. (1968) Physiological analysis of the effects of different soils on sugar beet crops in different years. *Journal of Applied Ecology* **5**, 339–357.

Hansen, A.D. & Wyse, R. (1982) Synthesis, translocation, and accumulation of betaine in sugar beet and its progenitors in relation to salinity. *Plant Physiology* **70**, 1191–1198.

Harris, P.M. (1972) The effect of plant population and irrigation on sugar beet. *Journal of Agricultural Science, Cambridge* **78**, 289–302.

Harvey, C.W. & Dutton, J.V. (1993) Root quality and processing. In: Cooke, D.A. & Scott, R.K. (eds) *The Sugar Beet Crop: Science into Practice*. Chapman and Hall, London, pp. 571–617.

Hayward, H.E. (1938) *The Structure of Economic Plants*. MacMillan, New York.

Hornsey, K.G. & Arnold, M.H. (1979) The origins of weed beet. *Annals of Applied Biology* **92**, 279–285.

Houba, V.J.G. (1973) Effect of nitrogen dressings on growth and development of sugar beet. *Agricultural Research Reports* 791. Wageningen, Pudoc.

Hsaio, T.C. & Läuchli, A. (1986) In: Tinker, P.B. & Läuchli, A. (eds) *Advances in Plant Nutrition, Vol. 2*. Praeger, New York, pp. 281–312.

Huijbregts, A.W.M. (1999) New Dutch recovery formula for sugar beet. *Zuckerindustrie* **124**, 698–701.

Jaggard, K.W & Werker, A.R. (1999) An evaluation of the potential benefits and costs of autumn sown sugar beet in N.W. Europe. *Journal of Agricultural Science, Cambridge* **101**, 91–102.

Jaggard, K.W., Lawrence, D.K. & Biscoe, P.V. (1981) An understanding of crop physiology in assessing a plant growth regulator on sugar beet. In: McLaren, J.S. (ed.) *Chemical Manipulation of Crop Growth and Development*. Butterworths Scientific Publications, London, pp. 139–150.

Jaggard, K.W., Wickens, R., Webb, D.J. & Scott, R.K. (1983) Effects of sowing date on plant establishment and bolting and the influence of these factors on yields of sugar beet. *Journal of Agricultural Science, Cambridge* **101**, 147–161.

Jaggard, K.W., Clark, C.J.A. & Draycott, A.P. (1999) The weight and processing quality of components of the storage roots of sugar beet (*Beta vulgaris* L.). *Journal of the Science of Food and Agriculture* **79**, 1389–1398.

Jarvis, P.J., Milford, G.F.J., Armstrong, M.J. & Barraclough, P.B. (2003) Recent research on potassium and sodium recommendations for sugar beet. *British Sugar Beet Review* **71** (4), 4–9.

Kubadinow, N. & Hampel, W. (1975) Le comportement des acides amines libres au cours de la séparation des jus. *Sucre Belge* **94**, 304–404.

Last, P.J. & Draycott, A.P. (1975) Growth and yield of sugar beet on contrasting soils in relation to nitrogen supply. II. Growth, uptake and leaching of nitrogen. *Journal of Agricultural Science, Cambridge* **85**, 27–37.

Launay, M. & Guérif, M. (2003) Ability for a model to predict crop production variability at the regional scale: an evaluation for sugar beet. *Agronomie* **23**, 135–146.

Leigh, R.A. & Johnston, A.E. (1983) Concentrations of potassium in the dry matter and tissue water of field-grown spring barley and their relationships to yield. *Journal of Agricultural Science, Cambridge* **101**, 675–685.

Leigh, R.A., Bambridge, L.W., Bell, C.I., Jones, J. & Milford, G.F.J. (1995) Interrelations between the concentration of solutes during the growth of sugar beet storage roots. *International Conference on the Transport of Photoassimilates*. Canterbury, Abstracts, p. 20.

Levy, Y.Y. & Dean, C. (1998) The transition to flowering. *Plant Cell* **10**, 1973–1989.

Lexander, K. (1980) Present knowledge of sugar beet bolting mechanisms. In: *Proceedings of the 43rd IIRB Congress*. Brussels, pp. 245–248.

Lexander, K. (1987) Characters related to the vernalization requirement of sugar beet. In: Atherton, J.G. (ed.) *Manipulation of Flowering*. Butterworths, London, pp. 147–158.

Loach, K. (1970) Analysis of differences in yield between six sugar-beet varieties. *Annals of Applied Biology* **7**, 427–438.

Longden, P.C. & Breay, T. (1995) Weed beet – the future. *British Sugar Beet Review* **63** (4), 16–17.

Longden, P.C., Scott, R.K. & Tyldesley, J.B. (1975) Bolting of sugar beet grown in England. *Outlook on Agriculture* **8**, 188–193.

Loué, A. (1985) Potassium and the sugar beet. *Potash Review* No. 7. International Potash Institute, Basel.

Mahn, K., Hoffmann, C. & Märländer, B. (2002) Distribution of quality components in different morphological sections of sugar beet (*Beta vulgaris* L.). *European Journal of Agronomy* **17**, 29–39.

Malnou, C., Jaggard, K.W. & Sparkes, D. (2003) Nitrogen usage by the sugar beet crop: the production of a canopy. *British Sugar Beet Review* **71** (1), 8–11.

Marcussen, C. (1985) Amino-N figures – as used in Denmark. *British Sugar Beet Review* **53** (4), 46–48.

Märländer, B. (1991) Zuckerrüben. Optimierung von Anbauverfahren, Züchtungsfortschritt, Sortenwahl. *Ute Bernhardt-Pätzhold Verlag, Stadthagen*.

Marschner, H. (1971) Why can sodium replace potassium in plants? In: *Potassium in Biochemistry and Physiology. 8th Colloquium of the International Potash Institute*. pp. 50–63.

Metzger, J.D. (1987) Hormones and reproductive development. In: Davies, P.J. (ed.) *Plant Hormones and Their Role in Plant Growth and Development*. Martinus Nijhoff, Dordrecht, pp. 431–462.

Milford, G.F.J. (1973) The development of the storage root of sugar beet. *Annals of Applied Biology* **75**, 427–438.

Milford, G.F.J. (1976) Sugar concentrations in sugar beet: varietal differences and the effects of soil type and planting density on the size of the root cells. *Annals of Applied Biology* **83**, 251–257.

Milford, G.F.J. & Houghton, B.J. (1999) An analysis of the variation in crown size in sugar-beet (*Beta vulgaris*) grown in England. *Annals of Applied Biology* **134**, 225–232.

Milford, G.F.J. & Riley, J. (1980) The effects of temperature on leaf growth of sugar beet varieties. *Annals of Applied Biology* **94**, 431–443.

Milford, G.F.J. & Thorne, G.N. (1973) The effect of light and temperature late in the season on the growth of sugar beet. *Annals of Applied Biology* **75**, 419–425.

Milford, G.F.J. & Watson, D.J. (1971) The effect of nitrogen on the growth and sugar content of sugar beet. *Annals of Botany* **35**, 287–300.

Milford, G.F.J., Biscoe, P.V., Jaggard, K.W., Scott, R.K. & Draycott, A.P. (1980) Physiological potential for increasing yields of sugar beet. In: Hurd, R.G., Biscoe, P.V. & Dennis, C. (eds) *Opportunities for Increasing Crop Yields*. Pitman, London, pp. 71–83.

Milford, G.F.J., Pocock, T.O. & Riley, J. (1985a) An analysis of leaf growth in sugar beet. II. Leaf appearance in field crops. *Annals of Applied Biology* **106**, 173–185.

Milford, G.F.J., Pocock, T.O., Jaggard, K.W., Biscoe, P.V., Armstrong, M.J., Last, P.J. & Goodman, P.J. (1985b) An analysis of leaf growth in sugar beet. IV. The expansion of the leaf canopy in relation to temperature and nitrogen. *Annals of Applied Biology* **107**, 335–347.

Milford, G.F.J., Pocock, T.O., Riley, J. & Messem, A.B. (1985c) An analysis of leaf growth in sugar beet. III. Leaf expansion in field crops. *Annals of Applied Biology* **106**, 187–203.

Milford, G.F.J., Travis, K.Z., Pocock, T.O., Jaggard, K.W. & Day, W. (1988) Growth and dry-matter partitioning in sugar beet. *Journal of Agricultural Science, Cambridge* **110**, 301–308.

Munerati, O. (1931) L'eredita della tendenza alla annualita nella commune basbabietola cultivate. *Pflanzenzüchtung* **17**, 84–89.

Owen, F.V., Carsner, E. & Stout, M. (1940) Photothermal induction of flowering in sugar beets. *Journal of Agricultural Research* **61**, 101–124.

Pack, D.A. (1927) Ring density of sugar beets as a character for selection. *American Journal of Botany* **14**, 238–245.

Pack, D.A. (1930) Selection characters as correlated with percentage of sucrose, weight and sucrose content of sugar beets. *Journal of Agricultural Research* **40**, 523–546.

Palmer, M. & Casburn, C. (1985) Amino nitrogen analyses and factory experience. *British Sugar Beet Review* **53** (1), 73–76.

Pidgeon, J.D., Werker, A.R., Jaggard, K.W., Richter, G.M., Lister, D.H. & Jones, P.D. (2001) Climatic impact on the productivity of sugar beet in Europe, 1961–1995. *Agricultural and Forest Meteorology* **109**, 27–38.

Pocock, T.O., Milford, G.F.J. & Armstrong, M.J. (1990) Storage root quality in sugarbeet in relation to nitrogen uptake. *Journal of Agricultural Science, Cambridge* **115**, 355–362.

Reinefeld, E., Emmerich, A., Baumgarten, G., Winner, C. & Beiss, U. (1974) Zur Voraussage des Melassezuckers aur Rübenanalysen. *Zucker* **27**, 2–15.

Richter, E. & Ewald, R. (1983) Apoplastic mobility of sucrose in storage parenchyma of sugar beet. *Physiologia Plantarum* **58**, 263–268.

Richter, G.M., Jaggard, K.W. & Mitchell, R.A.C. (2001) Modelling radiation interception and radiation use efficiency for sugar beet under variable climatic stress. *Agricultural and Forest Meteorology* **109**, 13–25.

Roden, L. & Mutasa-Göttgens, E. (2004) Unravelling the genetics of bolting and flowering in sugar beet: a model weed reveals all? *British Sugar Beet Review* **71** (2), 40–45.

Scott, R.K. & Jaggard, K.W. (1978) Theoretical criteria for maximum yield. *Proceedings of the 41st IIRB Congress.* Brussels, pp. 179–198.

Scott, R.K. & Jaggard, K.W. (1993) Crop physiology and agronomy. In: Cooke, D.A. & Scott, R.K. (eds) *The Sugar Beet Crop: Science into Practice.* Chapman and Hall, London, pp. 179–237.

Sheldon, C.C., Finnegan, E.J., Rouse, D.T., Tadege, M., Bagnall, D.J., Helliwell, C.A., Peacock, W.J. & Dennis, E.S. (2000) The control of flowering by vernalization. *Current Opinion in Plant Biology* **3**, 418–422.

Shimamoto, V., Tanada, T. & Abe, J. (1990) Analysis for bolting of sugar beet by means of test crosses of biennial lines with the annual line. *Proceedings of the Japanese Society for Sugar Beet Technology* 32, pp. 134–137.

Shore, M., Dutton J.V., Houghton, B. & Bowler, G. (1982) How much is that extra nitrogen fertiliser costing you? *British Sugar Beet Review* **50** (3), 54–56.

Simpson, G.G. & Dean, C. (2002) Arabidopsis, the Rosetta stone of flowering time? *Science* **296**, 285–289.

Smit, A.L. (1983) Influence of external factors on growth and development of sugar beet (*Beta vulgaris* L.). *Agricultural Research Report* 914, Wageningen.

Spitters, C.J.T., Van Kuelen, H. & Van Kraalingen, D.W.G. (1989) A simple and universal crop growth simulator: SUCROS87. In: Rabbinge, R., Ward, S.A. & Van Lars, H.H. (eds) *Simulation and System Management in Crop Protection.* Simulation Monographs, Pudoc, Wageningen, pp. 147–181.

Steven, M.D., Biscoe, P.V., Jaggard, K.W. & Paruntu, J. (1986) Foliage cover and radiation interception. *Field Crops Research* **13**, 75–87.

Stout, M. (1946) Relation of temperature to reproduction in sugar beets. *Journal of Agricultural Research* **72**, 49–68.

Subbarao, G.V., Ito, O., Berry, W.L. & Wheeler, R.M. (2003) Sodium – a functional plant nutrient. *Critical Reviews in Plant Sciences* **22**, 391–416.

Sung, Z.R., Chen, L., Moon, Y.H. & Lestpiuyapong, K. (2003) Mechanisms of floral repression in Arabidopsis. *Current Opinion in Plant Biology* **6**, 29–35.

Ulrich, A. (1952) The influence of temperature and light factors on the growth and development of sugar beets in controlled climatic environments. *Agronomy Journal* **44**, 66–73.

Ulrich, A. (1955) Influence of night temperature and nitrogen deficiency on the growth, sucrose accumulation and leaf minerals of sugar beet plants. *Plant Physiology* **30**, 250–257.

Van der Beek, M.A. & Huijbregts, A.W. (1986) Internal quality aspects of sugar beet. *Proceedings No. 25.* International Fertilizer Society, London.

Van de Sande Bakhuyzen, H.L. (1949) Growth and production of sugar beets. *Verslagen van Landbouwkundige Onderzoekingen* **55** (2), 1–227.

Watson, D.J. (1952) The physiological basis of variation in yield. *Advances in Agronomy* **4**, 101–145.

Watson, D.W., Motomatsu, T., Loach, K. & Milford, G.F.J. (1972) Effects of shading and seasonal differences in weather on the growth, sugar content and sugar yield of sugar-beet crops. *Annals of Applied Biology* **71**, 159–185.

Werker, A.R. & Jaggard, K.W. (1997) Modelling asymmetrical growth curves that rise and then fall: applications to foliage dynamics of sugar beet (*Beta vulgaris*). *Annals of Botany* **79**, 657–665.

Werker, A.R. & Jaggard, K.W. (1998) Dependence of sugar beet yield on light interception and evapotranspiration. *Agricultural and Forest Meteorology* **89**, 229–240.

Werker, A.R., Jaggard, K.W. & Webb, C.R. (1995) Some simple models to describe and analyse the growth of sugar beet crops. *Proceedings of the 58th IIRB Congress.* Dijon, pp. 545–549.

Wieninger, L. & Kubadinow, N. (1971) Bezihungen zwichen Rübenanalysen und technischer Bewertung van Zuckerüben. *Zucker* **24**, 599–604.

Winner, C. & Feyerabend, I. (1971) Ein Beitrag zur Morphologie und technischen Qualität des Rübenkopfes. 2. Verteilung qualitätbestimmender in der Rübe. *Zucker* **24**, 36–43.

Wood, D.W. & Scott, R.K. (1974) Sowing sugar beet in autumn in England. *Journal of Agricultural Science, Cambridge* **84**, 97–108.

Wood, D.W., Scott, R.K. & Longden, P.C. (1979) Effects of mother-plant temperature on seed quality in *Beta vulgaris* L. (sugar beet). In: Hebblethwaite, P.B. (ed.) *Seed Production*. Butterworths, London, pp. 257–270.

Wyn Jones, R.G. & Pollard, A. (1983) Inorganic plant nutrition. In: Läuchli, A. & Bielski, R.L. (eds) *Encyclopedia of Plant Physiology, New Series, Vol. 15*. Springer-Verlag, Berlin, pp. 528–562.

Wyse, R.E. (1979a) Parameters controlling sugar content and yield of sugar beet. *Journal of the American Society of Sugar Beet Technologists* **20**, 268–385.

Wyse, R.E. (1979b) Sucrose uptake by sugar beet tap root tissue. *Plant Physiology* **64**, 837–841.

Wyse, R.E. (1980) Partitioning within the taproot sink of sugarbeet: effect of photosynthate supply. *Crop Science* **20**, 256–258.

Zamski, E. & Azenhot, A. (1981) Sugarbeet vasculature: I. Cambial development and the three dimensional structure of the vascular system. *Botanical Gazette* **142**, 334–343.

Zeevaart, J.A.D. (1983) Gibberellins and flowering. In: Crozier, A. (ed.) *The Biochemistry and Physiology of Gibberellins, Vol. 2*. Praeger Publications, New York, pp. 333–374.

Chapter 4
Genetics and Breeding

Nils Olof Bosemark

INTRODUCTION

Since the middle of the twentieth century, sugar beet has changed from a labour-intensive agricultural crop with static yields to one that is highly mechanized and with steadily improving yields. This is illustrated by the labour requirement for sugar beet crops in western Europe, which, in the mid-1950s, was still 350–400 man-hours/ha, but by the early 1980s had been reduced to as little as 50 man-hours/ha. After an initially rather brutal mechanization and the transition to genetic monogerm varieties, the yield of sugar per hectare has increased continuously, since the 1980s by as much as 1.5% per year (Fig. 4.1).

Although for many reasons – edaphic, climatic, and economic – this development has not progressed equally fast in all beet-growing areas, it has always been the result of many interdependent and co-ordinated efforts, especially in the fields of machinery development, crop nutrition, weed and pest control, and breeding. Further progress in beet sugar production, needed to maintain the competitiveness of the beet sugar industry, will require continued, co-ordinated research efforts in all fields related to sugar beet growing and processing. With the increasing demand to adapt to a less input-intensive and pesticide-dependent agriculture, the relative importance of sugar beet breeding is likely to increase.

OBJECTIVES OF SUGAR BEET BREEDING

The objectives of sugar beet breeding programmes are to create stable, dependable varieties that give the highest possible yield of white sugar per unit area in relation to cost of production and meet various other requirements of the environment, growers and sugar factories. These objectives can

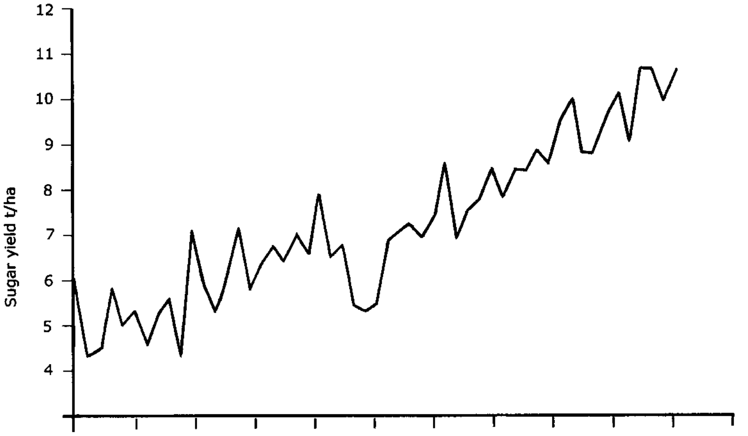


Fig. 4.1 The improvement of sugar yield in western Europe between 1950 and 2002 (average of yields in the UK, the Netherlands, Belgium, France and Germany).

only be fulfilled through selection for a variety of agronomic and technological characters, some of which are complex and some more simple in nature. Thus, selection for sugar yield, the product of root yield and sugar content, is basically selection for greater physiological efficiency. However, because there is almost invariably a negative correlation between root yield and sugar percentage, simultaneous, maximum expression of the two component characters of sugar yield is difficult to obtain. As a consequence, varieties are usually classified as being E-type (with emphasis on root yield, *Ertrag*), Z-type (with emphasis on sugar percentage, *Zucker*) or N-type (*Normal*, intermediate in both characters). Although, in recent years, there has been a general demand for varieties with higher sugar percentage, choice of varietal type for any particular area is influenced by several factors, including climate and system of payment for roots.

The efficiency of extracting white sugar in the factory is affected by the concentration in beet roots of sodium and potassium salts, amino acids and betaine, most of which are correlated with each other and with root yield and sugar percentage (see Chapter 16). Sugar beet breeding programmes aim to combine high sugar yield with a low and balanced concentration of these impurities. However, to produce the high and stable yields required today, sugar beet cultivars must have resistance or tolerance to important diseases and pests. Similarly, to counter effects of possible climatic changes in the years ahead, breeders may soon have to breed for tolerance to drought or other climatic or edaphic stress factors.

CHARACTERS SUBJECTED TO SELECTION

Morphological and anatomical characters

Morphological characters of the sugar beet plant (e.g. root shape) affect harvest operations, storage properties and the working of the factory. Anatomical characters (e.g. cell size) mainly affect factory operations. On the one hand, roots that are long and slender or are very fangy cause loss at harvest (through breakage below the soil surface) and during the factory washing operation (by unwanted extraction of sugar from the broken surfaces). Such roots also tend to give a higher proportion of short slices and fine pulp in the factory, thus affecting efficiency of the diffusion process. On the other hand, if plants are not sufficiently anchored in the soil, they may be thrown out of the row by toppers or flails of the harvester and left on the soil surface.

The selection process employed by the breeder should aim to produce well-filled roots that are not too long, that taper off gradually and have a minimum of fangs. Such roots tend to have shallower root furrows and a smoother skin (characteristics that give a lower dirt tare and make washing easier). They are also less subject to mechanical damage during harvesting, transport and factory operations.

The size and shape of the crown affect losses in the field and the quality of harvest work. Thus, beet with large, wide crowns require deeper topping with greater losses of root weight as a result. If such roots are under-topped they have poor storage characteristics and low technological quality.

The size and other characters of the leaves, although important to growers of livestock, are rarely selected for directly. However, there is good evidence that photosynthetic efficiency, competitive ability and reaction to differences in plant density are influenced by number, size and positioning of the leaves.

Anatomical characters (particularly cell size, thickness of cell walls and number of vascular bundles) affect the size of root slices (cossettes) that are required to give maximum extractability and minimum resistance to slicing. Both morphological and anatomical characters of roots are influenced by variety, soil type, climate and cultural practices.

Physiological characters

Maximum yields are obtained only when the growing season is as long as possible, and when growth is not unduly restricted. The most effective means of extending the growing season is by early sowing; however, this requires varieties with a high degree of resistance to bolting. Bolters are undesirable because their woody stems and fibrous roots interfere with machine-harvesting and reduce yield. This has made resistance to bolting an important selection character in all temperate beet-growing areas as well as in areas where autumn sowing is practised. Early sown beets would derive additional benefits from selection for improved germination at low temperatures and quicker development of young plants in early spring. However, little progress towards achieving these objectives appears to have been made so far.

With the introduction of genetic monogerm seed and sowing to a stand, seed with better germination and emergence capacity, and good sowing ability became a necessity. Fortunately, genetic monogerm seed turned out not only to emerge better than expected, but also to be more amenable to selection for other desirable characters. Stringent selection for seed yield, germination capacity, seed size, seed size distribution and seed shape is now possible, and is of benefit not only to the growers but also the seed producers by increasing the proportion of saleable seed that can be produced from a given acreage of seed production.

Although sugar beet genotypes differ in sensitivity to particular herbicides, no useful tolerance has been identified. However, transgenic herbicide tolerant sugar beet varieties have been developed and will, hopefully, be available in the near future.

Of the many factors which inhibit growth later in the season, the only ones which can be ameliorated through breeding are the effects of pests and diseases. In sugar beet, as in most other crops, breeding for resistance or tolerance to certain pests and diseases has been vital to ensure continued cultivation in several areas, and has contributed greatly towards improved yields and reduced pesticide inputs in others. With marker-assisted selection and gene transfer techniques now available, breeding for pest and disease resistance will be one of the surest ways of obtaining further yield increases in sugar beet.

The storability of beet roots is a complex physiological character which is influenced indirectly by shape of roots and directly by their handling during harvest and transport, and by their disease-resistance properties. However, it is also influenced by inherent physiological processes, in particular the rate of respiration. Lack of progress in selection for storability has been largely due to the practical difficulties in testing large numbers of breeding lines under realistic storage conditions. Progress is likely to require separate assessments of the main constituents of storability and equipment that permit simultaneous determination of the rate of respiration in large numbers of small beet samples.

Chemical characters

The morphological, anatomical and physiological characters that have been discussed so far affect the sowing and establishment of the crop, subsequent field operations, growth and final yield, storage, washing and slicing in the factory, and extractability in the diffusers. The chemical characters mainly affect the sugar crystallization processes. Roots should have high sugar percentage, and low concentrations (relative to the sugar percentage) of sodium and potassium salts, α-amino nitrogen and betaine. Also concentrations of simple sugars like glucose and raffinose should be small.

Summing up, many characters can be improved by selection but they do not all merit the same degree of attention. Since the relative importance of these characters depends on growing conditions, economic factors and factory procedures, breeders must use their judgement to arrive at the best compromise between what is desirable and what is practicable in a particular situation.

THE INHERITANCE OF SPECIFIC CHARACTERS

Growth habit

Biennial growth habit

All cultivated beets are basically biennial and require a period of low temperature to change from vegetative to reproductive stage (thermal induction). The duration of the thermal induction period is genetically determined and, if it is short enough, seed stalk development may be induced by low spring temperatures in the first year, a phenomenon known as bolting. Flower induction is influenced by day length as well as temperature (photothermal induction), and manipulation of these factors is important in forcing biennial genotypes to flower and set seed in the first year. The genetics of bolting is still unclear. Thus, McFarlane *et al.* (1948) stated that bolting resistance is very largely recessive while other studies have supported the view that bolting resistance is governed by several genes with different degrees of dominance (Marcum, 1948; Le Cochec & Soreau, 1989). More recently a diallel analysis of bolting in sugar beet (Jolliffe & Arthur, 1993) showed that genes with additive effects are highly important. However, significant dominance effects and indications of epistatic effects were also detected. Although there was a general trend for bolting resistance to be dominant, there was also evidence that the control was ambidirectional. Similar results were obtained by Sadeghian (1993). As suggested by Jolliffe (1990), the apparent complexity of the genetic control of bolting may simply reflect that the effects of temperature and light, which are under independent genetic control and independently affected by environmental factors, are assessed collectively.

Recently it has been demonstrated that the control of bolting and flowering in sugar beet involves many of the environmental and biochemical processes that also control flowering in *Arabidopsis*, and that *Arabidopsis* genes seem to function equally well in sugar beet. This suggests that information from the *Arabidopsis* genome-sequencing project can be used to resolve the genetics of bolting and flowering in sugar beet (Roden & Mutasa-Göttgens, 2003).

Annual growth habit

Many of the wild Mediterranean forms of *Beta* species (*B. maritima, B. macrocarpa*) are annuals, but biennial types also occur. In contrast to the biennial growth habit, genetics of the strictly annual growth habit is well understood and has been shown to be caused by a dominant gene B (Munerati, 1931; Abegg, 1936; Owen, 1954b). Given long days and reasonably high temperatures, plants carrying this gene run to seed extremely quickly. F_1 hybrids between annual and biennial types are somewhat slower to run to seed, probably due to modifying genes from the biennial parent. Under favourable conditions the segregation in the F_2 generation closely fits the expected 3:1 ratio. Recent molecular marker studies have located gene B to chromosome 2 of sugar beet (El Mezawy *et al.*, 2002). The markers are now being used in positional cloning of the gene B (Hohmann *et al.*, 2003).

The gene B for annual growth habit may be used in breeding work when a quick succession of seed generations is required. It can be used to speed up back-crossing programmes, to facilitate testing for sterility maintainers and in genetic research. Although it can be a very useful breeding tool when correctly handled, it can do considerable damage if allowed to contaminate breeding stocks or commercial seed crops. This risk exists in seed crops in southern Europe where wild *Beta* beets, or derivatives of such beet, carrying the gene B may occur in fields or on wasteland (See Chapter 5).

Self-incompatibility and self-fertility

Sugar beet is normally strongly self-sterile, setting few or no seeds under strict isolation. The underlying genetic mechanism was studied by Owen (1942), who concluded that most cases of self-incompatibility in sugar beet could be explained by two series of multiple alleles acting gametophytically. However, for some cases he had to assume the existence of some modifying genes.

Contrary to this, Larsen (1977a; 1978), after thorough studies, came to the conclusion that, in the material studied by him, self-incompatibility is conditioned by at least four linked and complementary interacting S-loci, acting gametophytically. Larsen denoted these four loci S_a, S_b, S_c, S_d, and the alleles they carry 1 and 2; 3 and 4; 5 and 6; 7 and 8, respectively. Each S-allele carried by the pollen must be matched by an identical allele in the pistil to result in compatibility. Owing to the high number of potential S-genotypes, this system permits mating between close relatives. However, according to Larsen (1982), the effect of this on homozygosity is counteracted by preferential fertilization favouring the most distantly related pollen source.

Self-incompatible plants usually set some seed after selfing. This pseudo-compatibility or pseudo-self-fertility, which is due to break-down of the incompatibility mechanism, occurs with different frequencies in different genotypes and is highly influenced by environmental conditions, above all temperature. Although not fully understood, pseudo-self-fertility is probably under polygenic control, with pseudo-compatibility being more frequent the higher the degree of S-gene heterozygosity in the style (Larsen, 1977b). Pseudo-compatibility is increased at low temperature (around 15°C) and at high temperatures (around 35°C).

Cases of almost obligate self-fertility are also known. Thus, the monogerm line SLC 101 carried a dominant gene for self-fertility (Savitsky, 1954), which was widely distributed with this material. Plants having this S^F gene in single or double dose usually set 95–100% selfed seed even if flowering openly and surrounded by unrelated self-sterile or self-fertile plants. Plants with this gene, which have been bagged to exclude pollen from other sources, also set plenty of seed, irrespective of temperature. The gene has thus greatly facilitated development of inbred lines, especially in countries with hot summers.

Male sterility

Cytoplasmic male sterility

Cytoplasmic male sterility (CMS) was first discovered and studied in sugar beet by Owen (1945), who found a low frequency of male-sterile plants in the curly-top resistant sugar beet variety US-1. Owen proposed that the sterility depends on the interaction between at least two recessive chromosomal genes and a 'sterile cytoplasm' (S). According to Owen, fully male sterile plants have the genotype (S)xxzz, while the remaining eight genotypes [(S)XXZZ……(S)Xxzz)] usually show varying degrees of pollen fertility. As Owen himself pointed out, the inheritance may, in fact, be more complex than this and several modifications of the original scheme have been proposed. However, recently molecular markers, closely linked to the dominant alleles X and Z, have made it possible to locate these two genes on chromosomes 3 and 4, respectively (Pillen *et al.*, 1993; Schondelmaier & Jung, 1997; Hjerdin-Panagopoulos *et al.*, 2002).

To obtain offspring from male-sterile plants, which are themselves male sterile, CMS plants must be pollinated by so-called maintainer plants (known in sugar beet terminology as O-types), which carry the same sterility genes as the male steriles but in normal cytoplasm ((N)xxzz). This genotype exists at low frequencies (3–5%) in most sugar beet populations, but can be identified only by test-crossing prospective O-types with CMS plants. If all the offspring from such a test cross are male sterile, the test-crossed pollinator plant is of the O-type genotype. By repeated selfing of an identified O-type, and subsequent repeated backcrossing to a CMS line, inbred O-type lines and their equivalent inbred CMS lines can be developed.

Since the first find by Owen, CMS has been found to be a surprisingly common and widely distributed phenomenon in wild *Beta* beets (Boutin *et al.*, 1987; Saumitou-Laprade *et al.*, 1993; Cuguen *et al.*, 1994). Several analyses of the mitochondrial DNA (mtDNA) from sugar beet, as well as from wild beets belonging to the section *Beta*, have shown that the cytoplasmic genetic determinants of CMS reside in the mtDNA (Powling, 1982; Mikami *et al.*, 1985; Halldén *et al.*, 1988). In more recent studies (Halldén *et al.*, 1990; Kubo *et al.*, 1999) it has been shown that spontaneously occurring CMS in the section *Beta* is associated with gross structural rearrangements of the mitochondrial genome, and is not due to interspecific organelle transfer.

Nuclear or Mendelian male sterility

In nuclear or Mendelian male sterility (NMS), again first described by Owen (1952), the sterility depends on a single recessive gene a_1. Since this does not permit development of a population or line where 100% of plants are male sterile, use of the gene a_1 is restricted to facilitating crossing and back-crossing on self-fertile lines and recombination in recurrent selection programmes with such materials.

The monogerm seed character

The SLC 101 source

In 1948 the Russian sugar beet geneticist V.F. Savitsky found five monogerm plants in a seed field of Michigan Hybrid-18 (Savitsky, 1950). Of these five plants, only two were true monogerms and only one became extensively used. The seed increases from this plant, designated SLC 101, were distributed to breeders in the USA in 1950 and, later, in Europe and elsewhere. Outside the former USSR it is practically the only source of the monogerm character in use today.

SLC 101 is self-fertile, and the original plant probably originated from a line which had selfed for several generations. In addition to its monogerm character, SLC 101 differs from multigerm plants in the branching of the inflorescence; either a lateral branch or a single flower can be born in the axil of a leaf but never both together, as they are in multigerms.

The monogermity in SLC 101 is conditioned by a single recessive gene m (Savitsky, 1952). Heterozygous plants (Mm) are multigerm but have fewer fruits per cluster than homozygous multigerm plants. F_2 generations from crosses between monogerm and multigerm plants segregate into roughly 25% monogerm and 75% bigerm and multigerm plants. However, as pointed out by Savitsky, owing to segregation for genes modifying the expression of gene m, a varying proportion of the homozygous mm plants carry some bigerm clusters, mainly in the basal part of the main floral axis and the basal part of the lateral branches. Since the proportion of bigerms varies depending on the modifiers received from the multigerm parent, as well as on environmental conditions, the proportion of acceptable monogerm plants in an F_2 generation may be as low as one in eight. With exception of this variation in degree of expression, transfer of gene m to multigerm breeding materials does not present any difficulties. Gene m appears to have no detrimental effects on yield or quality characteristics, but a strong tendency for fasciation in SLC 101 is often difficult to overcome completely. The M-m locus has been mapped to chromosome 4 of sugar beet (Barzen *et al.*, 1992).

Other sources of monogermity

By 1934, plants that had up to 90% monogerm fruits had been found in the USSR. These sources have been used in the development of genetic monogerm varieties in the USSR and some east European countries. According to Knapp (1967), the monogermity in Russian material studied by him is not due to gene m but is polygenic in nature. The same applies to monogerms of Polish origin and a monogerm variety produced by the German firm Schreiber in 1939–1952. However, recently Russian researchers have described a new recessive gene for monogermity denoted m^2 and mapped the gene to the same linkage group as the M-m locus. The distance between the two loci has been estimated to 32.2 centiMorgans (Shavrukov, 2000).

Hypocotyl and root colour

The roots of cultivated *Beta* beets can be either white, as in sugar beet, some fodder beets and most types of Swiss chard, or coloured as in beetroot (red) and most mangels (red or yellow). The coloration is due to betacyanin and betaxanthine pigments dissolved in the cell sap. Although all sugar beet plants have white roots, seedlings may have hypocotyls with more or less intense coloration.

Root colour, as well as the coloration of hypocotyl and foliage, is determined by genes in at least two loci, Y (or G) with the allelic series Y, Y^r and y, and R with the allelic series R, R^t, R^P, R^h, and r (Keller, 1936; Owen & Ryser, 1942; Pedersen, 1944). Plants carrying the dominant allele Y in combination with the recessive allele in the R locus (Yyrr or YYrr) have yellow roots and hypocotyls, those with the Y^r allele have a more intense lemon colour, while those homozygous for the recessive allele y have white roots and green hypocotyls. Plants with the dominant alleles R, R^t, R^P and R^h have white roots but coloured hypocotyls in the presence of the recessive allele y in the Y locus. In the presence of the dominant alleles in the Y locus, plants with dominant alleles in the R locus have red roots of different intensity. An exception to this rule is the allele R^h, which, in the presence of the Y allele results only in red hypocotyls. Thus Y is not only coding for yellow root colour but is also a requisite for the manifestation of red colour in the root. The R gene locus has been mapped to chromosome 3 of sugar beet (Barzen *et al.*, 1992). Hypocotyl colour is a useful marker, frequently used in controlled crosses in sugar beet.

AUTOTETRAPLOIDY IN SUGAR BEET

General features of polyploid sugar beet

By the end of the 1930s, several sugar beet breeders and research workers had started to produce autotetraploid sugar beets ($2n = 4x = 36$), where n represents the chromosome number of gametes (thus $n = 9$ in a diploid beet, $n = 18$ in a tetraploid beet); x represents the chromosome number of the basic genome (9 in sugar beet). Initially there were great hopes that these would result in substantial yield increases (Schwanitz, 1938; Frandsen, 1939; Rasmusson & Levan, 1939). Instead, root weight and sugar yield almost invariably turned out to be significantly lower than that in their diploid progenitors. However, it was soon discovered that diploids and tetraploids hybridized freely and that resultant triploids ($2n = 3x = 27$) frequently outyielded not only their tetraploid, but also their diploid parents (Peto & Boyes, 1940). This discovery resulted in the development of polyploid, or, more correctly, anisoploid sugar beet varieties and is the basis for the present triploid hybrid varieties made possible by the introduction of cytoplasmic male sterility.

As with most other induced autotetraploids, tetraploid sugar beet have fewer leaves than corresponding diploids, but larger and thicker leaf blades with smaller length–width index and shorter and thicker petioles. In addition, flowers and seed clusters are bigger. Most of these differences are due to an increase in cell size, readily observed in guard cells of stomata and in pollen grains.

Together with these morphological changes go physiological changes, which usually manifest themselves in a somewhat slower growth rate. Thus, tetraploids tend to need a longer vegetative period than diploids to realise their full yield potential.

Cytogenetic properties of autotetraploid sugar beet

The presence of four completely homologous genomes in the tetraploids results in the formation of a varying number of quadrivalents, trivalents, bivalents and univalents at metaphase I of meiosis, both on the male and the female side. The situation differs from meiocyte to meiocyte, depending on the degree of pairing and number and distribution of chiasmata. The result is a disturbed chromosome segregation and formation of gametes with too many or too few chromosomes. Although univalents and trivalents frequently result in an unequal distribution of the four homologous chromosomes at M_I, in sugar beet the majority of aneuploid gametes are the result of irregular distribution of the chromosomes in quadrivalents. As a consequence, on an average 45% of the gametes produced by euploid, 36-chromosome plants are chromosomally unbalanced. In aneuploids with 37 chromosomes, the corresponding figure is 65–70%.

Even if many of these unbalanced gametes are not viable, or participate in formation of zygotes which later abort, the percentage of aneuploids in most tetraploid sugar beet populations is as high as 30–40% (Rommel, 1965; Bosemark, 1966). Since in triploids only one of the parents contributes unbalanced gametes, the frequency is roughly half that in tetraploids, i.e. 10–20% when the tetraploid is the pollen parent, as is the case in present triploid hybrids (Bosemark, 1966), and 20–25% when the tetraploid is the female parent.

If measured in the field, where euploid and aneuploid plants are randomly distributed in the row and compete with each other, the root yield of aneuploid tetraploids is only 65–70% of that from euploid tetraploids, while aneuploid triploids give about 50% of the yield of their euploid counterpart. However, if these figures are used to calculate loss in yield due to an established frequency of aneuploids, the detrimental effect of the aneuploids is exaggerated, since the yield relationship between euploids and aneuploids is affected by competition. Estimates have shown that the true loss in yield is usually less than half that mentioned above (Bosemark, 1967a; Lichter, 1967). All the same, if aneuploids could be eliminated the yield of tetraploid sugar beet populations would increase by 4–6% and that of triploids by 2–3%. However, attempts to decrease permanently the frequency of aneuploids have been unsuccessful.

To explain the average superiority in performance of triploids, Knapp (1957) suggested that the difference between diploid, triploid and tetraploid sugar beet is due to a combination of largely negative physiological effects of an increase in genome number and the positive effects of a better utilization of heterozygosity and multiple allelism made possible by polyploidy. In triploids the combined effects were considered on average to be positive, whereas in tetraploids the combined effects were considered on average to be negative. Although it is now known that the negative physiological effects of an increase in genome number are small compared to the negative effects of aneuploidy (Bosemark, 1971a), it has been well established that heterozygosity is a requisite for the success of autotetraploids.

Inheritance in autotetraploids

Although the principles of Mendelian inheritance apply in tetraploids as well as in diploids, in tetraploids they are complicated by the fact that in somatic nuclei each locus is represented four times instead of twice. While in a diploid there are three possible genotypes for each pair of factors (AA, Aa and aa), in tetraploids there are five possible genotypes (AAAA, AAAa, AAaa, Aaaa and aaaa). As in diploids there can be either full dominance or intermediate inheritance; in the latter case, all or only some of the heterozygotes may be distinguishable from each other.

The segregation ratios for all possible selfings and cross-combinations can be calculated from the properties of gametes produced by the five somatic genotypes given earlier. However, it must be emphasized that these segregation ratios apply only if the genes in two sister chromatids always go to different poles in anaphase II of meiosis. This is often, but not always, the case. Besides, if aneuploids occur they will also disturb the segregation ratios. Without going into further details it may be concluded that Mendelian inheritance in autotetraploids is much more complicated than in diploids.

Genetic background to inbreeding depression and heterosis in autotetraploids

Hecker (1972) showed that the reduction in root weight upon inbreeding in autotetraploid sugar beet was greater than can be expected by the approach to homozygosity, and, on an average, the same for diploids and tetraploids, but he could not find a good genetic explanation.

Similar results, obtained in lucerne, a natural autopolyploid, were attributed to loss of first order interactions from multiple allelic loci (Busbice & Wilsie, 1966). Further evidence for the importance of multiple alleles for inbreeding and heterosis in autotetraploids was obtained from comparisons of single-cross (SC) and double-cross (DC) hybrids at the diploid and tetraploid levels, respectively (Demarly, 1963; Lundqvist, 1966; Levings *et al.*, 1967; Dunbier & Bingham, 1975). These studies showed that, whereas maximum heterosis at the diploid level is achieved already in the SC hybrid of inbred parents, in the autotetraploids heterosis is progressive with maximum heterozygosity and heterosis arrived at only in the DC or later generations. These results were therefore taken as evidence for both the existence and the importance of multiple alleles for maximum heterozygosity in autotetraploids. However, Demarly (1968) pointed out that multiple alleles at a locus cannot be distinguished from chromosome segments containing linked genes and introduced the term ‘linkat’ to describe a chromosome segment that contains linked genes and is defined by probability of recombination.

Although the breeding methods for maximizing heterozygosity are the same whether we are dealing with multiple alleles, chromosome segments or both, especially in population improvement, it is important to know what kind of gene action predominates. However, the complexity of tetrasomic segregation and the absence of highly homozygous inbred lines make it difficult to study gene action in autotetraploids. Fortunately, lucerne tetraploids produced by chromosome doubling of diploids have turned out to be extremely well suited to such studies. These ‘doubled diploids’ have a maximum of two alleles per locus, and no higher order allelic interactions can occur. If the performance of such ‘double haploid’ populations changes following sexual generations with selection, these changes must be due to changes in the frequency of one of the two alleles at diallelic loci, coinciding with changes in the dosage of linkats in which the loci reside. Thus, any improvement in performance must be due to an increase in frequency of favourable dominant alleles present in the original doubled diploid. The change in performance cannot be the result of increased heterozygosity or increased allelic interactions, since both could only decrease or remain the same in a closed population. Research on gene action in tetraploid two-allele populations in lucerne has since shown that there is greater complementary gene interaction in autotetraploids than in diploids (Bingham *et al.*, 1994) and that yield in tetraploid lucerne is more responsive to genetic diversity than is the case in comparable diploids (Kidwell *et al.*, 1994a,b). The abrupt and severe inbreeding depression in lucerne and several other natural or induced autotetraploids, including sugar beet, can now be explained as the result of rapid loss of complementary gene interaction as a result of inbreeding. Similarly, progressive heterosis, characteristic of autotetraploids, is most likely due to a progressive approach to maximum complementary gene interaction. This does not exclude multiple allelic interaction at some loci, especially not in an old natural autotetraploid such as lucerne, but strongly suggests that complementation of favourable dominant alleles must be the predominating phenomenon, especially in artificial autopolyploids, including tetraploid sugar beet.

Response to selection in autotetraploids

There are no experimental data describing the effectiveness of selection in tetraploid sugar beet populations. However, where a simply inherited recessive character is selected against in a tetraploid and in a diploid population with the same selection intensity, selection is nearly five times as effective in changing the frequency of a recessive gene in diploids as in tetraploids. To effectively increase the frequency of favourable dominant alleles in a tetraploid population would require selection under inbreeding, which has rarely, if ever, been practised in tetraploid sugar beet. There is thus reason to believe that selection in tetraploid sugar beet populations has affected mainly characters with high heritability such as root shape, sugar percentage and some of the quality characters, and that it has had little or no effect on root yield.

SELECTION METHODS

Mass selection

In mass selection, desirable plants in a population are selected on the basis of their phenotypic characteristics. The selected plants are then bulked and intermated. The degree of heritability is by far the most important of the factors that determine the efficiency of mass selection. From this, it follows that mass selection is most effective for characters determined by few genes and which can easily be seen or measured. Mass selection is much less effective for quantitative characters, such as yield, as they are determined by many genes and cannot be accurately judged on the basis of a single plant.

When employing mass selection it is important to try to reduce the environmental variation as far as possible. Thus, selection plots should be placed in fields that are known to be uniform, and measures should be taken to ensure a regular plant population without gaps or damage by pests and diseases. Even so, there will be spots in the field with particularly favourable environmental conditions. To ensure that all environments of the experimental area are sampled equally, it is advisable to divide the selection field into smaller areas, and to select a set number of plants from each sub-population. Such a system is usually referred to as gridded or stratified mass selection.

In sugar beet, mass selection usually means phenotypic selection for morphological characters in the field followed by selection for chemical characters in the laboratory (Fig. 4.2). Such mass selection has been effective in the improvement of morphological traits such as root shape, in the development of highly bolting-resistant populations (Campbell, 1953), and in breeding for resistance to certain diseases (Coons, 1954). Mass selection may also be effective for sugar percentage and those quality characteristics which are largely controlled by genes with additive gene action (Smith *et al.*, 1973) and which have a reasonable degree of heritability (Hecker, 1967; MacLachlan, 1972a,b,c).

For root yield, which is governed largely by genes with non-additive gene action, and which has low heritability, response to mass selection in adapted populations is, at best, slow and erratic. Contrib-

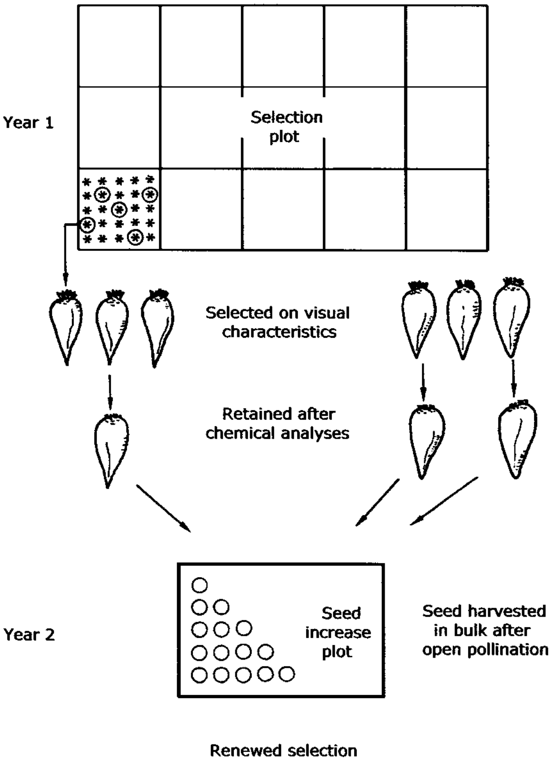


Fig. 4.2 Mass selection with sugar beet.

uting to the inefficiency of mass selection for root yield is the variation caused by inter-genotypic competition (Lichter, 1972). Thus, the competitional variance has been estimated to account for sometimes more than 50% of the total phenotypic variance (Lichter, 1975).

Since sugar yield, the most important character of the crop, is mainly determined by root yield, it also has a poor response to mass selection. In addition, the negative correlation between root weight and sugar percentage means that, if selections are made exclusively for sugar percentage, root yield usually decreases, often to the extent that the sugar yield is also reduced. If selections are made simultaneously for high root yield, high sugar percentage and a number of quality characteristics, the intensity of selection for each character is frequently reduced to a point where the breeder no longer selects extremes for any character, but largely intermediate combinations.

However, despite these limitations, it would be wrong to conclude that mass selection is always ineffective. It can still be an important technique, especially at the beginning of a breeding project, when starting materials may have to be adapted to new environmental conditions. It is also the first and most important selection method in sugar beet enhancement programmes utilizing germplasm from wild *Beta* beets to broaden the genetic base of sugar beet gene pools.

Progeny selection and line breeding

The best way to distinguish between plants that are superior owing to a particularly favourable environment and those that owe their superiority to their genotype is by progeny testing. Selection based on progeny testing is called progeny selection or family selection. Half-sib and full-sib progeny selection are differentiated by whether the breeder has control over one or both of the parents of a progeny.

Half-sib progeny selection

Half-sib progeny selection in sugar beet is usually carried out as individual selection followed by progeny testing. The starting material for the progeny mostly consists of roots selected in the field for size and morphological characters, and later reselected for sugar percentage and chemical characters, precisely as in mass selection. The selected roots are planted out and allowed to flower and set seed together. The seed is harvested from each plant separately and tested for bolting resistance, yield and quality characteristics in the following year. In that year, stecklings (young plants that will be grown on as seed bearers) are also grown from each progeny to permit progenies, selected on the basis of the trials, to be inter-crossed in the following year to produce the improved population.

The extent to which this procedure results in improved performance of the population depends not only on how well the field testing has discriminated between genetically superior and inferior progenies, but also on the type of gene action controlling the traits under selection. Frequently, both the number of progenies and the availability of seed prevent extensive testing of half-sib progenies. Further, if the major character under selection is yield, the best progenies usually owe most of their superiority to a high degree of heterozygosity and favourable allelic interactions, and this superiority will not be transmitted to the progeny.

To overcome partly this weakness in the method, the selected half-sib progenies may be propagated separately under isolation. On the basis of the resulting seed the progenies are again evaluated in comparative trials. This testing permits a better assessment of the breeding value of the progenies than did the previous test. This is due to the reduction in heterozygosity after half-sib mating and the larger number of locations and replications that can be sown from the seed increases. Progeny lines – usually called families – that are retained after this second selection may now be recombined into an improved population (Fig. 4.3). Population improvement through compositing of progeny lines is called line breeding or family line breeding. The use of repeated cycles of half-sib selection is referred to as recurrent half-sib selection.

Full-sib progeny selection

Another method of developing progenies is through pair-crosses between selected roots, so called full-sib selection (Fig. 4.4). This method permits a better separation of the original population than half-sib selection, since only two individuals contribute to the progeny. To assess correctly the breeding value of such progenies, it is even more important than in the case of half-sib progenies to make a seed increase before the final evaluation and selection. However, this generation is the result of full-sib matings, which next to selfing is the strongest form of inbreeding, and the performance of such progenies must be judged with this in mind. To subject full-sib progenies to a second full-sib selection is not to be recommended, unless the breeder aims to develop inbred lines. As with half-sib progeny selection, many variants of full-sib progeny selection have been developed and used with varying degrees of success (Hecker & Helmerick, 1985).

Progeny selection, first introduced by the famous French breeder Louis de Vilmorin in the middle of

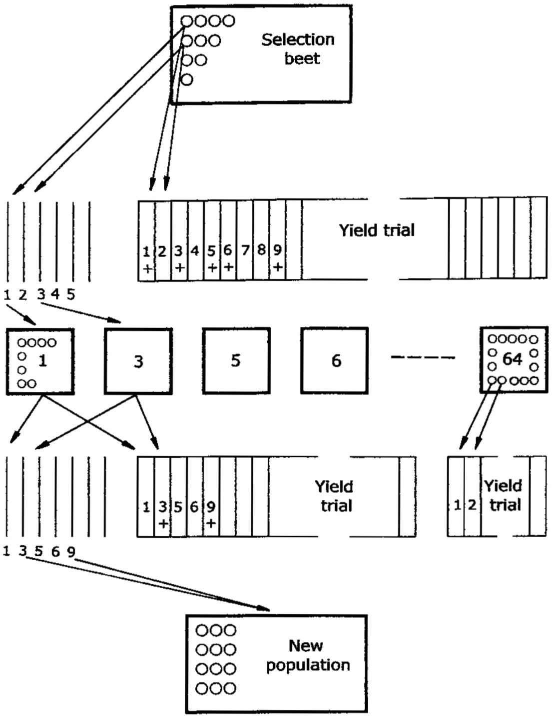


Fig. 4.3 Half-sib progeny selection with sugar beet.

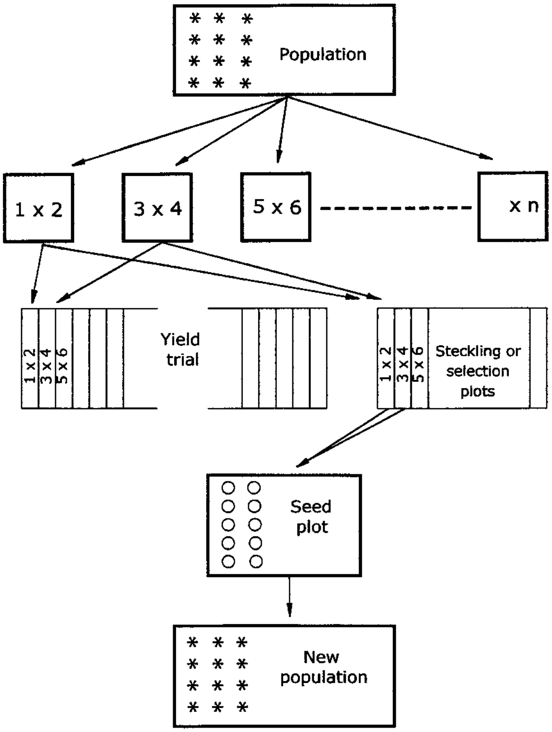


Fig. 4.4 Full-sib progeny selection with sugar beet.

the nineteenth century, is usually given credit for the rapid increase in sugar yield in the years up to 1920. Although undoubtedly more effective than simple mass selection, progeny selection and line breeding usually fail to improve sugar yield beyond a certain level. However, progeny selection is a very important method for characters for which there are few or no heterotic effects when crossing materials of different origin, and where the lines and populations themselves thus have to meet demands placed on commercial varieties.

Inbreeding

As has already been emphasized, in all selection work with cross-fertilizers it is important to have control over the pollination of the selected individuals. The strictest form of pollination control is achieved if the selected plants are subjected to enforced self-pollination. However, this is also the most severe form of inbreeding.

The main effects of inbreeding are:

- an increase in homozygosity;
- the appearance of lethal and sub-lethal types;
- the separation of material into different distinct types;
- a decrease in vigour and fertility.

However, species differ greatly with respect to reaction to inbreeding. On the one hand, sugar beet is rather sensitive, and although there is considerable variation between lines, only a few generations of selfing frequently produce lines that yield no more than half that of commercial varieties. On the other hand, already after one or two generations of selfing, sugar beet inbreds are usually remarkably uniform, especially in leaf and petiole characters (Stewart, 1933; Bandlow, 1965). When in spite of the reduced vigour of inbred lines, inbreeding is used in breeding work, it is usually for one or another of the following reasons:

- to facilitate selection and fixation of biotypes with special characteristics or combination of characteristics;
- to rid the population of recessive genes giving rise to abnormalities or weaknesses;
- to break down the heterozygosity of selected individuals and, through testing of a selfed generation, get better information on their true breeding value (S_1 testing); or
- to develop inbred lines for production of synthetic or hybrid varieties.

Apart from repeated progeny selection, which results in inbreeding through successive narrowing down of the genetic variability of the lines thus produced, inbreeding in its strict sense was rarely used in the development of the composite or synthetic varieties which preceded the current hybrid varieties. There are several reasons for this. For example, the difficulties of obtaining seed following the isolation of plants from highly self-sterile populations tend to favour plants and lines that self readily. When such pseudo-self-fertile lines are composited, there is often enough selfing to prevent maximum expression of hybrid vigour. Also, with the methods available at the time, it was difficult to assess the value of the inbreds as components of composite or synthetic varieties. Only after the introduction of cytoplasmic male sterility and hybrid breeding techniques has inbreeding become a major selection method in sugar beet breeding. Although the main objective of inbreeding in sugar beet is to produce inbred lines for the production of hybrids, in the process, advantage is also taken of the other benefits of inbreeding mentioned earlier.

The methods of developing inbred lines in sugar beet are similar to those in maize, and usually involve selecting plants during the inbreeding period on the basis of the appearance of a row of plants grown from the seed from the selfed plant. Undesirable lines are discarded as early as possible in the inbreeding period. Selfed seed from the most desirable plants are selected each year for the next generation of inbreeding. Plants may be selected on the basis of traits such as vigour, standability, branching, monogermity, seed size, seed yield, disease resistance and freedom from abnormalities. However, beyond the S_1-generation selection for yield must be based very largely on the performance of the lines in crosses.

Recurrent selection

Recurrent selection (RS) is a common name for a number of methods of population improvement originally developed to increase the frequency of desirable genotypes in maize populations to be used as sources for inbred lines.

Four main types of RS are usually recognized:

(1) simple recurrent selection (SRS) in which selection is solely on the phenotype or on S_1 progeny testing;
(2) recurrent selection for general combining ability (RSGCA) in which the selection is based on the performance of test-crosses to a heterozygous tester;
(3) recurrent selection for specific combining ability (RSSCA) in which the tester is chosen to provide information on specific combining ability of the selects;
(4) reciprocal recurrent selection (RRS) in which two populations, A and B, are involved. Each population is handled in the same way as in recurrent selection for general combining ability, except that population B is tester for A and A is tester for B.

As developed for maize, all recurrent selection methods require:

- that selected plans are selfed;
- that the selfed progenies of superior plants are crossed in all combinations;
- that equal amounts of seed from all crosses are bulked to form starting material for the next selection cycle.

However, the definition of recurrent selection given by Hull (1945) does not explicitly state that the selects must be recombined on the basis of selfed progeny. The only absolute requirement for a selection method to be called recurrent is that the selects are recombined before a new cycle of selection is initiated. With this definition, all repeated mass selections and progeny selections that fulfil this requirement qualify as recurrent selections.

Since selfing is an excellent way of preserving selected genotypes, and S_1 progeny testing is a useful selection method, it would be advantageous if both operations could be incorporated into a system of recurrent selection in sugar beet. If the object of the recurrent selection is to create populations from which superior inbreds can be extracted, the above requirements can be fulfilled by forming populations of plants carrying the gene for self-fertility and segregating for nuclear male sterility (Bosemark, 1971b).

One system of male sterile facilitated recurrent selection (MSFRS) possible with such populations consists of the following sequence of operations:

- recombination (obtained by harvesting seed on male-sterile segregants);
- production of S_1 seed from selected progenies;
- testing the S_1 progenies (followed by recombination of selected S_1 progenies).

Provided stecklings can be produced in the winter, one cycle thus takes 3 years (Fig. 4.5).

With this kind of population, various kinds of recurrent selection can be designed and practised, both in the development and continuous improvement of self-fertile, monogerm O-type populations and their cytoplasmic male sterile counterparts,

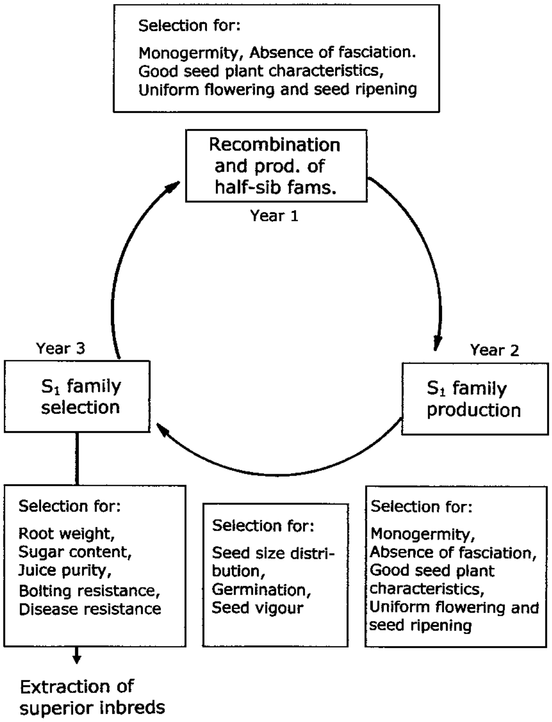


Fig. 4.5 Simple recurrent selection (SRS) in a self-sterile, monogerm, type O sugar beet population segregating for nuclear male sterility. The figure illustrates the characters that may be selected for in each of the 3 years of a selection cycle.

and for improvement of pollinator populations. Recently, Mackay *et al.* (1999) proposed a new class of full-sib family recurrent selection schemes, called accelerated recurrent selection (ARS), in which selection is based on the predicted performance of progeny families, estimated as the average of the parental families. As suggested by the authors, the 3-year cycle time normally required by MSFRS with S_1-family testing may be reduced to 2 years in an ARS scheme, provided that the selected families are recombined by producing full-sibs. Then the testing as well as the recombination of the S_1 families can be carried out in 1 year.

Some years ago Doney and Theurer (1978) proposed a system of reciprocal recurrent selection (RRS) in sugar beet, which utilized two self-fertile, monogerm, O-type populations segregating for nuclear male sterility. With root weight primarily conditioned by non-additive genetic effects, and sugar percentage by additive effects, RRS should be well suited for the development of parents for single-cross hybrids in sugar beet. Hecker (1978) reported that two cycles of RRS resulted in certain improvements in both populations. However, neither of the populations was improved in both root yield and sugar percentage, and crosses between them were no better than those between the starting populations. Inadequate precision in the test crosses, in which A × B and B × A had 96% and 45% hybrids respectively, probably contributed to this lack of improvement. In another similar study, Hecker (1985) carried out two cycles of RRS with separate emphasis on recoverable sugar, root yield and sugar percentage, which resulted in three populations from each source. In this study not only were the populations improved but the six AC2 × BC2 hybrids gave significantly higher sugar yields than the AC0 × BC0 hybrid, suggesting that RRS should be an effective method for development of single-cross sugar beet hybrids.

TRADITIONAL METHODS OF VARIETY DEVELOPMENT IN SUGAR BEET

Diploid synthetic varieties

At the beginning of the twentieth century, sugar beet varieties consisted of broad-based, open-pollinated populations maintained through a combination of mass selection and half-sib family selection. However, in the 1920s breeders began to develop kinds of synthetic varieties, which came to dominate the sugar beet seed market for many years to come and which thus merit description.

Usually, commercial seed of synthetic varieties consists of advanced generations of the crosses between constituent lines. Although in diploids a certain portion of the heterotic effect is lost in the F_2 generation, this is the only practicable system when synthetics are based on clones or inbred lines that are too difficult or expensive to reproduce on a large scale. However, where component lines can be multiplied to such quantities that the F_1 generation itself can be utilized as commercial seed, one can avoid the loss of yield in F_2. This is the system that was used by sugar beet breeders for nearly half a century before the advent of hybrid breeding. Many breeders refer to varieties produced by this system as ‘multi-strain varieties’ or composites, but where components have been selected on the basis of mutual combining ability, it is more appropriate to call them ‘first generation synthetic varieties’. Commercial seed of such sugar beet varieties was always produced anew from the constituent lines and consisted very largely of first generation hybrid seed.

The components of the synthetic varieties were usually more or less heterogeneous families or populations of diverse origin developed by progeny selection and line breeding (Fig. 4.6).

After evaluation of all potential components for root yield, sugar percentage, impurities, bolting resistance, etc., those populations that performed well by themselves were tested for general combining ability (GCA). This was done either by a top cross, a polycross or a series of single-cross tests. To decide which strains were the best combiners, the test-cross progeny were evaluated over a range of locations and the test-crossing repeated for 2 or 3 years.

When the populations thus selected had been increased to mother-seed quantities, an equal amount of mother seed from each strain was carefully mixed. This mother-seed mixture was used to produce stecklings from which seed of the new synthetic variety was grown.

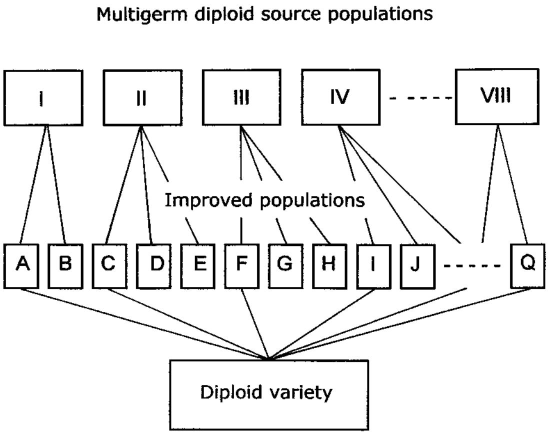


Fig. 4.6 Method of producing a diploid synthetic sugar beet variety. The improved populations, which are inter-crossed to produce the commercial seed of the synthetic, are selected on the basis of their general combining ability.

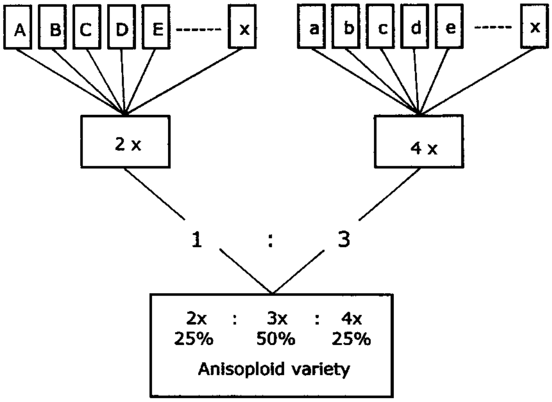


Fig. 4.7 Method of producing an anisoploid synthetic sugar beet variety. Since the tetraploids produce both a smaller amount of pollen and pollen that is less effective than that of the diploids, the mother seed lots of the diploid and tetraploid components have to be mixed in the proportions 1:3 to arrive at a commercial seed containing roughly the proportions of diploids, triploids and tetraploids indicated.

Anisoploid synthetic varieties

Seed of anisoploid sugar beet varieties (frequently but incorrectly called polyploid varieties) is produced by allowing diploid and tetraploid seed plants, grown in mixed stand, to pollinate each other freely. The resulting seed gives rise to a mixture of diploid, triploid and tetraploid plants in certain proportions (Fig. 4.7).

The reason for producing anisoploid varieties was that, on average, triploids were found to be more productive than either diploids or tetraploids. Forty years ago, when this type of variety was first developed, male sterility was not available in sugar beet and pure triploid seed could thus not be produced. All the same, anisoploid varieties gradually replaced diploid varieties in most European countries and, even before the advent of genetic monogerm varieties, relatively few multigerm diploid synthetic varieties were still in use. Since then there has been a similar replacement of the anisoploid varieties by hybrid monogerm varieties.

BACKGROUND TO HYBRID BREEDING IN SUGAR BEET

In the production of diploid and anisoploid first-generation synthetic varieties, the objective was to make use of the heterotic effects obtained when crossing certain unrelated genotypes. However, the discovery of cytoplasmic male sterility in sugar beet (Owen, 1945) made it possible to do this more efficiently by using male sterile lines in the production of strict hybrid varieties (Owen, 1948; 1950; 1954a). As a result, since the 1970s, hybrids have replaced synthetic varieties in practically all beet growing countries. Part of the reason for the rapid change over to hybrid varieties is that cytoplasmic male sterility and the monogerm seed character became available to sugar beet breeders almost simultaneously in the early 1950s, at a time when the labour situation in sugar beet growing had begun to cause concern in several countries.

Faced with the problem of having to quickly develop genetic monogerm varieties with satisfactory yield and quality characteristics, the choice of a hybrid programme for the monogerm breeding was natural for two reasons. Firstly, a hybrid programme only requires the incorporation of the monogerm seed character in part of the existing breeding material, and, secondly, the success of hybrid maize strongly favoured a similar approach in sugar beet breeding.

HYBRID BREEDING METHODS AND DEVELOPMENT OF HYBRID VARIETIES

Development of maintainer lines (O-types) and their male sterile (MS) equivalents

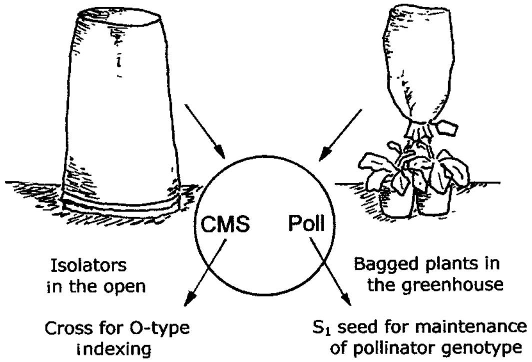
Although sugar beet breeders have been fortunate in having been able to fall back on experiences of hybrid breeding in other crops, in particular maize, they have had to cope with several problems specific to sugar beet.

Thus, female parent lines of monogerm sugar beet hybrids must not only be homozygous for the recessive gene for the monogerm seed character but must also be cytoplasmic male sterile. This means that sugar beet breeders, in contrast to maize breeders, could not initiate hybrid breeding by developing large numbers of inbred lines from existing open-pollinated varieties. Instead they first had to: (a) make controlled crosses between a monogerm source population and multigerm populations; (b) select acceptable monogerm segregants from the resultant F_2 generations; (c) test-cross and index the F_3 generation from selected monogerms for maintainer genotype; (d) select monogerm maintainer genotypes with acceptable agronomic characteristics and combining ability and, finally, (e) produce equivalent cytoplasmic male sterile lines of the best maintainer genotypes through repeated back-crossing to plants carrying 'sterile cytoplasm'.

To this should be added that the self-fertile monogerm source material was low yielding and defective in several respects. These restrictions all contributed to slowing down and to limiting the output of monogerm male-sterile lines that combined satisfactory characteristics with superior combining ability. However, in contrast to hybrid grain crops, where male parents of restorer genotype are required to restore the pollen fertility of cytoplasmic male-sterile female parents, this is not needed in sugar beet where the concern is only with the vegetative production of the commercial crop.

As has been described previously, maintainer genotypes, or O-types, have to be identified through test-crossings to CMS plants. These crosses may be carried out in the greenhouse or in the field using paper bags or isolators of one kind or another. Of the two seed lots harvested, that from the pollinator is selfed seed and is used to preserve the pollinator genotype until the cross has been scored for male sterility. To speed up this work an annual CMS line (ACMS) is often used for the test crosses to identify O-types. The advantage is that the test-cross progenies from ACMS plants will come to flower without photothermal treatment (Fig. 4.8).

Since sugar beet is normally self-sterile, development of inbred O-type lines from such source populations may present difficulties, especially in areas with hot summers where, under isolation, self-sterile beets set little or no seed. Under such conditions the genotypes of test-crossed plants are



		MS-classes %					Stecklings
		1	2	3	4		
Cross	1	37	29	14	20	Self 1	Discard
"	2	100	–	–	–	" 2	O-type
"	3	78	22	–	–	" 3	Test-cross S_1
"	4	41	24	25	10	" 4	Discard
"	5	89	11	–	–	" 5	Test-cross S_1
"	6	12	39	20	29	" 6	Discard

MS-class 1 = white, empty anthers. Male sterile
" 2 = } intermediate types
" 3 =
" 4 = shedding pollen

Fig. 4.8 Identification of maintainer (type O) genotypes through test-crossings. The results of the test-crosses show that cross 2 involved an O-type genotype, which may be propagated on the basis of the stecklings produced from S_1 seed (Self 2). The proportion of offsprings in MS-classes 1 and 2 in crosses 3 and 5 suggest that renewed test-crossing in the S_1 generation of the corresponding pollinators (Self 3 and 5) will yield good O-types.

frequently lost unless they are maintained by vegetative propagation. As a consequence, sugar beet breeders often retained the gene for self-fertility present in the original monogerm source SLC 101 (Savitsky, 1954).

The identified monogerm O-types may be handled in different ways depending both on the type of hybrids aimed at and the philosophy of the breeder. Thus, an O-type S_1 line may be increased through sib-mating, tested for its own performance as well as for combining ability with unrelated CMS-lines and, if approved of, used in variety production without further inbreeding.

The alternative is to continue the inbreeding through selfing for further generations, with or without test-crossing for combining ability and back-crossing to a prospective CMS counterpart. The inbreeding should be accompanied by selection for vigour and various seed characters; for some characters the selection can be made before isolation and flowering, for others only after the seed has been threshed and cleaned.

Lines that survive beyond the S_2–S_3 generation are now tested for specific combining ability. If a line is approved of, and the development of an equivalent CMS line has not been initiated concurrently with the development of the O-type inbred, it is advisable to do so afterwards, since this allows for more flexibility in the use of the line.

The propagation of O-types and male steriles must always be done under strict isolation to prevent contamination. Male sterile plants that begin to flower before the accompanying O-type plants are likely to pick up any stray pollen in the air. Inbred O-types, developed from self-sterile materials, are also very easily contaminated and, if possible, it is advisable to produce the elite seed of such materials in pollen-proof greenhouse compartments or outdoor cabins. As mentioned above, self-fertility in the O-type offers a considerable amount of protection against contamination.

Initially, identification and development of monogerm O-type lines and their CMS counterparts was the most laborious and expensive part of hybrid breeding in sugar beet. This was due to the scarcity of O-types with sufficiently good characteristics and combining ability. That genotypes capable of producing outstanding hybrids are rare is to be expected. However, the situation in sugar beet was aggravated by the low frequency of the O-type genotype and the need for female parents to be monogerm. Initially, the gene for self-fertility (S^F) also prevented the creation of more broad-based monogerm maintainer populations that could be recombined and reselected and used as sources for future O-type inbreds. As a result, many breeders have since eliminated the S^F gene from most of their monogerm breeding materials, permitting to intermate self-sterile, monogerm O-type lines to form self-sterile breeding populations. Alternatively, they use nuclear male sterility to facilitate hybridization. All the same, the total monogerm gene pool is still restricted and rarely subjected to systematic population improvement.

Testing for combining ability and incorporation of selected materials into hybrid varieties

As previously mentioned, in the early days of hybrid breeding in sugar beet, O-type lines that survived the initial screening for vigour and freedom from various defects were usually immediately tested for general combining ability (GCA). The seed for this test can be produced by propagating each inbred O-type and its prospective CMS counterpart together with an unrelated cytoplasmic male-sterile tester known to possess good GCA. In the crossing plots, the O-type, its male sterile equivalent and the male-sterile tester are planted in alternating strips to facilitate pollination and to allow the three seed lots to be harvested separately without risk of contamination. The seed harvested on the male-sterile tester plants is used for field trials to assess the GCA of the O-type lines.

Lines that appear to have satisfactory GCA may then take part in a diallel cross together with other accepted O-types and their male sterile equivalents to produce an array of F_1 MS combinations on which the specific combining ability (SCA) of the lines can be assessed. Alternatively, the new O-type lines may be tested in crosses with the best existing CMS lines. This has the advantage of speeding up the commercial use of the new O-type.

Based on result of these crosses, the best F_1 MS combinations are selected and crossed with a number of diploid or tetraploid pollinators to produce the final hybrid. After extensive testing of these crosses, the components of those hybrids that appear to be superior to existing commercial varieties are increased to permit production of larger quantities of seed under commercial seed-growing conditions. Only after further extensive testing and approval by official variety-testing authorities will a hybrid be released to the farmers.

Today, breeders more seldom start the development of new monogerm O-type inbred lines by making crosses with non-O-type multigerm sources. Instead the source materials consist of existing elite monogerm type O inbreds, advanced monogerm type O breeding lines and selected monogerm type O populations, and the selection procedure may be described as pedigree selection adapted to the requirements of hybrid sugar beet breeding (Fig. 4.9).

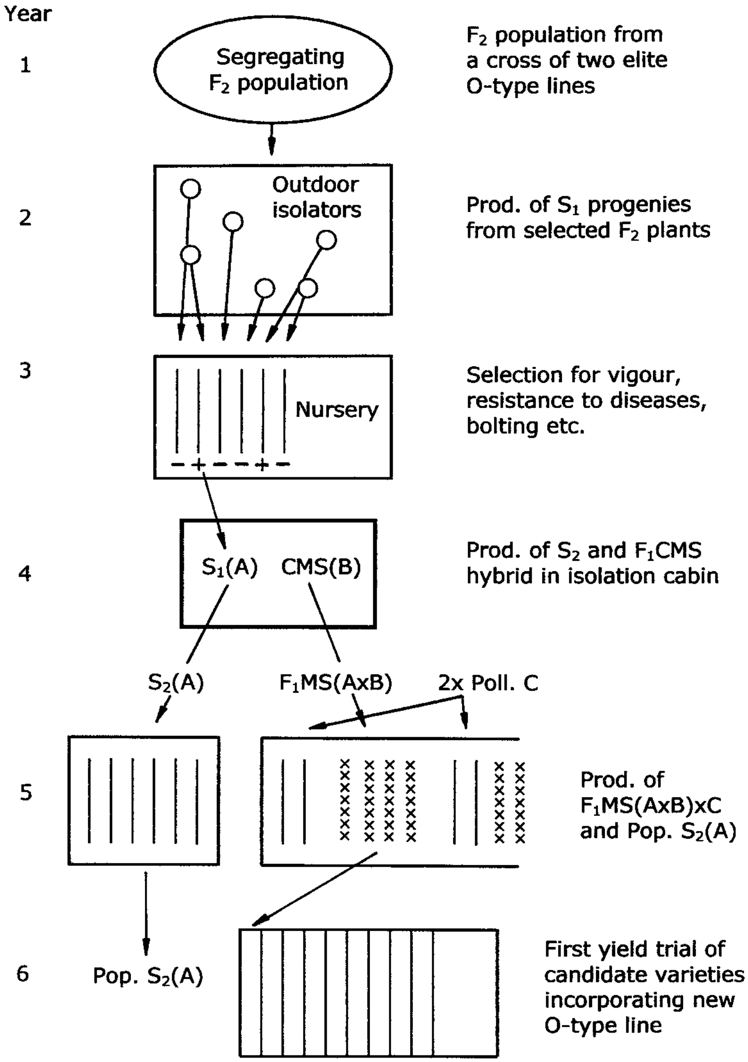


Fig. 4.9 Method of developing and testing monogerm, type O inbred lines.

Obviously, the procedure outlined above omits many possible alternative ways of developing and testing components and the hybrids themselves (Barocka, 1985; Hecker & Helmerick, 1985; Smith, 1987). Thus, depending on the importance attributed to SCA in the kind of hybrids aimed at, testing for SCA may be omitted altogether or severely restricted, and the development of male-sterile equivalents of the O-type lines may be delayed and limited to lines whose usefulness has been demonstrated.

Kind of hybrids	Pedigree
1. Single hybrid	A x B
2. Three-way cross	(A x B) x C
3. Double cross	(A x B) x (C x D)
4. Top-cross	A x open poll. population
5. Top-cross	(A x B) x open poll. population

(A, B, C and D stand for inbred lines)

Fig. 4.10 Kinds of hybrids and their corresponding pedigrees.

Kinds of hybrids possible

Diploid hybrids

With the introduction of cytoplasmic male sterility in sugar beet breeding, different hybrid programmes were made possible. In the USA, where polyploidy had not been introduced in conventional sugar beet breeding programmes, diploid hybrid programmes were seen as the next step forward. In Europe, the positive experiences with anisoploid sugar beet varieties made it natural to use the new techniques to produce 100% triploid hybrid varieties. As a consequence, until recently, all USA-bred commercial sugar beet varieties were diploid, whereas in Europe, the majority of the leading varieties were triploid, based on diploid male sterile females and tetraploid pollinators. However, in recent years the proportion of diploid varieties in Europe has steadily increased and diploid varieties now outnumber triploid varieties on the recommended lists in most countries. At the same time, some European breeding organizations have introduced triploid varieties in the USA. The reason for these changes will be discussed in another context.

In sugar beet, as in maize and other crops, diploid hybrids can be built up in different ways using a smaller or larger number of inbred or open-pollinated components (Fig. 4.10).

With the exception of some hybrids in the USA (Smith, 1987), hybrid sugar beet varieties have rarely been based solely on highly inbred lines, as is usually the case in maize (1, 2 and 3 in Fig. 4.10). Until recently, the most common system has been to use an F_1 hybrid between an inbred male sterile line and an unrelated inbred O-type as the female parent, and an open-pollinated line or population as the pollinator parent as outlined under 5 in Fig. 4.10.

The reason for this is that, at least at the beginning of a hybrid breeding programme, hybrids from a broad-based pollinator are likely to have a more stable performance over a range of environments than those from an inbred pollinator. Besides, in production of monogerm hybrid seed for commercial use, only the female parent needs to be monogerm, and it has therefore been possible to utilize existing, well-tried multigerm populations as pollinators in the final cross. However, inbred, diploid, multigerm pollinator lines are now produced by most sugar beet breeders and are used in commercial varieties. Some of these varieties have been built up in the same way as double-cross hybrids in maize, with the exception that the male parent has not been an F_1 hybrid but an advanced generation of a cross between two inbreds, produced without male sterility.

As proposed by Owen (1954a), double-cross hybrids may be produced by utilizing cytoplasmic male sterility in one of the single crosses and the final cross, and nuclear male sterility in the other single cross. A more convenient method, suggested by Theurer and Ryser (1969), consisted of production of double-cross restored hybrid varieties based on four inbreds: two cytoplasmic male sterile, one O-type and one pollen fertility restorer. However, it was not made clear to what extent restored single-cross hybrids can be relied upon to produce adequate pollen under adverse weather conditions, neither has it been demonstrated that such double-cross hybrids are higher yielding or have other advantages sufficient to offset the extra costs.

Over the last 15 years strict three-way hybrids, based on a single, more or less inbred diploid pollinator line have become steadily more important. Even some highly competitive diploid single-cross hybrids have appeared on the market. However, for diploid single-cross hybrids to be a viable commercial proposition, the parental inbred lines must not only produce hybrids with superior yields, quality and disease resistance, the lines themselves must be vigorous, easy to handle and capable of producing high yields of good quality seed. The fact that only a few single-cross hybrids have been made commercially available is likely to be due to high seed production costs with current inbred CMS females. However, parental lines with better vigour and seed production capacity may be developed from monogerm maintainer populations and multigerm pollinator populations, both subjected to recurrent S_1 selection as previously described. The populations can be selected either separately or in conjunction. In the latter case, S_1 selection within each population may be followed by selection for GCA based on test crosses with the opposite population.

Figure 4.11 illustrates such a system of reciprocal recurrent selection, in which population A consists of monogerm, self-fertile, O-type plants segregating for nuclear male sterility. This population will be the source of inbred O-type lines from which will be developed equivalent CMS inbreds to be used as females in hybrid production. Population B is a multigerm, self-fertile population also segregating for nuclear male sterility. This population will serve as the source of the inbred pollinator lines.

For a couple of cycles of selection after the establishment of the two populations it may be advantageous to conduct SRS with S_1 progeny testing in each population separately, and only after that to introduce the full RRS selection cycle. Breeders may also alternate between cycles of SRS only and SRS in combination with RRS as they see fit. However, it should be remembered that although the combination of SRS and RRS ought to be more effective than SRS alone, the increased cycle length and the higher cost of the RRS may outweigh its benefits.

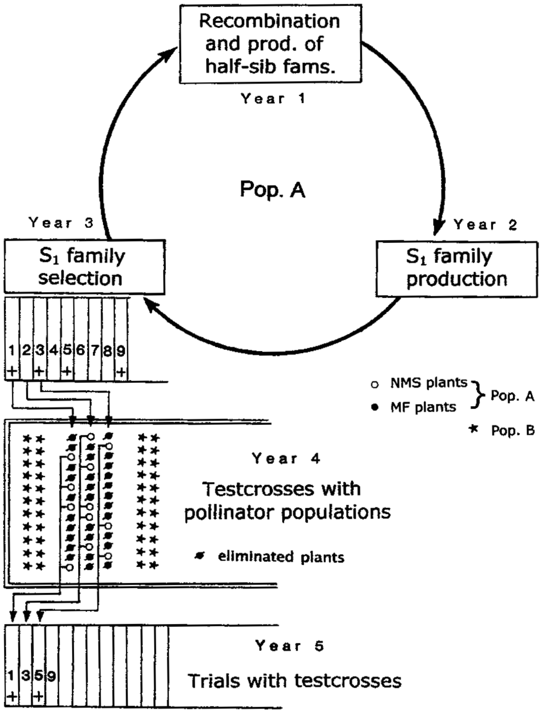


Fig. 4.11 Proposed system of RRS incorporating SRS with S_1 testing for each of the populations A and B separately, and selection for GCA with the opposite population. Population A is a self-fertile, monogerm type O population segregating for NMS. Population B is a self-fertile, multigerm pollinator population segregating for NMS. The figure shows the handling of population A only. Population B is handled in an identical way. For further explanation see text.

Triploid hybrids

In principle, triploid hybrids can be produced either on diploid or tetraploid male sterile, female parents. However, virtually all commercial triploid hybrids have been based on diploid male steriles and tetraploid pollinators, and it took several years before the reciprocal hybrids were even tested on a reasonable scale. The reason is that identification and development of tetraploid O-types, through test-crossing in tetraploid populations, is bound to be very difficult. Thus it was not until good, diploid monogerm O-types and male-steriles were available that it was possible to create tetraploid versions by chromosome doubling, and to use these in triploid hybrid production. Experience with such hybrids is also limited and reports that they will yield better than comparable triploids produced on diploid male steriles (Fitzgerald, 1975; Lahousse, 1976; Smith *et al.*, 1979) have not been confirmed in more extensive tests.

In triploid hybrid programmes the question of open-pollinated versus inbred pollinators has not arisen, since the production of high-yielding triploid hybrid varieties appears to be incompatible with inbred or too narrowly based tetraploid pollinators. Thus, tetraploid pollinator populations, used in the production of triploid hybrid seed, are usually developed in much the same way as diploid open-pollinated populations or synthetics. On the other hand, breeders quickly recognized the importance of genetic diversity for the performance of tetraploid populations and usually intermated selections from different tetraploid populations to form broad-base composites, which were used as components of anisoploid varieties as well as pollinators in triploid hybrid varieties. However, once a certain level of diversity and heterozygosity has been achieved, little or no further progress can be expected unless one can effectively increase the frequency of favourable alleles. This is the weakness of the traditional methods of developing tetraploid populations in sugar beet.

In recent years the development of efficient *in vitro* vegetative propagation methods (Saunders & Shin, 1986) has made possible the production of large numbers of clonal plants from individual tetraploid genotypes selected for specific traits and/or superior combining ability. Synthetics produced by intermating of a limited number of such clones can then be used as pollinators in triploid hybrid production (Middelburg, 1990; Depicker *et al.*, 1994).

Diploid versus triploid hybrids

When European sugar beet breeders had to decide between different methods of producing genetic monogerm varieties, most of them chose to develop monogerm triploid hybrids based on diploid monogerm male steriles and tetraploid pollinators. It was considered that development of triploid hybrids would be a quicker way to achieve monogerm varieties with acceptable yield and quality characteristics than alternative strategies, including using diploid hybrids. In triploid hybrids two of the three genomes would come from adapted tetraploid multigerm populations and only one from the monogerm male steriles, which still suffered from some of the weaknesses of the American source material.

These opinions were supported by the rapid appearance of several European monogerm, triploid hybrids with reasonably satisfactory characteristics, and for a considerable number of years, triploid hybrid varieties almost invariably produced a greater yield than comparable diploid hybrids. However, besides the higher costs and complexities of triploid hybrid breeding, triploid hybrids have several inherent disadvantages, all of which have to be balanced by a single, increasingly uncertain advantage – higher yield. The major weaknesses of triploid hybrids all relate to the presence of aneuploids, which affect both the uniformity and yield of the root crop and the yield and quality of the seed crop. Thus, with frequencies of aneuploids in the range of 12–18%, the loss of potential yield in a triploid hybrid variety may amount to over 3%. As for seed production, the lower pollen quality, due to aneuploidy and post-meiotic nuclear fragmentation (Bosemark, 1967a,b), and the fact that tetraploids release their pollen later in the morning than do diploids (Scott & Longden, 1970), results in lower pollinator efficiency, which can only partly be compensated for by increasing the proportion of pollinators in the seed production fields. Consequently, the seed yield from triploid seed crops is often lower than from diploid, and triploid seed crops are more easily contaminated by weed beets or other sources of unwanted pollen. As a result, growing high-quality triploid hybrid seed is more costly and requires more skill and experience than growing diploid hybrid seed. However, even given this extra attention, it is difficult for triploid seed to match the quality of good diploid seed.

In spite of these disadvantages, triploid hybrids dominated the hybrid seed market for nearly 25 years. The most likely reason was the limited genetic variability in the monogerm gene pool, caused by the need to first select for the monogerm and male sterility-maintainer-genotypes, and subsequently, within this restricted gene pool, to develop lines with vigour, satisfactory quality characteristics and good combining ability. This explanation is supported by a study in which a number of diploids and tetraploids were compared as pollinators on a range of diploid CMS lines (Lasa *et al.*, 1989). The results showed that the contribution of the tetraploid pollinators to the final yield of the triploid hybrids is quantitatively more important than that of the CMS lines, and that significant differences between the CMS lines in crosses with diploid pollinators were masked in the crosses with the tetraploid pollinators. Further, the triploid hybrids showed higher environmental stability than the diploid hybrids.

However, since then most breeders have greatly increased the genetic variability in their monogerm gene pools, and use various systems of selection to develop new improved monogerm, type-O inbreds and their male sterile equivalents. This, together with a similarly intensified breeding of diploid multigerm pollinator lines, has resulted in highly competitive diploid hybrid varieties and resulted in a dramatic decrease in the proportion of triploid sugar beet varieties in most European countries.

Although the need to develop varieties resistant to the rhizomania disease has accelerated the change over to diploid hybrids, without the developments described above, production of rhizomania-resistant varieties with competitive yield and quality characteristics, also under disease-free conditions, would not have been possible.

Summing up, without a significant yield advantage of triploid hybrids, there is little that argues in their favour. On the contrary, the old disadvantages due to aneuploidy, together with new disadvantages in connection with the use of molecular markers, gene transfer and gene expression, will probably make triploid hybrids disappear altogether in relatively few years' time.

BREEDING FOR SPECIFIC CHARACTERS

Bolting resistance

Varieties for spring sowing

In selection for bolting resistance, north-west European sugar beet breeders relied for a long time solely on early sowings in the field, usually in the same climatic area in which the varieties were to be grown. This dependency on weather conditions which do not always permit early sowing and sometimes result in very few bolters irrespective of sowing date, made it difficult to select for a high degree of bolting resistance. Also in years with conditions favourable for bolting induction, the percentage of bolters is frequently too low for mass selection to be effective beyond a certain level. Thus, a system was needed that permitted rigid bolting selection under severe and controlled conditions of bolting induction.

One of the first to propose methods by which this could be achieved was Bell in England (Bell & Bauer, 1942; Bell, 1946). Beginning in 1939, he studied the effect of low temperature and continuous light treatment on seedlings in a number of sugar beet strains and showed that different genotypes differ strikingly with respect to the length of treatment required for subsequent bolting and flowering. He also demonstrated that non-bolting plants, selected from strains in which the majority of the plants bolted, give rise to progenies with a very high degree of bolting resistance. These results were later confirmed by several other workers in more extensive studies on the physiology of flower induction in sugar beet (Gaskill, 1952; Curth, 1960; Margara, 1960).

As a result, it is now well established that young sugar beet plants can be induced to flower by photothermal treatment (5–8°C and 16 hours' light). The duration of this treatment required to induce 100% flowering ranges from 8 to 14 weeks, depending on the bolting resistance of the material. The longer treatment thus permits going from seed to seed in 1 year in virtually all materials, which has been of immense importance in accelerating breeding progress. Treatments of shorter duration than that required to induce all plants to bolt permit selection of genotypes with pronounced bolting resistance.

The methods and principles indicated by Bell were further developed and applied in sugar beet breeding work at the Plant Breeding Institute (PBI) in Cambridge (Campbell, 1953), where they resulted in two varieties which, at the time, were quite outstanding in bolting resistance. As a consequence, similar methods were adopted by virtually all north-west European sugar beet breeders and have resulted in considerable improvement in bolting resistance also in current sugar beet varieties.

Although a long day increases the efficiency of the cold treatment, and is necessary for subsequent flowering and anthesis, most genotypes can also be induced to bolt under short-day conditions, provided the subsequent growth takes place under long-day conditions. This means that areas where sugar beet can be sown outdoors sufficiently early for the seedlings to receive a month or more of effective thermal induction offer excellent opportunities for bolting selection. Thus, a great deal of the PBI selection work mentioned above was carried out near Edinburgh in Scotland, where the average April air temperatures are 2°C lower than in Cambridge.

Where it is not possible to sow outdoors early enough to get a satisfactory induction period, the material may be sown in a greenhouse and transplanted to the field when conditions permit. With this system, which was used on a large scale in Sweden in the early 1960s to improve the bolting resistance of diploid as well as tetraploid open-pollinated populations, the seed is sown in beds in a heated greenhouse without supplementary light at the end of January. When the plants are 3–4 weeks old, the ventilators are opened, and the heating adjusted so that the plants are subjected to a temperature of 3–8°C. As soon as soil and weather conditions allow, usually at the beginning of April, the young plants are transplanted to the field. On average this means 5–6 weeks of induction in the greenhouse followed by some additional induction in the field. When harvested at the end of October, the percentage of non-bolting plants in such selection plots ranges from 5 to 35%, depending on the material. Populations developed from such selections showed very good bolting resistance in the whole of north-western Europe.

The methods of bolting selection described so far require two seasons: one for the selection and one for the reproduction of the selected plants. For smaller volumes of material it is possible to sow the seed in the greenhouse in the autumn, give the young seedlings 4–5 weeks of photothermal induction in a growth room, and then bring them back to the heated greenhouse. If given continuous light, the more susceptible genotypes will quickly begin to produce a seed stalk. After removal of all plants showing signs of stem elongation, the remaining plants are taken back to the growth room for a second period of photothermal treatment of 12–14 weeks duration. If the first induction period is given early enough in the autumn, the second treatment will be finished in time for the plants to be transplanted to the field for reproduction in normal time in the spring.

Although the practical problems in connection with selection for bolting resistance have been largely solved, there are still several questions of a genetical and physiological nature, which, if better understood, would make the selection work easier and more efficient. One such question is the relative importance of resistance to long days and resistance to low temperatures in determining bolting resistance in different geographic zones. That such differences exist is clear from comparisons between south European and north-west European varieties in their respective areas of origin. While south European varieties always bolt excessively in north-western Europe, the difference in early sowings in southern Europe may be very small or none at all. There is thus good evidence that bolting and flower induction is conditioned by a delicate balance between the requirement for temperature and day length, on the one hand, and ecological and agricultural conditions on the other hand. If, as suggested by Bell (1946), the most efficient exploitation of the vegetative phase of development in terms of net assimilation and sugar storage is due to a similar balance, severe selection for resistance to long days may result in norms of reaction, which are necessary and beneficial in north-western Europe, but unnecessary or even detrimental in southern Europe. Thus, it may be important that breeding work for bolting resistance is carried out under the ecological conditions for which the variety is being developed, in the same way as it is important for breeding work in general.

Varieties for autumn sowing

What has been said above should apply equally to the development of varieties for autumn sowing in southern Europe or elsewhere. Such varieties, sown in the autumn and harvested in the following summer, need to be extremely bolting resistant while at the same time reaching their maximum sugar yield as early as possible in the summer.

In recent years there has been an increasing interest, not only in extending autumn sowing in southern Europe (Rosso *et al.*, 1999), but in introducing this system also in north-western Europe, primarily in England and Ireland. However, as pointed out by Jaggard and Werker (1999), sowing of beets in north-west Europe would produce both potential benefits and problems. Although the potential yield advantage of autumn sowing may be 25% or more, this might well be lost through greater sensitivity to summer droughts and various diseases such as rhizomania, virus yellows, the beet cyst nematode, powdery mildew and downy mildew.

To combine acceptable yield and quality characteristics with extreme bolting resistance, frost tolerance, drought resistance and resistance to a range of diseases will call for recurrent selection methods such as the modified MSFRS-system proposed by Jonsson (1999). However, to produce seed of such extremely bolting resistant varieties may require treatment of the seed crop with a growth hormone, or the introduction of the dominant gene B, combined with an inducible promoter through which the expression of the gene can be controlled (Jung & Hohmann, 2001).

Technological quality

Several morphological, anatomical and physiological characters directly or indirectly affect the technological value of the sugar beet crop and may be subjected to selection. However, all these are subsidiary to the main characters that constitute a high-quality sugar beet; these are high sugar percentage and low concentration of sodium, potassium and α-amino nitrogen relative to that of sugar. It is also important for the stability of the juice in the factory that the content of α-amino nitrogen is low relative to that of sodium and potassium. Under certain growing conditions raffinose and invert sugar cause sufficient losses and disturbances in the factory to merit attention by the breeders. For a comprehensive review of sugar beet quality problems and the possibilities of breeding for improved technological quality see Oltmann *et al.* (1984) and Jansen and Burba (2001).

There is a great deal of genetic variability in quality characters in most sugar beet populations, but there is also a considerable environmental influence, especially for sodium and α-amino nitrogen. In addition, some quality characters are significantly correlated both with each other and with root weight (Table 4.1).

Several studies have demonstrated that the heritability of all quality characters is sufficiently high for rigorous mass selection to be effective. This finding correlates with genetic studies of eight inbred lines and their 28 F_1 hybrids which showed that additive genetic variance is predominant for

Table 4.1 Simple correlations between sugar beet characteristics. Largely genetic correlations. Based on average values for 17 commercial varieties (one location, 12 replications).

	Sugar %	Sugar yield	K^+	Na^+	α-amino N
Root weight	–0.68	0.86	0.48	0.52	0.48
Sugar %		–0.25	–0.64	–0.50	–0.06
Sugar yield			0.20	0.33	0.30
K^+				0.46	0.47
Na^+					0.29

r = 0.48 for significance at 5% level, K^+ in mmol/100 g beet, Na^+ in mmol/100 g beet, α-amino N in mmol/100 g beet (blue number).

all quality characters, including sugar percentage, at both high and low applications of nitrogen fertilizer (Smith *et al.*, 1973). Smith *et al.* also confirmed previous reports of heterosis for low potassium concentration at low applications of nitrogen (Dudley & Powers, 1960) but did not find heterosis or dominance for sugar percentage as previously reported by Powers *et al.* (1959). Apart from betaine, all non-sugars showed increased means, ranges and variance components at the higher nitrogen application, suggesting that selection for lower concentration of these impurities would be most effective under high nitrogen conditions. In contrast to this, nearly 50% of the total genetic variance for root weight was additive at low nitrogen with an insignificant amount of additive variance at high nitrogen. These results suggest that breeding programmes designed to take advantage of the high amount of additive genetic variance for the non-sugars should result in notable improvements in processing quality.

Reliable and highly automated methods of analysis have been devised for the most important non-sugars, namely sodium, potassium and amino acids. These methods assist sugar beet breeders in assessing the processing quality of their breeding materials and experimental varieties. Over the years several formulae and indices have also been constructed (Carruthers & Oldfield, 1961; Reinefeld *et al.*, 1974), most recently the 'new Braunschweig formula' (Buchholz *et al.*, 1995) in which the impurities are weighted according to their relative influence on factory operations and yield of white sugar (Fig. 4.12).

Calculation of loss of sugar to molasses:
Standard Molasses Loss (SML)

$$\text{SML} = 0.12\,(\text{K} + \text{Na}) + 0.24\,\alpha\text{-N} + 0.48$$

where (K + Na) = sum of Potassium and Sodium in mmol/100 g beet
and α-N = α-amino-Nitrogen in mmol/100 g beet (blue-number)

Corrected sugar content (CSC):

$$\text{CSC} = \text{SC} - \text{SML} - \text{SFL}$$

where SC = Sugar Content in beet
and SFL = Standard Factory Loss (0.6)

Corrected Sugar yield (CS):

$$\text{CS} = \text{beet yield} \cdot \text{CSC}$$

Fig. 4.12 The new Braunschweig formula for calculation of standard molasses loss (SML) and formulas for calculation of corrected sugar content (CSC) and corrected sugar yield (CS).

Before the introduction of monogerm hybrid varieties progress in breeding for improved processing quality was rather slow. However, in the last 25 years the concentration of both (K + Na) and α-amino nitrogen has decreased considerably.

With continued stringent selection of parental lines for processing quality under inbreeding, and the use of such lines for skilful development of hybrids that take advantage of both heterosis for root yield and possible complementary effects on the various quality characteristics, the technological quality of future commercial varieties is likely to continue to improve.

Resistance to diseases

Seedling diseases caused by fungi

Blackleg

Blackleg is a term often used to describe the collapse (damping-off) of sugar beet seedlings as a result of infection by the seed-borne fungus *Phoma betae* or the soil-borne fungi *Pythium ultimum, Rhizoctonia solani* or *Aphanomyces cochlioides* (see Chapter 12). Owing to the effectiveness of fungicide seed treatments, efforts to develop varieties resistant to these pathogens have been limited. However, resistant lines or cultivars have been developed for *Phoma* and *Rhizoctonia* (Bugbee & Campbell, 1990; Panella & Ruppel, 1996) and for *Aphanomyces* (Schneider & Hogaboam, 1983; Runeson & Guillet, 1990). Resistant varieties are especially important against *Aphanomyces*, where the attack comes when the plants are 2–5 weeks old, and the chemical protection is less effective.

Foliar diseases caused by fungi

Powdery mildew

Powdery mildew, caused by the fungus *Erysiphe betae*, can be an important disease under conditions of high temperature and low air humidity. In recent years, phenotypic selection in sugar beet materials has resulted in hybrid varieties with considerable resistance. However, still higher levels of resistance are needed for yield not to suffer in the absence of chemical control (Francis, 2002). Useful sources of resistance to powdery mildew have been found in leaf-beet accessions (Asher *et al.*, 2001) and in accessions of *B. maritima* (Whitney, 1989; Luterbacher *et al.*, 2000; Asher *et al.*, 2001).

Although the moderate resistance to powdery mildew present in sugar beet breeding materials as well as many sources of resistance from *B. maritima* appear to be largely quantitative in nature (Francis, 1999; Janssen *et al.*, 2003), a single dominant resistance gene, designated Pm, has recently been found in accessions of *B. maritima* (Lewellen & Schrandt, 2001). The gene Pm has been introgressed into sugar beet breeding lines and made available to breeders and researchers (Lewellen, 2000). Introduction of the dominant gene Pm into lines with multigenic resistance is expected to result in both higher and more durable resistance (Janssen *et al.*, 2003). Molecular markers linked to the quantitatively inherited resistances as well as to the Pm gene have been generated (Francis, 1999; Weiland & Lewellen, 1999; Janssen *et al.*, 2003).

Downy mildew

Downy mildew (*Peronospora farinosa* f. sp. *betae*) affects sugar beet mainly in areas with cool, humid climates. Germplasm selected in the field under conditions of an artificially induced epidemic of the disease has been used to develop resistant commercial hybrids (Russell, 1969). This, together with an effective separation of seed crops and root crops, has reduced downy mildew to a minor sugar beet disease in most parts of the world.

Cercospora leaf spot

Cercospora leaf spot, caused by the fungus *Cercospora beticola*, is a widespread and damaging sugar beet disease. It requires warm and humid conditions and is particularly important in southern Europe, in eastern parts of North America and in Japan. Symptoms consist of circular lesions 3–5 mm in diameter. In susceptible varieties severe attacks result in coalescence of spots, premature death of many leaves and loss of more than 50% of potential sugar yield. Repeated and properly timed fungicide applications can reduce these losses considerably. However, even with the best chemicals complete control cannot be achieved. Besides, in recent years several fungicides have been rendered ineffective by the appearance of fungicide-resistant strains of the pathogen.

Cercospora-resistant sugar beet varieties have been developed in Europe, North America and in Japan. They all derive from material produced from 1910 to 1920 by the Italian sugar beet breeder Munerati. By crossing sugar beet with *B. maritima* from the estuaries of the River Po, followed by repeated selection and recombination in an area with severe *Cercospora* attacks, Munerati developed sugar beet populations that were highly resistant to the disease (Munerati, 1932). This material was released to Italian sugar beet breeders and used in the development of several resistant varieties. Some of these formed the basis for *Cercospora* resistance breeding in the USA (Coons *et al.*, 1955), Germany, Poland and elsewhere.

The early resistant varieties were mostly composites or synthetic varieties based on more or less inbred lines or families selected under conditions of natural infection. Although such varieties give quite good control of *Cercospora* where the density of inoculum is not too high, losses of 15–20% still occur under severe infections and without fungicide treatment. In disease-free conditions, resistant varieties are almost invariably lower-yielding than susceptible varieties (Koch, 1970). The inheritance of resistance to *Cercospora* was studied by Smith and Gaskill (1970), who suggested that resistance is conditioned by at least four or five pairs of genes. This is in good agreement with four recent quantitative trait loci (QTL) analyses (Nilsson *et al.*, 1999; Schäfer-Pregl *et al.*, 1999; Setiawan *et al.*, 2000), which revealed three, seven and four QTLs for *Cercospora* resistance, respectively. Since *Cercospora*-resistance genes tend to work additively, use of QTLs should eventually permit breeders to combine all available resistance genes in one genotype.

The first *Cercospora*-resistant monogerm hybrids all derived their resistance from multigerm pollinators. More recently, resistant monogerm CMS females have also been developed making it possible to produce hybrids with resistance genes in both parents. Although such hybrids have a higher degree of resistance, it is difficult to find genotypes that combine resistance with good combining ability, probably because of the limited genetic diversity in the resistant gene pool.

Although the importance of the pioneering work of Munerati has been generally recognized, few attempts to isolate and utilize additional resistant *B. maritima* biotypes have been made since those of (Bilgen *et al.*, 1969). To improve the *Cercospora* resistance and break the negative association between yield and resistance, it will be necessary to broaden the genetic variability in the *Cercospora*-resistant gene pool. This should preferably be done by introduction of both additional sugar beet germplasm and new sources of *Cercospora* resistance. Work aiming at precisely this has recently been initiated in the USA.

Diseases caused by viruses

Curly top

Curly top is caused by *Beet curly top virus* (BCTV), a gemini virus, and is transmitted by the beet leafhopper *Circulifer tenellus*. In the early part of the twentieth century, curly top caused severe damage to sugar beet crops in the western USA, especially to the west of the Rocky Mountains. Through repeated mass selection, multigerm lines and open-pollinated varieties with successively higher levels of curly top resistance were developed in the 1930s and 1940s. Later, curly top resistance was incorporated into monogerm hybrids through back-crossing to resistant multigerm inbreds. Although there has been no suggestion of resistance-breaking virus strains, numerous BCTV strains do exist, some of which are sufficiently virulent to cause severe damage on the most resistant varieties.

For many years, resistant varieties, supported by large scale insecticide spraying of over-wintering hosts of the leafhopper, performed well, in spite of the presence of BCTV. However, the sugar beet varieties, currently grown in California, have little or no BCTV-resistance. As a consequence, in 2001 and to a lesser extent in 2002, BCTV re-emerged as a seriously damaging disease, especially in California. With pressure to reduce pesticide usage, focus is again on development of high-yielding varieties with BCTV resistance (Wintermantel *et al.*, 2003).

Virus yellows

Virus yellows in sugar beet in Europe is caused primarily by two aphid-transmitted viruses, *Beet yellows virus* (BYV) and *Beet mild yellowing virus* (BMYV). Another virus, *Beet western yellow virus* (BWYV) is a major yellowing virus in California but does not infect sugar beet in Europe. Recently, a new strain of BMYV has been detected and given the name *Beet chlorosis virus* (BChV). It appears to cause less damage than BMYV, which may decrease yield by up to 30% and has been the predominant yellowing virus over the last 20 years. No source of immunity to the yellowing viruses has been found within the genus *Beta*, but, besides tolerance to the virus, a certain amount of resistance has been identified to the aphid vector, to infection and to virus multiplication.

Almost all selection work has been for virus tolerance. The first such attempts were in the Netherlands and in England during the late 1940s by Rietberg (1959) and Hull (1960), respectively, who showed that in most sugar beet populations some plants are much less damaged by virus yellows than others. These results inspired sugar beet breeders in many countries to take up virus tolerance breeding. At the Plant Breeding Institute in Cambridge, Russell (1964a,b) developed a system of selection for root weight under controlled virus infection and used the selected lines to create experimental virus-tolerant varieties. One such multigerm variety was Maris Vanguard, which was grown in some areas of eastern England during the late 1960s. Although Maris Vanguard had unacceptably low sugar content and high concentrations of certain impurities, it has since been shown that there is no direct relationship between these factors and virus tolerance. The inheritance of virus tolerance is incompletely understood, but an intermediate level of tolerance in crosses between tolerant and sensitive lines suggests that it has a polygenic background.

After the mid 1970s there was, for several years, a very low incidence of virus yellows in western Europe. As a result, growers lost interest in tolerant varieties, which yielded less than other varieties in the absence of the disease, and breeders reduced or discontinued virus yellows tolerance breeding in favour of breeding for resistance to another virus disease, rhizomania. However, in recent years incidence of virus yellows has again increased and caused substantial yield losses in some western European countries. This is partly the result of a rapid increase in the proportion of aphids highly resistant to organophosphorus insecticides in the 1960s, which resulted in poor control in many crops (Dunning, 1988a,b). Similarly, aphids with resistance to carbamates and pyrethroids have since appeared and made these insecticides less effective. Although seed treatment with imidacloprid (Gaucho), a neonicotinoid, gives good aphid control, there is obviously a risk of selecting for resistance also to this insecticide (Foster *et al.*, 2002). This has created interest both in a revival of traditional virus tolerance breeding and in resistance or immunity to the virus developed with recombinant-DNA techniques.

Rhizomania

Rhizomania is caused by the *Beet necrotic yellow vein virus* (BNYVV), which is transmitted in soil by the widely distributed fungus *Polymyxa betae* (Koch, 1982). The disease was first described in Italy in 1957, and has since been found in most other beet growing countries. Cultural practices and chemical treatments are relatively ineffective in reducing damage (Koch, 1982; Winner, 1987); however, sugar beet breeders have found useful resistance in sugar beet as well as in wild *Beta* species. Thus, repeated selections in *Cercospora*-resistant materials of Munerati origin, conducted in rhizomania-infected fields in Italy, resulted in highly resistant multigerm as well as monogerm lines. These were later used to develop the resistant variety Rizor, first marketed in 1985 (De Biaggi, 1987). Resistance in this material is caused by inhibition of virus multiplication and not by resistance to infection by the vector. Similar results were also obtained in the USA and, in both cases, resistance appears to be quantitatively inherited (Lewellen *et al.*, 1987). Lines with rhizomania resistance, developed from *Cercospora*-resistant sugar beet materials with *B. maritima* ancestry, have been used by several breeders as pollinators in monogerm rhizomania-resistant hybrids.

A more simply inherited resistance, governed by a single dominant gene (Rz1) was discovered in the USA in a monogerm CMS line, developed by the Holly Sugar Company (Lewellen *et al.*, 1987). The Rz1 gene has turned out to give almost complete resistance to rhizomania, and most sugar beet breeding organizations have incorporated this gene in their breeding materials and are producing rhizomania-resistant hybrids, many of which are competitive with susceptible varieties, also under non-disease conditions. Although the Rz1 gene is completely dominant in diploid hybrids, in triploid hybrids with only one resistance gene, the resistance is notably lower than in diploids. This has contributed to rapid increase in the number of diploid hybrid sugar beet varieties in most European countries.

An additional dominant gene giving resistance to rhizomania has been isolated in the USA in a *B. maritima* accession from Denmark (Lewellen & Whitney, 1993). This gene, which has been shown to be located at a locus closely linked to Rz1, has been named Rz2 (Scholten *et al.*, 1999). The combination of Rz1 and Rz2 has been reported to give higher resistance than Rz1 alone, especially in the presence of the new P-type of BNYVV (Harju & Richard-Molard, 2002). Recently, several breeding organizations have identified molecular markers closely linked to the Rz1 gene (Barzen *et al.*, 1992) and are using marker-assisted selection to speed up back-crossing and selection of segregants homozygous for the resistance gene (Kraft, 2001).

Resistance to pests

There has been less success with breeding for resistance to pests than there has been in the various disease resistance breeding programmes. However, sources of resistance to the beet cyst nematode (*Heterodera schachtii*), found in the wild species *B. procumbens, B. webbiana* and *B. patellaris*, belonging to section *Procumbentes* of *Beta*, have been transferred to sugar beet by interspecific hybridization (Savitsky, 1975; Löptien, 1984; Speckmann *et al.*, 1985; Lange *et al.*, 1990). Back-crossing monosomic addition lines ($2n = 18 + 1$) carrying the resistance gene(s) from *B. procumbens* has resulted in nematode-resistant lines ($2n = 18$) into which a chromosome segment with the resistance genes from *B. procumbens* have been introgressed through translocation (Savitsky, 1978; Jung & Wricke, 1987; Heijbroek *et al.*, 1988). The translocated segment, harbouring the nematode resistance gene $Hs1^{pro-1}$, as well as a second closely linked resistance gene, is located on chromosome IX of sugar beet (Heller *et al.*, 1996; Sandal *et al.*, 1997; Schondelmaier & Jung, 1997). Gene $Hs1^{pro-1}$ has been cloned and shown to confer full resistance to the beet cyst nematode when introduced into sugar beet hairy root cultures (Cai *et al.*, 1997). No reports of transgenic nematode-resistant sugar beet plants have appeared so far. However, nematode-resistant introgression material has been used in development of a number of nematode-resistant hybrid varieties. In yield trials in heavily infested fields such varieties have been shown to produce remarkably good yields in addition to showing considerable reduction in the nematode population (Porte *et al.*, 1995; Werner *et al.*, 1995). However, they still suffer from various abnormalities emanating from the translocated *procumbens* segment.

THE IMPACT OF PLANT BIOTECHNOLOGY ON SUGAR BEET BREEDING

Plant biotechnology – the sum of technologies originating from plant molecular and cell biology – is the latest development in plant breeding technology. With the tools of plant biotechnology, improvements can take place at the level of individual genes, and single genes, responsible for a particular trait, may be identified, selected for, isolated, inserted, deleted or modified. These advances are rapidly increasing our understanding of genes and genomes and thereby also of cellular biochemistry and physiology. In a longer perspective, this will dramatically increase the efficiency of plant breeding and permit the development of crop varieties offering benefits to farmers, food industry, consumers and environment. Plant biotechnology, as used in plant breeding, embraces a number of research areas and technologies including tissue culture techniques, molecular markers, genomics and genetic transformation.

Molecular markers

Molecular markers date back to the mid-1970s and the advent of the RFLP (Restriction Fragment Length Polymorphism) marker system. RFLP linkage maps were developed for most major crop species, including sugar beet (Barzen *et al.*, 1992; Pillen *et al.*, 1992; 1993; Halldén *et al.*, 1996; Schondelmaier *et al.*, 1996), and have been used to analyse a range of genetic situations. However, the RFLP marker system is laborious and difficult to automate, and besides relies upon radioactive labelling of cloned DNA sequences. As a result RFLPs were rapidly supplemented or replaced by the RAPD (Random Amplified Polymorphic DNA) (Barzen *et al.*, 1995; Halldén *et al.*, 1997) and AFLP (Amplified Fragment Length Polymorphism) marker systems, which are based on DNA amplification. Since such systems require extremely small amounts of source material and can be readily automated, they made DNA marker techniques quicker and cheaper, allowing a through-put of plants in realistic numbers for plant breeding purposes. However, whereas most RFLPs are co-dominant, and provide complete genetic information at a given locus, RAPD and AFLP are dominant marker systems, i.e. heterozygotes cannot be distinguished from one of the homozygotes. This is a serious limitation in certain situations. However, another PCR-based system, the co-dominant SSR (Simple Sequence Repeats) marker system, has turned out to be a very useful replacement for RFLP (Rae *et al.*, 2000). Alone or in combination, AFLP and SSR are currently the most commonly used marker systems in plant breeding contexts (Kraft, 2001). At the same time, a still more efficient co-dominant marker system, SNP (Single Nucleotide Polymorphism), which studies the variation at single base pairs, is now being developed for sugar beet (Jung & Hohmann, 2001).

In plant breeding, molecular markers can be used for a variety of purposes including: genetic mapping, assaying genetic variation, finger printing of specific genotypes or varieties, identifying markers linked to specific traits in bulked segregant analysis, and marker-assisted selection (MAS). Although all these are obviously important my comments are limited to marker-assisted selection.

The genes on which MAS may be practised can be divided into two groups. The first group includes both major genes, which are amenable by classical genetic analysis and whose inheritance is known, and major genes for traits whose effects may be heavily masked because of environmental variance and/or modifier genes. The second group are genes governing typical quantitative traits such as grain yield in cereals and root yield in sugar beet.

Examples of traits governed by major genes that have been mapped in sugar beet, and where MAS and marker-assisted back-crossing is already used in the practical breeding work, are: the chromosome segment carrying the gene for resistance to the sugar beet cyst nematode, emanating from *B. procumbens* (Werner *et al.*, 1995; Halldén *et al.*, 1997), and the gene Rz1 for resistance to rhizomania (Kraft, 2001). The value of MAS in introduction and selection of this kind of gene is undisputed and generally considered the most important contribution of plant biotechnology to plant breeding so far.

Mapping markers linked to quantitative trait loci (QTLs) identify regions of the genome that contain genes or clusters of genes involved in the trait in question. To map such regions requires careful genotypic as well as phenotypic evaluation of large populations. Traits in sugar beet for which QTLs have been mapped include: *Cercospora* leaf spot resistance (Nilsson *et al.*, 1999; Schäfer-Pregl *et al.*, 1999; Setiawan *et al.*, 2000); restoration of the Owen CMS (Pillen *et al.*, 1993; Schondelmaier *et al.*, 1996; Hjerdin-Panagopoulos *et al.*, 2002); and sucrose content, yield and quality characters (Schneider *et al.*, 2002).

However, the use of MAS for quantitative traits is less straightforward than for major genes. Thus, genes rarely function independently of each other but form part of a complex network of interacting genes. This means that QTLs are not necessarily consistent across populations. Another potential complication concerns the inconsistency of QTLs when evaluated in varying environments. Although statistical procedures that can detect interactions among genes, as well as between genes and the environment, are being developed, to translate these into effective MAS strategies for a trait like sugar yield is likely to be quite an undertaking.

Genomics

Marker-facilitated techniques may permit transfer of known genetic variation in the form of QTLs from one genotype to another. However, to more precisely modify a trait and/or create variability that does not exist in natural populations, it is necessary to understand the structure and function of all genes involved in the expression of the trait in question. This requires co-ordinated research efforts, including gene library construction, gene sequencing, gene expression studies, gene mapping, studies of syntenic relationships, protein identification and bioinformatics to establish the relationship between genes/proteins and traits, to enable genes to be isolated (Stuber *et al.*, 1999).

Although there are several projects in sugar beet genomics at research institutes in the USA as well as in Europe, there is less basic research in this area in sugar beet than in many other major crops. However, within the framework of the German genome project GABI (**G**enom**a**nalyse im **bi**ologischen System Pflanze) there are four projects which deal with sugar beet (Koch, 2003). One, GABI-BEET provides tools, methodology, information and genetic materials to the three more breeding oriented projects GABI-BOLT and GABI-SWEET and BREATH-LESS GABI. In GABI-BEET seven partners, representing four public research institutes, two breeding companies and one sugar company, collaborate with the objective to provide new technologies for molecular breeding of sugar beet. As stated, the main goals of GABI-BEET are: (a) sequencing of ESTs of sugar beet and provision of related bioinformatics; (b) development of high density marker maps based largely on SNPs; (c) studies of genome organization in cultivated and wild *Beta* species, and (d) development of large insert libraries (Jung & Hohmann, 2001; Schneider *et al.*, 2001; Bellin *et al.*, 2002; Schneider *et al.*, 2002; Hunger *et al.*, 2003).

Genetic transformation

As in other major crops, the first trait in sugar beet introduced via genetic transformation was herbicide resistance. Although resistance has been introduced to several herbicide active ingredients, for the time being, glyphosate (Roundup®) and glufosinate (Liberty®) are likely to be of most interest to sugar beet growers (D'Halluin *et al.*, 1992; Mannerlöf *et al.*, 1997). Both types of herbicide tolerance have been shown to have the potential to provide better and more environmentally friendly weed control strategies at a considerably lower cost than conventional herbicide systems (Dewar, 2000; May, 2000; 2003; Wevers, 2000; Dewar *et al.*, 2003). Although breeding companies have been ready to market herbicide tolerant sugar beet varieties for a number of years, this has so far been prevented by the moratorium on release of genetically modified crops in the European Union and the generally negative public attitudes towards plant genetic modification. However, the European Commission recently lifted its 6-year moratorium by authorizing the placing on the market of a particular variety of genetically modified sweet corn. Hopefully, this will be followed by a resumption of the process of reviewing applications for commercial planting of genetically modified crops as well.

Another important trait introduced via genetic transformation is rhizomania resistance, obtained through introduction of a coat protein gene from the BNYVV. Tests of a transformant with multicopy T-DNA insertions have shown a high level of resistance in the glasshouse as well as in field trials. Hybrids combining the Rz1 resistance gene and the coat protein gene had similar resistance as the Rz1 alone under moderate infection, but showed a higher degree of resistance under very severe disease conditions (Mechelke & Kraus, 1998). Varieties combining the two sources of resistance have not yet been marketed.

Finally, sugar beet has been modified to produce fructan by insertion of a single gene from Jerusalem artichoke encoding an enzyme that converts sucrose into low molecular weight fructan. Under greenhouse conditions the plants looked normal, produced the same amount of total sugars as normal sugar beet, but had converted more than 90% of the stored sucrose into fructans (Sevenier *et al.*, 1998). This is a good example of how genetic transformation may alter plant metabolic pathways to produce new products with both food and nonfood applications.

In summary, molecular markers and marker-assisted selection are already indispensable tools in introduction and selection of qualitative traits, and in elucidation and improvement of many qualitative traits. With current rapid technological development, the use of DNA-based markers for improvement of multigenic traits will, no doubt, greatly increase in the future. However, even so, marker-assisted selection is unlikely to replace traditional phenotypic selection for complex, quantitative traits, but should instead be integrated with the classical methods to increase the efficiency of artificial selection (Lande & Thompson, 1990).

The potential of transgene technology in sugar beet breeding has been well demonstrated. Once governmental and public confidence in genetic engineering and GM derived food has been regained, genetic transformation is likely to be the main instrument in development of durable resistance to pests and diseases, improved tolerance to major abiotic stress conditions and novel food and industrial uses. However, only if the transgenes are introduced into elite germplasm, so that the many other traits necessary for a successful variety are also present, will the goal be reached. It is thus important not to neglect the traditional breeding, but to invest also in further developing and refining the classical breeding methods.

STRATEGIES IN A COMPREHENSIVE HYBRID BREEDING PROGRAMME WITH SUGAR BEET

The method of producing diploid, multigerm, first-generation synthetic varieties required breeders to develop and regularly reselect many more or less close-bred open-pollinated populations of diverse origin. This resulted in the maintenance of a wide sugar beet gene pool and commercial varieties with a broad genetic base. These broad-based varieties had wide adaptability, restricted mainly by major differences in climate and prevailing diseases. With all varieties on the market available as source materials for continued breeding, all sugar beet breeders had, in principle, access to a common gene pool, based on a wide range of the very best elite populations.

As described earlier, the change to monogerm hybrid breeding required both introduction of the gene for the monogerm seed character into part of the diploid multigerm gene pool and a subsequent search for sterility maintainer genotypes and development of their CMS counterparts. As a result, strict inbreeding and back-crossing became the major selection methods and the development of monogerm inbred lines and assessment of their combining ability came to constitute a major part of the breeding work. At the same time, the number of open-pollinated diploid multigerm populations subjected to selection decreased dramatically, which resulted in the loss of many such populations of less immediate value.

Although monogerm hybrid varieties are always based on a more restricted germplasm than were the conventional cultivars, for a long period of time most hybrids in Europe were either triploid or diploid top-cross hybrids, and they thus still contained much genetic variation. Today a majority of European monogerm cultivars are diploid three-way hybrids, based on more or less inbred pollinators, and the genetic variability is correspondingly reduced. A few diploid single-cross hybrids with competitive yield and quality characteristics have already been marketed. However, low seed yields and seed quality problems appear temporarily to hamper this development. All the same, there are striking similarities between the development of hybrid breeding in maize and current developments in sugar beet. This development raises a number of questions relating to selection strategies and resource allocation in a long-term comprehensive hybrid breeding programme with sugar beet.

To remain competitive in today's hybrid seed market, breeders have to develop and market a continuous flow of varieties with improved performance and incorporating new desirable traits such as resistance to diseases and pests or improved quality. For the varietal procedures to result in rapid gain, it is necessary to apply a high selection pressure on individual genotypes in an elite germplasm pool. However, such procedures are likely to lead to a rapid restriction of the genetic variation and thereby also hamper long-term genetic progress. Conversely, a moderate selection pressure, imposed on broad-based populations, is unlikely quickly to result in materials immediately suitable for production of commercial varieties, but favours recombination and retention of genetic variation and long-term selection advance. It is this fundamental difference between short-term varietal production and intermediate- to long-term population improvement that makes it necessary to separate these operations.

Short-term varietal production

Short-term breeding operations, designed to quickly develop new, competitive hybrids, usually involve pedigree and back-cross selection to produce new inbred lines or to incorporate new traits into existing and otherwise useful genotypes. Of particular interest in these contexts will be the access to molecular markers, making possible quick and reliable transfer of genes governing qualitative as well as quantitative traits, both between lines and from genetic resources to elite lines. The more efficient recycling of elite inbreds, made possible with the help of marker-assisted back-crossing, is likely to lead to an increased use of this breeding strategy. However, too strong an emphasis on recycling of elite inbreds and single-cross source populations is likely to result in increasing relatedness and a corresponding reduction in genetic variability in the elite germplasm. Thus, the useful genetic variability in the elite germplasm may quickly be exhausted unless it is supplemented by new genetic variation from outside. Since few competitive public sugar beet lines are released, and private breeding lines protected or not generally available, breeders themselves have to take the whole responsibility for the inflow of new genetic variability into their elite germplasm pools.

Intermediate-term population improvement

To secure continued breeding progress, it is thus important that parallel with development of components of new hybrids via pedigree and backcross breeding goes development and continuous improvement of source populations designed to capitalize on a broader gene pool. The choice of method of population improvement is likely to be influenced by several factors, including breeder preference. However, with self-fertile materials the obvious choice would be the system of MSFRS described previously. With this system one can practise SRS with S_1 selection in monogerm, type-O populations as well as in multigerm pollinator populations. Besides selection for yield and quality characteristics and resistance to diseases and pests, the method offers excellent opportunities to select for seed plant vigour, seed yield, seed size, seed size distribution and seed germination as well as absence of twins. Since many of these characters appear to be more or less fixed already in the first generation of selfing, repeated cycles of S_1 selection and recombination would facilitate the development of well adapted inbreds combining the various qualities required for production of hybrids with satisfactory agronomic as well as seed production characteristics.

Also the recycling of self-fertile elite inbreds would benefit from an effective system of recurrent selection. Thus, an ARS version of MSFRS in sugar beet, as proposed by Mackay *et al.* (1999), is likely to result in more efficient use of the total genetic potential of the elite lines. At the same time, the F_2 (S_1) generations, based on full-sib families, and used to initiate pedigree selection, would take no more time to produce than traditional two-parental crosses.

A crucial factor in efficient hybrid breeding is the identification and maintenance of heterotic groups of germplasm. For historical reasons, no heterotic groups comparable to the classical heterotic groups in maize exist in sugar beet. As a consequence, additions to the genetic variability of the monogerm, type-O genepool have to come from the present diploid multigerm pollinator populations or, alternatively, from old multigerm populations that may not have been subjected to selection for 40 years or more. With the first alternative there is the risk that the degree of heterosis that can be obtained in future hybrids is compromised; with the second alternative the wider genetic gap is likely to render the work more tedious and costly. Irrespective of which alternative is chosen, it is important to organize and conduct the intermediate-term population improvement in a way that increases, or at least maintains, the genetic distance between current monogerm and multigerm source populations.

Long-term genetic resources development

Access to a wide range of germplasm is essential to deal successfully not only with existing problems, but also emerging problems with respect to pest and disease control and various abiotic stress conditions. Although the value of primitive and wild materials as sources of genes governing resistance to pests and diseases is indisputable, unspecific genetic diversity and a broader germplasm base is practically useless unless known to encompass genes that are useful in themselves or in combination with existing germplasm (Smith & Duvick, 1989). That various wild *Beta* beets may indeed contain useful genetic variation for both root yield and sugar content, has been repeatedly demonstrated in lines derived from sugar beet × wild beet crosses subjected to repeated cycles of selection (Bosemark, 1989; Jolliffe, 1990; Doney, 1996). However, we need to learn how to identify useful gene combinations in more or less exotic materials and develop better methods of successfully incorporating them into adapted, high performing breeding populations (Dudley, 1987; Pfarr & Lamkey, 1992). Here, ongoing and future genomics research will, undoubtedly, play a decisive part and will, hopefully, continue to be undertaken by public institutions.

Although commercial breeders are often reluctant to engage in long-term genetic resources development, or will do so on a very limited scale, they usually support and collaborate with public breeders and researchers in pre-competitive research and pre-breeding utilizing primitive or wild germplasm. Examples of such collaboration is the screening of wild *Beta* accessions in the European Union funded GENRES CT 95–42 project, and the collaboration within the Working Group on *Beta* of the European Cooperative Programme for Crop Genetics Resources Network (ECP/GR).

REFERENCES

Abegg, F.A. (1936) A genetic factor for the annual habit in beets and linkage relationship. *Journal of Agricultural Research* **53**, 493–511.

Asher, M.J.C., Luterbacher, M.C. & Frese, L. (2001) Wild *Beta* species as a source of resistance to sugar-beet pests and diseases. *Proceedings of the 64th IIRB Congress.* June 2001, Bruges, Belgium, pp. 141–152.

Bandlow, G. (1965) Untersuchungen über Inzuchtlinien der Zuckerrübe und ihre Kombinationseignung. *Der Züchter* **35**, 239–250.

Barocka, K.H. (1985) Zucker-und Futterrüben (*Beta vulgaris* L.). In: Hoffmann, W., Mudra, A. & Plarre, W. (eds) *Lehrbuch der Züchtung landwirtschaftlicher Kulturpflanzen, Bd.* 2, Spezieller Teil. Paul Parey, Berlin and Hamburg, pp. 245–287.

Barzen, E., Mechelke, W., Ritter, E., Seitzer, J.F. & Salamini, F. (1992) RFLP markers for sugar-beet breeding: chromosomal linkage maps and location of major genes for rhizomania resistance, monogermy and hypocotyl colour. *Plant Journal* **2**, 601–611.

Barzen, E., Mechelke, W., Ritter, E., Schulte-Kappert, E. & Salamini, F. (1995) An extended map of the sugar beet genome containing RFLP and RAPD loci. *Theoretical and Applied Genetics* **90**, 189–193.

Bell, G.D.H. (1946) Induced bolting and anthesis in sugar beet and the effect of selection of physiological types. *Journal of Agricultural Science, Cambridge* **36**, 167–183.

Bell, G.D.H. & Bauer, A.B. (1942) Experiments on growing sugar beet under continuous illumination. *Journal of Agricultural Science, Cambridge* **32**, 112–141.

Bellin, D., Werber, M., Theis, T., Weisshaar, B. & Schneider, K. (2002) EST sequencing, annotation and macroarray transcriptome analysis identify preferentially root-expressed genes in sugar beet. *Plant Biology* **6**, 700–710.

Bilgen, T., Gaskill, J.O., Hecker, R.J. & Wood, D.R. (1969) Transferring *Cercospora* leaf spot resistance from *Beta maritima* to sugar beet by backcrossing. *Journal of the American Society of Sugar Beet Technologists* **15**, 444–449.

Bingham, E.T., Groose, R.W., Woodfield, D.R. & Kidwell, K.K. (1994) Complementary gene interactions in alfalfa are greater in autotetraploids than diploids. *Crop Science* **34**, 823–829.

Bosemark, N.O. (1966) On the origin and consequences of aneuploidy in triploid and tetraploid sugar beet. *Journal of the International Institute for Sugar Beet Research* **2**, 9–34.

Bosemark, N.O. (1967a) The effect of aneuploidy on yield in anisoploid sugar beet varieties. *Journal of the International Institute for Sugar Beet Research* **2**, 145–161.

Bosemark, N.O. (1967b) Post-meiotic nuclear fragmentation and pollen sterility in autotetraploid sugar beet. *Hereditas* **57**, 217–238.

Bosemark, N.O. (1971a) Haploids and homozygous diploids, triploids and tetraploids in sugar beet. *Hereditas* **69**, 193–204.

Bosemark, N.O. (1971b) Use of Mendelian male sterility in recurrent selection and hybrid breeding in beets. Eucarpia Fodder Crops Section. *Report of meeting in Lusignan.* 15–17 September, 1970, pp. 127–136.

Bosemark, N.O. (1989) Prospects for beet breeding and use of genetic resources. In: *International Crop Network Series. 3. Report of an International Workshop on Beta Genetic Resources.* International Board for Plant Genetic Resources, Rome, pp. 89–97.

Boutin, V., Pannenbecker, G., Ecke, W., Schewe, G., Saumitou-Laprade, P., Jean, R., Vernet, Ph. & Michaelis, G. (1987) Cytoplasmic male sterility and nuclear restorer genes in a natural population of *Beta maritima*: general and molecular aspects. *Theoretical and Applied Genetics* **73**, 625–629.

Buchholz, K., Märländer, B., Puke, H., Glattkowski, H. & Thielecke, K. (1995) Neubewertung des technischen Wertes von Zuckerrüben. *Zuckerindustrie* **120**, 113–121.

Bugbee, W.M. & Campbell, L.G. (1990) Combined resistance in sugar beet to *Rhizoctonia solani*, *Phoma betae*, and *Botrytis cinerea*. *Plant Disease* **74**, 353–355.

Busbice, T.H. & Wilsie, C.P. (1966) Inbreeding depression and heterosis in autotetraploids with application to *Medicago sativa* L. *Euphytica* **15**, 52–67.

Cai, D., Kleine, M., Kifle, S., Harloff, H.J., Sandal, N.N., Marcker, K.A., Klein-Lankhorst, R.M., Salentijn, E.M.J., Lange, W., Stiekema, W.J., Wyss, U., Grundler, F.M.W. & Jung, C. (1997) Positional cloning of a gene for nematode resistance in sugar beet. *Science* **275**, 832–834.

Campbell, G.K.G. (1953) Selection of sugar beet for resistance to bolting. *Report of the 16th IIRB Congress.* p. 5.

Carruthers, A. & Oldfield, J.F.T. (1961) Methods for the assessment of beet quality. *International Sugar Journal* **63**, 72–74, 103–105, 137–139.

Coons, G.H. (1954) Breeding for resistance to disease. In: *Yearbook of Agriculture 1953.* United States Department of Agriculture, pp. 174–192.

Coons, G.H., Owen, F.V. & Stewart, D. (1955) Improvement of the sugar beet in the United States. *Advances in Agronomy* **7**, 89–139.

Cuguen, J., Wattier, R., Saumitou-Laprade, P., Forcioli, D., Mörchen, M., Van Dijk, H. & Vernet, Ph. (1994) Gynodioecy and mitochondrial DNA polymorphism in natural populations of *Beta vulgaris* ssp *maritima*. *Genetics, Selection and Evolution* **26**, (Suppl. 1), 87–101.

Curth, P. (1960) Der Übergang in die reproduktive Phase bei der Zuckerrübe in Abhängigkeit von verschiedenen Umweltfaktoren. *Beiträge zur Rübenforschung* 4, 7–80. Deutsche Akademie der Landwirtschaftswissenschaften zu Berlin, 1960.

De Biaggi, M. (1987) Methodes de selection – un cas concret. *Report of the 50th IIRB Congress. II: BNYVV.* pp. 157–163.

Demarly, Y. (1963) Génétique des tétraploids et amélioration des plantes. *Annales de l'Amelioration des Plantes* **13**, 307–400.

Demarly, Y. (1968) La sélection des varietetes synthétiques. *Proceedings of the 5th Eucarpia Congress.* Milan, pp. 269–295.

Depicker, A., De Loose, M. & Van Bockstaele, E. (1994) The role of biotechnology in plant breeding. *Acta Horticulturae* **335**, 195–207.

Dewar, A.M. (2000) Control of pests by manipulation of weeds in GM herbicide-tolerant sugar beet. *Proceedings of* *the 63rd IIRB Congress*. February 2000, Interlaken, Switzerland, pp. 187–198.

Dewar, A.M., May, M., Woiwod, I., Haylock, L., Champion, G., Garner, B.H., Sands, R.J.N., Qi, A. & Pidgeon, J. (2003) A novel approach to the use of genetically modified herbicide tolerant crops for environmental benefit. *Proceedings of the Royal Society B* **270** (1513), pp. 335–340.

D'Halluin, K., Bossut, M., Bonne, E., Mazur, B., Leemans, J. & Botterman, J. (1992) Transformation of sugar beet (*Beta vulgaris* L.) and evaluation of herbicide resistance in transgenic plants. *Bio/Technology* **10**, 309–314.

Doney, D.L. (1996) *Beta* evaluation and sugar beet enhancement from wild sources. In: Frese, L., Panella, L., Srivastava, H.M. & Lange, W. (eds) *International Beta Genetic Resources Network*. A Report on the 4th International *Beta* Genetic Resources Workshop and World *Beta* Network Conference held at the Aegean Agricultural Research Institute, Izmir, Turkey, 28 February–3 March 1996, pp. 73–76.

Doney, D.L. & Theurer, J.C. (1978) Reciprocal recurrent selection in sugar beet. *Field Crops Research* **1**, 173–181.

Dudley, J.W. (1987) Modification of methods for identifying populations to be used for improving parents of elite single crosses. *Crop Science* **27**, 940–943.

Dudley, J.W. & Powers, L. (1960) Population genetic studies on sodium and potassium in sugar beets (*Beta vulgaris* L.). *Journal of the American Society of Sugar Beet Technologists* **11**, 97–127.

Dunbier, M.W. & Bingham, E.T. (1975) Maximum heterozygosity in alfalfa: results using haploid-derived autotetraploids. *Crop Science* **15**, 527–531.

Dunning, R.A. (1988a) Incidence. In: *Virus Yellows Monograph*. International Institute for Sugar Beet Research, Pests and Diseases Study Group, pp. 1–7.

Dunning, R.A. (1988b) Control. In: *Virus Yellows Monograph*. International Institute for Sugar Beet Research, Pests and Diseases Study Group, pp. 55–58.

El Mezawy, A., Dreyer, F., Jacobs, G. & Jung, C. (2002) High-resolution mapping of the bolting gene *B* of sugar beet. *Theoretical and Applied Genetics* **105**, 100–105.

Fitzgerald, P. (1975) Value of sugar beet triploids as affected by reciprocal crosses. *Report of the meeting of the Study Group 'Genetics and Breeding'*. International Institute of Sugar Beet Research, Carlow, Ireland.

Foster, S., Denholm, I., Harrington, R. & Dewar, A. (2002) Why worry about insecticide resistant aphids? *British Sugar Beet Review* **70** (2), 20–29.

Francis, S. (1999) Using molecular markers to understand rhizomania and powdery mildew resistance. *British Sugar Beet Review* **67** (4), 16–19.

Francis, S. (2002) Sugar-beet powdery mildew (*Erysiphe betae*). *Molecular Plant Pathology* **3** (3), 119–124.

Frandsen, K.J. (1939) Colchicininduzierte Polyploidie bei *Beta vulgaris* L. *Der Züchter* **11**, 17–19.

Gaskill, J.O. (1952) Induction of reproductive development in sugar beets by photothermal treatment of young seedlings. *Proceedings of the American Society of Sugar Beet Technologists 7*. pp. 112–120.

Halldén, C., Bryngelsson, T. & Bosemark, N.O. (1988) Two new types of cytoplasmic male sterility found in wild *Beta* beets. *Theoretical and Applied Genetics* **75**, 561–568.

Halldén, C., Lind, C., Säll, T., Bosemark, N.O. & Bengtsson, B.O. (1990) Cytoplasmic male sterility in *Beta* is associated with structural rearrangements of the mitochondrial DNA and is not due to interspecific organelle transfer. *Journal of Molecular Evolution* **31**, 365–372.

Halldén, C., Hjerdin, A., Rading, I.M., Säll, T., Fridlundh, B., Johannisdottir, G., Tuvesson, S., Åkesson, C. & Nilsson, N.-O. (1996) A high density RFLP linkage map of sugar beet. *Genome* **39**, 634–645.

Halldén, C., Säll, T., Olsson, K., Nilsson, N.-O. & Hjerdin, A. (1997) The use of bulked segregant analysis to accumulate RAPD markers near a locus for beet cyst nematode resistance in *Beta vulgaris*. *Plant Breeding* **116**, 18–22.

Harju, V. & Richard-Molard, R. (2002) Rhizomania P type – a new threat to growers? *British Sugar Beet Review* **70** (3), 22–27.

Hecker, R.J. (1967) Evaluation of three sugar beet breeding methods. *Journal of the American Society of Sugar Beet Technologists* **14**, 309–318.

Hecker, R.J. (1972) Inbreeding depression in diploid and autotetraploid sugarbeet, *Beta vulgaris* L. *Euphytica* **21**, 106–111.

Hecker, R.J. (1978) Recurrent and reciprocal recurrent selection in sugarbeet. *Crop Science* **18**, 805–809.

Hecker, R.J. (1985) Reciprocal recurrent selection for the development of improved sugarbeet hybrids. *Journal of the American Society of Sugar Beet Technologists* **23**, 47–58.

Hecker, R.J. & Helmerick, R.H. (1985) Sugar-beet breeding in the United States. In: Russell, G.E. (ed.) *Progress in Plant Breeding, Vol. 1*. Butterworth, London, pp. 37–61.

Heijbroek, W., Roelands, A.J., de Jong, J.H., van Hulst, C.G., Schoone, A.H.L. & Munning, R.G. (1988) Sugar beets homozygous for resistance to beet cyst nematode (*Heterodera schachtii* Schm.), developed from monosomic additions of *B. procumbens* to *B. vulgaris*. *Euphytica* **38**, 121–131.

Heller, R., Schondelmaier, J., Steinrücken, G. & Jung, C. (1996) Genetic localization of four genes for nematode (*Heterodera schachtii* Schm.) resistance in sugar beet (*Beta vulgaris* L.). *Theoretical and Applied Genetics* **92**, 991–997.

Hjerdin-Panagopoulos, A., Kraft, T., Rading, I.M., Tuvesson, S. & Nilsson, N.-O. (2002) Three QTL regions for restoration of Owen CMS in sugar beet. *Crop Science* **42**, 540–544.

Hohmann, U., Jacobs, G., Telgmann, A., Gaafar, R.M., Alam, S. & Jung, C. (2003) A bacterial artificial chromosome (BAC) library of sugar beet and a physical map of the region encompassing the bolting gene B. *Molecular Genetics and Genomics* **269** (1), 126–136.

Hull, F.H. (1945) Recurrent selection for specific combining ability in corn. *Journal of the American Society of Agronomy* **37**, 134–145.

Hull, R. (1960) The selection of sugar beet varieties for tolerance to virus yellows. *Report of the 23rd IIRB Congress*. pp. 407–417.

Hunger, S., Di Gaspero, G., Möhring, S., Bellin, D., Schäfer-Pregl, R., Borchardt, D.C., Durel, C.E., Werber, M., Weisshaar, B., Salamini, F. & Schneider, K. (2003) Isolation and linkage analysis of expressed disease-resistance gene analogues of sugar beet (*Beta vulgaris* L.). *Genome* **46** (1), 70–82.

Jaggard, K.W. & Werker, A.R. (1999) Potential benefits and problems of autumn sown beet in NW Europe. *Proceedings of the 62nd IIRB Congress.* June 1999, Seville, Spain, pp. 153–164.

Jansen, R. & Burba, M. (2001) Fortschritte in der Rübenqualität durch Züchtung. *Proceedings of the 64th IIRB Congress.* June 2001, Bruges, Belgium, pp. 195–204.

Janssen, G.J.W., Nihlgård, M. & Kraft, T. (2003) Mapping of resistance genes to powdery mildew (*Erysiphe betae*) in sugar beet. *Proceedings of the 1st Joint IIRB–ASSBT Congress.* 26 February – 1 March 2003, San Antonio, USA, pp. 175–180.

Jolliffe, T.H. (1990) Genetical studies in relation to breeding objectives in sugar beet. PhD thesis, University of East Anglia, Norwich, England.

Jolliffe, T.H. & Arthur, A.E. (1993) Diallel analysis of bolting in sugarbeet. *Journal of Agricultural Science, Cambridge* **121**, 327–332.

Jonsson, B.O. (1999) Development of a winter beet alternative for S. Europe. *Proceedings of the 62nd IIRB Congress.* June 1999, Seville, Spain, pp. 69–76.

Jung, C. & Hohmann U. (2001) *Genomforschung an Zuckerrüben.* GenomXPress, 2/01, pp. 10–14.

Jung, C. & Wricke, G. (1987) Selection of diploid nematode-resistant sugar beet from monosomic addition lines. *Plant Breeding* **98**, 205–214.

Keller, W. (1936) Inheritance of some major colour types in beets. *Journal of Agricultural Research* **52**, 27–38.

Kidwell, K.K., Bingham, E.T., Woodfield, D.R. & Osborn, T.C. (1994a) Relationships among genetic distance, forage yield and heterozygosity in isogenic diploid and tetraploid alfalfa populations. *Theoretical and Applied Genetics* **89**, 323–328.

Kidwell, K.K., Woodfield, D.R., Bingham, E.T. & Osborn, T.C. (1994b) Molecular marker diversity and yield of isogenic 2x and 4x single-crosses of alfalfa. *Crop Science* **34**, 774–783.

Knapp, E. (1957) The significance of polyploidy in sugar beet breeding. *Proceedings of the International Genetics Symposia.* Tokyo 1956, Supplement Volume of Caryologia, pp. 300–304.

Knapp, E. (1967) Die genetischen Grundlagen der Einzelfrüchtigkeit (Monokarpie) bei *Beta vulgaris. Tagungsberichte* **89**, 189–235. Deutsche Akademie der Landwirtschaftswissenschaften zu Berlin.

Koch, F. (1970) Lestungsfähigkeit von Cercospora-resistenten Zuckerrübensorten. *Journal of the International Institute of Sugar Beet Research* **5**, 12–23.

Koch, F. (1982) Die Rhizomania der Zuckerrübe. *Proceedings of the 45th IIRB Congress.* pp. 211–238.

Koch, G. (2003) GABI-BEET: The German sugar beet genome initiative. *Proceedings of the 1st Joint IIRB–ASSBT Congress.* 26 February – 1 March 2003, San Antonio, USA, pp. 249–260.

Kraft, T. (2001) Molecular markers – where are we today? *Proceedings of the 64th IIRB Congress.* June 2001, Bruges, Belgium, pp. 159–166.

Kubo, T., Nishizawa, S. & Mikami, T. (1999) Alterations in organization and transcription of the mitochondrial genome of cytoplasmic male sterile sugar beet (*Beta vulgaris* L.). *Molecular and General Genetics* **262** (2), 283–290.

Lahousse, R. (1976) Use of monogerm tetraploid male-steriles and realization of triploid varieties of sugar beet. *Report of the meeting of the Study Group 'Genetics and Breeding'.* International Institute for Sugar Beet Research, Bologna, Italy.

Lande, R. & Thompson, R. (1990) Efficiency of marker-assisted selection in the improvement of quantitative traits. *Genetics* **124**, 743–756.

Lange, W., Jung, Chr. & Heijbroek, W. (1990) Transfer of beet cyst nematode resistance from *Beta* species of the section *Patellares* to cultivated beet. *Proceedings of the 53rd IIRB Congress.* pp. 89–102.

Larsen, K. (1977a) Self-incompatibility in *Beta vulgaris* L. I. Four gametophytic, complementary S-loci in sugar beet. *Hereditas* **85**, 227–248.

Larsen, K. (1977b) Pseudo-compatibility in *Beta vulgaris* L. A quantitative character, dependent on the degree of S-gene heterozygosity. *Incompatibility Newsletter* **8**, 48–51.

Larsen, K. (1978) Four S-genes in one linkage group in *Beta vulgaris* L. *Incompatibility Newsletter* **9**, 78–82.

Larsen, K. (1982) The breeding system of *Beta vulgaris* L. Abstract, 10th meeting of the Scandinavian Association of Geneticists, 1982. *Hereditas* **97**, 325.

Lasa, J.M., Romagosa, I., Hecker, R.J. & Sanz, J.M. (1989) Combining ability in diploid and triploid sugarbeet hybrids from diverse parents. *Journal of Sugar Beet Research* **26**, 10–18.

Le Cochec, F. & Soreau, P. (1989) Mode d´action des gènes et hétérosis pour le charctère montée à graines dans le croisement de deux lignées fixées de betterave à sucre (*Beta vulgaris* L.). *Agronomie* **9**, 585–590.

Levings, C.S., Dudley, J.W. & Alexander, D.E. (1967) Inbreeding and crossing in autotetraploid maize. *Crop Science* **7**, 72–73.

Lewellen, R.T. (2000) Registration of powdery mildew resistant sugarbeet germplasms CP01 and CP02. *Crop Science* **40**, 1515.

Lewellen, R.T. & Schrandt, J.K. (2001) Inheritance of powdery mildew resistance in sugar beet derived from *Beta vulgaris* subsp *maritima. Plant Disease* **85**, 627–631.

Lewellen, R.T. & Whitney, E.D. (1993) Registration of germplasm lines developed from composite crosses of sugar beet x *Beta maritima. Crop Science* **33**, 882–883.

Lewellen, R.T., Skoyen, J.O. & Erichsen, A.W. (1987) Breeding sugarbeet for resistance to rhizomania: evaluation of host-plant reactions and selection for and inheritance of resistance. *Report of the 50th IIRB Congress. II: BNYVV.* pp. 139–156.

Lichter, R. (1967) Konkurrenzbeziehungen zwischen eu- und aneutetraploiden Pflanzen in tetraploiden Zuckerrüben. *Zucker* **20**, 351–355.

Lichter, R. (1972) A method of evaluating competitional variance in plant populations. *Zeitschrift für Pflanzenzüchtung* **68**, 51–63.

Lichter, R. (1975) Genetical aspects of different ploidy levels, especially of autotetraploids, with crosspollinating plants. *Report of Meeting of Fodder Crops Section of Eucarpia.* Zürich-Reckenholz, 23–25 April, 1975, pp. 21–33.

Löptien, H. (1984) Breeding nematode resistant beets. I. Development of resistant alien additions by crosses between *Beta vulgaris* L. and wild species of the section *Patellares. Zeitschrift für Pflanzenzüchtung* **92**, 208–220.

Lundqvist, A. (1966) Heterosis and inbreeding in tetraploid rye. *Hereditas* **56**, 317–366.

Luterbacher, M.C., Smith, J.M., Asher, M.J.C. & Frese, L. (2000) Disease resistance in collections of *Beta* species. *Journal of Sugar Beet Research* **37** (3), 39–47.

Mackay, I.J., Caligari, P.D.S. & Gibson, J.P. (1999) Accelerated recurrent selection. *Euphytica* **105**, 53–62.

MacLachlan, J.B. (1972a) Estimation of genetic parameters in a population of monogerm sugar beet (*Beta vulgaris*). 1. Sib-analysis of mother-line progenies. *Irish Journal of Agricultural Research* **11**, 237–246.

MacLachlan, J.B. (1972b) Estimation of genetic parameters in a population of monogerm sugar beet (*Beta vulgaris*). 2. Offspring/parent regression analysis of mother-line progenies. *Irish Journal of Agricultural Research* **11**, 319–325.

MacLachlan, J.B. (1972c) Estimation of genetic parameters in a population of monogerm sugar beet (*Beta vulgaris*). 3. Analysis of a diallel set of crosses among heterozygous populations. *Irish Journal of Agricultural Research* **11**, 327–338.

Mannerlöf, M., Tuvesson, S., Steen, P. & Tenning, P. (1997) Transgenic sugar beet tolerant to glyphosate. *Euphytica* **94**, 83–91.

Marcum, W.B. (1948) Inheritance of bolting resistance. *Proceedings of the American Society of Sugar Beet Technologists 5.* pp. 154–155.

Margara, J. (1960) Recherches sur le déterminisme de la l´elongation et de la floraison dans le genre Beta. Thésis, Série A, No. 3614. Faculté des Sciences de l´Université de Paris, pp. 13–117.

May, M.J. (2000) Efficiency and selectivity of RR and LL weed control techniques compared to classical weed control systems. *Proceedings of the 63rd IIRB Congress.* February 2000, Interlaken, Switzerland, pp. 163–170.

May, M.J. (2003) Economic consequences for UK farmers of growing of GM herbicide tolerant sugar beet. *Annals of Applied Biology* **142**, 41–48.

McFarlane, J.S., Price, C. & Owen, F.V. (1948) Strains of sugar beet extremely resistant to bolting. *Proceedings of the American Society of Sugar Beet Technologists 5.* pp. 151–153.

Mechelke, W. & Kraus, J. (1998) Ergebnisse von Freilandversuchen mit Zuckerrüben mit transgener Rizomaniaresistenz. *Proceedings of the 61st IIRB Congress.* February 1998, Brussels, Belgium, pp. 351–355.

Middelburg, M.C.G. (1990) Tissue culture as a tool in a sugar beet breeding program. In: Demarly, Y. & Sibi, M. (eds) *Amélioration des Plantes et Biotechnologie.* pp. 27–29.

Mikami, T., Kishima, Y., Sugiura, M. & Kinoshita, T. (1985) Organelle genome diversity in sugar beet with normal and different sources of male sterile cytoplasms. *Theoretical and Applied Genetics* **71**, 166–171.

Munerati, O. (1931) L’eridità della tendenza alla annualità nella comune barbabietola coltivata. *Zeitschrift für Pflanzenzüchtung* **17**, 84–89.

Munerati, O. (1932) Sull’incrocio delle barbabietola coltivata con la beta selvaggia della costa adriatica. *Industria Saccarifera Italiana* **25**, 303–304.

Nilsson, N.-O., Hansen, M., Panagopoulos, A.H., Tuvesson, S., Ehlde, M., Christiansson, M., Rading, I.M., Rissler, M. & Kraft, T. (1999) QTL analysis of *Cercospora* leaf spot resistance in sugar beet. *Plant Breeding* **118**, 327–334.

Oltmann, W., Burba, M. & Bolz, G. (1984) Die Qualität der Zuckerrübe: Bedeutung, Beurteilungskriterien und züchterische Massnahmen zu ihrer Verbesserung. *Fortschritte der Pflanzenzüchtung* **12**, 1–159. Paul Parey, Berlin and Hamburg.

Owen, F.V. (1942) Inheritance of cross- and self-sterility and self-fertility in *Beta vulgaris. Journal of Agricultural Research* **64**, 679–698.

Owen, F.V. (1945) Cytoplasmically inherited male-sterility in sugar beets. *Journal of Agricultural Research* **71**, 423–440.

Owen, F.V. (1948) Utilization of male sterility in breeding superior-yielding sugar beets. *Proceedings of the American Society of Sugar Beet Technologists, 5.* pp. 156–161.

Owen, F.V. (1950) The sugar beet breeder’s problem of establishing male-sterile populations for hybridization purposes. *Proceedings of the American Society of Sugar Beet Technologists, 6.* pp. 191–194.

Owen, F.V. (1952) Mendelian male sterility in sugar beets. *Proceedings of the American Society of Sugar Beet Technologists, 7.* pp. 371–376.

Owen, F.V. (1954a) Hybrid sugar beets made by utilizing both cytoplasmic and Mendelian male sterility. *Proceedings of the American Society of Sugar Beet Technologists, 8 (2).* pp. 64.

Owen, F.V. (1954b) The significance of single gene reactions in sugar beets. *Proceedings of the American Society of Sugar Beet Technologists, 8 (2).* pp. 392–398.

Owen, F.V. & Ryser, G.K. (1942) Some Mendelian characters in *Beta vulgaris* and linkages observed in the Y-R-B group. *Journal of Agricultural Research* **65**, 155–171.

Panella, L. & Ruppel, E.G. (1996) Availability of germplasm for resistance against *Rhizoctonia* sp. In: Sneh, B., Jabaji-Hare, S., Neate, S. & Dijst, G. (eds) *Rhizoctonia Species: Taxonomy, Molecular Biology, Ecology, Pathology and Disease Control.* Kluwer Academic Publishers, Dordrecht, pp. 515–527.

Pedersen, A. (1944) Om bederoernes farver (On the colours of beets (*Beta vulgaris*)). *Årsskrift -Kongelige Veterinae – og Landbohöjskole* 1944, pp. 60–111.

Peto, F.H. & Boyes, J.W. (1940) Comparison of diploid and triploid sugar beet. *Canadian Journal of Research* **18**, 273–282.

Pfarr, D.G. & Lamkey, K.R. (1992) Comparison of methods for identifying populations for genetic improvements of maize hybrids. *Crop Science* **32**, 670–677.

Pillen, K., Steinrücken, G., Wricke, G., Herrmann, R.G. & Jung, C. (1992) A linkage map of sugar beet (*Beta vulgaris* L.). *Theoretical and Applied Genetics* **84**, 129–135.

Pillen, K., Steinrücken, G., Herrmann, R.G. & Jung, C. (1993) An extended linkage map of sugar beet (*Beta vulgaris* L.) including nine putative lethal genes and the restorer gene X. *Plant Breeding* **111**, 265–272.

Porte, C., Caubel, G. & Muchembled, C. (1995) La resistance de la betterave sucriere au nematode a kyste *Heterodera schachtii. Proceedings of the 58th IIRB Congress.* June 1995, Beaune, France, pp. 233–241.

Powers, L., Finkner, R.E., Rush, G.E., Wood, R.R. & Peterson, D.F. (1959) Genetic improvement of processing quality in sugar beets. *Journal of the American Society of Sugar Beet Technologists* **10**, 578–593.

Powling, A. (1982) Restriction endonuclease analysis of mitochondrial DNA from sugar beet with normal and male-sterile cytoplasms. *Heredity* **49**, 117–120.

Rae, S.J., Aldam, C., Dominguez, I., Hoebrechts, M., Barnes, S.R. & Edwards, K.J. (2000) Development and incorporation of microsatellite markers into the linkage map of sugar beet (*Beta vulgaris* ssp). *Theoretical and Applied Genetics* **100**, 1240–1248.

Rasmusson, J. & Levan, A. (1939) Tetraploid sugar beets from colchicine treatments. *Hereditas* **25**, 97–102.

Reinefeld, E., Emmerich, A., Baumgarten, G., Winner, C. & Beiss, U. (1974) Zur Voraussage des Melassezuckers aus Rübenanalysen. *Zucker* **27**, 2–15.

Rietberg, H. (1959) Virus yellows of sugar beet and its control. *Report of the 22nd IIRB Congress*. pp. 269–309.

Roden, L. & Mutasa-Göttgens, E. (2003) Unravelling the genetics of bolting and flowering in sugar beet: a model weed reveals all? *British Sugar Beet Review* **71** (2), 40–45.

Rommel, M. (1965) Cytogenetics of autotetraploid sugar beet (*Beta vulgaris*). Part I: Tetraploid varieties. *Der Züchter* **35**, 219–222.

Rosso, F., Meriggi, P., Amaducci, M.T. & Venturi, G. (1999) La culture de la betterave automnale en Italie au-dessus du 42ème parallèle de latitude. *Proceedings of the 62nd IIRB Congress*. June 1999, Seville, Spain, pp. 133–152.

Runeson, I. & Guillet, J.-M. (1990) Pied-noir de la betterave: une response de la genetique. *Cultivar* **275**, 21–22.

Russell, G.E. (1964a) Breeding for tolerance to beet yellows virus and beet mild yellowing virus in sugar beet. I. Selection and breeding methods. *Annals of Applied Biology* **53**, 363–376.

Russell, G.E. (1964b) Breeding for tolerance to beet yellows virus and beet mild yellowing virus in sugar beet. II. The response of breeding material to infection with different virus strains. *Annals of Applied Biology* **53**, 377–388.

Russell, G.E. (1969) Recent work on breeding for resistance to downy mildew (*Peronospora farinosa*) in sugar beet. *Journal of the International Institute for Sugar Beet Research* **4**, 1–10.

Sadeghian, S.Y. (1993) Bolting in sugar beet. Genetics and physiological aspects. PhD thesis, The Swedish University of Agricultural Sciences, Department of Plant Breeding, Svalöv, Sweden.

Sandal, N.N., Salentijn, E.M.J., Kleine, M., Cai, D., Arens-de Reuver, M., Van Druten, M., de Bock, Th.S.M., Lange, W., Steen, P., Jung, C., Marcker, K., Stiekema, W.J. & Klein-Lankhorst, R.M. (1997) Backcrossing of nematode-resistant sugar beet: a second nematode resistance gene at the locus containing $Hs1^{pro-1}$? *Molecular Breeding* **3**, 471–480.

Saumitou-Laprade, P., Rouwendal, G.J.A., Cuguen, J., Krens, F.A. & Michaelis, G. (1993) Different c ms sources found in *Beta maritima* ssp *maritima*: mitochondrial variability in wild populations revealed by rapid screening procedures. *Theoretical and Applied Genetics* **85**, 529–535.

Saunders, J.W. & Shin, K. (1986) Germplasm and physiologic effects on induction of high-frequency hormone autonomous callus and subsequent shoot regeneration in sugarbeet. *Crop Science* **26**, 1240–1245.

Savitsky, H. (1954) Self-sterility and self-fertility in monogerm beets. *Proceedings of the American Society of Sugar Beet Technologists 8 (2)*. pp. 29–33.

Savitsky, H. (1975) Hybridization between *Beta vulgaris* and *Beta procumbens* and transmission of nematode (*Heterodera schachtii*) resistance to sugar beet. *Canadian Journal of Genetics and Cytology* **17**, 197–209.

Savitsky, H. (1978) Nematode (*Heterodera schachtii*) resistance and meiosis in diploid plants from interspecific *Beta vulgaris* x *Beta procumbens* hybrids. *Canadian Journal of Genetics and Cytology* **20**, 177–186.

Savitsky, V.F. (1950) Monogerm sugar beets in the United States. *Proceedings of the American Society of Sugar Beet Technologists, 6*. pp. 156–159.

Savitsky, V.F. (1952) A genetic study of monogerm and multigerm characters in beets. *Proceedings of the American Society of Sugar Beet Technologists, 7*. pp. 331–338.

Schäfer-Pregl, R., Borchardt, D.C., Barzen, E., Glass, C., Mechelke, W., Seitzer, J.F. & Salamini, F. (1999) Localization of QTLs for tolerance to *Cercospora beticola* on sugar beet linkage groups. *Theoretical and Applied Genetics* **99**, 829–836.

Schneider, C.L. & Hogaboam, G.J. (1983) Evaluation of sugarbeet breeding lines in greenhouse tests for resistance to *Aphanomyces cochlioides*. *Journal of the American Society of Sugar Beet Technologists* **22**, 101–107.

Schneider, K., Weisshaar, B., Borchardt, D.C. & Salamini, F. (2001) SNP frequency and allelic haplotype structure of *Beta vulgaris* expressed genes. *Molecular Breeding* **8**, 63–74.

Schneider, K., Schäfer-Pregl, R., Borchardt, D.C. & Salamini, F. (2002) Mapping QTLs for sucrose content, yield and quality in a sugar beet population fingerprinted by EST-related markers. *Theoretical and Applied Genetics* **104**, 1107–1113.

Scholten, O.E., De Bock, T.S.M., Klein-Lankhorst, R.M. & Lange, W. (1999) Inheritance of resistance to beet necrotic yellow vein virus in *Beta vulgaris* conferred by a second gene for resistance. *Theoretical and Applied Genetics* **99**, 740–746.

Schondelmaier, J. & Jung, C. (1997) Chromosomal assignment of the nine linkage groups of sugar beet (*Beta vulgaris* L.) using primary trisomics. *Theoretical and Applied Genetics* **95**, 590–596.

Schondelmaier, J., Steinrücken, G. & Jung, C. (1996) Integration of AFLP markers into a linkage map of sugar beet (*Beta vulgaris* L.). *Plant Breeding* **115**, 231–237.

Schwanitz, F. (1938) Die Herstellung polyploider Rassen bei Beta-Rüben und Gemüsearten durch Behandlung mit Colchicin. *Der Züchter* **10**, 278–279.

Scott, R.K. & Longden, P.C. (1970) Pollen release by diploid and tetraploid sugar-beet plants. *Annals of Applied Biology* **66**, 129–135.

Setiawan, A., Koch, G., Barnes, S.R. & Jung, C. (2000) Mapping quantitative trait loci (QTLs) for resistance to *Cercospora* leaf spot disease (*Cercospora beticola* Sacc.) in sugar beet (*Beta vulgaris* L.). *Theoretical and Applied Genetics*

100, 1176–1182.

Sevenier, R., Hall, R.D., van der Meer, I., Hakkert, H.J.C., van Tunen, A.J. & Koops, A.J. (1998) High level fructan accumulation in a transgenic sugar beet. *Nature Biotechnology* **16**, 843–846.

Shavrukov, Y.N. (2000) Localization of new monogerm and late-bolting genes in sugarbeet using RFLP markers. *Journal of Sugar Beet Research* **37**, 107–115.

Smith, G.A. (1987) Sugar beet. In: Fehr, W.R. (ed.) *Principles of Cultivar Development*. Macmillan, New York, pp. 577–625.

Smith, G.A. & Gaskill, J.O. (1970) Inheritance of resistance to *Cercospora* leaf spot in sugarbeet. *Journal of the American Society of Sugar Beet Technologists* **16**, 172–180.

Smith, G.A., Hecker, R.J., Maag, G.W. & Rasmuson, D.M. (1973) Combining ability and gene action estimates in an eight parent diallel cross of sugarbeet. *Crop Science* **13**, 312–316.

Smith, G.A., Hecker, R.J. & Martin, S.S. (1979) Effects of ploidy level on the components of sucrose yield and quality in sugarbeet. *Crop Science* **19**, 319–323.

Smith, J.C.S. & Duvick, D.N. (1989) Germplasm collections and the private plant breeder. In: Brown, A.D.H., Frankel, O.H., Marshall, D.R. & Williams, J.T. (eds) *The Use of Plant Genetic Resources*. Cambridge University Press, pp. 17–31.

Speckmann, G.J., de Bock, Th.S.M. & de Jong, J.H. (1985) Monosomic additions with resistance to beet cyst nematode obtained from hybrids of *Beta vulgaris* and wild *Beta* species of the section *Patellares*. *Zeitschrift für Pflanzenzüchtung* **95**, 74–83.

Stewart, G. (1933) Some effects of inbreeding in sugar beets. *Journal of the American Society of Agronomy* **25**, 237–258.

Stuber, C.W., Polacco, M. & Senior, M.L. (1999) Synergy of empirical breeding, marker-assisted selection, and genomics to increase crop yield potential. *Crop Science* **39**, 1571–1583.

Theurer, J.C. & Ryser, G.K. (1969) Inheritance studies with a pollen fertility restorer sugarbeet inbred. *Journal of the American Society of Sugar Beet Technologists* **15**, 538–545.

Weiland, J.J. & Lewellen, R.T. (1999) Generation of molecular genetic markers associated with resistance to powdery mildew (*Erysiphe polygoni* DC) in sugar beet (*Beta vulgaris*). *Proceedings of the 9th International Congress of Plant-Microbe Interactions*. p. 215.

Werner, T., Karlsson, G., Rydström, G. & Halldén, C. (1995) Breeding for beet cyst nematode (*Heterodera schachtii*) resistance. *Proceedings of the 58th IIRB Congress*. June 1995, Beaune, France, pp. 163–164.

Wevers, J.D.A. (2000) Herbicide tolerance and effects on the environmental contamination. *Proceedings of the 63rd IIRB Congress*. February 2000, Interlaken, Switzerland, pp. 179–185.

Whitney, E.D. (1989) *Beta maritima* as a source of powdery mildew resistance in sugar beet. *Plant Disease* **73**, 487–489.

Winner, C. (1987) Fortschritte im Kampf gegen die Rizomania – Forschung und Züchtung im strategischen Verband. *Zucker industrie* **112**, 19–23.

Wintermantel, W.M., Mosqueda, N.F., Cortez, A.A. & Anchieta, A.G. (2003) Beet curly top revisited: factors contributing to re-emergence in California. *Proceedings of the 1st Joint IIRB–ASSBT Congress*. 26 February – 1 March 2003, San Antonio, USA, pp. 295–302.

Chapter 5
Seed Production and Quality

Albert Kockelmann and Uwe Meyer

INTRODUCTION

High quality seed is fundamental to the success of the crop, especially since monogerm varieties are drilled to a final stand. Seed is produced in areas with favourable conditions for the European and American monogerm sugar beet growing markets: the south of France and northern Italy for the European demand and Oregon (USA) for the North American market. Considerable acreages of sugar beet seed can also be found in the northern regions of Turkey mainly for their national sugar production. Chile produces seed, both for the Chilean market and for export to Europe and North America (Table 5.1). Seed production in eastern European countries, like Hungary and Croatia, has decreased recently because of uncertain seed quality and yield.

Among the favourable conditions required for sugar beet seed production is several weeks of low temperatures for the vegetative beet plants – to induce complete and homogeneous bolting of seed bearers in the second year, but with little risk of losses due to severe frost. In addition, climatic conditions with a probability of temperatures higher than 15°C immediately after vernalization should be avoided, because of possible devernalization of the plants (Longden, 1986). Continental climatic conditions are therefore less suitable for seed production than regions close to the sea. Good growing conditions in the favoured seed production regions, especially during flowering, maturation and seed harvest are essential to assure high seed quality and stable seed yields. Flowering of sugar beet seed plants requires moderate relative air humidity of 60–70%, and temperatures that do not exceed 35°C (Wood *et al.*, 1980). The flowering period should preferably be concentrated into a relatively short period of time to guarantee a uniform maturation of the seed and, optimally, there should be little probability of rain during harvest. The risk of pre-vernalization on the seed plant due to low temperatures as described by Bornscheuer (1972), Lexander (1980) and Wood *et al.* (1980) is reduced, and thus undesired bolting in the subsequent sugar beet root crop. These climatic conditions are found more or less around the 40–45th latitude in the northern and the southern hemisphere (Fig. 5.1).

Table 5.1 Monogerm sugar beet seed producing countries and areas grown (in ha).

Country/Year	2000	2001	2002	2003	2004	Average
France [1]	2716	2504	2643	3429	4194	3097
Italy [2]	2188	2287	2154	3625	3540	2759
Turkey	3700	3700	1470	1520	2230	2524
USA (Oregon)	1200	1200	1200	1200	1200	1200
Chile	110	100	100	240	250	160
Total	9914	9791	7567	10014	11414	9740

[1] Groupement national interprofessionnel des semences et plants (GNIS), [2] Ente Nazionale Sementi Elette (ENSE).

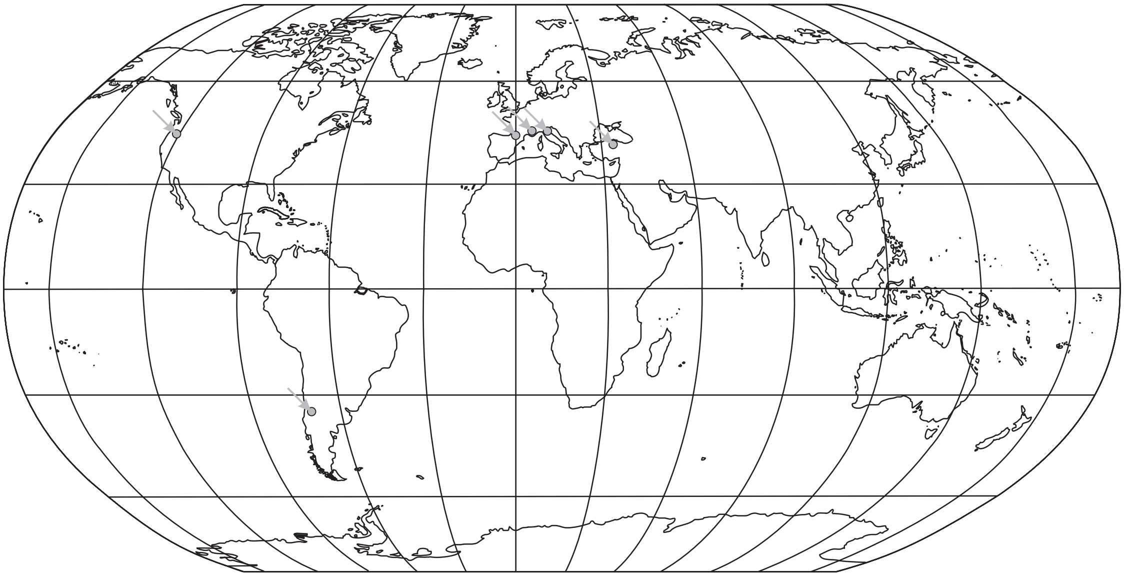


Fig. 5.1 Monogerm sugar beet seed production areas in the world.

Seed production for multigerm varieties can still be found outside the above-mentioned monogerm production regions, in both England and Denmark.

Great attention is then paid to processing and selection for high germination and seed vigour. Calibration (grading), seed treatment, pelleting and certification are the final processes before delivery of sugar beet seed to growers.

METHODS OF BEET SEED PRODUCTION

Seed of monogerm hybrid varieties are produced on cytoplasmic male sterile monogerm plants that are pollinated by corresponding male diploid or tetraploid multigerm male components. The hybrid components are normally grown in blocks (e.g. 6 or 8 rows of male sterile + 2 rows of pollinator) to facilitate separation before seed harvest. Only the seed on the male sterile plants is harvested; the pollinator plants are usually destroyed once pollination is complete and well before the harvest of the seed crop.

Although the sugar beet plant is biennial, the cycle of seed production is often completed within 12 months. Sowing of basic seed for monogerm varieties in western European and American production regions generally takes place in July and August, with seed harvest in July and August of the following year. The whole seed production process consists of two important phases: the vegetative growth from basic seed to vernalized young beet plants (stecklings) and seed production on vernalized plants. Both could take place in the same field (direct production method), or in two different specialized fields as two different crops (steckling transplanting method).

The principles of seed production for multigerm varieties are not much different from those for monogerm varieties. Multigerm seed is mainly produced using the direct production method.

Transplanting method

The predominant production system in western Europe and Turkey is the transplanting method using stecklings. The vegetative phase of the seed production cycle is considered as a separate crop in specialized steckling nurseries. Male sterile and pollinator stecklings are grown in separate plots, where each genetic component can be treated according to its individual requirements. Stecklings are then harvested, usually after vernalization, and processed for transplanting. Transplanting of stecklings into the seed production fields in France and Italy is done from February to March. In Turkey, transplanting in the autumn is also quite common, with the advantage of good conservation of winter soil moisture. The labour requirement for the transplanting method is high. The working hours for transplanting alone could be estimated as 35–45 hours per ha of seed production.

Despite the high costs for steckling harvesting and transplanting, there are several advantages for the steckling method:

- The use of basic seed is more efficient. Basic seed requirements for direct-sown crops depend on the growing region and can be 1.5–5 times higher compared to the steckling production method.
- Steckling fields can either be protected efficiently against severe frost, or alternatively stecklings can be harvested and stored in clamps.
- Requirements for rotation between two seed production fields of 5 years can be less stringent because transplanted fields, with their defined planting system and planting distances between and within rows, allow easy control of volunteer beet.
- Breeders can be more flexible in adjusting their seed production area according to commercial performance of their sugar beet varieties and trial results (released in the autumn or winter) and thus fine-tune seed production to meet the latest demands of the market.

Characteristics of beet seed production methods are shown in Table 5.2.

Steckling production

Field and rotation requirements

Steckling production fields are normally concentrated in large nurseries supervised by breeding companies. In the past, a high proportion of steckling production was harvested manually, with expenditure of about 75 man-hours of labour per hectare of seed bearer field. Greater efficiency and mechanization of the steckling harvest require fields with light soil conditions. In northern Italy, steckling production systems have therefore been established on sandy soils along the Adriatic coast, and in south-west France on appropriate soils in the Medoc and Bordeaux regions.

Steckling production requires a rotation of 5 years or more between two sugar beet nurseries. All fields, where sugar beet seed, sugar beet roots or any other *Beta* species have been grown in the past are excluded from the rotation for steckling production. To avoid problems for varietal purity in the subsequent rotation, fields must be continuously rogued for 'volunteer' plants that could produce and shed seed in the rotation between two steckling crops. The risk of infection from aphid-

Table 5.2 Characteristics of the two sugar beet seed production methods.

	Transplant method	Direct sowing method
Minimum interval between seed crops	5 years	10 years
Use of basic seed	Propagation ratio: 1:300–1:800	Propagation ratio: 1:150–1:550
Frost protection	Possibility of covering steckling fields with fleece	Risk of plant or crop losses while overwintering
Selection for off-types	Feasible	High effort
Control of volunteer beet in seed crops	Feasible	Limited
Expenditure	High costs for steckling harvest and transplanting	No costs for steckling harvest and transplanting
Flexibility for breeders to adapt production area according to variety performance	Flexible	Limited

transmitted viruses is decreased by ensuring that steckling plots are not in the neighbourhood of other *Beta* species. The soil of steckling fields in intensive production regions, such as northern Italy, is checked for rhizomania (bait-plant test with subsequent enzyme-linked immunosorbent assay (ELISA)) and infection with beet cyst nematode (*Heterodera schachtii*) before sowing the basic seed. Any field that tested positive would be eliminated from the production plan to avoid infection of young plants and transmission into seed production fields.

Suitable preceding crops are cereal (wheat) and vegetable crops. The particularities of the preceding crop needs special consideration, e.g. regarding hosts for beet pathogens or the possibility of herbicide residues.

Sowing of basic seed

The seedbed should be prepared with appropriate techniques to enable accurate sowing and quick, homogeneous high field emergence. After deep ploughing, soils are levelled to diminish the risk of water logging and then worked with rotary harrows or spading machines to give a well-structured seedbed to ensure deep root development.

The calibrated basic seed is treated with fungicide (hymexazol) and insecticide (imidacloprid) to minimize damping-off diseases and early infestation with aphids. Pneumatic precision drilling machines ensure a homogenous field establishment of stecklings.

All production techniques in steckling fields aim at a high recovery of vigorous and healthy stecklings with an optimal top diameter of 2–4 cm and a weight of 40–80 g. Good nursery production should produce 300 000–400 000 plantable stecklings per hectare. The result can be especially influenced by date of sowing and sowing density of basic seed. In general, late sowing reduces average steckling weight and produces a higher proportion of small plants that do not have sufficient development for transplanting. In France and Italy, basic seed is sown from the end of July up to the end of August. The risk of foliar fungal diseases that comes with sowing too early is thus reduced and there is a high recovery of stecklings at the correct stage of development when they are harvested at the end of winter. In regions where transplanting is in October (Turkey), or where stecklings are stored over winter in clamps (eastern European countries) sowing may be as early as April to May.

Early sowing dates in France or Italy, end of July to beginning of August, require high seeding densities of about 1.1 million germinating seeds per ha to achieve a high number of even-sized stecklings. With a common row width of 20–25 cm, spacing within the row is 3–5 cm. Well-prepared fields allow sowing depths of 1.5–2 cm. Basic seed sowing should be finished by the end of August in order to achieve a high recovery of usable stecklings. In the instance of late sowings, the planting rate should be decreased by about 10–20% to support the development of single plants with less competition between plants.

It is necessary to ensure that drills are cleaned carefully to avoid any possible contamination of hybrid components. Male and female hybrid components are sown in separate plots and recorded on field maps. GPS co-ordinates can be kept with records to ensure clear identification and to help manage the rotation between two steckling crops.

Crop management

Steckling beds are generally irrigated immediately after sowing with an appropriate technique, which will avoid capping and crusting of the seedbed. Seedlings emerge 5–8 days after sowing. Keeping the soil surface wet during the early development stages is essential to reduce wind erosion and seedling damage on sandy soils. Depending on climatic conditions, two to five irrigations with small quantities of water (15–25 mm) may be necessary to ensure homogenous crop development. Steckling growers in Italy apply 12–15 t/ha of manure immediately after sowing in order to avoid wind damage.

Appropriate nutrition is an important factor in steckling production, especially on sandy soils to achieve a high production of well-calibrated stecklings. The nutritional status of the soil should be determined by soil analysis to adapt the rates of fertilizer. Potassium, phosphorus and about 50% of nitrogen are applied before sowing, the remain-

Table 5.3 Nutrition of sugar beet stecklings on sandy soils in France and Italy (kg/ha).

Nutrition	Time of application	France	Italy
N	Sowing (August)	60–70	50–60
	4/6 leaves (beginning of September)	30–40	40–50
	10/12 leaves (end of September)	–	0–20
P_2O_5	Pre-sowing	40–50	120–140
K_2O	Pre-sowing	60–70	100–120

der of nitrogen when between four and eight true leaves have been formed (Table 5.3). As boron, an important trace element for the development of beet, is possibly limited in sandy soils, steckling crops often receive between one and three boron applications of 100–120 g boron/ha each.

The weed control programme is essentially the same as for the sugar beet root crop. It is necessary to test new sensitive hybrid lines for specific interaction with herbicides in order to avoid damage to steckling crops. It is also essential to maintain steckling health to assure a high recovery of vigorous stecklings. Two to four treatments with appropriate insecticides, such as synthetic pyrethroids and carbamates, are generally necessary against pests of different Lepidoptera (*Agrotis* sp., *Spodoptera exigua, Scrobipalpa ocellatella*) and *Aphis* sp., starting at the development stage of about two to four true leaves. Major fungal diseases, *Pythium, Cercospora, Ramularia, Alternaria* and *Phoma* leaf spot, are treated several times according to epidemiological conditions between the end of August and the middle of October. Moist and cool weather conditions in autumn and winter could enhance downy mildew (*Peronospora farinosa*), especially in less developed beet from late sowing dates. Treatments with appropriate fungicides, such as mefenoxam or fosetyl-Al, can be necessary to reduce disease development.

In autumn, steckling fields are cultivated and the beet rows ridged up with 2–3 cm of soil beside the young beet plants in order to achieve:

- good soil aeration;
- better frost protection of stecklings;
- more upright position of beet leaves to simplify mechanical harvest of stecklings.

Over-wintering and steckling harvest

Sugar beet varieties commonly require vernalization temperatures of about 4–10°C for a duration of 15–20 weeks (Wood *et al.*, 1980; Longden, 1986). In the case of autumn transplanting, such as in Turkey, vernalization takes place in the seed production fields. In the main steckling growing areas, such as France and Italy, stecklings stay over winter in the nurseries – where temperatures are low enough to vernalize the beet plants, but are not too low to damage the crop. Healthy and vigorous sugar beet stecklings can withstand frost to about $^{-}6$–$^{-}8$°C without being damaged, depending on genetic type, development stage, leaf mass and the duration of the frost period. However, nurseries of some genetic components need additional protection for critical temperatures, to avoid plant losses due to frost. This can be achieved by covering the steckling plots before the cold periods (mid-December) with a fleece (17–28 g/m^2) to keep temperatures below the fleece 2–5°C higher than above the covering (Fig. 5.2).

Before harvest, the foliage of stecklings is removed to a height of 2–3 cm (Italy) or 7–8 cm (France) above the crown, depending on regional experience and available techniques, using mowers or chopper units, and ensuring that the growing point of the plants is not damaged. Harvesting methods are either:

- semi-mechanized, using a tractor-drawn lifter, followed by hand labour to pull and collect the stecklings, or
- completely mechanized, with converted sugar beet or vegetable harvesters, now common in France and Italy (Fig. 5.3).

The harvest of stecklings is done immediately before transplanting them, in order to minimize water losses and respiration, with consequent heterogenity of seed-producing plants. Stecklings should be stored in cool conditions of not more than 6–8°C (Nardi, 1998) in case poor weather conditions do not allow immediate planting.

Fig. 5.2 Covering of steckling fields for frost protection with fleece.

Fig. 5.3 Mechanical harvest of stecklings.

In regions with extremely cold winters or continental climate, stecklings are harvested in autumn and stored in field clamps or storage buildings for over-wintering. Field clamps, which have a width of 0.80 m and a depth of 0.60 m, are first left open at the top to release heat that is formed in the stack. With decreasing temperatures, clamps are successively covered with layers of soil of up to 0.60 m. Conditioning in storage buildings should ensure constant temperatures of 2–3°C and maximum relative air humidity above 90% in order to minimize development of clamp rots caused by pathogenic fungi and bacteria, desiccation of stecklings and following uneven growth of the seed crop.

Stecklings are calibrated after harvest to a top diameter of 2–4 cm using devices with oscillating riddles or cylinders. Those stecklings with a length of 8–12 cm are the best to make good soil contact for taking root in the seed production fields. With a recovery of 300 000–400 000 plantable stecklings per ha, the ratio of transplanting (steckling area:seed production area) could be 1:8 up to 1:12.

Seed production

Field and rotation requirements

Field requirements for seed production differ from those of steckling production, as the soil needs to be deep and fertile with a high water-holding capacity to sustain plant growth during dry periods. The best soils are loamy, with 40–70% of silt and 20–50% of clay, with neutral to slightly alkaline pH reaction. In some regions (e.g. Italy) fields are tested systematically for nematode infection (*Heterodera schachtii*) and excluded from seed production if the pest is present.

In order to maintain varietal purity, seed crops from stecklings can only be planted in fields that have not grown sugar beet seed for at least 5 years. Beet root crops and seed productions of other *Beta* species must be excluded completely from the rotation. Best preceding crops are those that are harvested early enough to allow ploughing and following cultivation of soils in good conditions before winter, such as cereal (wheat) or vegetable crops.

To avoid cross-pollination, minimum distances between seed crops of *Beta* species are prescribed both by law and, often, by even more stringent safety measures applied by breeding companies. Minimum distances according to European Union regulations and the Organisation for Economic Co-operation and Development (OECD) scheme are shown in Table 5.4. Presence of beet root crops in the immediate vicinity of seed production fields should be avoided, to minimize virus transmission and to avoid any problems with cross-pollination from eventual bolters in the root crop.

Table 5.4 Minimum isolation distances according to EU and OECD rules (metres).

	Basic seed	Certified seed
Diploid pollinator to tetraploid pollen source	1000	600
Tetraploid pollinator to diploid pollen source	1000	600
Between sugar beet seed fields of the same ploidy level	1000	300
Between two seed production fields in which male sterility is not used	1000	300
To any other sources of pollen of the genus *Beta*	1000	1000

Transplanting and cultivation methods

Soil preparation and quality of transplanting are key factors for high seed yield and seed quality. Cultivation of soil must ensure a structure that enables plants to settle their roots easily in the soil and preserve soil moisture.

Stecklings for production of monogerm hybrid varieties are planted in blocks with specific ratios of female and male plants, which are decided by the breeding companies. The right ratio to assure a high seed set and quality depends on factors like flowering time, ploidy and fertility of pollinators. With most sugar beet seed varieties, the ratio varies from 2:1 to 4:1. The female component is planted usually in blocks of four, six or eight rows, the pollinator in two rows (Fig. 5.4).

Several seed companies test new variety components for their specific regional agro-technical requirements, before going to commercial scale production. Planting density, as a major factor in seed production, depends on the productivity, vigour and the branching ability of the female components. Total plant population of both female and male components varies between 32 000 and 42 000 plants per ha (Table 5.5).

Common spacings vary from 50 to 75 cm between rows, and within rows from 30 to 45 cm. Even distribution of plants both within and between rows is best for homogenous development and avoidance of lodging, but technical feasibility does not allow for row distances narrower than 50 cm. Depending on machinery available and chosen harvesting technique, distance between female rows and pollinator rows could be double to avoid damage to seed plants when passing with the tractor for pollina-

Fig. 5.4 Seed production in 8:2 ratio (female:male) in Italy.

Table 5.5 Population of female and male plants per ha in prevailing transplanting systems in France, Italy and Turkey.

Country Ratio female:male:open	Spacing between rows (cm)	Spacing within rows (cm)	Number of plants/ha 000s
France 6:2:2	70	33	35
France 8:2:2	55	33	42
Italy 6:2	75	42	32
Italy 8:2	53	42	40
Turkey 6:2	70	45	32

tor elimination or cutting of seed plants (e.g. 6:2:2 planting system in the south-west of France).

Spring transplanting, as in France and Italy, should be as early as possible (February–March) in order to obtain a long vegetative period. Early planting ensures better rooting and an earlier start to foliage development, bolting, flowering and maturity of seed crops and thus higher seed yields. Phoma-susceptible components should be fungicide treated (e.g. with iprodione) before transplanting, to keep plants healthy from the outset. Planting is mostly done with semi-automatic planting machines, which are often produced locally and adapted to suit regional soil and growing conditions. Nevertheless, large areas of beet seed multiplication in Turkey are still transplanted by hand. Stecklings need to be planted straight and firmly in the soil and at a depth where the crown of the stecklings is about 1–2 cm below the soil surface. Irrigation immediately after transplanting with 25–30 mm of water may be necessary to ensure rapid establishment and root development.

Crop management

Fertilizer application should be done according to soil analysis, taking into account the preceding crop and regional experiences in production (Table 5.6). Phosphorus and potassium are incorporated usually before transplanting with the primary cultivation whereas nitrogen is split in several applications. The total amount of nitrogen varies between 160 and 250 kg/ha; 35–50% of this amount is applied at transplanting in spring, 30%

Table 5.6 Standard practice for fertilizer application in transplanted sugar beet seed plants in France and Italy (kg/ha).

Nutrition	Time of application	France	Italy
N	Transplanting	80–100	60–80
	Rosette growth (end March to mid-April)	40–50	60–80
	Beginning of bolting – topping (end April to mid-May)	40–50	60–80
P_2O_5	Autumn-spring	180–200	180–200
K_2O	Autumn-spring	120–140	0–100

at the vegetative development end of March/mid-April and the rest not later than bolting at the end of April/mid-May. Too late and too high nitrogen applications may cause delayed maturity and reduced seed quality. However, nitrogen uptake of seed plants is much higher than the amount given in fertilizer. Information on the total mobilization of nitrogen through seed bearers is given by Nardi (2000) with 250 kg/ha for the south-west of France and Lejealle (1986) with 300–400 kg/ha for plant populations of 80 000 plants/ha in direct-sown crops in the Beauce region of France. In addition to the main nutrients, seed producers often apply about 100–120 g/ha boron twice, at the stages of topping and beginning of flowering. Positive results of boron on pollination and fruit setting in sugar beet seed production are also reported by Lehnhardt and Bonk (1991). Draycott and Christenson (2003) have recently reviewed nutrition of the seed crop.

Seed fields must be protected systematically against pests and diseases to ensure healthy crops that produce certified monogerm seed of the high quality demanded by root-crop growers. Main pests and diseases of seed bearers are shown in Table 5.7.

One of the most important factors in beet seed multiplication is the irrigation of seed plants (Fig. 5.5). A lot of research has been done recently to improve irrigation techniques to ensure stable seed yields and seed quality. Appropriate water quantities and correct timing of irrigation is especially important at flowering time and during the maturity period, when daily water use of a sugar beet crop can reach up to 5–7 mm. Good irrigation practice can be managed with canon and sprinkler

Table 5.7 Plant protection measures in sugar beet seed crops.

Pest or diseases	Time of attack	Possible treatment
Conorhynchus sp. *Lixus* sp. *Cassida* sp.	Bolting to beginning of flowering (end of April to end of May)	Synth. pyrethroides
Aphis fabae, Myzus persicae	Bolting to maturation (May to July)	Carbamates, synth. pyrethroides
Peronospora farinosa	Vegetative development to beginning of bolting (April to beginning of May)	Acylalanine types
Alternaria sp. *Ramularia beticola* *Phoma betae* *Uromyces betae*	Bolting (end of April to mid-May)	Triazoles, strobilurines, copper fungicides, thiocarbamates, dicarboximides
Cercospora beticola	Beginning of flowering to end of flowering (end of May to June)	Triazoles, strobilurines
Erysiphe betae	Maturation (June to July)	Morpholines, strobilurines, sulphur

Fig. 5.5 Irrigation of seed fields with cannon.

irrigation, but nowadays many growers, especially in Italy, have introduced drip irrigation systems in sugar beet seed production (Fig. 5.6). The advantage of this irrigation technique is the high flexibility and the possibility of giving small water quantities at any time, e.g. in windy conditions.

Direct production method

In the direct production method, the plants of the first year's vegetative crop stay in the same field over winter for seed production in the second year. This method is largely used for seed production

Fig. 5.6 Drip irrigation in seed production.

Table 5.8 Sowing rate and plant population in direct-sown crops.

Country	Spacing between rows (cm)	Spacing within rows (cm)	Approx. viable germs/ha 000s	After winter number of plants/ha 000s
Chile	75	7	190	130
France	60/75	13/10	130	90
USA (Oregon)	61	5	250	150
England (multigerm)	50	4	600	250

of monogerm varieties in Oregon (USA), in Chile, in the Beauce region of France and in south-east France, while the seed production via stecklings has increased also in these regions recently. Beside the above-mentioned monogerm production regions, seed production for multigerm varieties is still found in the Lincolnshire area of England and in Denmark.

Direct-sown crops are established with seeding rates as high as 600 000 seeds per ha to withstand problems with weak or lost plants after frost or diseases (Table 5.8). The method is less labour and cost intensive compared to the transplant system, as the costs for steckling harvest and transplanting are removed.

Field and rotation requirements

The field requirements for direct-sown crops arise mainly from the demands of the second year's growth for seed production. The best security for stable productivity and seed quality is found on deep fertile loams as described for seed production with stecklings. The time since a previous beet crop with over-wintering seed production needs to be a minimum of 10 years, since detection and elimination of weed beet, especially within the rows is more difficult because of high plant populations. A long rotation reduces the occurrence of emerging beet plants and thus the risk of cross-pollination with undesired pollen. Good preceding crops are wheat or other early-harvested crops that allow sufficient time for field preparation; in Oregon, sugar beet seed fields are also drilled after grass seed crops.

Sowing and cultivation methods

In general there are two cultivation methods known for direct-sown crops:

(1) Sowing in spring under a cover crop. In England and Denmark, sowing is quite common in April for multigerm seed production, in combination with barley as a cover crop in the first year. After harvesting of the cover crop in summer, beet plants remain in the field for vernalization, over-wintering and seed harvest in the following year.

(2) Sowing in August as a main crop into open fields. After harvesting the preceding crop in June or July, the soil is ploughed and prepared to allow for sowing and to produce even emergence. This method is mainly used in direct sown monogerm seed production in France, the USA and Chile.

Hybrid varieties are sown in strips in female:male ratios of 6:2, 8:2 or 12:4. Multigerm synthetic varieties may also be drilled in specific mixtures of the single variety components. Common row spacings are 50–80 cm and within the row 6–14 cm. The resulting plant populations in different production regions are shown in Table 5.8. Irrigation immediately after sowing improves emergence and even plant development.

Crop management

Principles of crop management are similar to those for seed production with stecklings. Some specific requirements are:

- Safe over-wintering of directly sown crops in years of unexpected low temperatures is closely related to plant population and plant size range. Plants with a top diameter of 1–2 cm are best for over-wintering; large plants are killed more easily by frost. Therefore sowing densities need to be high enough to avoid too wide spacing between plants.

- Sowing should not be later than August, so that the time to grow before winter is sufficient to allow the plants to develop 10–12 leaves. Plants with fewer leaves risk attack from Downy mildew (*Peronospora farinosa*), which will result in no bolting in the second year.
- Beet rows should be ridged up before winter to give better frost protection.
- Winter conditions can reduce the beet population by about 50%. In cases of mild winters, thinning of too crowded beet stands may be necessary for even plant development with good branching of seed bearers.

Nutrition of direct-sown crops depends on specific soil conditions, the preceding crop and regional production experience. The fertilizer used for seed crops in autumn is generally about 60–80 kg N, 60–80 kg P_2O_5 and 60–100 kg K_2O per ha. In the second year of growth, crops will receive an additional 160–200 kg of nitrogen, about 50% at the beginning of the vegetative phase in spring and the remainder not later than beginning of bolting at the end of April. Seed producers in Oregon apply about 10 kg/ha of sulphur at sowing time and 25 kg/ha in early spring and in April. Pests and disease protection measures are similar to transplanted crops (see Table 5.7). As the older leaves of beet in the second year may carry infections like *Alternaria* or *Phoma* from over-wintering, one additional fungicide treatment may be necessary at the beginning of May to reduce disease development.

FLOWERING, MATURATION AND SEED HARVEST

Flowering

After being vernalized for an extended period, sugar beet switch from vegetative to reproductive growth in lengthening days. The full effective range for vernalization is cited by Wood *et al.* (1980) as 1–15°C. High temperatures above 15°C immediately after vernalization can devernalize plants (Longden, 1986). The interaction of vernalization period and day length on bolting was investigated by Smit (1983). In growth room trials, vernalization time and photoperiod could be interchanged to some degree; a shorter cold treatment could be compensated by a longer light phase per day. A bolting susceptible line bolted even without any vernalization period in day length conditions of 24 hours. After elongation of the apex, new shoots develop in the axils of leaves and form the seed bearer plants with second, third or fourth branching order. A common technique in seed production to improve growth of seed bearers is clipping (or topping) of the primary shoot of bolted female plants, with the following aims:

- Enhancement of side branch development. This results in a more homogeneous flowering and time of maturity for the seed plants. The result is a more uniform seed size in the required seed calibration (grade) with optimal maturity.
- A reduction of plant height. This improves stability of the crop and avoids lodging problems.
- Improved synchronization of flowering. An appropriate topping technique should be applied to delay or prolong flowering time to ensure that a maximum number of flowers are pollinated and any cross-pollination from outside the crop is minimized.

Normally 10–15 cm of the primary shoot is cut off between 10 and 20 May (France, Italy), when plants have reached a height of about 60–80 cm. At this height, 10–15 secondary branches should be left on plants, as especially in cases of late topping, seed yield and seed quality can be decreased drastically (Fig. 5.7). Topping can be done by hand, using a knife or a sickle, or with machines (Fig. 5.8) Mechanical topping requires homogeneous development of individual plants in the crop, in order to

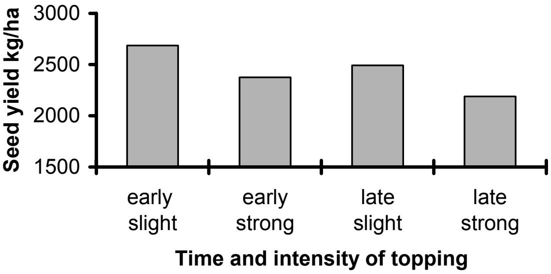


Fig. 5.7 Influence of date of topping and topping intensity on seed yield in experiments by Kleinwanzlebener Saatzucht (KWS).

Fig. 5.8 Mechanical topping of seed plants.

reach each plant and cut it to the right extent. In special cases, plants can be cut back more strongly at the beginning of bolting to enhance intensive branching and flowering. This method described by Leguillette (1987) is called 'broyage' in France.

Most sugar beet variety components flower over a period of 3–4 weeks (Fig. 5.9). Large stecklings will begin flowering earlier than small stecklings (Fig. 5.10). Wood *et al.* (1980) describe most suitable flowering conditions with average temperatures of 15–20°C and a maximum of 35°C. The highest daily pollen intensity in crops grown in England occurred in the morning, with increasing temperatures and decreasing relative humidity to 60–70%. Rainfall should be minimal during pollination; rain in the morning especially decreases pollen release (Scott, 1970). In sugar beet seed production the empty grain rate can reach more than 20%. One of the reasons can be deficient fertilization due to low pollen tube lengthening capacity, which is related to climatical factors (Alcaraz *et al.*, 1998). Sugar beet are mainly pollinated by wind, but also by insects, which could contribute to cross-pollination with undesired foreign pollen sources (Free *et al.*, 1975). According to Crane and Walker (1984), stigmas of sugar beet flowers may stay receptive for more than 2 weeks, depending on weather conditions.

Fig. 5.9 Seed plants at beginning of flowering.

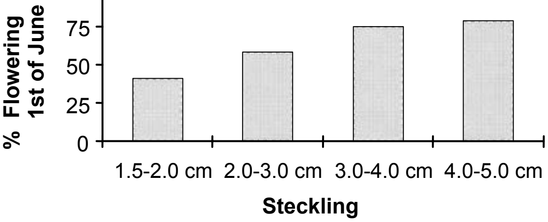


Fig. 5.10 Influence of steckling size on beginning of flowering of seed plants in experiments by Kleinwanzlebener Saatzucht (KWS).

Maturation and harvest of sugar beet seed

Pollinator plants are removed 2–3 weeks before harvest, to ensure that only hybrid seed matured on the female plants is harvested. This can be done by hand or mechanically with choppers (Fig. 5.11). Any shattered seed is incorporated only slightly into the soil to encourage rapid emergence, with subsequent destruction of these plants in order to prevent carryover to following years.

Seed quality is essentially influenced at the latest stage of maturity (Fig. 5.12). Harvesting too early can cause loss of germination and seed vigour. The determination of harvesting time of seeds with optimal physiological maturity requires special experience, taking into consideration:

Fig. 5.11 Elimination of pollinator plants after flowering.

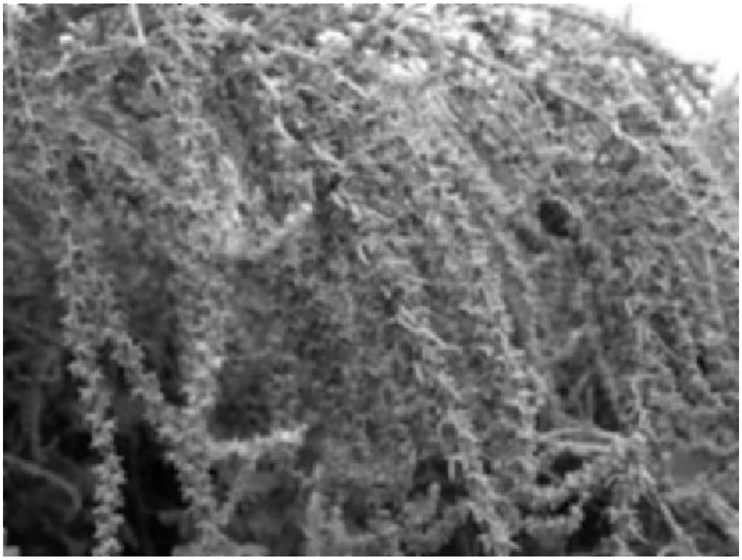


Fig. 5.12 Maturation of seeds.

- method of harvesting;
- appearance and colour of plants and seed;
- texture of the seed-perisperm and colour of the testa;
- seed shattering; and
- homogeneity of the crop.

At harvest, the majority of true seed should have a farinaceous texture with a brownish testa. To judge maturity, seed of the third order of branching should be taken into consideration, since more than 60% of seed in most sugar beet seed varieties is produced on these branches. Several authors discuss the accumulated temperature (heat units) from the beginning of flowering to define optimal harvesting stage. Snyder (1971) and Grimwalde *et al.* (1987) report heat unit requirements of 456–612°C, applying a base temperature of 7–7.2°C, in order to reach maximum germination. The interval from the beginning of flowering to physiological maturity averaged 53–55 days under greenhouse conditions. Roquigny and Lejòsne (1988) measured 1146 heat units with a base temperature of 0°C to achieve maximum germination of harvested seed under field conditions in France. Also, the dry matter content of seeds may give some indication of physiological maturity, since it increases rapidly before the optimal harvesting stage. The dry matter content should reach a minimum of 40% at the stage of cutting of seed plants to reach best seed quality (Roquigny & Lejòsne, 1988).

There are two principle methods for harvesting sugar beet seed:

(1) Cutting onto a swath and subsequent threshing.
(2) Direct threshing after desiccation.

Cutting on swath

Cutting of seed bearers onto a swath is usually done by machine, using different techniques of mower bars or swathers, with cutting capacities of about 1 ha per hour. The cutting technique needs to avoid shattering the best physiological matured seed and achieve efficient ventilation and drying of the seed plants and seeds before threshing. The specially developed cutting devices for sugar beet seed plants in south-west France lay plants smoothly on stubbles of about 30 cm. This technique reduces soil contact of seeds and thus the development of fungal diseases especially under moist conditions during harvesting time (Fig. 5.13).

The threshing of seeds can usually be done about 4–8 days after swathing, depending on weather conditions and the mass of green plant material. Under optimal conditions, seed would have a moisture content below 12% when threshed. Combine

Fig. 5.13 Cutting system in south-west France.

Fig. 5.14 Threshing of sugar beet seed.

harvesters are equipped with special pick-up devices (Fig. 5.14). These comprise a belt with finger attachments that is mounted on two cylindrical rolls and enables the swath to be pulled into the threshing section with a minimum of seed losses. The correct setting of the threshing machine, e.g. reduced speed of the cylinder and a wider distance of the concave, are both important factors determining the quality of threshed seed. It is important to thresh as gently as possible in order to minimize the number of smashed pieces of stalk and bruised seeds. Threshing capacities reach about 4–6 ha per day.

Seed fields should be cultivated after harvest with appropriate machines to work shed seed superficially into the soil. After germination the young seedlings can be destroyed to minimize volunteer beet in the rotation.

Direct threshing after desiccation

In the past, desiccation followed by direct threshing of commercial seed crops was used on large farm units in Hungary, Croatia and the former German Democratic Republic. The application of diquat, as a desiccant, causes green plant tissue to wilt rapidly allowing direct threshing. Fürste *et al.* (1983) advised the use of diquat with a preceding application of a growth regulator Camposan (ethephon), especially under climatic conditions giving a long flowering period and thus a heterogeneous maturation. In recent years, direct threshing has spread to south-west France, as more hybrid components came into production with less branching and higher tendency for seed shattering. Also, risk of rain at harvesting time could give preference to use of desiccation. The technique of harvesting after diquat application requires special experience to secure a high seed quality:

- The moisture content of seed should be a maximum of 30–40% at first application of diquat. This is normally a few days later than when cutting onto the swath. Diquat is applied twice in doses of 500 g a.i./ha (active ingredient). A second application may be necessary about 2–3 days after the first treatment.
- Threshing is undertaken 5–7 days after the last treatment. Moisture content of seed at threshing could be as high as 25%. Immediate drying of seed is therefore vital to preserve seed quality. Finally, direct threshing after desiccation requires about one week's more time to reach harvest compared to swathing (Thibaud, 2002).

Drying and cleaning

Drying of threshed seed

Moisture level of seeds threshed from the swath is normally 10–14%, but, depending on weather and method of harvesting, it can be higher than 20%, especially when harvesting after desiccation. Seed with a moisture content of more than 12% requires immediate drying after threshing in order to conserve seed quality. Common drying systems in commercial seed production are:

- Drying in farm installations. Especially in growing regions with some risk of rainfall during harvest or where direct threshing after desiccation is the usual practice, farmers are equipped with drying capacities large enough to handle their own production. This system is quite common in south-west France.
- Drying at seed companies' premises. Individual seed lots are dried when necessary after some pre-cleaning. The system is an insurance measure in production regions with low risk of rainfall during harvest.
- Drying in mobile containers. Containers with capacities of about 6 t of seed can be used for transport of threshed seed from the field and then connected to drying units at central storage depots. These containers are provided with a double floor to enable air to be blown through the seed bulk. This is probably the most flexible system to ensure that harvested seed is stabilized after harvest to the correct moisture level (Fig. 5.15).

Drying is preferably done at 25–30°C. Temperatures should never be higher than 38°C to avoid deterioration of seed quality.

Pre-cleaning of raw seed

Raw seed lots contain seed stalks, beet pieces, seed of other crops, weed seed, soil particles, stones and other foreign matter. Seed companies usually plan to receive and pre-clean large quantities of raw seed as quickly as possible after harvest in order to:

- Eliminate major impurities. Generally pre-cleaning combines a calibration to separate very big and very small particles from seed, and an air separation of light particles and empty seed. Pieces of green stalks or beet must be removed because these can harm seed quality owing to their high moisture content.
- Take representative samples of seed by automatic samplers out of the seed stream. From this sample the moisture content as a first quality parameter is measured to decide whether the seed

Fig. 5.15 Drying of seeds immediately after harvest.

lot has to be dried. In addition, other parameters like technical purity, calibration, percentage of empty seed and germination are checked to get the first assessment of quality of the seed lot. These results determine the further steps necessary and the intensity of processing.

- Determine the remuneration to the seed grower (based on company-specific contract agreements).

Pre-cleaned seed may be stored for several months without problem before further processing.

Cleaning

The pre-cleaned seed lots still contain empty fruit clusters without true seeds, small seeds and other foreign matter. Generally, the cleaning process of seed lots consists of:

- Calibration into several size fractions within the range of about 3.25–6.00 mm to optimize all following separation processes.
- Processing on gravity tables, to separate particles depending on weight from light to heavy. To optimize separation efficiency, each fraction is processed separately. The discard material is the light fraction with empty clusters plus the extreme heavy fraction, which contains soil particles, stones and some bigerm clusters.
- Elimination of stalks on belt sorting units or indented cylinders.

Afterwards all the single fractions are combined again, filled into containers and kept ready for final processing. The level of technical purity after the cleaning process reaches more than 99%; generally the proportion of filled clusters in cleaned seed is about 94% or higher. During the pre-cleaning and cleaning processes about 35–40% of the harvested raw seed is discarded.

Seed yield and propagation ratios

Seed yield depends on production region, method of seed production and variety-specific production techniques. The payment to farmers is often based on a reception sample of raw or pre-cleaned seed, which is further cleaned in a laboratory according to contract standards (defining for example lower and upper screening, humidity, percentage of filled clusters, germination). After seed processing, only 20–30% of cleaned seed bought from the farmer can normally be used in the finished seed, marketed by weight or in units of 100 000 seeds. Average yields of current monogerm varieties in the main production areas are shown in Table 5.9.

Seed production can also be measured by the ratio between the number of basic seeds sown and the number of certified marketable seeds harvested. Using the transplanting method this ratio varies between 1:300 and 1:800 and with the direct production method between 1:150 and 1:550 for the important sugar beet seed production areas.

SEED PROCESSING

The physiological quality of seeds is determined by the growing conditions in seed production, especially during flowering and maturation phases of the seed. In general, the basic physiological quality of single seeds cannot be improved by processing. Therefore the main aim of seed processing is the optimal separation or selection of fractions with the best seed quality within a seed lot. To en-

Table 5.9 Average sugar beet seed yield and propagation ratios in different planting systems.

Production system	Weight of cleaned seed (100 kg/ha)	Number of units*/ha	Propagation ratio from basic seed 1:
Monogerm seed transplanting system 6:2	22–26	400–700	350–800
Monogerm seed transplanting system 6:2:2	18–22	350–600	300–650
Monogerm seed direct system 6:2 France	22–26	400–700	300–550
Monogerm seed direct system 12:4 USA	22–26	400–700	150–300
Multigerm seed	25–30	–	150–200

*1 unit = 100 000 seeds.

Table 5.10 Distribution of different seed forms as a percentage based on sugar beet acreage.

	Monogerm pelleted seed	Monogerm encrusted seed	Multigerm seed
Europe	99	< 1	
Russia	30	70	
Ukraine	16	84	
North Africa	< 1		99
Near East	2	25	73
North America	35/65*		
Others			
Turkey		100	
China		10	90
Japan	97	3	
Chile	100		

* minimum build

sure high seed quality, processing has to be continuously controlled with suitable testing methods. The distribution of certified, monogerm pelleted, encrusted and multigerm seed over the different markets is given in Table 5.10.

Monogerm seed

Processing of cleaned seed

The preparation of sugar beet seed prior to pelleting is a complex process, which combines in principal three stages: polishing, calibration and gravity separation. The combination and intensity of each has to be adjusted individually to every single seed lot, depending on specific physical characteristics of the seeds. In general, the course of processing is as follows (Fig. 5.16):

- Calibration of cleaned seed lots of 3.25–6.00 mm into different size fractions.
- Polishing of each fraction separately to reduce the pericarp. The aim of polishing is to reduce seed size to an optimal grade suitable for pelleting. Removing the pericarp also leads to an increase in the speed of germination, because germination inhibitors, located in the pericarp, are removed and water uptake is improved. Nevertheless, polishing must be done gently to avoid cracks in the pericarp and damage to the embryo, especially the radicle.

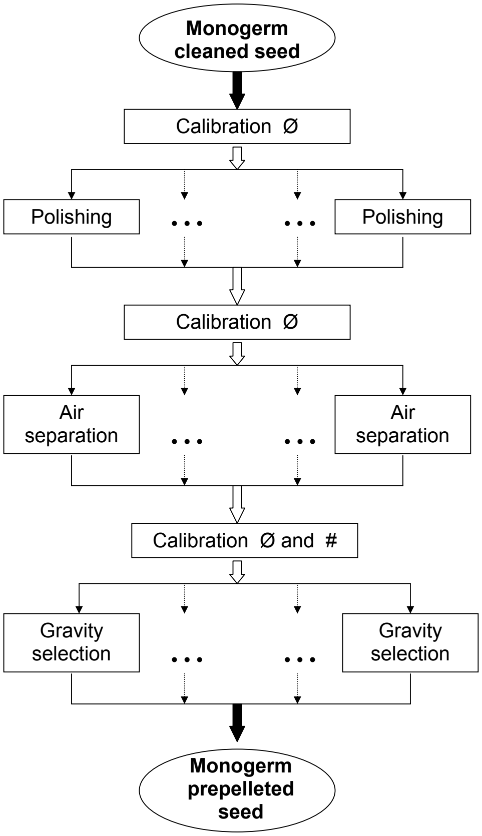


Fig. 5.16 General processing scheme of monogerm sugar beet seed (∅ round hole, # slot hole sieves).

- Several calibrations with round-hole sieves follow polishing, to remove small particles of pericarp and also those seeds which are too small or still too big. The object is to produce seed fractions with a narrow size range. This is necessary for the following calibration with suitable slot hole sieves to eliminate bigerm seeds.
- Processing of remaining monogerm seed fractions with air separators and/or gravity tables, to eliminate clusters with shrunken true seeds (Fig. 5.17) These seeds show only small differences in weight compared to well-filled clusters and therefore the process has to be continuously controlled by X-ray to optimize machine adjustments and the recovery rate of well-filled clusters. The goal of this selection process is 100%

Fig. 5.17 Gravity table for the selection of clusters with well-formed seeds.

filled clusters, which contain complete and well-formed true seeds. The different fractions of a seed lot are normally kept separate in containers for the further processing.

Pelleting

Pellets should have a round shape and a normal distribution between the required minimum and maximum size. Usually all fractions of different sizes from one lot are used if their seed quality meets the requirements. The most common pellet sizes in Europe are 3.50–4.75 or 3.75–4.75 mm; only markets in Finland and Sweden require sizes of 4.00–5.00 mm diameter. The thickness of the surrounding layer of pelleting material is 0.5–0.75 mm, which causes an increase in seed weight of about 180% on average, ranging from 150 to 200%, depending also on the specific pelleting material used. The USA market uses, in addition to these pellet sizes, the seed form 'minimum build', which has a coating of only 20–40%. Starting from 2005 all seed sold in the US market will have some pelleting material applied. For both the pelleted and 'minimum build' seed, several different size ranges are commonly used.

The production of sugar beet seed pellets combines the following processing steps. The seed is moistened or washed before or at the beginning of the pelleting process. Any remaining inhibitors after polishing may be reduced by washing and the seed quality can be thus improved. The appropriate amount of pelleting material is then added, depending on the seed size and the final required pellet size. The wet pellets have to be dried carefully with temperatures not exceeding 38°C to retain the quality of the pelleted seed. Calibration of pelleted seeds can be integrated directly into the pelleting process with calibration of wet pellets or after drying.

There are various types of pelleting equipment and drying systems (e.g. fluidized bed dryers, continuous flow dryers) as well as different recipes for the composition of pelleting material and chemical additives. Generally each producer has special expertise for pelleted seeds. The pelleting process ends with dried, calibrated pelleted seeds.

Chemical treatment

As a final process, pelleted seed has to be treated with different fungicides and insecticides depending on the specific demands of different markets (countries). In this process a specific suspension, containing fungicides as well as insecticides, is applied to the pelleted seed, usually in combination with a colour, which can either be specific to a breeding company or, as in the UK market, specific to the chemical treatment applied (Fig. 5.18). The same treatment process is also applied for non-pelleted seed to produce finished encrusted seed. The result of the treatment is routinely controlled by chemical analysis (e.g. high-performance liquid chromatography) to ensure that the exact amount of different active ingredients is applied to each seed.

Fig. 5.18 Pelleted sugar beet seed after the chemical treatment.

Priming

For sugar beet seed, the time from sowing to field establishment is a critical phase, especially under sub-optimal emergence conditions. Therefore there have been many attempts to develop suitable priming methods from those already in use for horticultural seeds (Bradford, 1986; Taylor *et al.*, 1998). The technique is based on the hydration of the seeds, followed by incubation under controlled conditions for a certain time and subsequent redrying before sowing. The hydration should permit pre-germinative physiological processes in the seed, but should be stopped before germination is completed to prevent emergence of the radicle. Generally three different technologies of controlled water uptake can be differentiated (Halmer, 2003).

(1) Osmopriming, where seeds are placed in osmotic solutions to limit the water uptake.
(2) Solid matrix priming, where seeds are mixed with solid particles and water in a predetermined specific ratio.
(3) Hydropriming, where a limited amount of water is added to the seeds ('Drum priming') or the seeds are imbibed in water for a short period (steeping).

In non-controlled water uptake systems, the seeds are moistened in water, which is freely available, and then re-dried to a defined moisture content before incubating. Generally the specific treatment conditions, especially the moisture content at which the seeds have to be incubated, must be evaluated for each lot individually.

The priming of sugar beet seed with water and/or with different salt solutions usually improves germination rate (Longden, 1971; Durrant *et al.*, 1983a,b; Durrant & Jaggard, 1988; Capron *et al.*, 2000; Mukasa *et al.*, 2003) and also results in more rapid emergence, but final emergence is not necessarily increased (Durrant *et al.*, 1983b; Thomas *et al.*, 1994; Mukasa *et al.*, 2003). The time between sowing and emergence can be reduced by priming, and this beneficial effect will generally be greater under sub-optimal conditions, than under normal conditions. Additionally, priming offers the possibility of sowing earlier, e.g. up to 10 days (Thomas *et al.*, 1994), which results in a longer growing period and, in consequence, can lead to higher sugar yields of up to 5% (Durrant *et al.*, 1993; Mukasa *et al.*, 2003). Therefore, especially in northern Europe and also for some regions in the USA there is a developing demand for commercial primed seed. The percentage of primed seed sown in 2004 was about 75% for the UK and about 10% for the Finnish market.

Multigerm seed

The processing of multigerm seed is less complex than that for monogerm seed. Cleaning combines calibration, processing with belt sorting units and air separation. Because multigerm seed is not marketed as pellets, the processing procedure is reduced to an air separation to achieve 100% filled clusters and an exact grading to the final required size. Seed is commonly treated with a fungicide to control diseases such as *Phoma betae*, which could be seed-borne and cause black-leg (damping-off) in young seedlings.

QUALITY TESTING

The main objective of seed testing is to ensure that a seed lot delivers a high emergence and gives a good final stand in the field. Methods of seed testing should:

- give a good indication of the field value of individual seed lots;
- be reproducible; and
- give comparable results between testing stations.

The laboratory seed testing methods which have been developed within the framework of the International Seed Testing Association (ISTA) are the most widely used and give the most uniform and comparable data. For the American market other methods described by the Association of Official Seed Analysts (AOSA) are used.

The fundamental prerequisite for seed testing is a representative sample of a seed lot. Non-pelleted sugar beet seed in particular differs in a wide range according to size and weight and therefore tends to segregate during handling and/or transport. For example, larger seeds tend to move towards the outer and upper areas of the container, while smaller seeds concentrate in the central and lower position. Therefore, in a modern seed processing plant, beginning with cleaning, up to the final treatment of pelleted seeds and packaging, automatic seed samplers are installed. Small samples are taken continuously during processing at short intervals out of the complete seed stream to get a representative sample of the whole seed lot. The sampling intensity, depending on the seed lot size, procedures of sampling up to the stage of getting the working sample in the laboratory for single tests, and different instruments for sampling are described by ISTA (ISTA, 2004).

Laboratory methods

For the certification of seeds the following investigations are obligatory:

- technical purity;
- moisture content;
- germination; and
- seeds of other species.

Additionally, weight and size grading can be determined. The general principles of these tests and the methods used are described in detail by ISTA (ISTA, 2004); for testing the germination ability of sugar beet seed the following specification is generally accepted and most commonly used. For testing non-pelleted, and non-encrusted seeds, seeds should be washed for 2–4 hours in running water at a temperature of 25°C with subsequent drying at max. 25°C (e.g. at room temperature overnight) to remove naturally occurring inhibitory substances located in the pericarp. Additionally, seeds must be treated with a fungicide to control *Phoma betae*, to eliminate the difficulty of distinguishing between secondary fungal-infected seedlings from primary ones, which could cause deviating results in testing (Bekendam, 1984).

Pleated filter paper, which corresponds to the prescribed substrat BP (between paper), is used as substrate. At present, filter paper from the manufacturer Schleicher and Schüll (with designated number 3014 for the pleated part and number 0858 for the covering part), or another paper of the same quality, is used. For sugar beet seed the amount of water in the filter paper that is necessary to germinate the seed is very important. For the paper described above the optimal weight ratio between paper and water, depending on seeds tested, is between 1:0.9 and 1:1.2. Values outside this range usually result in decreasing germination results. The most common absolute amount is 35 ml of water for the pleated paper described above.

At a constant temperature of 20°C, the germination is completed after 10–12 days; after this the normal seedlings can be removed and the final count should be made after 14 days. This allows the more accurate identification of abnormals, which are not included as germinated seeds. Clear definitions of abnormal seeds are given in the Handbook for Seedling Evaluation (ISTA, 2003). Correct statistical procedures, including the application of tolerance tables (ISTA, 2004), have to be applied for the interpretation of germination results. The objective of this germination test is to determine the maximum germination potential of a seed lot under optimal conditions.

To gain further information on the seed quality of sugar beet seed, especially regarding the field emergence potential under sub-optimal emergence conditions, a wide range of different vigour test-methods have been developed. Most of them are direct methods, which try to simulate sub-optimal field conditions or at least one or more of the specific limiting factors, such as water, temperature and mechanical impedance, by germination or emergence tests in various substrates. The results obtained are not always very consistent. Depending on whether the seed lots are also tested under sub-optimal conditions in the field, the standard germination percentage can correlate well with field emergence, especially if seed lots with considerable differences in germination are compared (Hutin *et al.*, 1975; Kraak *et al.*, 1984; Durrant *et al.*, 1985; Durrant & Gummerson, 1990). The laboratory packed-sand test, which combines a mechanical barrier of a thick layer of sand with a low temperature of 10°C, resulted in better correlation to field emergence than the standard germination test (Akeson & Widner, 1981), but gave no reproducible results in a collaborative ISTA-test (Perry, 1984). Germination at low temperature (10°C) in pleated paper as well as in sand (Van Swaaij *et al.*, 2001) and germination with high amounts of water (Lovato & Cagalli, 1992) showed better correlation with field emergence compared to the standard germination test.

Various indirect vigour tests have been described, e.g. accelerated ageing (Kraak *et al.*, 1984), controlled deterioration (Matthews, 1980) and conductivity tests (Longden & Johnson, 1974). Special biochemical vigour tests have also been reported e.g. quantifying extractable high molecular weight nucleic acids (BVT) and the RNA to DNA ratio (Redfearn *et al.*, 1995; Redfearn, 1996). Only the BVT and the controlled deterioration showed higher correlation to field emergence than the standard germination test.

Generally, breeding companies use a range of different vigour test methods, in addition to the standard germination test, to select seed lots with high seed quality. However, on the basis that commercial seed lots will have only small differences in field emergence potential, application of vigour tests is limited. Different genetics as well as different pellet types can interact with some specific test conditions, which can lead to misinterpretation of (non-reliable) results. Therefore up till now, for sugar beet seed no vigour test that gives reproducible and comparable results is recommended by ISTA.

In addition to final germination percentage, speed of germination, as indicated by one first count (e.g. after 96 hours) in the germination test, becomes more and more important as a quality criterion. The results are highly influenced by availability of water and the temperature. Only small differences can significantly influence the results. To get reproducible results within one laboratory, as well as comparable results between different laboratories, it is essential to have absolutely the same germination conditions. Moreover the germination criterion also has to be exactly defined, as e.g. 'visible root tip'.

X-ray analysis is predominantly used as a method in process control, especially for adjustment of gravity tables. With X-ray the fractions of clusters containing completely developed seeds, completely empty clusters, clusters containing shrunken seeds, bigerm clusters and clusters containing two seeds (doubles) can be differentiated (Fig. 5.19).

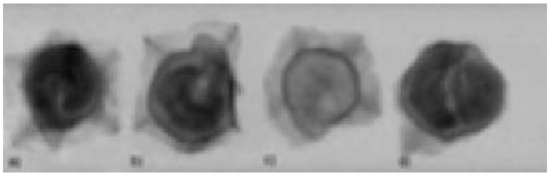


Fig. 5.19 X-ray picture of monogerm sugar beet seeds (a) cluster with well-filled seed, (b) cluster with shrunken seed, (c) empty cluster, (d) cluster with two seeds (twins).

Field tests

Field tests can be used as both a general assessment of seed quality and as a stress test at the same time. The biggest difficulty with it is the definition of conditions under which the trial is performed. Temperature, soil moisture, soil texture, soil structure, seed placement and soil pathogens, can all influence emergence. In order to obtain reliable results in spite of these problems, seed lots have to be tested at several different locations. In contrast to laboratory tests, absolute levels of emergence in field tests are not consistent. To compensate for this, it is necessary to include standard seed lots in the test, against which other seed lots can be judged. The duration of time between sowing and counting depends upon sowing depth, soil temperature and soil moisture. Emergence is usually between 1 and 4 weeks after sowing. In order to get information on the speed of emergence of seed lots, an early count should be made when about 30% field emergence has been reached by the first lot. The emergence test can be concluded with a final count of plants, when the first true leaves are formed. In general, field tests, which are quite labour and time consuming, are not applied routinely in quality control systems for commercial seed production.

SEED LAW REQUIREMENTS

Beet seed can only be placed on the European Union market if it has been officially certified as 'basic seed' or 'certified seed' and if the variety is included in the Common Catalogue of Varieties. Both supervision of seed field crops and seed quality testing are prerequisites for certification of seed lots. The official examination of seed is carried out in accordance with current international methods described by ISTA. Rules for seed sampling, packaging, sealing, labelling and minimum conditions for analytical purity, germination, and moisture content are regulated by the European Commission in the directive 2002/54/EC 'On the Marketing of Beet Seed'. This directive is supplemented by national rules for seed marketing, enacted by member states of the European Union.

The movement of beet seed between OECD member states is basically comparable with the European Union system and is prescribed in the 'OECD Scheme for the Varietal Certification of Sugar Beet and Fodder Beet Seed Moving in International Trade, 2003'. In the North American market there are no official minimum standards for seed quality and no certification system for seed lots provided to growers. Therefore seed companies there are responsible for meeting market-specific demands for varietal identity and seed quality.

REFERENCES

Akeson, W.R. & Widner, J.N. (1981) Laboratory packed sand test for measuring vigour of sugar beet seed. *Crop Science* **20**, 641–644.

Alcaraz, G., Genter, T., Laillet, G. & Rageot, D. (1998) Sugar beet pollen biology. *Proceedings of the 61st IIRB Congress*. Brussels, pp. 393–399.

Bekendam, J. (1984) Report of the germination working group on the germination method for *Beta vulgaris*: the influence of fungicide pretreatment upon dependability and uniformity of germination testing of *Beta vulgaris*. *Seed Science and Technology* **12**, 111–127.

Bornscheuer, E. (1972) Influence of different production regions on sugar beet seed. *Proceedings of the 35th IIRB Congress*. Report No. 2.1, pp. 1–8.

Bradford, K.J. (1986) Manipulation of seed water relations via osmotic priming to improve germination under stress conditions. *HortScience* **21** (5), 1105–1112.

Capron, I., Corbineau, F., Dacher, F., Job, C., Come, D. & Job, D. (2000) Sugarbeet seed priming: effects of priming conditions on germination, solubilization of 11-S globulin and accumulation of LEA proteins. *Seed Science Research* **10**, 243–254.

Crane, E. & Walker, P. (1984) *Pollination Directory for World Crops*. International Bee Research Association, London.

Draycott, A.P. & Christenson, D.R. (2003) *Nutrients for Sugar Beet Production: Soil Plant Relationships*. CABI Publishing, Wallingford.

Durrant, M.J. & Gummerson, R.J. (1990) Factors associated with germination of sugar-beet seed in the standard test and establishment in the field. *Seed Science and Technology* **18**, 1–10.

Durrant, M.J. & Jaggard, K.W. (1988) Sugar-beet seed advancement to increase establishment and decrease bolting. *Journal of Agricultural Science* **110**, 367–374.

Durrant, M.J., Payne, P.A. & McLaren, J.S. (1983a) The use of water and some inorganic salt solutions to advance sugar beet seed. 1. Laboratory studies. *Annals of Applied Biology* **103**, 507–515.

Durrant, M.J., Payne, P.A. & McLaren, J.S. (1983b) The use of water and some inorganic salt solutions to advance sugar beet seed. 2. Experiments under controlled and field conditions. *Annals of Applied Biology* **103**, 517–526.

Durrant, M.J., Brown, S.J. & Bould, A. (1985) The assessment of the quality of sugar beet seed. *Journal of Agricultural Science* **104**, 71–84.

Durrant, M.J., Mash, S.J. & Jaggard, K.W. (1993) Effects of seed advancement and sowing date on establishment, bolting and yield of sugar beet. *Journal of Agricultural Science* **121**, 333–341.

Free, J.B., Williams, I.H., Longden, P.C. & Johnson, M.G. (1975) Insect pollination of sugar-beet (*Beta vulgaris*) seed crops. *Annals of Applied Biology* **81**, 127–134.

Fürste, K., Schmidt, J. & Pöckel, H.G. (1983) Erzeugung von Hochzucht Zuckerrübensaatgut in hoher Qualität durch Einsatz von Composan in Kombination mit Reglone. *Institut für Rübenforschung Kleinwanzleben, Tagungsbericht Akademie der Landwirtschaftswissenschaften*, DDR, Berlin, **212**, 53–63.

Grimwalde, J.A., Grierson, D. & Whittington, W.J. (1987) The effect of differences in time to maturity on the quality of seed produced by different varieties of sugar beet. *Seed Science and Technology* **15**, 135–145.

Halmer, P. (2003) Methods to improve seed performance in the field. In: Benech-Arnold, R.L. & Sanchez, R.A. (eds) *Seed Physiology: Applications to Agriculture.* Food Product Press, New York, pp. 125–166.

Hutin, C., Chesneaux, M.T. & Christmann, M.J. (1975) Essais de levée en terre et de détermination de la faculté germinative au laboratoire de semences enrobées de betterave à sucre. *Journal of the International Institute for Sugar Beet Research* **7**, 1, 33–54.

ISTA (2003) *ISTA Handbook for Seedling Evaluation*, 3rd edn. International Seed Testing Association, Zurich.

ISTA (2004) *International Rules for Seed Testing.* International Seed Testing Association, Zurich.

Kraak, H.L., Vos, J., Perry, D.A. & Bekendam, J. (1984) Studies on field emergence and vigour of sugar beet and onion seeds. *Seed Science and Technology* **12**, 731–745.

Leguillette, V. (1987) *Production de semences de betterave à sucre. Étude d'une nouvelle technique culturale: le Broyage.* Deleplanque et Cie., Maisons-Lafitte, France.

Lehnhardt, L. & Bonk, M. (1991) Untersuchungen zum Einfluss einer Bordüngung blühender Zuckerrübenpflanzen auf Entwicklung und Eigenschaften ihrer Samen. *Brandenburgische Landeshochschule Potsdam* **35**, 65–71.

Lejealle, F. (1986) Influence du mode de production et de la fertilisation azotée sur la qualité des semences. *Proceedings of the 49th IIRB Congress.* Brussels, pp. 101–121.

Lexander, K. (1980) Present knowledge of sugar beet bolting mechanisms. *Proceedings of the 43rd IIRB Congress.* Brussels, pp. 245–258.

Longden, P.C. (1971) Advanced sugar-beet seed. *Journal of Agricultural Science* **77**, 43–46.

Longden, P.C. (1986) Influence of the seed crop environment on the quality of sugar beet seed. *Proceedings of the 49th IIRB Congress.* Brussels, pp. 1–16.

Longden, P.C. & Johnson, M.G. (1974) Predicting sugar beet seedling emergence in the field. *Seed Science and Technology* **2**, 337–342.

Lovato, A. & Cagalli, S. (1992) Sugar beet (*Beta vulgaris* L.) seed vigour compared in laboratory and field tests. *Seed Science and Technology* **21**, 61–67.

Matthews, S. (1980) Controlled deterioration: a new vigour test for crop seeds. In: Hebblethwaite, P.D. (ed.) *Seed Production.* Butterworths, London, pp. 647–660.

Mukasa, Y., Takahashi, H., Taguchi, K., Ogata, N., Okazaki, K. & Tanaka, M. (2003) Accumulation of soluble sugar in true seeds by priming of sugar beet seeds and the effects of priming on growth and yield of drilled plants. *Plant Production Science* **6**, 74–82.

Nardi, L. (1998) Repiquage des plants: bien implanter, por bien mulitplier. *Bulletin Semences* **142**, 33–34.

Nardi, L. (2000) Premiers pas pour raisonner la fertilisation azotée. *Bulletin Semences* **152**, 35–36.

Perry, D.A. (1984) Report of the vigour test committee 1980–1983. *Seed Science and Technology* **12**, 287–299.

Redfearn, M. (1996) A new seed vigour test: is it important for the beet crop? *British Sugar Beet Review* **64** (1), 16–18.

Redfearn, M., Clarke, N.A., Halmer, P., Osborne, D.J. & Thomas, T.H. (1995) A biochemical test for seed vigour. *Proceedings of the 58th IIRB Congress.* Brussels, pp. 133–137.

Roquigny, C. & Lejòsne, M. (1988) *Betterave sucrière porte-graine: contribution à la détermination du stade optimal de récolte.* Deleplanque et Cie, Maisons-Lafitte, France.

Scott, R.K. (1970) The effect of weather on the concentration of pollen within sugar-beet seed crops. *Annals of Applied Biology* **66**, 119–127.

Smit, A.L. (1983) Influence of external factors on growth and development of sugar-beet (*Beta vulgaris* L.). *Agricultural Research Report Wageningen* 914.

Snyder, F.W. (1971) Relation of sugar beet germination to maturity and fruit moisture at harvest. *Journal of the Association of American Sugar Beet Technologists* **16**, 541–551.

Taylor, A.G., Allen, P.S., Bennet, M.A., Bradford, K.J., Burris, J.S. & Misra, M.K. (1998) Seed enhancements. *Seed Science Research* **8**, 245–256.

Thibaud, N. (2002) Itinéraires de récolte: la tendence est à la dessication chimique. *Bulletin Semences* **166**, 31–32.

Thomas, T.H., Jaggard, K.W., Durrant, M.J. & Mash, S.J. (1994) The physiological advancement of sugar beet seed. In: *Seed Treatment: Progress and Prospects.* British Crop Protection Council Monograph 57, Farnham, pp. 391–396.

Van Swaaij, A.C.P.M., Heijbroek, W. & Basting, J.L. (2001) Testing and improving seed vigour in sugar beet. *Proceedings of the 64th IIRB Congress.* Brussels, pp. 237–246.

Wood, D.W., Scott, R.K. & Longden, P.C. (1980) The effects of mother plant temperature on seed quality in *Beta vulgaris* L. (sugar beet). In: Hebblethwaite, P.D. (ed.) *Seed Production.* Butterworths, London, pp. 257–270.

Chapter 6
Soil Tillage and Crop Establishment

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OBJECTIVES OF TILLAGE

The main objectives of tillage are to produce suitable soil physical conditions for the sowing operation and for seed germination, seedling emergence, plant establishment and crop growth by:

- loosening and sometimes re-compacting soil;
- controlling weeds;
- burying plant residues and disintegrating clods;
- preventing spread of some plant diseases; and
- incorporating manure, fertilizers, soil amendments or chemicals.

In any specific situation, tillage may have one or more of these objectives. However, it also has some adverse effects, and no tillage operation should be carried out unnecessarily. The optimum method and number of operations vary greatly depending on factors such as soil type, climate, previous crop, amount of trash and weed infestation.

PRIMARY TILLAGE

Sugar beet is usually grown as a spring-sown crop in temperate regions and mouldboard ploughing has traditionally been the most common primary tillage method. In most beet-growing areas, ploughing is in autumn or winter and is sometimes preceded by stubble cultivation soon after harvesting the previous crop. This chapter largely deals with soil management systems which includes mouldboard ploughing, but various kinds of reduced tillage, without this operation, are being successfully introduced in some areas (Ecclestone, 2001). There is increasing interest in these methods, which are discussed later (in Reduced tillage) because they may be quicker, cheaper and more environmentally friendly.

Stubble cultivation

When stubble cultivation is carried out before mouldboard ploughing, its main objective is to control weeds, especially perennials such as couch grass (*Elymus repens* L. Gould) (Wevers *et al.*, 1986). Annual weeds and volunteers of the previous crop are also destroyed, and weed seeds in the soil are induced to germinate so that the plants can be killed later. Tined cultivators and disc tillers are the most commonly used implements for carrying out this operation. Heavy disc tillers are usually able to work through the whole surface in one pass, whereas two passes at an angle to each other are usually needed when using tined cultivators, unless they are equipped with ducksfoot shares (Kritz, 1986).

Another objective of stubble cultivation may be to mix straw and other crop residues more uniformly into the soil. On the one hand, if straw is buried spot-wise in too thick a concentration and the soil is wet, microbial decomposition may create anaerobic conditions leading to hampered root growth. On the other hand, in dry and compact soil, root growth is often impeded and may be limited to the least dense parts of the soil where straw is concentrated. In neither case is the soil completely exploited by crop roots.

To be most efficient as a measure to control perennial weeds, stubble cultivation should be carried out soon after harvest of the previous crop. However, this induces a rapid decomposition of crop residues, particularly under warm and moist conditions. The resulting mineralization of plant nutrients may lead to considerably increased nutrient leaching during the autumn and winter (Stenberg *et al.*, 1999), unless a well-developed catch crop is immediately established. However, sowing of a catch crop after harvest of the previous main crop is meaningful only where the frost-free period after harvest is reasonably long. If a catch crop is undersown in the previous main crop, stubble cultivation is impossible.

In a series of Swedish field trials (Blomquist & Larsson, 2003), there was a slight tendency that stubble cultivation before autumn ploughing decreased the sugar beet yield, both in plots with 'normal' and 'double' amounts of winter-wheat straw. The stubble cultivation reduced the number of earthworms and influenced the attack of some pests and diseases in the beet crop. The effects on pests and diseases, however, probably depend on the local conditions. It may be concluded that stubble cultivation before mouldboard ploughing should usually only be made in fields with a large amount of perennial weeds or for the establishment of an autumn-sown catch crop; otherwise the negative effects may dominate.

Mouldboard ploughing

Mouldboard ploughing, usually carried out to a depth of 20 cm or more, is an expensive operation and may not be justified in areas with soil erosion problems. Timing, depth and method of ploughing must be chosen with regard to local soil and climatic conditions. In a traditional tillage system the plough layer undergoes an annual cycle of loosening by ploughing, and then re-compaction by traffic during seedbed preparation and sowing (Fig. 6.1). Ploughing raises the level of the soil surface by several centimetres (Andersson & Håkansson, 1966; Poesse & van Ouwerkerk, 1967). Thereafter, the soil starts settling, but after winter the plough layer is usually still relatively deep. The soil becomes compacted during seedbed preparation and sowing, and the resultant depth of the plough layer persists virtually unchanged throughout the growing season (Håkansson, 1966). At harvest some further compaction of the soil occurs.

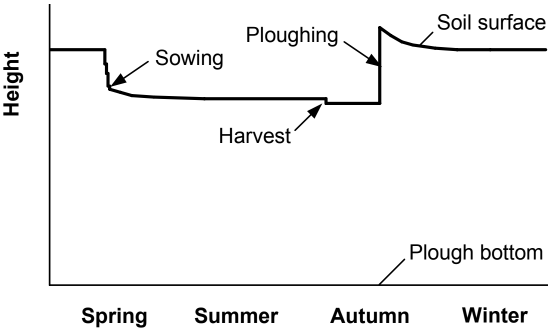

Fig. 6.1 Normal variations of the depth of the plough layer throughout a year in a mechanized farming system with autumn mouldboard ploughing and spring seedbed preparation (after Andersson & Håkansson, 1966).

Time of ploughing

In northern Europe, most sugar beet fields have by tradition been ploughed in autumn prior to sowing. The time of ploughing has been discussed by Jorritsma (1985), Kunze *et al.* (1985) and Wevers *et al.* (1986). On clay soils in areas with annual freezing, seedbed preparation is facilitated by the fine crumb structure (frost mould) which results from the action of winter frosts in the surface layer; it is normally very difficult to obtain a sufficiently fine seedbed on heavy soils after spring ploughing.

The soil moisture content normally increases throughout the autumn and on the one hand, ploughing should usually be carried out before the soil gets too wet in order to produce the best results. Although it is technically possible to plough wet soils, this may cause compaction and poor plough performance. On the other hand, as late a ploughing as possible is desirable to minimize leaching of plant nutrients (Stenberg *et al.*, 1999).

Autumn ploughing is an important component of many sugar beet weed-management systems. Weed control can be improved by stubble cultivation before ploughing or by harrowing after ploughing, in both cases in combination with effective ploughing. While perennial weeds can be controlled effectively by either of these systems, ploughing followed by harrowing may give best control of annuals, since this may lead to increased germination of weed seeds in autumn. Early ploughing without subsequent cultivation may increase the weed problem, since weeds that germinate and survive until spring may be larger and more difficult to control by seedbed preparation or by herbicide applications (Wevers *et al.*, 1986).

Spring ploughing has been increasingly used during recent years. It may be an inevitable consequence of growing green cover crops to prevent nitrate leaching during the autumn and winter or of spreading manure in the spring. Spring ploughing usually poses no problems on light mineral soils where good seedbeds are easily prepared. On cold and wet silty soils, it can improve soil conditions by accelerating drying and warming. When fields are ploughed in spring, a furrow press should be attached to the plough in order to re-compact the furrow slices, level the soil surface and reduce the need for secondary cultivations. Spring ploughing can usually be carried out some days before the autumn ploughed fields have dried sufficiently for traditional seedbed preparation. For cereal crops, a system with early spring ploughing with a furrow press attached to the plough was tested on sandy soils in Sweden (Arvidsson, 1997). As the only subsequent operation, sowing took place immediately afterwards by a seeder that combined sowing and fertilizing. The tractor-seeder unit was equipped with wide wheels and loaded press-units to optimally re-compact soil over the entire working width. Compared to traditional autumn ploughing and spring seedbed preparation this increased the cereal yield by about 20%. A similar system might be useful even for sugar beet on sandy soils, provided the base of the seedbed can be adequately re-compacted.

In a Mediterranean climate with mild, rainy winters and dry, hot summers, sugar beet is sown in the autumn (Castillo Garcia & Lopez Bellido, 1986). For rain-fed crops, tillage operations start in summer and for irrigated crops at the beginning of autumn, after harvesting summer crops. Traditionally, primary tillage is ploughing to 40 cm or subsoiling to even greater depth. On clay soils, large clods are formed that must be weathered by the action of autumn rain or irrigation before suitable seedbeds can be produced. Because of the high costs this system is now sometimes replaced by a reduced tillage system (Menacho Román, 1999).

Ploughing depth

Ploughing depth gradually increased during the twentieth century. Now it is normally 20–25 cm in northern Europe, but often considerably deeper in southern Europe. Sometimes soil is ploughed to different depths prior to different crops in the rotation, traditionally with a relatively deep ploughing before sugar beet.

In Italy, most sugar beet are produced on heavy and poorly drained soils. In experiments in such soils (Tugnoli, 1997) the highest sugar yield was obtained by ploughing to a depth of 55 cm. Mole drainage at a depth of 70 cm and ploughing to 45 cm resulted in nearly the same yield, whereas ploughing to only 35 cm reduced the yield. In Yugoslavia, Dragović *et al.* (1982) and Molnar *et al.* (1982) compared ploughing depths from 15 to 45 cm and found that the yield of sugar beet increased with ploughing depth down to about 30 cm. In a comprehensive series of Swedish long-term experiments with various crops (Håkansson *et al.*, 1998) the conventional ploughing depth of about 22 cm was usually most profitable. However, with 6 cm deeper ploughing the control of weeds (especially perennials) was improved and this increased yield by 1–6% in some of the experiments. Similar results were obtained in a long-term Norwegian experiment (Børresen & Njøs, 1994). In the Swedish experiments, however, at sites with silty soils the shallowest ploughing (about 15 cm) increased yields, probably because of increased concentration of organic material near the surface, and at sites with sandy soils the deepest ploughing (about 28 cm) resulted in the highest yields even at sites with no weed problems, probably because of improved root growth at depth.

Quality of ploughing

Sugar beet crops usually require a fine, homogeneous seedbed. This is usually facilitated by good ploughing, with uniform furrow slices and complete incorporation of weeds and trash. Henriksson (1974) showed that the soil surface at autumn ploughing normally should be as level and even as possible, especially in self-mulching clay soils. If the surface is left too rough after ploughing alone, it may be levelled by a furrow press or other implement attached to the plough. Harrowing after ploughing is another possibility if the soil is sufficiently dry. However, soils where a surface crust is easily formed should not be levelled, since this may lead to a massive surface structure in spring, making seedbed preparation more difficult.

Reduced tillage

Reduced tillage, often called conservation tillage, in which crop residues are left on the surface, is increasingly used for sugar beet in some areas, although it has been more commonly used for some other crops. The extreme form of this technique is direct sowing without any preceding tillage operation at all. More often, however, mouldboard ploughing is replaced by disc, chisel or sweep ploughing – the largest portion of the crop residue being left on the soil surface following sweep ploughing and the smallest following disc ploughing. The crop residue protects the soil from wind as well as from water erosion.

The replacement of mouldboard ploughing and the surface accumulation of crop residues have various effects on growing conditions. In a dry climate a surface mulch may reduce evaporation, since on an unprotected soil, rainfall may lead to surface hardening, restoration of capillary conductivity and increased evaporative water losses. This effect is largest if several small rain showers occur, since the evaporation may be increased for some period after each rain (Rydberg, 1987). However, a surface mulch also delays warming up of soil in spring. Furthermore, shallow tillage normally results in a higher bulk density in the deeper parts of the previous plough layer, which may reduce yield and/or increase fanging of sugar beet roots (Cavalaris & Gemtos, 2002). Reduced tillage may also lead to increased weed infestation, especially of perennials such as couch grass and thistles.

In recently emerged sugar beet crops, arthropod and nematode pests become concentrated in the rows and the seedlings may be severely damaged. When residues of previous crop are present at the soil surface between the rows, this concentration is less pronounced (Heitefuss, 1988), possibly resulting in less damage to the crop. Ruppel (1991) reported that survival of *Rhizoctonia solani* was influenced by the depth of burial of infected sugar beet root tissue in the soil. This means that the tillage method may influence the survival, but the effects are likely to depend on the climatic conditions.

Direct sowing has occasionally resulted in crop yield of sugar beet similar to that after conventional tillage (Halvorson & Hartman, 1984) but usually crop establishment and yield have been considerably poorer (Cavalaris & Gemtos, 2002; Pringas & Märländer, 2004), indicating that direct sowing is a viable option only under specific conditions. Reduced tillage, however, seems to be more widely useful. On light soils, reduced tillage is desirable since it decreases the risk of erosion. It also reduces the risk of surface layer hardening, which is of interest particularly on soils with a high silt content. Such soils are common in some regions with extensive sugar beet production, e.g. in Germany and France. On fine-textured soils with a more stable structure, reduced tillage may be profitable because of the saving of time and energy which results from its use. However, sandy soils in particular are easily compacted, and relatively deep annual loosening may be a prerequisite for normal root development. As a result of a large series of trials on various soils in Sweden, Rydberg (1987) reported mainly negative effects of reduced tillage on various crops on sandy soils and positive effects on silty soils. On clay soils the results varied but were often positive.

In experiments in sugar beet, reduced tillage has sometimes resulted in yields as high as those achieved using conventional tillage methods and occasionally even higher yields (Miller & Dexter, 1982; Michel *et al.*, 1983; Sommer *et al.*, 1987; Vullioud & Charles, 2000; Pringas & Märländer, 2004). For instance, in experiments in Montana, USA, shallow tillage limited to an 18 cm-wide strip in the row zone resulted in the highest yield (Halvorson & Hartman, 1984). In other experiments, conventional tillage has been superior (Westmaas Research Group, 1980; 1984; Smith & Yonts, 1986; Rydberg, 1987; Ehlers *et al.*, 1994; Stockfisch & Koch, 2000; Cavalaris & Gemtos, 2002). The relatively positive results in the experiments in Germany reported by Pringas and Märländer (2004) agree with the results for various crops reported by Rydberg (1987), since all of their sites were located on silty soils. Hoffman (1998) studied the effects of continuous reduced tillage to sugar beet in a silty soil in Germany. This increased the early growth rate, possibly due to concentration of P and K in the surface layer, but reduced the growth rate at later stages.

A requirement for successful use of reduced tillage in sugar beet is that the seed drill can cope with an increased trash content in the surface layer. This may be difficult to achieve, and in some of the experiments in sugar beet, reduced tillage has resulted in a somewhat lower plant population than traditional tillage (Vullioud & Charles, 2000; Pringas & Märländer, 2004). Experience in northern Europe shows that the depth of seedbed preparation may have to be increased to enhance warming up of the seedbed layer in spring.

As an alternative to use of tined or disc implements when reducing tillage depth, some manufacturers now offer mouldboard ploughs designed specifically for shallow ploughing at a high work rate. In some soils and crop rotations, use of such a plough may be an attractive compromise between the traditional ploughing and reduced tillage.

SECONDARY TILLAGE, SOWING AND POST-SOWING TILLAGE

Most sugar beet are grown as a spring-sown crop in humid temperate regions where the soils are wet at the end of winter, but where dry periods occur during spring. Since yields are usually increased by extending the growing period, sowing date should normally be as early as possible. Accordingly, in many studies in various countries (Märländer, 1991; Ayala & Salazar, 1997; Raininko, 1998; Hoikkala, 1999; Hansen, 2000; Larsson & Hellgren, 2003), the highest sugar beet yield has been obtained when seedbed preparation and sowing have been carried out as soon as soil has dried sufficiently for an adequate seedbed to be produced, 'as soon as the first sowing window is opened'. In a review of reports from several countries Blomquist *et al.* (2002) show that a delay of the sowing date by 1 day during the earliest part of the sowing period typically reduces the sugar yield by 0.2–0.3% and during the latest part by 1% or more.

These results have been obtained even though early sowing may increase both the incidence of bolting if cold weather follows and the risk of damage by soil-inhabiting arthropod pests. There is also an increased risk of soil over-compaction that must be minimized by using suitable wheel equipment on these machines. Set against this, late sowing not only shortens the growing period, it may also lead to poor crop establishment due to drought, and to increased damage from pests or diseases with high optimum temperatures (e.g. *Heterodera schachtii* and *Aphanomyces cochlioides*). However, sowing should always be avoided a short time before 'a sowing window' is closed by rain, since this may cause surface crusting.

True seeds of sugar beet are small and have a low energy content. When sowing to a stand seeds must be positioned accurately, and the great majority of them (greater than 70% when using normal seed spacing) must produce plants that survive until harvest if yields are not to be decreased (see Fig. 6.2 and Chapter 7). A good seedbed is a crucial factor in achieving satisfactory crop establishment, making sugar beet in this respect a very demanding crop.

Requirements for seed germination and plant emergence

Like most other crops, sugar beet has the following requirements for seed germination:

- healthy and undamaged seed with a sufficient energy content;
- adequate temperature;
- adequate water and oxygen supply; and
- no substances that are toxic or which impede germination.

The seed coat is relatively impervious to water and gases. In the first phase of germination, oxygen has to enter through a small basal pore and excess water can reduce the intake rate. Some initial uptake of water is, however, necessary to cause the seed to swell and the coat to open up, facilitating further uptake of water and gases and emergence first of the radicle and then the hypocotyl. The germina-

Fig. 6.2 Quick and uniform establishment of plants from more than 70% of seeds sown is a prerequisite for rapid development of a leaf area that facilitates efficient collection of solar energy and high yield (Photograph: Jens Blomquist).

tion process is sensitive both to over-dry and over-wet soil.

A temperature of at least 3°C is required to start germination (Gummerson & Jaggard, 1985), and 90°C days above that temperature are needed for attainment of 50% emergence in otherwise suitable conditions (Gummerson, 1986; 1989). There are some additional requirements for crop emergence. Because the seed's energy reserves are limited, the distance from the seed to the soil surface must not be too large. Furthermore, mechanical resistance to seedling growth must not be excessive, and the sensitive seedling must not be damaged physically, chemically or by pests or diseases. Any delay in the emergence leads to smaller and more sensitive plants throughout the early growth period, thereby delaying leaf cover and reducing final yield (see Sowing and placement of seed).

Objectives of seedbed preparation

The primary objectives of seedbed preparation are to produce soil conditions in which the requirements of seeds and seedlings can be met throughout germination, emergence and establishment periods, irrespective of weather. This is made difficult by the fact that the properties of the seedbed change rapidly depending on the weather. Seedbed preparation must also facilitate adequate function of the seed drill, and as far as possible should be an integral part of the weed control system.

Seed must be placed in a position where water can be taken up quickly, and the covering soil layer, without being too deep, must provide protection against evaporation until roots have developed. However, the seedbed must function well even in rainy weather, and the risks of crust formation and wind and water erosion should be minimized. To ensure an appropriate seed placement and a uniform emergence, the seedbed must be reasonably homogeneous. Tractors and other heavy vehicles must be fitted with suitable wheels to prevent the formation of deep ruts.

The function of the seedbed

Heinonen (1985) described a model seedbed that ensures the provision of sufficient water for crop establishment, even in dry weather conditions. The seed should be placed directly on an untilled, firm and moist seedbed base and covered with a layer of loose soil that gives sufficient protection against evaporation. The most efficient protection is given by an aggregate size range of 0.5–5 mm. Placing seed in a tilled loose layer is more hazardous. This model seedbed was focused on cereals. It was discussed on the basis of additional experimental results and slightly simplified by Håkansson *et al.* (2002). An adaptation to sugar beet is illustrated in Fig. 6.3. Although close proximity of seed to a firm and moist basal layer is most important in heavy soils, an investigation in Sweden (Blomquist *et al.*,

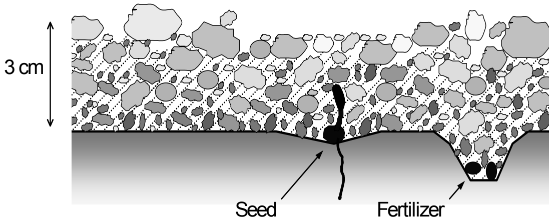

Fig. 6.3 A seedbed suitable for a dry weather situation. The seed is pressed on to a firm, moist basal layer and covered with soil dominated by aggregates < 5 mm. Fertilizer is placed somewhat deeper than the seed row and a few cm at the side without disturbing the seedbed base in the row. The shaping of the surface over the row (flat, as indicated, concave or convex) may influence soil temperature around the seed and incidence of surface crusting.

2002) shows that this is a great advantage for sugar beet establishment and yield even in sandy loam and loam soils when dry weather follows sowing. It was concluded that the 'sowing depth index' (defined by Kritz, 1983, as the sowing depth in per cent of the depth of the loose seedbed in the row zone) should be near or even higher than 100.

The model in Fig. 6.3 also shows fertilizer placement some centimetres to the side of the seed row and slightly deeper, although the utilization of this technique in sugar beet production has so far been limited. However, it was successfully introduced in Finland several years ago (Raininko, 1988; cf. Table 6.1) and is now spreading in northern Europe. In Scandinavia this technique is widely used for the application of nitrogen fertilizer in cereal crops. In these crops, it has been shown to considerably increase efficiency of nitrogen uptake and to increase early growth and final crop yield, particularly at moderate nitrogen doses. Consequently, it reduces fertilizer requirement to some extent and the amount of nitrate in the soils after harvest prone to leaching. At the same fertilizer doses cereal yields have often increased by 5–10%. Olanders (1996) and Vandergeten *et al.* (1997) report positive effects even in sugar beet.

With small grain cereal crops, Håkansson and von Polgár (1984) found that good emergence is obtained if seed is placed on a firm seedbed base with an initial moisture content of at least 5% (w/w) of plant-available water, and covered by a layer at least 4 cm deep that is dominated by aggregates smaller than 5 mm. This is true even if the weather is very dry. For sugar beet, however, a sowing depth of 2–3 cm is usually recommended; sowing deeper than 3–3.5 cm can result in reduced emergence (J. von Polgár, 1974, unpublished results; Jorritsma, 1985) and more vulnerable plants (Wilson *et al.*, 1990; Dürr & Boiffin, 1995). If the layer of soil covering the seed is only 2–3 cm deep, the content of plant-available water at sowing depth must be 6–7%. If the content is too low or the protective ability of the seedbed too poor, there is a risk of poor germination or dehydration of the seedlings, sometimes even after emergence (Durrant *et al.*, 1988). Gummerson (1989) showed that adequate protective ability of a seedbed for sugar beet requires that it contains more than 50% aggregates < 5 mm. The risk of poor germination is decreased by using seeds that germinate rapidly and produce seedlings with a high growth rate (Håkansson & von Polgár, 1984; Durrant & Gummerson, 1990). This requires suitably prepared and sufficiently large seeds of good quality. Some seed lots may be improved by some priming or advancing treatment, well adapted to the lot (Van Swaaij *et al.*, 2001), but such treatments also involve some risks (Lamprecht, 2001).

Rapid germination and seedling growth is an advantage not only with respect to the per cent emer-

Table 6.1 Effects of sowing time and of methods of seedbed preparation and fertilizer application on root yield of sugar beet in nine experiments on clay soils in Finland in 1983–1985 (after Raininko, 1988).

	Normal sowing time		Early sowing	
Method of seedbed preparation	Br[1]	Pl[1]	Br	Pl
Three times with Dutch harrow	100[2]	103	101	107
Once with powered harrow	104	105	110	114

[1] Br = Fertilizer broadcast; Pl = Fertilizer placement.
[2] 100 = 36.1 t/ha.

gence. It has also been shown (Dürr *et al.*, 1992) that the more rapidly the seedlings emerge, the more rapidly they will grow even after the emergence. Consequently, the leaf area required for efficient light interception is reached more rapidly and yield is increased.

Seedbed moisture conditions in Swedish soils at sowing of spring cereals were investigated by Kritz (1983) and are illustrated in Fig. 6.4. Moisture requirement for germination of cereal seeds, as formulated by Håkansson and von Polgár (1984), can usually be met by using a sowing depth of 4–6 cm, which is acceptable for cereals. The moisture situation at sowing of sugar beet may be assumed to be similar to that in Fig. 6.4 in most sugar beet districts. If sowing is made very early, it is only marginally better. This implies that, within an acceptable sowing depth for sugar beet (up to 3.5 cm), the moisture requirements can only be met on soils with clay contents below 30%. On soils with a high silt fraction, the content of plant-available water is somewhat greater than shown in Fig. 6.4 (Kritz, 1983) and capillary transport from below may also contribute to the water supply to the seeds. On other heavier soils, however, to be able to place the seed on a basal layer of sufficiently moist soil, it may be necessary to move some of the dry surface soil aside, in order to limit the depth of the layer covering the seed.

In the case of rainy weather after sowing the seedbed has other requirements. In adequately drained fields, oxygen deficiency seldom impedes crop emergence, but may do so if it rains continuously, water infiltrates slowly, the temperature is high and the seedbed contains readily degradable organic material (Håkansson & von Polgár, 1979; Richard & Guerif, 1988). When rainfall shortly after sowing is followed by dry weather, surface crusting (capping) may hamper emergence and seedling growth, unless the crust can be broken as soon as it starts hardening. Other reasons for failure of seedlings to emerge after germination are diseases, pest damage, large aggregates and stones (Durrant *et al.*, 1988).

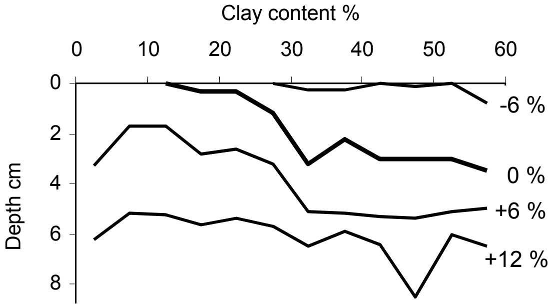

Fig. 6.4 Normal content of plant-available water (%, w/w) in the seedbed immediately after spring sowing in Sweden as a function of the depth and clay content of the soil (after Kritz, 1983).

Techniques and implements for seedbed preparation

Appropriate techniques for seedbed preparation and the required tillage intensity vary. One or two shallow cultivations before sowing may be sufficient on an autumn-ploughed field with a smooth surface and a good frost mould, or on a sandy soil ploughed in the spring with a furrow press attached to the plough. In some situations, indeed, seeds can be sown directly into ploughed and furrow-pressed soil (see Time of ploughing). On sandy soils, this has been shown to be a useful technique for cereals (Arvidsson, 1997), but it may be equally useful for sugar beet. In contrast, if the soil is massive or cloddy, if the surface is uneven, or if the weed population is high, the number and sometimes the depth of cultivations must be increased.

To obtain the desired shallow, uniform seedbed, a harrow with efficient depth control is required. One solution, developed particularly for sugar beet, is a harrow with narrow sections carried by front and rear rollers, which have sufficiently high bearing capacity for even the loosest parts of the fields. An even seedbed base, a uniform depth and a fine tilth are obtained by narrowly spaced and suitably designed tines and by levelling and clod-crushing boards or rollers. The use of this harrow significantly improved sugar beet stand by 6% and sugar yield by 3% relative to a traditional S-tine harrow (Henriksson, 1989).

Power harrows may also be used to prepare sugar beet seedbeds. Larney *et al.* (1988) found that they were very efficient in preparing seedbeds in few passes on poorly structured soils with hard, dry or cloddy surface layers overlying moist, plastic layers. On well-structured soils, however, towed harrows were just as efficient and could produce an even larger proportion of fine aggregates.

If deep harrowing is carried out, some re-compaction of the deeper parts of the loosened layer is essential for the restoration of capillary conductivity. This can be achieved by a separate rolling or by suitable rollers in a combined implement. To avoid too much compaction by tractor wheels in underlying layers, the harrow must be efficient so that the seedbed can be prepared in few operations.

In Finland, which has a short growing season, a once-over system was developed for preparing seedbeds and sowing sugar beet on clay soils (Raininko, 1988). It consists of a rotary harrow and a combi-seeder placing fertilizer at the side of the seed row and makes it possible to carry out the sowing 1–2 weeks earlier than the traditional system. In the experiments, this system increased root yields by 10–15% compared with the traditional system as a result of reduced compaction, earlier sowing and better use of nutrients (Table 6.1) and the sugar yield was increased by 15–20% (Erjala, 1998).

Sowing and placement of seed

In modern sugar beet production without manual thinning, seeds must be sown with great care and the drill must be well maintained and adjusted to suit the field conditions. This is required to reach the goal that the number of plants established should be at least 70% of the number of seeds sown. It is crucial to place the seed at the right depth, normally 2–3 cm, and with correct alignment. Speed of the drill must be regulated with regard to the properties of both machine and seedbed. The risk of seeds moving away from the desired horizontal positions is minimized if they reach the ground without any horizontal speed component. Since the soil surface is often reshaped by the sowing unit, it is necessary to distinguish between the sowing depth in relation to the previous soil surface and the depth of the soil layer over the seed.

The first component of a traditional drill unit is often a clearer that moves trash, clods and stones aside. This is of particular importance when a reduced (conservation) tillage system is used. In a dry seedbed the clearer may be set to remove the dry surface layer of soil. The clearer is followed by a wheel for depth control and an opener forming a furrow into which the seed is placed and on to the base of which it is pressed by a press wheel. A coverer restores the correct amount of soil to cover the seed adequately. Finally, the soil is usually compacted and the surface shaped by a second press wheel, which may compact the whole seedbed or just its deeper parts leaving the surface loose (Wahode, 1985). The shape of the soil surface over the row (concave, flat or convex) may influence soil temperature and risk of surface crusting (Loman, 1986).

It is always important to match seedbed preparation and sowing methods with sowing date in such a way that as early emergence and as rapid seedling growth as possible is achieved (Boiffin *et al.*, 1992; Dürr *et al.*, 1992). Delay in development of leaf cover reduces light interception in the early stages and cannot be compensated for later. This is because the increase in leaf area during the early stages is exponential, and a plant that emerges slower can at best increase its leaf area with the same relative growth rate as a plant that emerges quicker. Therefore sowing depth should be uniform and neither too deep nor too shallow. Large aggregates in the seedbed or at the soil surface impair both emergence and subsequent increase in leaf area (Dürr & Aubertot, 2000) so there should be as few large aggregates in the row zone as possible. Depending on its construction the seeder itself may move some of the large aggregates away from the row zone (Aubertot *et al.*, 1999).

Crust formation and crust breaking

A surface crust (cap) is sometimes formed before the plants emerge, and this may lead to a very poor stand. This problem is greatest on silty soils, where the entire seedbed may harden. Clay and clay loam soils usually form a thinner crust with loose soil underneath, and in sandy soils the crust is weaker. A rain of short duration, even a relatively small one, soon after sowing followed by continuously dry weather is sometimes the worst combination of weather conditions, since this can cause the earliest hardening (Håkansson & von Polgár, 1979).

Therefore, sowing just before rain should always be avoided (Blomquist *et al.*, 2002).

Initial soil water content, time, amount and intensity of rainfall, drying rate and surface micro-relief all influence the strength of crust in the row zone. A coarse seedbed sometimes results in a slightly weaker crust than a fine seedbed, but usually the crust is still hard enough to be equally detrimental (Duval & Boiffin, 1994; Blomquist *et al.*, 2002). A fine seedbed, on the other hand, facilitates shallow sowing on a firm base and quicker emergence, before the crust is formed, and this is usually much more important (Håkansson & von Polgár, 1979; Uppenkamp, 1986; Stenberg *et al.*, 1995). Risk of crust formation may be diminished by adding organic material or lime to soil.

If an early formed crust is thin, its chief detrimental effect is a reduction and/or delay of crop emergence. Since this leads to slower development of leaf cover and to reduced light interception in spring and early summer, it also affects yield. A thin crust can sometimes be broken by rollers or tined implements, but to ensure a good emergence it must be broken as soon as it starts hardening. If it cannot be broken immediately or if it is too thick to be broken without severe damage to the seedlings, re-sowing is often unavoidable.

If the entire seedbed is hardening, which occurs mainly on silty soils with low organic matter content, detrimental effects are not limited to a reduction in emergence. As reported by Stenberg *et al.* (1995) it may lead to a substantially increased capillary transport of water to the soil surface and large evaporative water losses. Furthermore, upward water stream induces a transport of soluble salts, e.g. nitrate, to the soil surface where it is inaccessible to the plants. Therefore, such hardening may be harmful even when it appears after crop emergence.

Adaptation to local conditions

Profitability can be greatly increased by adapting crop production techniques to suit local conditions; an example of this is the once-over technique, developed by Raininko (1988) and mentioned previously in the section on techniques and implements for seedbed preparation, which partly overcomes the disadvantage of a short growing season.

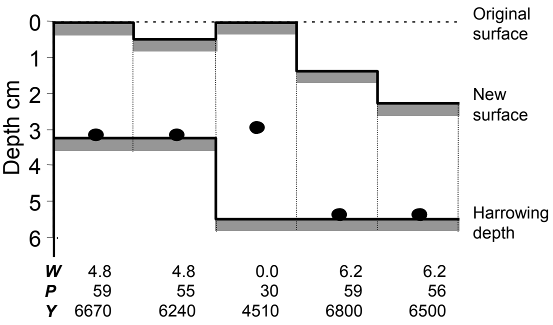

Fig. 6.5 Influence of harrowing depth and seed placement on the content of plant-available water (W, % w/w) around the seed at sowing time, and on the establishment of beet plants (P, % of seeds sown) and yield (Y, kg sugar/ha) on clay soils with a dry surface layer. In three out of five treatments, various amounts of surface soil have been moved aside by a scraper attached to the sowing unit (J. von Polgár, 1981, personal communication).

On Swedish clay soils, in which the upper 3 cm normally dries out to below the wilting point before sowing, a scraper is placed in front of the sowing unit to remove some of the dry surface soil. Then the seed can be placed on a firm, moist furrow base, up to 6 cm below the initial soil surface, without being covered with too deep a layer of soil (Sperlingsson, 1981). This technique has produced good plant stands and has increased final yields (Fig. 6.5).

In a wet, cool climate, seeds should be placed in a dry part of the soil; for example in Ireland, this has been achieved successfully by sowing in the tops of ridges (Fortune & Burke, 1987). In the UK (Chamen *et al.*, 1988; Spoor *et al.*, 1988), the Netherlands (Lamers *et al.*, 1986) and Sweden (L. Henriksson, 1985, unpublished results), controlled traffic systems have been tested for sugar beet and these have resulted in energy saving and yield improvement on soils most sensitive to compaction.

MECHANICAL WEED CONTROL

Before the introduction of sowing to a stand and modern herbicides, most sugar beet crops were thinned and weeded by hand and by mechanical inter-row hoes. Even following the development of herbicides capable of controlling most weeds, some mechanical inter-row weeding is still practised. To minimize use of herbicides, for instance by band spraying, and where weed beet are a problem (Longden *et al.*, 2002) its importance has increased again (Wevers, 2000). This has led to the development of new implements for inter-row cultivation that are more effective. Improved steering devices allow higher speeds and decrease the danger of damaging the beet plants (Tillett & Wiltshire, 2001).

Terpstra and Kouwenhoven (1981) showed that the efficiency of mechanical hoeing is influenced by the working depth of the implement, soil type, plant height and soil moisture content. However, if young sugar beet plants are not protected they may also be damaged. In mechanical weed control, uprooting of weeds and bringing them to the soil surface where they may become desiccated is one important effect. Covering weeds with soil is also very important (Terpstra & Kouwenhoven, 1981), particularly since even weeds at the sides of the cultivated area become covered (Johansson & Rydberg, 1997). In experiments in crops without weeds, Küster *et al.* (1984) found that hoeing had no effect on sugar yield. When reviewing the literature they found reports of positive effects on yield in continental climates but not in maritime climates.

Summarizing results of a study of various integrated weed control strategies, Olsson (1997) reported that low-dose applications of herbicides in combination with inter-row cultivation gave better weed control and higher sugar yield than standard dose applications of herbicides alone. Dubois and Ammon (1997) showed that the combination of herbicide band application and late inter-row hoeing resulted in practically the same sugar yield as repeated broadcast spraying of herbicides. Late hoeing also reduced spread of the beet mild yellowing virus by aphids.

To completely replace chemical weed control with mechanical it may be necessary to use methods that also employ efficient control of the weeds in the crop rows. Manual weeding may then be necessary to maintain yield and weed control particularly where weed beet are present (Olsson, 1997; Westerdijk *et al.*, 1997). Weed harrowing can be made from the four-leaf stage of the crop with good weed control effects, with only moderate losses of sugar beet plants and with as high sugar yield as with a standard chemical weed control system (Ascard & Bellinder, 1996). This technique is important in organic sugar beet growing where chemical weed control cannot be used.

SOIL COMPACTION

Factors determining compaction

Seedbed preparation and sowing operations normally lead to a considerable decrease in the depth of the plough layer (Fig. 6.1). The central and deeper parts of the plough layer are compacted by the wheels of the machines, and only the shallow seedbed remains loose. For sugar beet crops, as many as nine operations for seedbed preparation, spraying, fertilizing and sowing may be carried out, some of them in a random pattern. The total track area from tractor wheels and other heavily loaded wheels during these operations may be more than three times the field area, and thus most of the area is compacted (Jaggard, 1984). Several aspects of soil compaction in sugar beet production are discussed in Märländer *et al.* (1998).

The extent and pattern of plough layer compaction is determined by many factors such as soil moisture content, wheel track distribution, number of passes by wheels, load on the wheels and wheel arrangement and characteristics including ground pressure (Ljungars, 1977; Håkansson, 2000). Ground pressure is usually unevenly distributed in the ground contact area of the wheels but its mean value is often slightly higher than the tyre inflation pressure.

Short-term effects of compaction

A very loose soil, e.g. one which has been freshly ploughed, does not usually provide the best conditions for plant growth. Maximum crop yield is normally obtained after a moderate re-compaction (Håkansson *et al.*, 1988), but too intensive re-compaction can seriously reduce the yield (Draycott *et al.*, 1970). The optimum state of compactness varies with several factors, such as the soil moisture conditions throughout the growing season and the type of crop. In some experiments, e.g. in those carried out by Jaggard (1977) with sugar beet, highest yield was obtained on the least dense soil.

The state of compactness of a soil may be characterized by means of various parameters, dry bulk density being most frequently used. A disadvantage is that maximum crop yield is obtained at different bulk densities on different soils. To overcome this disadvantage, bulk density should be related to a reference bulk density obtained by a standardized packing of the same soil (Carter, 1990; da Silva *et al.*, 1994). Håkansson (1990) defined the 'degree of compactness' as the bulk density of the soil as a percentage of such a reference bulk density. When using this method, maximum crop yield was obtained at the same degree of compactness irrespective of soil type (Riley, 1983; Håkansson, 1990; Lipiec *et al.*, 1991).

Håkansson (2000) summarized a comparison of the yield response of several crops to the degree of compactness of the layer between harrowing depth and ploughing depth. In the trials, the seedbed quality and crop stand had been kept adequate irrespective of the compactness of the layer below. For barley, wheat and sugar beet the optimal degree of compactness turned out to be higher than for oats, peas, field beans, rape or potatoes. These results agree with other Swedish compaction experiments with sugar beet (Anon., 1978). Conversely, Brereton *et al.* (1986) reported sugar beet to be more sensitive to compaction than barley. However, in their studies sowing was made at different times for the two crops, and moreover, in sugar beet the traffic treatment greatly impaired the plant population, which was not the case in Håkansson's experiments. Furthermore, more fanging of sugar beet roots has been found in compacted than in loose soils (Jaggard, 1977; Merkes & von Müller, 1986), and this may cause higher losses when machine-harvesting. The effects of soil compaction on yield may therefore be affected by harvesting technique. Different cultivars of the same crop may also react differently (Håkansson, 2000), but in this respect no studies have been made in sugar beet.

Long-term effects of plough-layer compaction

Ploughing may seem to alleviate the effects of plough-layer compaction if these are measured solely by the average bulk density or degree of compactness of the plough layer. However, compaction can affect soil in other ways. When ploughing a previously compacted soil, furrow slices become more massive and coherent and the soil surface more uneven (Fig. 6.6). This reduces crop yields,

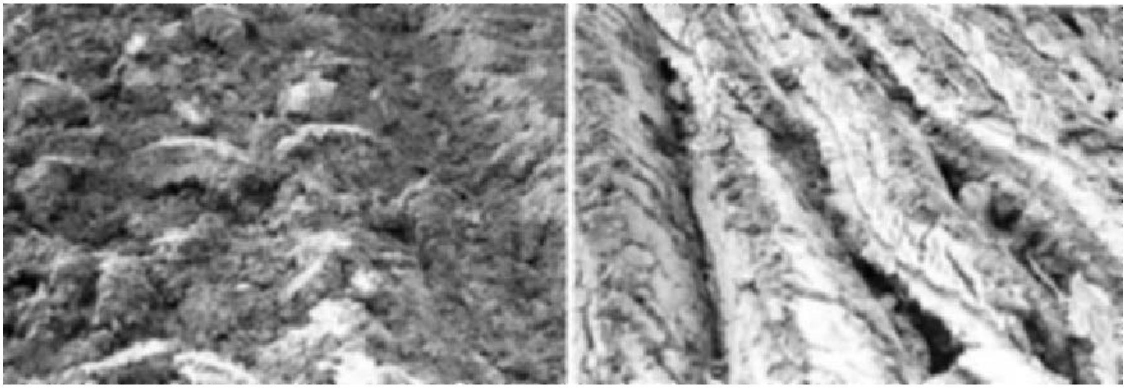

Fig. 6.6 The soil surface in a compaction experiment on a clay soil in Sweden after ploughing. To the left, a control plot; to the right, a plot in which the soil surface was compacted over its whole area by contiguous wheelings made by a tractor and trailer shortly before ploughing. The irregular, massive furrow slices in the compacted plots made subsequent seedbed preparation difficult.

partly by making subsequent tillage operations more difficult, seedbeds coarser and less uniform, and crop establishment poorer.

Residual effects of plough-layer compaction on crop yields were studied in an extensive series of long-term experiments with various crops in Sweden (Arvidsson & Håkansson, 1996). Effects were small on light soils but increased as clay content increased. On clay soils they persisted for up to 5 years, even though the soils were ploughed annually. Damage to soil increased with soil moisture content when vehicles were operating, and with ground pressure of the vehicles. They also increased proportionally to traffic intensity. Various cereals were the dominating crops in the experiments, but for sugar beet crops, which require high-quality seedbeds, effects may be even more important. The results show that, on clay soils, long-term effects of compaction are sometimes more important than short-term effects.

Thus in beet-growing areas, and particularly on heavy soils, it is important to avoid machinery traffic on wet soil, to use low-pressure tyres on vehicles, and to keep the traffic intensity to a minimum. Traffic intensity can be expressed as the product of the weight of vehicles and the travelling distance per unit area (e.g. tkm/ha). In small-grain cereal production, the total annual traffic intensity is often about 150 tkm/ha. For sugar beet, this intensity is often exceeded during harvest alone, and traffic intensity during the whole year may be twice as great (Arlauskas & Velykis, 1997; Håkansson, 2000). Since harvesting is often carried out under wet conditions with vehicles having a high ground pressure, adverse effects on subsequent crops may be larger than after other crops.

Calculations on the basis of experimental data have shown that short-term and long-term compaction effects caused by the machinery traffic lead to 'soil compaction costs' that are very important in practice. When operating with a heavy vehicle on wet soil, the compaction costs may be as high as, or even higher than, the machinery and labour costs together (Håkansson, 2000). Thus, machinery systems can be economically optimized only if soil compaction costs are taken into account; however, these costs can be accurately estimated only where many locally applicable experimental data are available, and this is not usually the case. In the long term, even subsoil compaction contributes to these costs.

Subsoil compaction

Vehicles used in crop production have gradually become heavier, and in sugar beet production this particularly applies to harvesters (Fig. 6.7). One- or two-row harvesters have now been largely replaced by very heavy 6-row or even 9-row tanker harvesters (Guiraud de Willot, 2000). The first of a new

Fig. 6.7 Competitive sugar beet production requires an efficient harvest technique. However, the heavy sugar beet harvesters used today often cause permanent compaction damage to the subsoil, even though damage to the plough layer may be kept within acceptable limits by the use of wide tyres (Photograph: Robert Olsson, SBU, Sweden).

generation of 12-row harvester are now appearing, all of which raises the issue of just how deeply soils are affected by sugar beet harvesting.

Generally the higher the load per wheel, and the higher the ground pressure, the deeper into the subsoil compaction penetrates. This may affect root growth and impair root function. Unless the ground pressure is very low, wheel loads exceeding 3 t can cause compaction to more than 40 cm depth. At these depths compaction effects are very persistent, possibly even permanent, and may cause very persistent reductions in crop yields (Håkansson & Reeder, 1994; Alakukku, 2000). Therefore, subsoil compaction is regarded as a serious threat to long-term soil productivity. However, in fields already trafficked by heavy machines for many years, an additional pass sometimes causes only a small additional effect (Schäfer-Landefeld *et al*., 2004). Furthermore, even when subsoil properties have been negatively influenced, crop responses have not always been negative (Arvidsson, 2000). This may be because of varying soil moisture and weather conditions. Although field operations should usually be carried out under as dry conditions as possible, measurements by Trautner (2003) indicate that dry conditions do not necessarily protect deep subsoil layers from compaction.

To avoid impermissible permanent compaction effects, various load limits have been recommended. When only relatively narrow tyres with high ground pressure were available for high loads, simple wheel or axle load limits were sometimes recommended, e.g. 2 t per wheel in eastern Germany (Petelkau, 1984) and 6 t per axle in Sweden (Håkansson, 1987). Since wider tyres with lower inflation pressure are now available, even the ground pressure should now be considered. Van den Akker and Schønning (2004) proposed limits based on estimated stresses, calculated as functions of depth, wheel load, wheel arrangement and ground pressure. To avoid more rigorous restrictions than necessary they argued that the limits should be set with regard to local soil and climatic conditions.

It may seem difficult to follow such recommendations when harvesting root crops but if they are not followed, productivity of soils may be permanently impaired. Furthermore, the recommendations do not necessarily imply that the total weight of a machine must be restricted. For instance, in measurements by Keller and Arvidsson (2004) a very heavy (54 t) sugar beet harvester with modern rubber tracks caused less subsoil compaction than a much lighter (27 t) harvester with traditional wheels.

SUBSOIL LOOSENING

In most climatic regions, root development into deep subsoil layers is necessary to maintain an adequate water supply to the crop in dry periods. In soils with suitable properties, sugar beet roots reach a depth of 2 m or more (Biancardi *et al*., 1998; Draycott & Christenson, 2003). In a dense subsoil, however, root development may be limited by too high mechanical resistance and the function of the roots may be impaired by oxygen deficiency. In both cases decreased water and nutrient uptake may depress sugar beet yield.

A compact subsoil may be of pedogenic origin or may be caused by machinery traffic. Where fields have been ploughed at a constant depth for many years with tractor wheels running in the bottom of the furrows a dense plough-pan may be present just below ploughing depth. In an effort to eliminate problems, deep tillage is common in some countries. The prospects of success are better where the dense layer is of pedogenic origin than where it is machinery-induced. Deep tillage should only be undertaken if apparent problems with root development are established by visual examination of the soil profile, because unnecessary cultivations may do more harm than good. Often the conditions vary greatly within an individual field.

Deep ploughing, or some other form of deep mixing, may be appropriate if root growth through the upper part of the subsoil is restricted by a thin layer of humus-free sand or other material with an adverse mechanical composition. The root growth may be improved if such a layer is mixed with deeper or shallower layers of more favourable composition. However, mixing of humus-free soil from below into a topsoil with an initially low humus content may impair the function of the surface layer. Furthermore, if topsoil with a high biological activity and oxygen consumption is buried deeply and compacted by machinery traffic, aeration problems may be induced.

Subsoiling with some kind of tined subsoiler is a frequently used method of deep tillage. It must be carried out when the soil is reasonably dry, otherwise it may cause more harm than good. There is a critical depth below which the soil gets compacted, instead of loosened, by a subsoiler tine. This depth decreases with soil moisture content but increases with tine width (Spoor & Godwin, 1978). The efficiency of the operation is considerably improved by wings on the tines and by leading tines operating to a shallower depth (Spoor & Godwin, 1978).

Significant increases in sugar beet yield have sometimes been obtained in subsoiling experiments (Johnson & Erickson, 1991; Ehlers *et al.*, 1994), but in most cases the effects have been small and sometimes even negative (Dragović *et al.*, 1982; Molnar *et al.*, 1982; Marks, 1985; Larney & Fortune, 1986; Ide *et al.*, 1987; Pittelkow *et al.*, 1988). Subsoiling reduces the structural stability of the subsoil and increases its susceptibility to compaction, and re-establishment of structural stability (age-hardening) may take months or years (Dexter, 1988). Machinery traffic during that period can lead to a rapid loss of the loosening effect, sometimes within 1 year, making the subsoil even more compact than it was originally (Marks, 1985; Larney & Fortune, 1986; Fortune & Burke, 1987; Schäfer-Landefeld *et al.*, 2004). However, with conservation tillage the loosening effect may be more persistent than with annual ploughing (Ehlers *et al.*, 1994).

PROTECTION AGAINST WIND EROSION

When sugar beet crops are grown with traditional tillage methods, the soil surface remains unprotected from wind for a prolonged period after sowing. Particularly on poorly structured soils such as light sands and peats, wind erosion during this period can be a serious problem. The seedbed, and even the seed, can be blown away or re-deposited. After emergence, abrasion by wind-blown soil particles can damage seedlings, which may also become covered by soil. In severe cases, re-sowing may be necessary. This results in additional costs, and yet the yield will be low owing to the delay of crop establishment.

In many cases, the most relevant method to protect soil from wind erosion is a cultural practice that leaves an adequate amount of crop residues on the soil surface (Fornstrom & Miller, 1998). This usually means some form of reduced tillage (see section of that name). Recent technical development has made it possible to adopt a reduced tillage technique for most soils without suffering from substantial crop yield losses.

Where a reduced tillage method cannot be applied or where the amount of residues is too limited, other methods are available. Techniques for protection against wind erosion in systems with mouldboard ploughing were reviewed by Matthews (1983). They depend on either creating wind barriers or stabilizing the soil surface. Hedges or tree belts may be planted as permanent wind-breaks, and barriers of straw bales or other material may be used temporarily. Planting straw between every fifth or sixth sugar beet row to reduce wind speed at ground level can be made by machines using large straw bales.

A frequently used form of wind barrier is a cereal cover crop, either sown overall or between the prospective beet rows. For example, this crop could be rye sown in the autumn and sprayed before sugar beet sowing, or barley sown 3 weeks before the planned sowing date and sprayed a couple of weeks after beet emergence (Fornstrom & Miller, 1998). A spring-sown cover crop may delay beet sowing and make the use of herbicides complicated in the early stages by the need to protect both crop species. In Nebraska, USA, Wilson and Smith (1992) compared several systems of autumn-sown cereal cover crops. In a year without problems with blowing sand, the effects on sugar beet stand and yield were insignificant, but in a year with severe problems, particularly a rye cover crop led to drastic improvements. In Wyoming, USA, Fornstrom & Miller (1996; 1998) found practically no influence on the beet yield of an autumn-sown or a spring-sown cereal cover crop and concluded that the extra costs to establish and kill it were warranted if one sugar beet re-sowing could be avoided every 4 or 5 years.

The soil surface can be stabilized by various materials usually applied on the soil surface immediately after sowing. Commercial products to bind sand particles together have very limited use. Natural materials, such as farmyard manure, slurry or factory lime, can be spread on the soil surface after sowing. However, in some countries the application of manure on the soil surface is limited by strict regulations. A tillage system to stabilize the seedbed surface on sandy soils by rolling when the soil is wet and then harrowing it to form clods was developed in England (Palmer *et al.*, 1977). However, this may delay sowing, and may be replaced by the use of a plough and furrow press in the late winter or early spring to create a surface into which beet can be sowed directly (Selman, 1987).

REFERENCES

Alakukku, L. (2000) Response of annual crops to subsoil compaction in a field experiment on clay soil lasting 17 years. *Advances in GeoEcology* **32**, 205–208.

Andersson, S. & Håkansson, I. (1966) Strukturdynamiken i matjorden. En fältstudie (with English summary). *Grundförbättring* **19**, 191–228.

Anon. (1978) Försöksverksamhet i sockerbetor 1977. Fältförsök. Sockernäringens samarbetskommitté. Jordbrukstekniska avdelningen, Staffanstorp, Sweden.

Arlauskas, M. & Velykis, A. (1997) Effect of primary tillage on the elimination of detrimental consequences of soil compaction. Fragmenta Agronomica 2A. *Proceedings of the 14th Conference of International Soil Tillage Research Organization.* Pulawy, Poland, pp. 39–42.

Arvidsson, J. (1997) Tidig sådd – ett system för reducerad bearbetning vid vårsådd. Fältförsök 1992–1996 (with English summary). *Swedish University of Agricultural Sciences, Uppsala, Reports from the Division of Soil Management*, no. 92.

Arvidsson, J. (2000) Subsoil compaction caused by heavy sugarbeet harvesters. I. Results from six long-term field experiments in southern Sweden. *Swedish University of Agricultural Sciences, Uppsala, Reports from the Division of Soil Management*, no. 100, pp. 66–78.

Arvidsson, J. & Håkansson, I. (1996) Do effects of soil compaction persist after ploughing? Results from 21 long-term field experiments in Sweden. *Soil and Tillage Research* **39**, 175–197.

Ascard, J. & Bellinder, R.R.B. (1996) Mechanical in-row cultivation in row crops. *Proceedings of the 2nd International Weed Control Congress.* Copenhagen, pp. 1121–1126.

Aubertot, J.N., Dürr, C., Kiêu, K. & Richard, G. (1999) Characterization of sugar beet seedbed structure. *Soil Science Society of America Journal* **63**, 1377–1384.

Ayala, J. & Salazar, A. (1997) Integrated control of the beet-cyst nematode, *Heterodera Schachtii. Proceedings of the 60th IIRB Congress.* Cambridge, pp. 395–401.

Biancardi, E., Mandolino, G. & Boschetti, W. (1998) Genetic and environmental factors influencing the development of the sugar beet root system. *Proceedings of the 61st IIRB Congress.* Brussels, pp. 411–417.

Blomquist, J. & Larsson, H. (2003) Betor kräver ingen stubbearbetning. In: *Mot Sockerskörd på Europanivå.* Sockernäringens Betodlingsutveckling, Bjärred, Sweden, pp. 40–42.

Blomquist, J., Wildt-Persson, T. & Rydberg, T. (2002) *Uppkomst, etablering och tillväxt.* Swedish Farmers' Foundation for Agricultural Research, Project 4T, Final Report.

Boiffin, J., Dürr, C., Fleury, A., Marin-Laflèche, A. & Maillet, I. (1992) Analysis of the variability of sugar beet (*Beta vulgaris* L.) growth during the early stages. I. Influence of various conditions on crop establishment. *Agronomie* **12**, 515–525.

Børresen, T. & Njøs, A. (1994) The effect of ploughing depth and seedbed preparation on crop yields, weed infestation and soil properties from 1940 to 1990 on a loam soil in south eastern Norway. *Soil and Tillage Research* **32**, 21–39.

Brereton, J.C., McGowan, M. & Dawkins, T.C.K. (1986) The relative sensitivity of spring barley, spring field beans and sugar beet crops to soil compaction. *Field Crops Research* **13**, 223–237.

Carter, M.R. (1990) Relative measures of soil bulk density to characterize compaction in tillage studies on fine sandy loams. *Canadian Journal of Soil Science* **70**, 425–433.

Castillo Garcia, J.E. & Lopez Bellido, L. (1986) Growth and yield of autumn-sown sugar beet: effects of sowing time, plant density and cultivar. *Field Crops Research* **14**, 1–14.

Cavalaris, C.K. & Gemtos, T.A. (2002) Evaluation of four conservation tillage methods in the sugar beet crop. *Agricultural Engineering International: The CIGR Journal of Scientific Research and Development*, Manuscript LW 01 008, Vol. IV.

Chamen, W.C.T., Vermeulen, G.D., Campbell, D.J., Sommer, C. & Perdoc, U.D. (1988) Reduction of traffic-induced soil compaction by using low ground pressure vehicles, conservation tillage and zero traffic systems. *Proceedings of the 11th Conference of International Soil Tillage Research Organization.* Penicuik, Scotland, pp. 227–232.

da Silva, A.P., Kay, B.D. & Perfect, E. (1994) Characterization of the least limiting water range of soils. *Soil Science Society of America Journal* **58**, 1775–1781.

Dexter, R.A. (1988) Advances in characterization of soil structure. *Soil and Tillage Research* **11**, 199–238.

Dragović, S., Panić, Ž. & Rožić, R. (1982) Effect of tillage depth, with and without subsoiling, and different levels of nitrogen fertilization and irrigation on the yield and quality of sugarbeet grown on the soils of heavy texture. *Proceedings of the 9th Conference of International Soil Tillage Research Organization.* Osijek, Yugoslavia, pp. 340–345.

Draycott, A.P. & Christenson, D.R. (2003) *Nutrients for Sugar Beet Production.* CABI Publishing, Wallingford.

Draycott, A.P., Hull R., Messem, A.B. & Webb, D.J. (1970) Effects of soil compaction on yield and fertilizer requirement of sugar beet. *Journal of Agricultural Science, Cambridge* **75**, 533–537.

Dubois, D.M. & Ammon, H.U. (1997) Habitat-management of sugar beet pests by a different strategy of weed control. *Proceedings of the 60th IIRB Congress.* Cambridge, pp. 243–251.

Dürr, C. & Aubertot, J-N. (2000) Emergence of seedlings of sugar beet (*Beta vulgaris* L.) as affected by the size, roughness and position of aggregates in the seedbed. *Plant and Soil* **219**, 211–220.

Dürr, C. & Boiffin, J. (1995) Sugarbeet seedling growth from germination to first leaf stage. *Journal of Agricultural Science* **124**, 427–435.

Dürr, C., Boiffin, J., Fleury, A. & Coulomb, I. (1992) Analysis of the variability of sugar beet (*Beta vulgaris* L.) growth during the early stages. II. Factors influencing seedling size in field conditions. *Agronomie* **12**, 527–535.

Durrant, M.J. & Gummerson, R.J. (1990) Factors associated with germination of sugar-beet seed in the standard test and establishment in the field. *Seed Science and Technology* **18**, 1–10.

Durrant, M.J., Dunning, R.A., Jaggard, K.W., Bugg, R.B. & Scott, R.K. (1988) A census of seedling establishment in sugar-beet crops. *Annals of Applied Biology* **113**, 327–345.

Duval, Y. & Boiffin, J. (1994) A daily emergence disturbance index for sugar beet based on soil crusting. *Proceedings of the 13th Conference of International Soil Tillage Research Organization.* Aalborg, Denmark, pp. 633–638.

Ecclestone, P. (2001) Minimum tillage options for economic sugar beet production. *British Sugar Beet Review* **69** (3), 24–29.

Ehlers, W., Werner, D. & Fenner, S. (1994) Reconsolidation of a deep-loosened silt loam under ploughing and conservation tillage. *Proceedings of the 11th Conference of International Soil Tillage Research Organization.* Aalborg, Denmark, pp. 55–60.

Erjala, M. (1998) Combining different work stages maintains the porosity of clay soil. In: Märländer, B., Tijink, F.G.J., Hoffmann, C. & Beckers, R. (eds) *Soil Compaction and Compression in Relation to Sugar Beet Production.* International Institute for Beet Research, Brussels, pp. 67–76.

Fornstrom, K.J. & Miller, S.D. (1996) Sugarbeet establishment in living mulches. *Journal of Sugar Beet Research* **33**, 15–29.

Fornstrom, K.J. & Miller, S.D. (1998) *Cover Crops for Wind Erosion Protection of Sugar Beets.* University of Wyoming, Cooperative Extension Service, B-1052.

Fortune, R.A. & Burke, W. (1987) Soil compaction and tillage practices in Ireland. In: Monnier, G. & Goss, M.J. (eds) *Soil Compaction and Regeneration.* Balkema, Rotterdam, pp. 115–124.

Guiraud de Willot, D. (2000) Evolution du machinisme: les raisons d´une disparité. *Proceedings of the 63rd IIRB Congress.* Interlaken, pp. 115–128.

Gummerson, R.J. (1986) The effect of constant temperature and osmotic potentials on the germination of sugar beet. *Journal of Experimental Botany* **37**(179), 729–741.

Gummerson, R.J. (1989) Seed-bed cultivations and sugar-beet seedling emergence. *Journal of Agricultural Science, Cambridge* **112**, 159–169.

Gummerson, R. & Jaggard, K. (1985) Soil temperature measurements and sowing date decisions. *British Sugar Beet Review* **53** (1), 63–65.

Håkansson, I. (1966) Försök med olika packningsgrader i matjorden och alvens översta del (with English summary). *Grundförbättring* **19**, 281–332.

Håkansson, I. (1987) Modern tekniks långsiktiga inverkan på markens odlingsegenskaper (with English summary*). Kungliga Skogs- och Lantbruksakademiens Tidskrift* **126**, 35–40.

Håkansson, I. (1990) A method for characterizing the state of compactness of the plough layer. *Soil and Tillage Research* **16**, 105–120.

Håkansson, I. (2000) Packning av åkermark vid maskindrift. *Swedish University of Agricultural Sciences, Uppsala, Reports from the Division of Soil Management*, no. 99.

Håkansson, I. & Reeder, R.C. (1994) Subsoil compaction by vehicles with high axle load – extent, persistence and crop response. *Soil and Tillage Research* **29**, 277–304.

Håkansson, I. & von Polgár, J. (1979) Effects on seedling emergence of soil slaking and crusting. *Proceedings of 8th Conference of International Soil Tillage Research Organization.* University of Hohenheim, BRD, Vol. 1, pp. 115–120.

Håkansson, I. & von Polgár, J. (1984) Experiments on the effects of seedbed characteristics on seedling emergence in a dry weather situation. *Soil and Tillage Research* **4**, 115–135.

Håkansson, I., Voorhees, W.B. & Riley, H. (1988) Vehicle and wheel factors influencing soil compaction and crop response in different traffic regimes. *Soil and Tillage Research* **11**, 239–282.

Håkansson, I., Stenberg, M. & Rydberg, T. (1998) Long-term experiments with different depths of mouldboard ploughing in Sweden. *Soil and Tillage Research* **46**, 209–223.

Håkansson, I., Myrbeck, Å. & Etana, A. (2002) A review of research on seedbed preparation for small grains in Sweden. *Soil and Tillage Research* **64**, 23–40.

Halvorson, A.D. & Hartman, G.P. (1984) Reduced seedbed tillage effects on irrigated sugarbeet yield and quality. *Agronomy Journal* **76**, 603–606.

Hansen, M. (2000) Såning 2000. *Sukkerroenyt* **2**.

Heinonen, R. (1985) *Soil Management and Crop Water Supply*, 4th edn. Swedish University of Agricultural Sciences, Department of Soil Sciences, Uppsala, Sweden.

Heitefuss, R. (1988) Pflügen oder nich pflügen – Konsequenzen für den Pflanzenschutz. Integrierter Pflantzenbau, Bodenbearbeitung. Fördergemeinschaft Integrierter Pflanzenbau e.v., Bonn, *Integrierter Pflanzenbau* **3** (88), 52–60.

Henriksson, L. (1974) Studier av några jordbearbetningsredskaps arbetssätt och arbetsresultat (with English summary). *Agricultural College of Sweden, Uppsala, Reports from the Division of Soil Management*, no. 38.

Henriksson, L. (1989) Effects of different harrows on seedbed quality and crop yield. In: Dodd, V.A. & Grace, P.M. (eds) *Agricultural Engineering, 3: Agricultural Mechanisation.* Balkema, Rotterdam, pp. 1569–1574.

Hoffman, C. (1998) Influence of continuous reduced tillage on the growth of sugar beet. *Proceedings of the 61st IIRB Congress*. Brussels, pp. 443–447.

Hoikkala, P. (1999) Sådd. *Betfältet* 3.

Ide, G., Hofman, G., Ossemerct, C. & Van Ruymbeke, M. (1987) Subsoiling: time-dependency of its beneficial effects. *Soil and Tillage Research* **10**, 213–223.

Jaggard, K.W. (1977) Effects of soil density on yield and fertiliser requirements of sugar beet. *Annals of Applied Biology* **86**, 301–312.

Jaggard, K.W. (1984) Pre-drilling land work and yield loss. *British Sugar Beet Review* **52** (2), 9–11.

Johansson, D. & Rydberg, T. (1997) Improved methods for mechanical weed control in conventional distance between rows. Fragmenta Agronomica 2A. *Proceedings of the14th Conference of International Soil Tillage Research Organization*. Pulawy, Poland, pp. 315–318.

Johnson, B.S. & Erickson, A.E. (1991) Sugarbeet response to subsoiling and wheel traffic. *Agronomy Journal* **83**, 386–390.

Jorritsma, J. (1985) *De teelt van suikerbieten*. Instituut voor Rationele Suikerproduktie, Bergen op Zoom, The Netherlands.

Keller, T. & Arvidsson, J. (2004) Mätningar av tryck och deformation i marken vid betupptagning. *Swedish University of Agricultural Sciences, Uppsala, Reports from the Division of Soil Management*, no. 107, pp. 52–56.

Kritz, G. (1983) Såbäddar för vårstråsäd. En stickprovsundersökning (with English summary). *Swedish University of Agricultural Sciences, Uppsala, Reports from the Division of Soil Management*, no. 65, 187pp.

Kritz, G. (1986) The effects of various implements for stubble cultivation. *Swedish University of Agricultural Sciences, Uppsala, Research Information Centre, Report* no. A84, pp. 21.1–21.14.

Kunze, A., Lucius, J. & Herrmann, E. (1985) Verfahren der Grundbodenbearbeitung und Einordnung der organischen Düngung im Zuckerrüben (with English summary). *Tagungsberichte der Akademie der Landwirtschaftswissenschaften der DDR*, Berlin, **229**, 119–124.

Küster, H.J., Krüger, K.W. & Lanfermann, M. (1984) Untersuchungen zum Einfluss der Maschinenhacke auf Ertrag und Qualität von Zuckerrüben. *Archiv für Pflanzenbau und Bodenkunde*, Berlin, **28**, 169–178.

Lamers, J.G., Perdok, U.D., Lumkes, L.M. & Klooster, J.J. (1986) Controlled traffic farming systems in the Netherlands. *Soil and Tillage Research* **8**, 65–76.

Lamprecht, H. (2001) Vorbehandlung von Rübensaatgut – Chansen und Risiken. *Proceedings of the 64th IIRB Congress*. Bruges, pp. 357–364.

Larney, F.J. & Fortune, R.A. (1986) Recompaction effects of mouldboard ploughing and seedbed cultivations on four deep loosened soils. *Soil and Tillage Research* **8**, 77–87.

Larney, F.J., Fortune, R.A. & Collins, J.F. (1988) Intrinsic soil physical parameters influencing intensity of cultivation procedures for sugar beet seedbed preparation. *Soil and Tillage Research* **12**, 253–267.

Larsson, H. & Hellgren, O. (2003) Fyra variabler förklarar skörden. In*: Mot Sockerskörd på Europanivå*. Sockernäringens Betodlingsutveckling, Bjärred, Sweden, pp. 66–69.

Lipiec, J., Håkansson, I., Tarkiewicz, S. & Kossowski, J. (1991) Soil physical properties and growth of spring barley as related to the degree of compactness of two soils. *Soil and Tillage Research* **19**, 307–317.

Ljungars, A. (1977) Olika faktorers betydelse för traktorernas jordpackningsverkan. Mätningar 1974–1976 (with English summary). *Agricultural College of Sweden, Uppsala, Reports from the Division of Soil Management*, no. 52.

Loman, G. (1986) *The Climate of a Sugar Beet Stand*. Royal University of Lund, Sweden, Department of Geography, Dissertations, C1.

Longden, P.C., May, M.J. & Fisher, S. (2002) Weed beet control 2002. *British Sugar Beet Review* **70** (2), 38–41.

Marks, M.J. (1985) Subsoil loosening and deep placement of phosphate potash fertiliser. In: *Reference Book, Crop Nutrition and Soil Science*. ADAS, Ministry of Agriculture, Fisheries and Food, no. 253 (83), pp. 42–54.

Märländer, B. (1991) *Zuckerrüben – Optimierung von Anbauverfahren, Züchtungsfortschritt, Sorthenwahl*. Ute Bernhardt-Pätzold Druckerei und Verlag, Stadthagen, Germany.

Märländer, B., Tijink, F.G.J., Hoffmann, C. & Beckers, R. (eds) (1998) *Soil Compaction and Compression in Relation to Sugar Beet Production*. International Institute for Beet Research, Brussels.

Matthews, K. (1983) Beating the blow: available techniques. *British Sugar Beet Review* **51** (1), 65, 68–69.

Menacho Román, J.M. (1999) Préparation du lit des semailles de la betterave d´automne. *Proceedings of the 62nd IIRB Congress*. Sevilla, pp. 9–17.

Merkes, R. & von Müller, A. (1986) Einfluss einer Bodenverdichtung unter den Saatbett auf Wuchsform und Erdanhang der Zuckerrübe. *Zuckerindustrie* **111**, 19–23.

Michel, J.A., Fornstrom, K.J. & Borelli, J. (1983) A chisel-based tillage system for irrigated row crops. *American Society of Agricultural Engineering*, ASAE, St. Joseph, MI, Paper no. 83–1033.

Miller, S.D. & Dexter, A.G. (1982) No-till crop production in the Red River Valley. *North Dakota Farm Research* **40** (2), 3–5.

Molnar, I., Vuković, R. & Jenovai, Z. (1982) Effect of meliorative and regular cultivation and fertilization of hydromorphic black soil/humogley/on the yields of wheat, corn and sugarbeet grown in three-crop rotation. *Proceedings of the 9th Conference of International Soil Tillage Research Organization*. Osijek, Yugoslavia, pp. 18–25.

Olanders, J. (1996) Sockerbetans etablering och tidiga tillväxt. Skörderesultat och växtnäringsanalys. *Swedish University of Agricultural Sciences, Alnarp, Reports from the Dept. of Crop Science*, no. **6**, 22–37.

Olsson, R. (1997) Good weed control in sugar beets with green methods – a realistic alternative or a dream? *Proceedings of the 60th IIRB Congress*. Cambridge, pp. 533–538.

Palmer, M.A., Armstrong, J. & Rope, D.N.E. (1977) Beating the blow. *British Sugar Beet Review* **45**, 30–31.

Petelkau, H. (1984) Auswirkungen von Schadverdichtungen aut Bodeneigenschaften und Pflanzenertrag sowie Massbahmen zu ihrer Minderung (with English summary). *Tagungsberichte der Akademie der Landwirtschaftswissen-*

schaften der DDR, Berlin, **227**, 25–34.

Pittelkow, U., Reich, J., Werner, D. & Mäusezahl, C. (1988) Ergebnisse zur Krumenbasislockerung auf Löss- und Berglehmsubstraten. *Archiv für Acker- und Pflanzenbau und Bodenkunde*, Berlin, **32**, 23–30.

Poesse, G.J. & van Ouwerkerk, C. (1967) *Mouldboard Shape and Ploughing Speed* (with English summary). Institute of Agricultural Engineering, Wageningen, The Netherlands, Report no. 103.

Pringas, C. & Märländer, B. (2004) Einfluss konservierender Bodenbearbeitung auf Ertrag, Qualität, Rentabilität und Cercosporabefall von Zuckerrüben – Ergebnisse einer Versuchsserie auf Grossflächen. *Pflanzenbauwissenschaften.*

Raininko, K. (1988) Seed bed preparation and simultaneous placement of fertiliser at drilling in one operation to save costs and increase yield. *Proceedings of the 51st IIRB Congress.* pp. 23–32.

Raininko, K. (1998) Kunde man tidigarelägga sådden? *Betfältet* **2**.

Richard, G. & Guerif, J. (1988) Influence of aeration conditions in the seedbed on sugar beet germination: experimental study and model. *Proceedings of the 11th Conference of International Soil Tillage Research Organization.* Penicuik, Scotland, pp. 103–108.

Riley, H. (1983) Forholdet mellom jordtetthet og kornavling (with English summary). *Forskning of Forsøk i Landbruket* **34**, 1–11.

Ruppel, E.G. (1991) Survival of *Rhizoctonia solani* in fallow field soil and buried sugarbeet roots at three depths. *Journal of Sugar Beet Research* **28**, 141–153.

Rydberg, T. (1987) Studier i plöjningsfri odling i Sverige 1975–1986 (with English summary). *Swedish University of Agricultural Sciences, Uppsala, Reports from the Division of Soil Management*, no. 76.

Schäfer-Landefeld, L., Brandhuber, R., Fenner, S., Koch, H.-J. & Stockfisch, N. (2004) Effects of agricultural machinery with high axle load on soil properties of normally managed fields. *Soil and Tillage Research* **75**, 75–86.

Selman, M. (1987) Growing sugar beet on sandland – Gleadthorpe experience and practice. *British Sugar Beet Review* **55** (4), 26–29.

Smith, J.A. & Yonts, C.D. (1986) Emergence of corn, sugarbeets and beans with conservation tillage. *American Society of Agricultural Engineering*, ASAE, St. Joseph, MI, Paper no. 86–1029.

Sommer, C., Zach, M. & Korte, K. (1987) Mit konservierender Bodenbearbeitung mehr Bodenschutz im Zuckerrübenanbau. *Die Zuckerrübe* **36**, 58–63.

Sperlingsson, C. (1981) The influence of the seed bed soil physical environment on seedling growth and establishment. *Proceedings of the 44th IIRB Congress.* pp. 59–77.

Spoor, G. & Godwin, R.J. (1978) An experimental investigation into the deep loosening of soil by rigid tines. *Journal of Agricultural Engineering Research* **23**, 243–258.

Spoor, G., Miller, S.M. & Breay, H.T. (1988) Timeliness and machine performance benefits from controlled traffic systems in sugar beet. *Proceedings of the 11th Conference of International Soil Tillage Research Organization.* Penicuik, Scotland, pp. 317–322.

Stenberg, M., Håkansson, I., von Polgár, J. & Heinonen, R. (1995) Sealing, crusting and hardsetting soils in Sweden – occurrence, problems and research. In: So, B.H., Smith, G.D., Raine, S.R., Schafer, B.M. & Loch, R.J. (eds) *Proceedings of the Second International Symposium on Sealing, Crusting and Hardsetting Soils: Productivity and Conservation.* Australian Society of Soil Science Inc., Queensland Branch, Brisbane, Australia, pp. 287–292.

Stenberg, M., Aronsson, H., Lindén, B., Rydberg, T. & Gustafson, A. (1999) Soil mineral nitrogen and nitrate leaching losses in soil tillage systems combined with a catch crop. *Soil and Tillage Research* **50**, 115–125.

Stockfisch, N. & Koch, H.J. (2000) Wachstum von Zuckerrüben nach erstmaligem Pflugeinsatz auf langjährig reduziert bearbeitetem Boden. *Proceedings of the 63rd IIRB Congress.* Interlaken, pp. 399–404.

Terpstra, R. & Kouwenhoven, J.K. (1981) Inter-row and intra-row weed control with a hoe-ridger. *Journal of Agricultural Engineering Research* **26**, 127–134.

Tillett, N. & Wiltshire, J. (2001) New vision-guided tractor hoe. *British Sugar Beet Review* **69** (4), 40–43.

Trautner, A. (2003) On soil behaviour during field traffic. PhD thesis, Acta Universitatis Agriculturae Sueciae, Agraria 372.

Tugnoli, V. (1997) The importance of soil preparation for a good sugarbeet sowing in Italy. *Proceedings of the 60th IIRB Congress.* Cambridge, pp. 359–366.

Uppenkamp, N. (1986) Mechanische Massnahmen zur Sicherung des Feltaufganges von Zuckerrüben bei verkrusteter Bodenoberfläche. *Forschungsbericht Agrartechnik des Arbeitskreises Forschung und Lehre der Max-Eyth-Gesellschaft*, 127, Bonn.

Van den Akker, J.J.H. & Schønning, P. (2004) Subsoil compaction and ways to prevent it. In: Schønning, P., Elmholt, S. & Christensen, B.T. (eds) *Managing Soil Quality: Challenges in Modern Agriculture.* CABI Publishing, Wallingford, pp. 163–184.

Vandergeten, J.-P., Duval, R. & Vereerstraeten, R. (1997) Enfouissement localise de doses reduites d´engrais azote en culture betteraviere: aspects economiques, mecaniques et ecologiques. *Proceedings of the 60th IIRB Congress.* Cambridge, pp. 63–90.

Van Swaaij, A.C.P.M., Heijbroek, W. & Basting, J.L. (2001) Testing and improving seed vigour in sugar beet. *Proceedings of the 64th IIRB Congress.* Bruges, pp. 237–246.

Vullioud, P.A. & Charles, R. (2000) Culture de la betterave sucrière sans labour: possibilités et limits. *Proceedings of the 63rd IIRB Congress.* Interlaken, pp. 379–385.

Wahode, J. (1985) Entwicklung einer Methode zur quantitativen Erfassung von Rückverfestigungen im Saatbett. *Forschungsbericht Agrartechnik des Arbeitskreises Forschung und Lehre der Max-Eyth-Gesellschaft*, 104, Bonn.

Westerdijk, C.E., Van der Weide, R. & Wevers, J.D.A. (1997) Integrated weed control (harrowing) in sugar beet. *Proceedings of the 60th IIRB Congress.* Cambridge, pp. 579–584.

Westmaas Research Group (1980) Experiments with three tillage systems on a marine loam soil. I: 1972–1975. *Centre for Agricultural Publishing and Documentation, Wageningen*, Agricultural Research Reports, no. 899.

Westmaas Research Group (1984) Experiments with three tillage systems on a marine loam soil. II: 1976–1979. *Centre for Agricultural Publishing and Documentation, Wageningen*, Agricultural Research Reports, no. 925.

Wevers, J.D.A. (2000) Weed control, prospective aspects. *Proceedings of the 63rd IIRB Congress*. Interlaken, pp. 111–114.

Wevers, J.D.A., Aarts, H.F.K. & Kouwenhoven, J.K. (1986) The effect of pre-drilling cultural practices on weed problems and control methods in sugar beet. *Proceedings of the 49th IIRB Congress*. pp. 303–319.

Wilson, R.G. & Smith, J.A. (1992) Winter wheat and winter rye cover crops for the establishment of sugarbeets. *Journal of Sugar Beet Research* **29**, 23–30.

Wilson, R.G., Smith, J.A. & Yonts, C.D. (1990) Effect of seeding depth, herbicide and variety on sugarbeet (*Beta vulgaris*) emergence, vigor and yield. *Weed Technology* **4**, 739–742.

Chapter 7
Agronomy

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INTRODUCTION

The word 'agronomy' is used in several senses. At a local and technical level it deals with husbandry, concentrating on the current 'state of the art'. On a world scale it is an umbrella term used to cover the work of scientists from a number of disciplines, including soil science, plant breeding and crop protection. In this chapter it is used to encompass a critical appraisal of sugar beet production practices against the background of a knowledge of crop growth.

Chapters about agronomy usually concentrate on the influence on final yield of only those factors over which the grower has some control. Everybody involved in crop improvement soon becomes aware that the responses to husbandry change from season to season in degree and even, on occasion, in direction. Moreover, influences of site and season frequently dwarf effects of husbandry: therefore this chapter begins by analysing the impact of site and season. In that it stores simple carbohydrate, sugar beet is an ideal choice to illustrate that yield is directly related to photosynthesis. Through an understanding of the influence of site, season, cultural practices and variety it is then possible to analyse, generalize and predict. Factors that the farmer can control have their effects through allowing the crop to exploit seasonal weather patterns to a greater or lesser degree.

This chapter begins with an outline of the current state of knowledge of how the crop grows in the field in response to the outdoor environment. Consideration is then given to mathematical growth models as a way of assembling these physiological relationships into a meaningful framework that should describe how crop plants behave. The chapter then analyses the effect of agronomic variables in physiological terms and concludes by considering how the application of physiological principles can be relevant to aspects of the future development of the industry.

Much of the evidence used in this chapter is based on experiments made in the temperate climate of north-west Europe, and throughout reference is made to months of the year as a shorthand way to describe particular climatic conditions in this region. There are regional shifts in the time of year when these conditions occur. The climate in continental and Mediterranean regions is often very different from that of temperate maritime areas, and an attempt has been made to highlight the impact of these differences on agronomy. However, these time-of-year effects have not been transcribed so that they can be read directly by beet agronomists working in the southern hemisphere, for example in Chile.

In crop physiology and agronomy crop growth is often studied in relation to the total amount of incident light intercepted or absorbed by the canopy. Various terms are used to describe the incident light. In this chapter, the following terms are used interchangeably: incident radiation, radiation, light, sunlight, light energy, solar energy, solar radiation and global radiation.

CROP GROWTH

Patterns during the growing season

To set the scene, Table 7.1 shows the final results of a series of experiments in which the object was to chart the influence of seasons, with all other factors

Table 7.1 Yield, solar radiation and water consumption data for a series of standard, irrigated crops grown at Broom's Barn, Suffolk, UK.

Year	Dry matter yield (t/ha)			Root yield (t/ha)	Sugar concentration (%)	Sugar yield (t/ha)	Intercepted radiation (MJ/m^2)	E_T (kg/m^2)	Sugar root dry matter ratio	Harvest index
	Roots	Tops	Total							
1978	11.2	6.5	17.7	45.9	17.6	8.1	978	–	0.72	0.46
1979	15.1	7.2	22.3	62.8	17.8	11.2	1440	–	0.74	0.5
1980	13.6	4.8	18.4	54.3	17.9	9.7	1087	388	0.72	0.53
1981	13.3	7.5	20.8	56.2	17.7	10.2	1429	340	0.77	0.49
1982	22.9	4.4	27.3	86.9	17.7	15.4	1684	331	0.67	0.56
1983	16.0	5.0	21.0	69.4	17.3	12.0	1285	452	0.76	0.58
1984	15.6	5.3	20.9	67.0	17.8	11.9	1269	280	0.76	0.57
1985	16.4	6.4	22.8	64.6	19.3	12.5	1436	323	0.76	0.55
1986	13.3	5.9	19.2	55.8	17.7	10.0	1300	337	0.75	0.52
1987	13.3	5.1	18.4	56.3	18.4	10.3	1200	327	0.78	0.56
1988	16.4	6.2	22.6	67.0	18.7	12.6	1427	357	0.77	0.56
1989	18.9	5.8	24.7	76.6	18.9	14.5	1580	456	0.77	0.59
1990	18.1	4.7	22.8	74.4	18.0	13.4	1627	508	0.74	0.59

as standard as possible. Thus the crops were grown at the same point in the farm rotation, basic culture was consistent and only two stocks of seed were used. An essential component of the system was to investigate seasonal differences in temperature and radiation, without introducing the constraint of markedly differential water stress; irrigation was a standard treatment. The consistent approach was to sow at the first opportunity in spring, i.e. when the soil was fit, but to avoid the early March period when, in the UK, there is an excessive risk of vernalization. The crops were harvested late so that the season's influence was complete. To avoid introducing harvesting efficiency as a variable, all crops were harvested by hand.

It is striking that, despite this standardization, root and sugar yields changed almost twofold (from 46 to 87 t/ha and from 8 to 15 t/ha respectively) and biomass yields ranged from 17 to 27 t/ha. Sugar yields generally reflected root yields, although there was a trend for sugar concentrations to be greater in later years. Top weights did not change in parallel with sugar yields; they ranged from 4 to 7 t/ha but there was hardly any association between the extremes of yield of tops and roots. Yields were outstandingly large in 1982 and 1989, but poor in 1978, 1980 and 1986, though not so depressed as when virus yellows devastated the crop from 1974–1976. Disease infection was never extensive on these experiments.

To trace seasonal effects on the build-up of yield we have chosen the extremes from a period when the crops were sampled at frequent intervals, 1978 and 1982. Several aspects of the growth of these crops are contrasted in Fig. 7.1. Figure 7.1a shows the differences in rates of biomass accumulation; yields of total biomass were markedly different in mid-July, when the crop in 1982 was growing at approximately 200 g/m^2/week, whereas in 1978 growth was about 100 g/m^2/week. From then on, growth rates were similar in each year with the differential simply maintained. Weights of tops increased rapidly to an early (August) peak in 1982, to be maintained at approximately 5 t/ha thereafter (Fig. 7.1b). By contrast, in 1978 top weights increased slowly but progressively until they reached 8 t/ha in late September. In both years there was a progressive increase in the weight of the taproot, slowly at first, then a phase of rapid and almost constant growth, followed by a period when growth became progressively slower (Fig. 7.1c). Clearly, the disadvantage in root yield in 1978 resulted from slow early growth and a maintained slower rate throughout. Although there was a phase when biomass was accumulated at similar rates in each year, rates of growth of the storage root were never

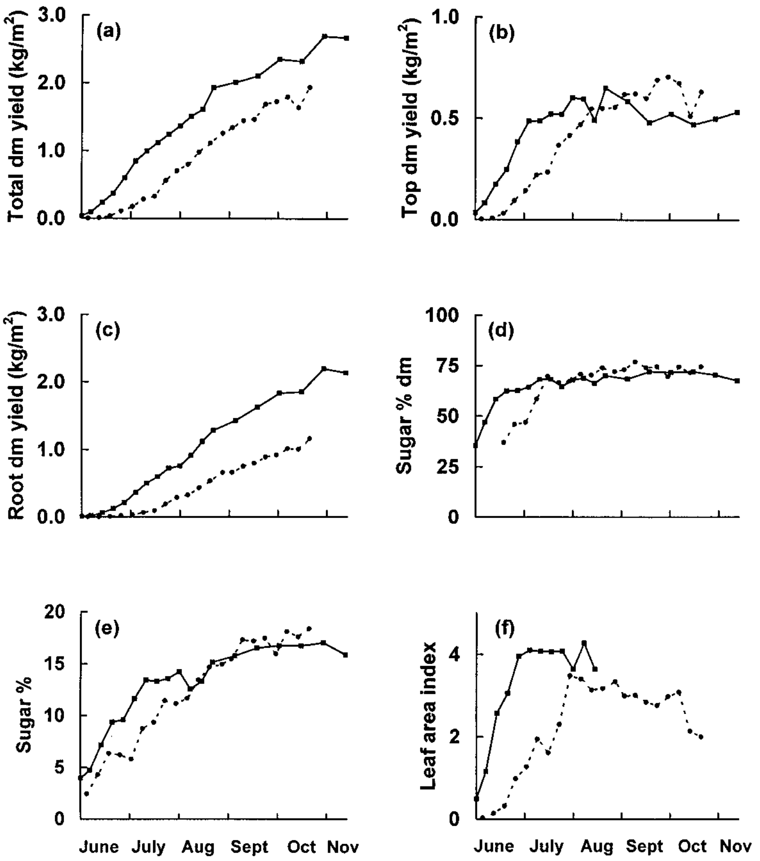


Fig. 7.1 Changes in dry matter yield components, sugar concentration on a fresh and dry matter basis, and leaf area index throughout two contrasting seasons, 1978 (dashed line) and 1982 (solid line) of sugar beet crops grown in a sandy loam soil at Broom's Barn in eastern England. In both seasons the intention was to use recommended husbandry practices to grow the best crop in the weather and soil conditions that prevailed: both crops were irrigated to prevent water stress.

as great in 1978, a reflection of the continued increase in the weight of tops in that year.

Within the root, the distribution of dry matter to sugar started at a low concentration (25%) and increased to reach a stable value of 75% of the dry matter (Fig. 7.1d). Milford (1973) reported a detailed analysis of the changes in root structure and composition that accompany this development. The plateau level was reached as early as the beginning of July in 1982 but not until late September in 1978. In general, the concentration of sugar on a fresh weight basis (Fig. 7.1e) tended to increase from less than 5% in early June to reach 15–21% in October and November, the precise value fluctuating with soil water status and rainfall. Whether the final value will be 15 or 21% is poorly understood. In part it depends on the water content of the beet, which in turn depends upon water availability in a short period before harvest, but this fails to explain much of the variation.

In a series of papers, Milford and co-workers (1985a,b,c,d) described patterns of leaf appearance, expansion and longevity on many of the crops detailed in Table 7.1. Like previous researchers (e.g. Clark & Loomis, 1978), they found that, after emergence, beet leaves were produced continuously throughout the growing season; the first pair appear synchronously and later leaves appear singly on a 5:13 phyllotaxis (i.e. on a spiral of five turns there are 13 leaves). Milford *et al.* (1985c) showed that two to three leaves appear each week during the summer months (at intervals of 30°C day – see also Chapter 3). By the beginning of September in 1978 and 1982 numbers had increased to 37 and 42 respectively. The interval over which leaves stayed alive increased from 500°C day for the first leaf, to exceed 1000°C day for the tenth leaf. In each year the first pair of leaves had died by the middle of June; subsequent leaves died in sequence to the point when 10–12 leaves were dead by the end of September. The maximum size attained by individual leaves increased progressively until about the 12th leaf (the largest leaves reached an area of 500 cm^2) and then decreased progressively with later-formed leaves (Milford *et al.*, 1985d). Leaves 5–20 accounted for almost all the leaf area duration.

While the overall pattern of production and maintenance of leaf area of the two crops was of a similar form, it was considerably displaced in time (Fig. 7.1f). However, in both years, maximum leaf area index (L) exceeded 3.0, the value that Goodman (1966) showed was required to achieve the maximum rate of growth, but there was a marked difference in how quickly it was reached: by mid-June in 1982, but not until late July 1978. Although there was some decline from peak L values later in the season, L still exceeded 2.5 by mid-September.

While no measurements of the fibrous root system were made in 1978, they were in 1982 and some of the subsequent years. Figure 7.2 shows the depth to which the root system penetrated the profile of a soil which had no obvious physical barriers to growth (Brown & Dunham, 1986; Jaggard *et al.*, 1996). In this work, root depth was defined as the depth at which root length density reached 0.1 cm/cm^3 of soil. From about 40 days after sowing the 'rooting front' deepened at the rate of 1.6 cm/day. This constant rate continued well into the summer and downward growth was maintained into the autumn. When the plants had two to four leaves, the roots were 20 cm deep, and by the time the foliage covered about 30% of the ground, 70 days after sowing, they had reached 50 cm. By the middle of June 1982, when a full canopy was achieved, the root system already extended down to 1 m, a stage not reached until early July in some other seasons. Later in the summer, roots were detected at depths of 1.5 m or more. On deep, stone-free soils Weaver (1926) reported rooting to a depth of 1.8 m and Windt and Märländer (1994) to a depth of 2.6 m, but in neither case was a threshold density defined.

From the two-leaf stage, the root system extended laterally at about 0.4 cm/day until approximately 80 days after sowing; after this, the root systems of plants growing in adjacent rows intermingled. The overall effect of these patterns of lateral and vertical penetration was that, while the system was able to explore new soil in both dimensions, the volume of fresh soil exploited increased progressively day

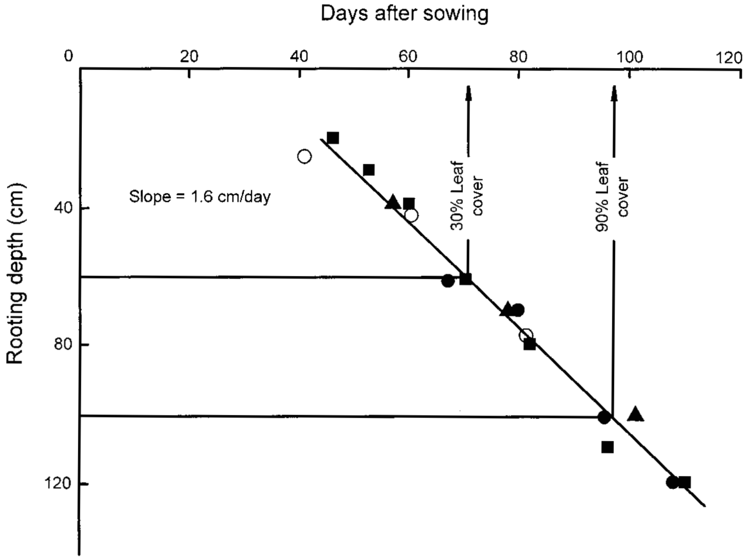


Fig. 7.2 Increase in effective rooting depth with time for sugar beet crops grown at Broom's Barn 1982 (■), 1983 (●), 1984 (▲) and between 1969 and 1971 (O) (after Brown & Dunham, 1986).

by day. However, after the systems from plants in adjacent rows met, the volume of new soil exploited each day, and thus the additional nutrients and water available was, at best, only maintained.

Brown and Biscoe (1985) found that most of the fibrous root system was in the top 30 cm, i.e. in the plough layer, and for a time it became progressively (almost exponentially) less extensive from the surface downwards. From August onwards, however, the roots in all layers between 50 and 120 cm were equally abundant, indicating that, at depth, roots followed existing fissures and worm-holes. By the end of the summer, the total length of root extending from the individual plant into the top 30 cm of soil exceeded 600 m. Beneath one square metre of soil surface, the total root length at full extension was 8–10 km; this compares with values at other sites of about 12 km (Jaggard *et al.*, 1996) and 15 km (Windt & Märländer, 1994), but 30 km for mature wheat crops. If the sugar beet root system was uniformly distributed throughout the top metre, there would be a single 1 m strand running the depth of the profile for every one square centimetre of the soil surface.

On the basis of weight, Brown *et al.* (1987) found that the fibrous root system accounted for a progressively decreasing proportion of total biomass, from approximately 10% of the total in early June to about 3% in late summer. Similarly Windt (1995) found that fibrous root dry matter reached 80 g/cm^2 or about 3% of total dry weight, by September. These values are probably underestimates for two reasons: first, during the process of washing and cleaning, soluble components are dissolved away, and, secondly, some of the system is always dying and is being replaced. There are no estimations for this 'turnover' in beet, but in cereals about 3.5% of the root system dies and has to be replaced each day (Sylvester-Bradley *et al.*, 1990). The fibrous root system and its turnover are not included in the values for biomass quoted elsewhere in this chapter – thus values for the efficiency of converting light to biomass are underestimated wherever biomass was based on the weight of a sample of plants.

If no rain falls, the root system dries the surface layers of soil (99% of the 'available' water can be pulled out of the top 30 cm by late summer) and water uptake is from progressively deeper in the profile (Brown *et al.*, 1987). In these conditions the roots near the surface eventually die, but on re-wetting, new roots quickly grow and water uptake resumes near the surface. When all the available water has been removed in a particular horizon, the nutrients in that part of the profile are no longer available. In many soil profiles nitrogen, potassium and phosphorus are available in largest quantities in the top soil. There are, however, some clay soils in which potassium is available to a similar extent throughout the profile. Armstrong *et al.* (1986) showed that there is always a rapid initial phase of nitrogen uptake, followed by a phase either of slower but maintained uptake or of no further uptake. The initial phase lasts for the period when the canopy is closing and while the roots are penetrating the surface metre of soil. The roots in the top soil are more active per unit root length or are distributed more uniformly than the deeper roots, and water is removed preferentially from the surface layers.

Photosynthesis and growth

A more direct way of analysing crop performance in relation to the environment has developed with the ability to monitor gas exchange by field crops on time scales extending from minute-by-minute to the whole growing season. Glauert (1983) demonstrated clearly that for much of the growing season of the UK beet crop, the environmental variable with the dominant effect on assimilation was the amount of radiant energy absorbed by the canopy. He measured carbon dioxide exchange and assimilation by using transparent enclosures that covered a group of six plants within the 'standard' crop that provided the 1980 data for Table 7.1. Figure 7.3 shows the relationship between carbon dioxide uptake and irradiance throughout 24 July 1980. It is striking how tightly coupled the two parameters were; both increased progressively through the morning, to decline later in the day. There was a distinct and immediate decrease in assimilation whenever the sun was obscured by cloud. When the data were plotted to show the response of carbon dioxide uptake to radiation there was an increase over the whole range (0–800 W/m^2 total radiation) but with a diminishing response. At this stage, when most of the leaves were young, the canopy did not become completely saturated with light, even in the brightest conditions. Closer examination of Fig. 7.3 also shows a displacement in values for carbon dioxide uptake at the same irradiance; values in the morning were greater than in the afternoon. This ‘hysteresis’ effect occurred only on bright days and was probably caused by the partial closing of stomata in the afternoon in response to internal water stress.

Glauert followed patterns of carbon dioxide uptake from mid-June until mid-December. Figure 7.4 shows that the photosynthesis/light response curve was maintained in an essentially similar position until September. Only then did the diminished responsiveness of an ageing canopy become evident. The fact that the response of sugar beet is maintained until September reflects the continued production of leaves. However, there comes a time when the overall age of the leaf surface increases because new leaves expand less than their older counterparts and contribute a smaller and smaller part of the light-intercepting area (Hodanova, 1981). Glauert found that, after remaining constant through June, July and early August, the net photosynthesis at 500 W/m^2 then declined throughout autumn to about half its summertime value. Although temperatures also declined over this period, cooler conditions were not the cause. At intervals from mid-June until mid-October, Glauert made sets of observations with the daytime temperature maintained at 20°C. Photosynthesis was maintained at the same rates

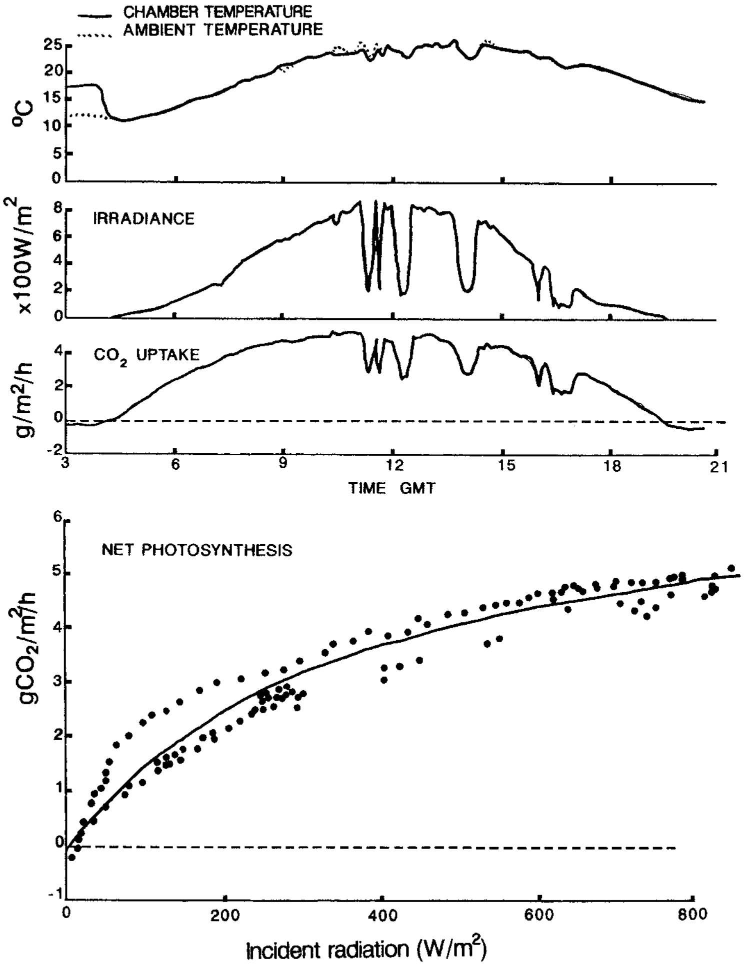


Fig. 7.3 Changes in temperature, irradiance and carbon dioxide uptake by a sugar beet crop during 24 July 1980. The response curve of net photosynthesis (per unit of land covered by foliage) in response to incident radiation was constructed from data collected on that day (after Glauert, 1983).

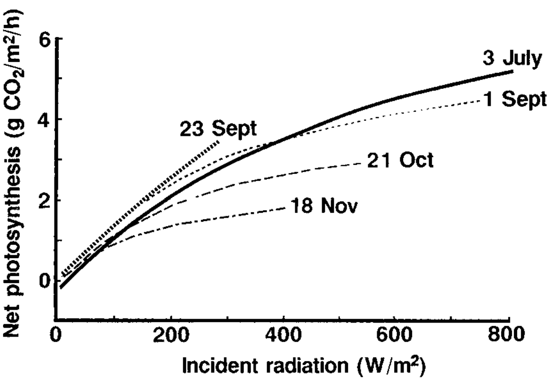


Fig. 7.4 Relationships between net photosynthesis and incident radiation of a sugar beet crop on various dates during summer and autumn 1980 (after Glauert, 1983).

during these episodes as when temperature in the enclosures followed the ambient. The lack of a temperature effect is also illustrated by the results shown in Fig. 7.5. Photosynthesis/light response curves were similar on 15 November, a warm day when the temperature did not fall below 12°C, and on 16 November, a bright, cold day when the temperature remained close to 5°C (Fig. 7.5). It was not until as late as 29 November, when the temperature in the gas exchange system never exceeded 2°C, that the response to light was diminished. Clearly, the diminished responsiveness of the canopy late in the season is under internal control, probably an ageing effect, and is not directly controlled by the weather.

Glauert's (1983) system enabled him to estimate night respiration from mid-June until early December. The average loss of dry matter during the night was estimated at 2 g/m^2/day, and there was no clear evidence of any systematic change as the season progressed, despite increases in the amount of respiring biomass and a longer dark period. To compensate, conditions became cooler and an increasing part of the biomass was in the form of storage tissue in the taproot, which probably had a low rate of maintenance respiration. The rate of dark respiration was related to the amount of dry matter assimilated during the previous day. Whenever dry matter accumulation exceeded approximately 15 g/m^2/day, the respiration rate in the 2 hours after dusk increased from the usual value of about 0.15 g/m^2/hour (Fig. 7.6); on occasions the respiration after dusk was doubled.

The daily increment in dry matter can be estimated from the measured amount of carbon dioxide taken up by the crop during a day. Glauert (1983) showed that this was directly proportional to the amount of radiant energy intercepted by the foliage during that day (Fig. 7.7). The 60 points presented here were from days dispersed throughout the season and it is clear that the 'conversion coefficient' was maintained close to 1.9 g/MJ of total radiation intercepted, surprisingly independent of tempera-

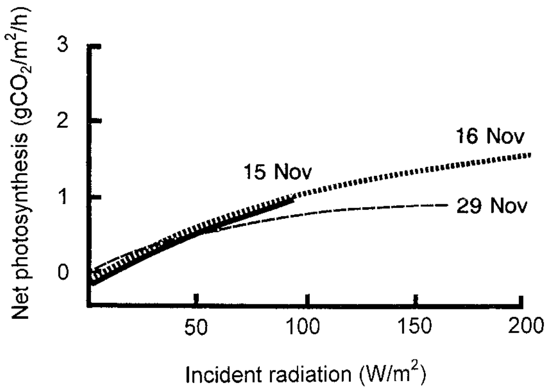


Fig. 7.5 Relationships between net photosynthesis and incident radiation of a sugar beet crop on a warm, dull day (15 November), a clear, cool day (16 November) and a cold day (29 November) (after Glauert, 1983).

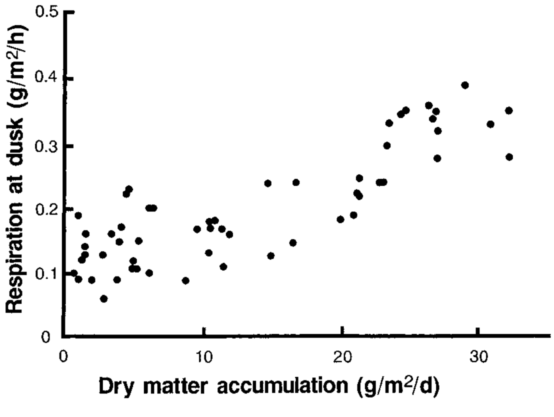


Fig. 7.6 Correlation between the amount of dry matter accumulated by a sugar beet crop during the day and its rate of respiration in the 2 hours after dusk (after Glauert, 1983).

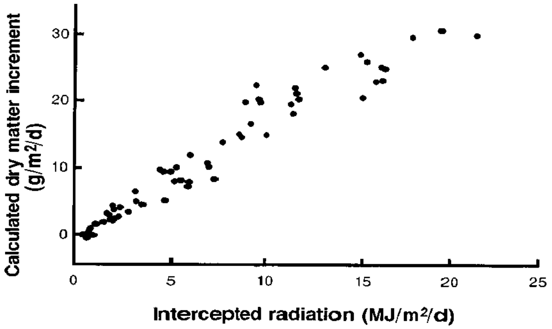


Fig. 7.7 The correlation between the increment of dry matter (calculated from integrals of the daily carbon dioxide uptake) and solar radiation intercepted by the foliage of a sugar beet crop on days throughout summer and autumn 1980 (after Glauert, 1983).

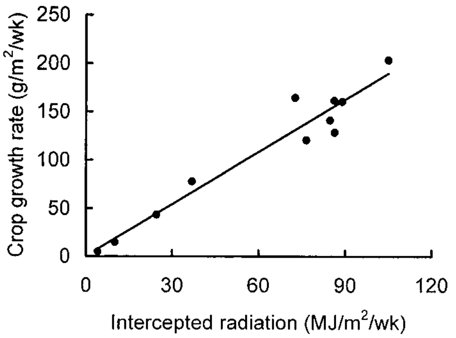


Fig. 7.8 Relationship between the amount of solar radiation intercepted by the foliage of a sugar beet crop and its rate of growth, as assessed by samples dug during summer 1981.

ture, plant size and the age of the crop. The coefficient did decrease on bright days when, for many hours, radiation reached the levels on the least responsive part of the light response curve (Fig. 7.3); overall, the conversion coefficient was 1.72 g/MJ. The clear implication from Fig. 7.7 is that biomass production during the season would relate directly to the amount of radiation intercepted by the foliage between sowing and harvest.

There must always be concern about the validity of extrapolating to the outdoor environment from measurements made on enclosed plants. Light quality was slightly affected by the enclosure and, despite satisfactory control of temperature, the air within the enclosure was often more humid than the air outside. Glauert checked whether these differences were critical. He estimated biomass production by integrating net carbon fixation as carbohydrate equivalents on a 24-hour basis, and compared the accumulated total with measurements of standing crop weight from conventional growth analysis over the season as a whole. He found remarkable agreement: 18.04 t/ha estimated from gas exchange and 18.3 ± 0.48 t/ha from growth analysis. The error on the gas exchange measurement is not known. All other things being equal, it might be expected that the gas exchange estimate would exceed the growth analysis value because the latter excludes carbon in the fibrous root system and in leaves shed before final harvest.

Figure 7.7 shows how estimates of daily crop dry weight gain, based on measurements of carbon dioxide exchange, are related to the amounts of light energy intercepted by the crop canopy. A similar relationship, but based on weekly increments of plant weight and weekly measurements of light interception (the integrated output from tube solarimeters), is shown in Fig. 7.8. The same stock of the variety Bush Mono G was used to establish the 1980 crop, on which gas exchange measurements were made, and the 1981 crop, which was subject to detailed and frequent growth analysis. In both years crops were irrigated to requirement and maintained free from yellowing viruses. The coefficient for the conversion of light energy to biomass until mid-September averaged 1.81 g/MJ (± 0.188); this compares with an estimate from gas exchange of 1.72 g/MJ.

Light interception and yield

The approach of measuring light interception with tube solarimeters and integrating their output can be extended for a whole season. Figure 7.9 shows how light energy intercepted between sowing and harvest is related to biomass, root and sugar yields for the 13 crops that provide the data presented in Table 7.1. Clearly, direct proportionality between intercepted light energy and biomass still holds; overall the efficiency was approximately 1.6 g/MJ. There are good reasons why this value should be less than that of the previous two values. By the end of the season, leaves had been severed and not all biomass was recovered. Throughout the 1981 season this loss was estimated by catching shed leaves

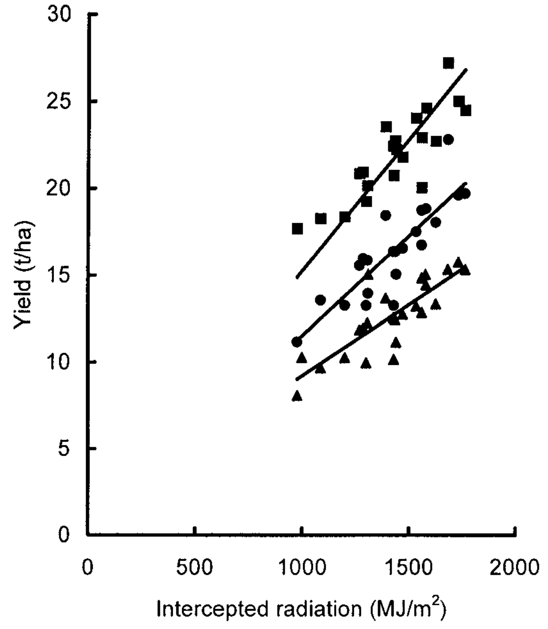


Fig. 7.9 Relationships between the amount of solar radiation intercepted by the foliage throughout the growing season and total dry matter (■), root dry matter (●) and sugar (▲) yields. Each data point represents the yield of a crop grown with recommended husbandry practices, including irrigation, at Broom's Barn between 1978 and 2004.

on a mesh held above the soil and measuring their biomass. Accumulated losses were approximately 200 g/m^2. The data of Milford *et al.* (1985a) would lead us to expect this order of loss: their records show that by the end of the season the first 12–15 leaves were dead. At peak leaf area these constituted the equivalent of 2.5–3.0 units of *L*. When the leaf area attained this value, foliage weight was around 300–400 g/m^2. Allowing for the weight of crown and the material retranslocated back into the living tissue, these values seem compatible. When the 200 g/m^2 is added back to the median biomass yield in Fig. 7.9 the equivalent conversion coefficient becomes 1.71 g/MJ, a value similar to that estimated from gas exchange.

Data from 1978 and 1982 crops fall close to the overall line on Fig. 7.9; the extra biomass produced by the 1982 crop was directly related to additional light energy intercepted. At the time this was the record yield in the UK environment; a direct result of the unusually large proportion of June's radiation intercepted by the foliage. The behaviour in the two crops precisely confirms Watson's (1956) observation that the predominant factor controlling yield in north-west Europe is the extent of coincidence in leaf area growth curves with the seasonal trend in radiation receipts. It is striking that when husbandry is standardized, crops grown on adjacent fields in different seasons exhibit such a range (1000–1700 MJ/m^2) in the amount of light energy intercepted by the foliage; this difference of 700 MJ/m^2 is equivalent to the amount of solar energy received during 5 midsummer weeks in north-west Europe or during the whole of June at the holiday resorts in Spain and Greece.

The relationship between root dry matter yield at harvest and light energy intercepted during growth is also shown in Fig. 7.9. The fitted line is parallel to that for biomass, with the displacement representing the weight of foliage, which was about 5.5 t/ha, irrespective of biomass or intercepted light energy. Thus, increases in season-long radiation interception increase root yield proportionately. There is a divergence in the lines for root and sugar yield; this reflects the stable proportion (72–75%) accounted for by sugar within the dry weight of the storage root. The coefficient representing the conversion of intercepted light to sugar is 0.97 g/MJ. From Fig. 7.9 it is evident that the ratio of the weight of root to weight of total biomass tends to increase as the seasonal radiation interception and yield increase. This also occurs in relation to sugar, but less markedly.

It is noticeable that the root and sugar data in Fig. 7.9 are more scattered about the line than the biomass data. The extra scatter represents the annual differences in harvest index – the ratio of sugar yield to total biomass yield. Taking the average yield of total biomass from the crops in Table 7.1 (21.4 t/ha) the extremes of the seasonal range in harvest indices (0.46–0.59) represent a change in sugar yield from 9.8 to 12.6 t/ha. How does this come about?

Water use, light intercepted and yield

It is essential to recognize that the yields in Fig. 7.9 and Table 7.1 were obtained from crops irrigated to requirement. The increased potential in seasons like 1982 and 1989, when leaf cover was early, could only be realized if the crop was allowed to obtain more water than usual during the growing season. The chances are that, in eastern England, rainfall will be inadequate and that irrigation will be required to supplement soil reserves and rainfall. There is no simple relationship between rainfall during the growing period and yield without irrigation. Wet years are often dull years that have a low yield potential, an example being 1978. In contrast, bright years are often dry and they can be low-yielding too. In 1989, the yield of unirrigated plots was only 11.4 t/ha; this was 3.1 t/ha less than the yield of irrigated plots (Table 7.1).

Just as there is a direct relationship between growth and intercepted radiation, so a similar relationship exists between growth and water use (Fig. 7.10). This arises because the potential for photosynthesis, and thus dry matter production, and the potential for transpiration, are both set by the amount of solar radiation intercepted by the canopy. In addition, the way the crop exploits this potential is related to the transfer of carbon dioxide into, and water vapour transfer out of, the leaves, both of which are regulated by the stomata and the boundary layer resistances.

The concentration gradient of carbon dioxide across the stomata is relatively stable during daylight but the gradient of water vapour potential varies greatly according to the dryness of the atmosphere, thus it would be expected that, in terms of biomass production, less water would be used in temperate than in arid environments. In recent years at Broom's Barn the dry matter/water use ratio, sometimes called *q* has ranged from 5–7 g/kg. By contrast, in California the ratio found by Ghariani (1981) was as low as 2.3 g/kg. Regional and seasonal variation in *q* arise owing to differences in the drying power of the atmosphere, in particular, the mean saturation vapour pressure deficit. This was shown with barley (Monteith, 1986) and pearl millet and ground nut (Squire, 1990).

In temperate climates sugar beet crops spend little time in very bright sunlight and therefore their canopies are not light-saturated for long. Thus total biomass production is closely related to the amount of radiation intercepted. Nearer the equator radiation is more intense so canopies can become light saturated, especially in continental climates where there is little cloud. There, the relationship between growth and radiation interception is not so consistent. In dry regions, such as Greece and California,

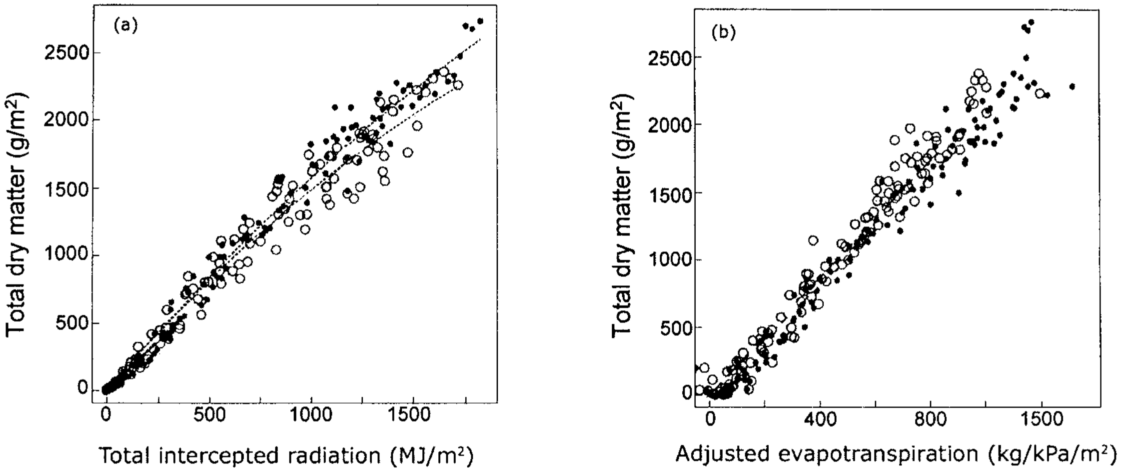


Fig. 7.10 Fitted and observed total dry matter yields of irrigated (●) and rainfed (○) crops grown at Broom's Barn during 1980–1991, against (a) intercepted radiation and (b) estimated transpiration scaled to the mean saturation deficit for each season. In (a) the lines represent a common initial conversion coefficient (ε = 1.76 g/MJ) which decayed faster in rain-fed than in irrigated crops (after Werker & Jaggard, 1998).

the overriding control of yield is via the amount of water available and the dryness of the atmosphere. Therefore it is not always predictable whether yield should be related to light energy intercepted or to an estimate of water consumed, E_T, or indeed whether one or the other should predominate throughout the growing season. Werker and Jaggard (1998) investigated this with data from most of the crops in Table 7.1 and their rain-fed counterparts. Dry matter yield was related to total intercepted radiation (Fig 7.10a), but the common initial conversion coefficient (1.76 g/MJ) decayed faster in rain-fed crops than in irrigated crops. Figure 7.10b shows that dry matter yield was also related to an estimate of water transpired by the crops (E_T-E_O, where E_O represents water lost from the bare soil surface). The crop transpiration was scaled to the mean saturation deficit ($\check{D}$). Growth rate per unit water transpired, q, was slightly faster in rain-fed than irrigated crops. Contrary to expectations, seasonal variations in q could not be eliminated by allowing for variation in $\check{D}$. In summary, Werker and Jaggard (1998) found that whenever the crops could not use water at the potential rate, 0.62% of potential yield was lost for every 1% loss of E_T.

Harvest index

In the experiments presented in Table 7.1 there was a systematic shift in harvest index when the variety was changed from Bush Mono G to the higher-yielding Regina. Over the seasons 1978–1981 (Bush Mono G) the average harvest index was 0.495 (ranging from 0.46–0.53), but from 1982–1990 (Regina) the average was 0.564 (ranging from 0.52–0.59). In 1984, when the two seed stocks were each grown with standard husbandry in the same experiment, both intercepted the same amount of radiation and partitioned assimilates similarly until late July, when 500 MJ/m^2 had been intercepted; thereafter Regina retained less in the top (Scott & Jaggard, 2000). Each intercepted a similar amount of radiation and produced similar yields of biomass (23.4 t/ha) but because of its more economical growth pattern, Regina produced an extra 2 t/ha of sugar. It is possible that one of the factors involved in the renewed upward trend in sugar yields in north-west Europe through the 1980s is that breeders selected plants that had a more desirable growth pattern late in the season. In its day, the Bush variety was noted for achieving early ground cover. Regina's more economical, late-season growth pattern was not associated with any slowing of initial investment in leaf growth; this would have been a most undesirable trait.

In addition to differences due to variety, there were clear seasonal effects on harvest index (Table 7.1). In years when harvest indices were small (1978, 1981 and 1986), the tops continued to increase in weight after early August; in the other years top weights reached about 6 t/ha at that time, then declined slowly to reach about 5.5 t/ha. Two factors known to modify patterns of top growth are the availabilities of nitrogen and water. A continuous uptake of nitrogen increases the growth of the leaves that appear late (Houba, 1973) and prolongs the period of foliage-dominated growth. Armstrong *et al.* (1986), using some of the crops whose data are in Table 7.1, showed that in many sites and years crop nitrogen uptake was arrested by mid-August, the time when top weights usually reached their maximum. However, they also showed that where both nitrogen and water continued to be available, nitrogen uptake continued and at final harvest the weight of foliage was large and the harvest index small.

Some confirmation of this pattern is seen when comparing growth of crops on mineral soils, which generally contain little inorganic nitrogen, with crops grown with a plentiful and continuous nitrogen supply; and when comparing growth of crops with and without serious water stress. Figure 7.11a shows the change in top dry matter in relation to total dry matter as weight increases throughout the season for crops of Regina grown on mineral soil at Broom's Barn from 1987–1989, in comparison to the relationship on nitrogen-rich sites in the same seasons. Early on, when crop weight was small, dry matter was partitioned similarly in all years and on all sites. Subsequently, crops growing in the nitrogen-rich soils partitioned much more of their biomass to the growth of tops, and root and sugar yield suffered in consequence. Similarly, Brown *et al.* (1987) showed how water stress affects leaf expansion and light interception. Data from their 1983 experiment with the variety Regina at Broom's

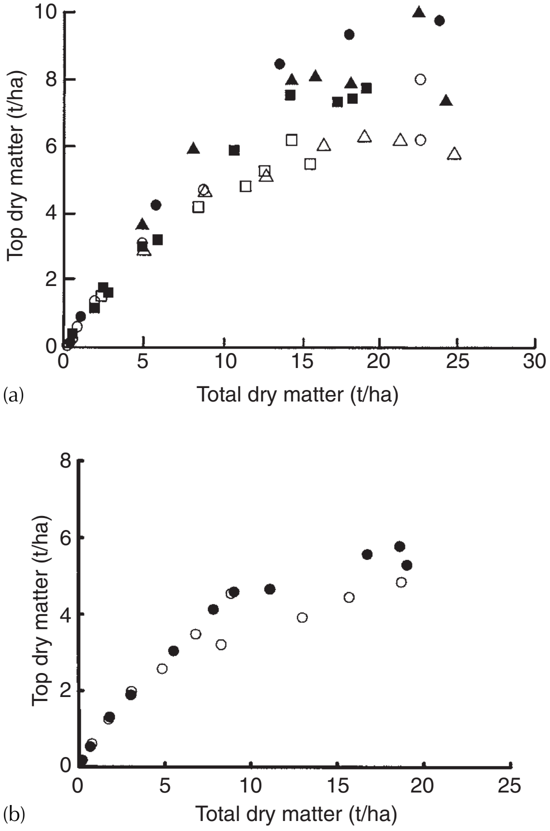


Fig. 7.11 Changes in the yields of top dry matter in relation to total dry matter in sugar beet crops grown on sandy loam soil (a) at Broom's Barn in 1987 (■), 1988 (●) and 1989 (▲) in comparison with crops grown on an organic soil in 1987 (□) and on sands given a heavy dressing of organic manure in 1988 (○) and 1989 (△) and (b) at Broom's Barn in 1983 under rain-fed (○) and irrigated (●) conditions.

Barn are depicted in Fig. 7.11b. Water stress in the rain-fed crop restricted foliage growth and shifted partitioning of dry matter in favour of the root and sugar yields. Green *et al.* (1986) postulated that the distribution of dry matter in sugar beet had distinct phases: an early phase of foliage-dominated growth followed, after an abrupt shift, to a phase dominated by growth of the storage root, followed by a stage of sugar storage. This was refuted by Milford *et al.* (1988), who analysed data from some of the crops used in Table 7.1. They showed that rather than distinct phases, there was a gradual shift in the allocation of dry matter, with an increasing proportion of new material directed to root and sugar storage as plant weight and yield increased. This gradual shift, based on plant weight, was used by Werker *et al.* (1999) to model partitioning on the basis of the allocation of assimilates to structural and sugar dry matter, when small shifts in the partition function were caused by the effects of drought and soil nitrogen.

ANALYSING AGRONOMY IN PHYSIOLOGICAL TERMS

Assessing light interception

The principal target for agronomy is clear: to maximize radiation interception. To do this the agronomist needs a rapid and straightforward way to assess radiation capture by the foliage throughout its life. This can be done indirectly, on the basis of the curved relationship with leaf area index, L (Fig. 7.12a). When the canopy is 'complete', the petioles of many leaves are almost upright, but the laminae usually bend towards the ground with the result that much of the leaf surface is near horizontal. In consequence, 85–95% of the indirect light is intercepted by L of only 3 or 4: much less than would be required in a cereal crop. An easier, and in some ways more useful assessment to make is foliage cover. As shown in Fig. 7.12b, this is directly and linearly related to radiation interception (Steven *et al.*, 1986).

Sowing date

From the foregoing, it is clear that delayed sowing decreases potential yield. Scott *et al.* (1973) showed that the yields of crops sown on a range of dates were directly related to the amount of radiation intercepted by their foliage between sowing and harvest. What defines the limits of how early the crop can be sown? One limit is set by the base temperature for germination, and this is 3°C (Gummerson, 1986). There is little point in sowing during February in the UK because the average temperatures near the soil surface are usually still close to 3°C. It is not until March, when air temperatures rise to about 5 or 6°C that it is worth placing the

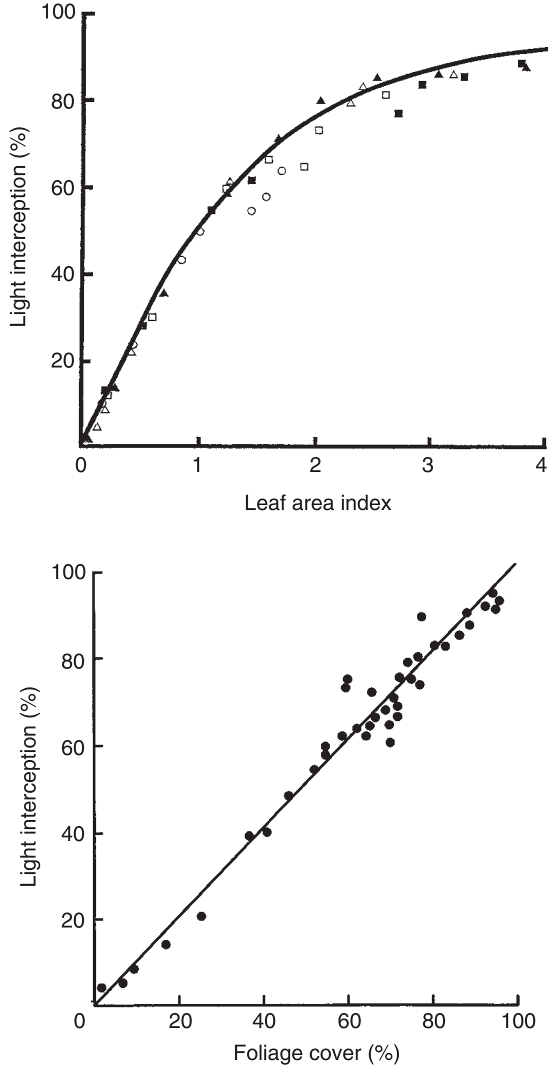


Fig. 7.12 Relationship between the percentage of solar radiation intercepted by sugar beet crops and their leaf area index or foliage cover. The crops were grown at densities of approximately 75 000 plants/ha in rows 50 cm apart. In (a) the crops were sown either early (▲) or late (△) in 1978. In 1979 the crops were irrigated and given nitrogen fertilizer (■), given no fertilizer (○), or were fertilized but given no water (□). The line was obtained by fitting the equation $I_L/I_O = (s + (1 - s)\tau)^L$ from Szeicz (1974) where τ was assumed to be 0.25 and where s was calculated as 0.32. In (b) the foliage cover was assessed indirectly from measurements of red and infra-red reflectance.

seeds in the ground. If seed is in the ground earlier than this, temperatures are usually little above the threshold, the germination process proceeds very slowly and the germinating seed and below-ground 'seedling' are vulnerable to soil-borne pests and diseases for a long time. Thus there is a great risk of poor establishment and a gappy crop. In warmer climates e.g. northern Italy, it is often worth sowing in early February.

The second limiting factor is bolting. Beet plants become reproductive and inefficient at producing sugar after exposure to low, vernalizing temperatures and lengthening days. The critical temperature range for vernalization is approximately 3–12°C (Stout, 1946; Smit, 1983) but at the warmer end of the range the process proceeds slowly. Vernalization can begin on the mother plant (Lexander, 1969). There has been debate about whether some foliage (a cotyledon or a leaf) is necessary for the detection of the vernalization signal, but Smit (1983) showed clearly that the proportion of beet that bolted was decreased by warming the soil and advancing the date of seedling emergence. The reverse effect was produced by cooling the soil before emergence. These results indicate that at least part of the vernalization stimulus can be detected before seedlings emerge. Modern, bolting-resistant varieties produce less than 1% of bolters if they are exposed to fewer than 40 'cool' days, i.e. when temperatures remain below 12°C (Jaggard *et al.*, 1983). This has set the limit to how early the crop can be sown in areas where devernalization conditions are rare. Since 1990 in beet-growing areas of the UK there have been an average of 3 cool days in May, 12 in April and 20 in March. Thus on the basis of the average, it would be permissible to start sowing before the beginning of March. However, to have appreciable numbers of bolters every other year is an unacceptable strategy.

Since 1990, sowing on 15 March would incur a serious risk of bolting in only 1 year, and this seems acceptable. This 'acceptable date' is earlier than it used to be, not because varieties have become more resistant to bolting, but because March and April weather has become appreciably warmer. In fact, many would argue that the safe start date to sowing has now moved even further forward to about 5 March: there would be almost no bolting (> 0.1%) from sown seed in 10 of the years between 1990 and 2004. In the other years some plants would bolt and could produce viable seed. However, in much of north-west Europe this is now of little consequence because the fields are already heavily infested with viable beet seeds. These produce many bolters, which have to be controlled, and a few extra bolters from the crop plants hardly affect the situation.

Beet plants can be devernalized by temperatures above about 20°C (Chroboczek, 1934). In parts of the beet growing region of France, well away from coastal influences, high temperatures (> 25°C) are common and tend to occur on many consecutive days sufficiently soon after sowing that bolting has not started. In these conditions devernalization occurs and bolting is therefore rare so the vernalization effects of sowing date can be ignored (Fauchere *et al.*, 2003).

As the environment becomes more favourable for growth, the effect of the loss of a day's growth becomes progressively larger. Jaggard *et al.* (1983) showed that there was a slight loss from delays in late March, and Hull and Webb (1970) showed that the yield penalty gradually increased with further delay until it reached 0.6% per day in mid-May. It is, however, crucial to take soil conditions into account. In March, soils are often wet and to adhere rigidly to 5 or 15 March as the universal start date would be to incur the risk of creating a cloddy seedbed underlain by a compacted layer. Jaggard (1977) has shown that compaction resulting from running a tractor wheel on moist soil slows early growth. The key is to be able to complete sowing as quickly as possible once soil conditions are suitable. Current systems of beet growing have been devised to minimize the number of operations (and therefore opportunities to compact soil) necessary between ploughing and sowing. Apart from nitrogen, fertilizers can now be applied before the primary cultivation and attention is given to leaving the cultivated surface as uniform as possible, by rapid ploughing, by using a furrow press or by using combinations of tines, discs and levelling harrows. On sandy soils it is then possible to sow the seed into the ploughed surface; on heavier soils it should be possible to create a seedbed in one pass with shallow cultivation equipment. These developments have led to more timely completion of sowing and contributed to the upward trend in yield.

Once conditions are suitable for sowing to start, it should be completed as rapidly as possible. Delays into late April and beyond increase the risk that soils will dry out, either during seedbed preparation or during the time when seeds are germinating. Gummerson (1986) demonstrated that the germination rate of seeds is related quantitatively not only to their temperature experience but also to their water potential; as potentials become more negative, rates slow. In these conditions depredations by pests and diseases can lead to gappy stands and inefficient utilization of light.

Transplanting seedlings into the field at normal sowing time advances leaf growth, increases radiation interception and improves yield (Scott & Bremner, 1966). The technique is expensive but it is still used to good effect in Japan on small farms and where family labour is plentiful. For many years other ways of obtaining part of the benefit, mainly by pre-treatment of seed, have been explored. The aim is to enable the seed to complete all or part of the germination process before it is sown. On an experimental scale it has been possible to germinate seeds to the point where the radical is up to 1 cm long, and then sow them suspended in a fluid. However, difficulties of mechanically handling the 'seedlings' to achieve precision spacing, and of storing chilled seeds without inducing bolting have proved too great for commercial application for sugar beet. Pre-treatment to a less advanced stage or 'advancing' has proved possible. In this process seeds are taken close to the point of germination, but are then dried for pelleting and long-term storage. By advancing imbibed seeds at 15°C, Durrant *et al.* (1983) showed that emergence could be 5 days earlier, with potential for increased sugar yield. However, there is a limit to what can be achieved by such pre-treatment unless the crop can safely be sown earlier. Using the relationship between hydrothermal time and germination established by Gummerson (1986), Durrant *et al.* (1993) showed that seed could be imbibed to start the germination process and then partially dried to prevent germination. In the partially dried state the seed is still active and viable and was incubated at 25°C for 3–5 days. The seed was then thoroughly dried and stored for subsequent use. After sowing, the seeds produced seedlings more rapidly than their untreated counterparts, and in some early-sown experiments incidence of bolting was reduced. This treatment is similar to that marketed as 'Advantage', which has never caused a yield reduction and has occasionally produced large yield increases.

In an analysis of the changes in the weather and farming practices since 1970, Scott and Jaggard (2000) showed that advancing the date of sowing, associated with warmer spring weather, was responsible for increasing the UK's national sugar yield by 0.6 t/ha.

How does the background to decision-taking in relation to sowing date differ in regions other than the maritime part of north-west Europe, i.e. in continental and Mediterranean regions? In contrast to the slow and somewhat unsteady increase in temperatures from February until May in the UK, the trend in continental regions, exemplified by Kiev, in the Ukraine, and Fargo, North Dakota, is a marked transition from sub-zero conditions that persist until March to a complete change in May with maxima of 20°C and minima of 6–9°C. Sowing is out of the question until the thaw is complete and then there is only a very short transition period when sugar beet seedlings are likely to experience vernalizing temperatures, i.e. in the range 3–12°C. Thus, bolting resistance is not such a priority target in breeding for these areas. On the other hand, resistance to direct damage by frosts is of concern in North Dakota and Minnesota, where temperatures at night often go down to -10°C in April and to -3°C in May. Thus, sowing date decisions are based on the balance between the risk of (a) seedlings being exposed to damaging night-time temperatures if sowing is too early; (b) seeds being sown into soil which is drying so rapidly that many fail to germinate; and (c) seeds being sown into soil which is so warm and moist that the seedlings suffer from serious infection by *Aphanomyces* (see Chapter 12).

In some Mediterranean regions, (Andalucia in south-west Spain, southern Italy, northern Egypt, Tunisia and Morocco) beet is sown in the autumn. This has the advantage that the crop is growing and using water during the wet winter period and avoids the times of excessive water demand when the atmosphere is extremely dry in summer. Sowing begins in September and is complete by mid-November. This is possible because, for example in Alexandria in Egypt, average minimum temperatures are 12°C from December until March; however, average maxima exceed 18°C for this period, so there are few vernalizing days. Throughout this period frost is very rare. Thus the plants do not bolt and their foliage is not killed by frost.

Plant establishment and spacing

Spacing and light interception

For radiation interception to be maximized it is crucial that establishment and spacing are right. If there are gaps not covered by foliage when plants are fully grown then yield is lost. This was shown by Scott (1964) who found that when 75 000 and 37 000 plants/ha had reached the stage when the leaf surface was maximal (late July and early August) the dense population was intercepting 89% of incident radiation but the sparse population only 75%. Both converted intercepted radiation to biomass at the same efficiency (1.6 g/MJ) and, over the late summer, crop growth rates were, for the dense population, 169 g/m^2/week and the sparse population 146 g/m^2/week, values that relate directly to the percentage interception. The differences in final yield between the two populations were directly accountable in terms of radiation interception.

It has proved difficult to measure light interception by sparse plant stands of sugar beet, particularly early in the season, because the areas to be sampled have to be very large to be representative: too large for conventional instruments. A black and white aerial photograph taken on film sensitive to near infra-red light is a reasonable surrogate (Fig. 7.13). Foliage reflects near infra-red strongly and appears bright on the picture, whereas the soil is a poor reflector and appears dark. The relationship between infra-red reflectance and L (Guyot, 1990) is of the same form as the relationship between light interception and L (Fig. 7.12a) so that there is direct proportionality between near infra-red reflectance and light interception. Thus, the areas that the film records as being very reflective (the white areas on Fig. 7.13) are areas where much light is being intercepted and where the potential for dry matter production should be greatest.

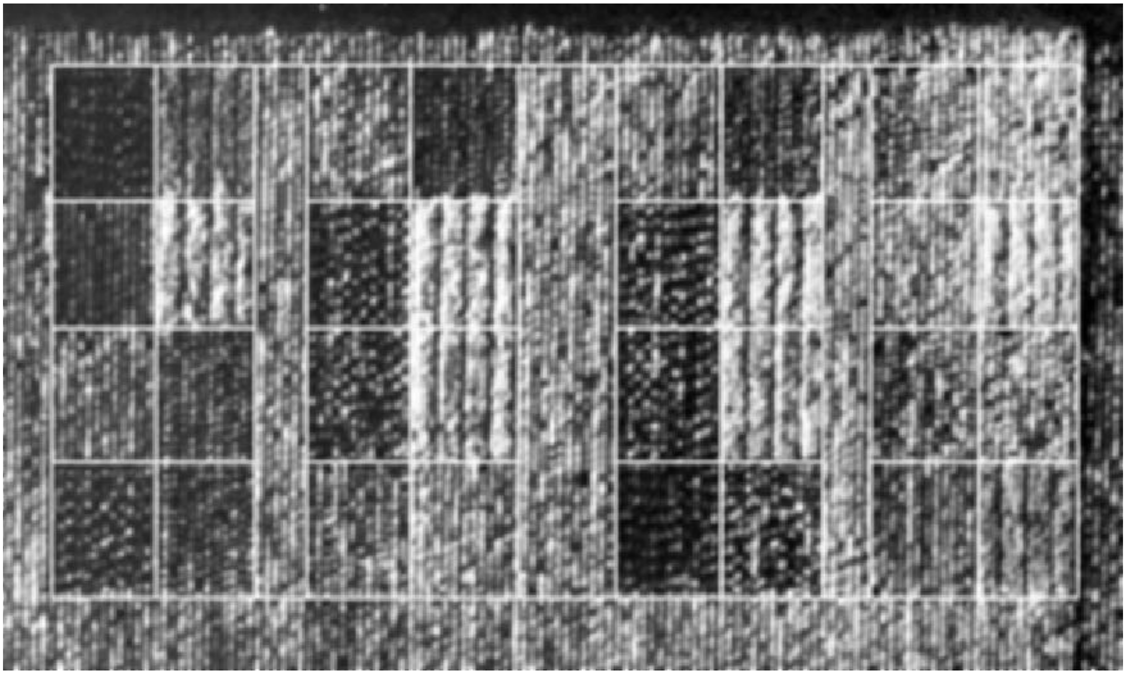


Fig. 7.13 Aerial photograph on infra-red sensitive film of two blocks of a factorial experiment designed to examine the effects of plant population and nitrogen fertilizer. The photograph was taken on 29 June 1969. (Crown Copyright. Courtesy of ADAS Aerial Photography Unit.)

The photograph was taken 29 June 1969 at Broom's Barn and it shows plots having 18 000, 37 000, 74 000 or 125 000 plants/ha; the greatest density was grown in beds of rows separated by 25 cm. These treatments were in factorial combination with four rates of nitrogen fertilizer: zero, 75, 150 or 225 kg N/ha. The photograph was analysed with an image analysis system which assigned a value for each plot to the integral of the progression in 'greyness' from white to black. These values have been plotted against the total dry matter and sugar yields that were measured in November (Fig. 7.14). The regression lines on Fig. 7.14 have been fitted to all the data, and it is clear that the sparse plots that intercepted little light produced only small yields, whereas the dense stands that already intercepted most of the light eventually produced large yields. Overall, these estimates of the proportion of light being intercepted accounted for 59% of the variation in total dry matter and 56% of the variation in sugar yield.

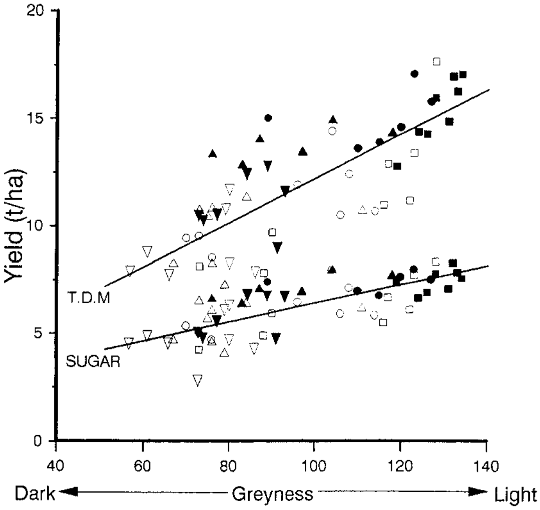


Fig. 7.14 Relationships between the greyness of the photographic image and the yields of total dry matter and sugar. The plant populations per hectare were 18 000 (▽,▼); 37 000 (△,▲); 75 000 (○,●); 150 000 (□,■). Plots represented by open symbols were treated with either zero or 75 kg N/ha, those by closed symbols either 150 or 225 kg N/ha.

Much of the scatter in the relationship with total dry matter can be attributed to the nitrogen treatments. Many of the data points for 225 kg N/ha fall above the line, especially for sparse crops that produced more dry matter than predicted by the relationship, probably because the nitrogen promoted large increases in canopy growth and light interception later in the season, after the photograph was taken. The points from the plots given no nitrogen fertilizer, particularly those with dense stands, tend to fall below the line, suggesting that, later in the summer the crop was not able to maintain its canopy and lost some of its ability to intercept light. When nitrogen is scarce the crop uses that which is available to support growth of the storage root rather than to maintain its canopy. It is evident from Fig. 7.14 that nitrogen treatments cause much less scatter around the line for sugar yield than for the dry matter yield.

Many experiments like the one just described show that on mineral soils a population of 75 000/ha is the minimum required for maximum sugar yield. Usually, biomass yields have increased asymptotically with increased population, but these same experiments have demonstrated that sugar yields normally fail to increase with increased populations above 75 000/ha (Fig. 7.15). Why is there no benefit from exceeding 75 000, either by having plants closer than 25 cm in the row, or closer than 50 cm between rows? Surely this should result in interception of extra light when the canopy is incomplete but expanding. When extra plants are crowded into the row, the leaves of adjacent plants overlap at an early stage and the benefits to radiation interception are very small. This was demonstrated in an experiment at Broom's Barn comparing plant spacings of 25 × 50 cm, 12.5 × 50 cm and 19 × 38 cm. As early as mid-June, when light interception was no more than 10% (the fifth leaf was approaching half its final size), there was already considerable overlap between the leaves of adjacent plants in the two dense stands (Fig. 7.16). By the beginning of July, by which time differences in interception had disappeared, the cumulative amount of light intercepted by the three canopies only differed by 15 MJ/m^2 in 80 MJ/m^2. At the end of season the crops had intercepted between

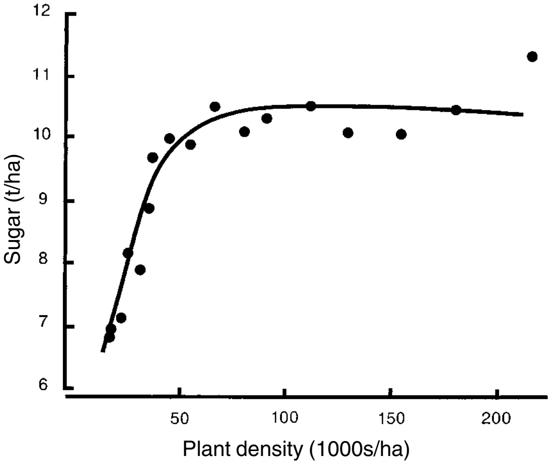


Fig. 7.15 Relationship between sugar yield and plant density for crops grown 'on the square' in England in 1967.

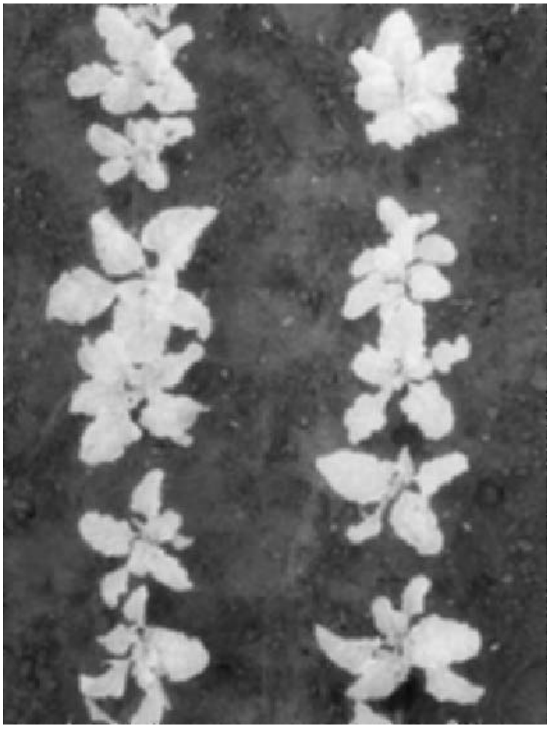


Fig. 7.16 A photograph taken on 1 June 1982 at Broom's Barn on infra-red sensitive film. Beet plants (*c.* 80 000/ha) are growing in rows 50 cm apart. Foliage covers less than 20% of the ground but already the leaves of adjacent plants overlap and compete for light.

1370 and 1410 MJ/m^2; the highest value giving a calculated increase of 0.68 t/ha biomass over the lowest. Measured biomass yields were 20.3, 21.3, 21.1 (SED ± 0.38) t/ha respectively.

Increases in density usually lead to an increasing retention of biomass in the foliage, and in this experiment root dry matter and sugar yields from the three populations were identical. In summary, the failure of populations above 75 000 to give extra yield arises because overlapping of leaves from adjacent plants occurs early (when cover is as little as 10%) and as overlap becomes more extensive individual plants trap less light. In consequence, the individual plant produces less dry matter, its leaves expand more slowly and the benefit to light interception, on a ground area basis, from having additional plants is eroded.

Spacing, arrangement and yield: a general model

How far is it possible to generalize from the information given so far to account for observed effects in experiments that have examined the various facets of plant establishment and spacing in sugar beet crops? To consider response to population and the proximity of adjacent plants, it is instructive to begin by considering responses where there is no row structure and plants are grown 'on-the-square'. Farazdaghi (1968) and Clayphan (K. Clayphan, Nottingham University, 1969, personal communication) did this and found that, where the crop was irrigated and adequately fertilized, a population of 75 000/ha was required for maximum yield. Some of Clayphan's data are shown in Fig. 7.15. When 75 000 plants/ha are grown in this way the sides of the squares are 36 cm long, and the distance across the diagonal is 51 cm. Because this arrangement produced maximum sugar yield, it can be inferred that radiation interception was maximized, provided plants were no more distant from their neighbours. If the land area that the foliage of the individual plant covers is represented by a circle, then the maximum radius must be 25.5 cm. All the area between the plants is within the circles, so all land is exploited and yield is maximized (Fig. 7.17a). The extent of overlap is a measure of the intensity of inter-plant competition; while this will affect weight per plant, it does not affect weight per unit area. The concept that there is a direct relationship between the proportion of the land surface not covered by these circles (a measure of the failure to intercept light) is now examined in relation to yield responses in a number of experiments comparing a wide range of plant spacing and arrangement.

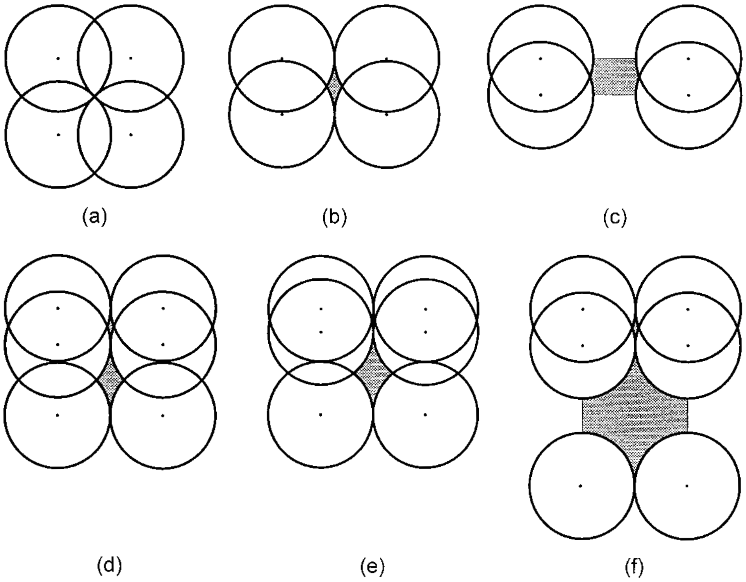


Fig. 7.17 Circles of influence, radius 25 cm, drawn around sugar beet plants grown in various arrangements: (a) 74 000 plants/ha 'on the square'; (b) 74 000 plants/ha in 51 cm rows; (c) 74 000 plants/ha in 72 cm rows; (d) plants spaced 18 and 36 cm apart along rows separated by 51 cm; (e) plants spaced 11 and 43 cm apart along rows separated by 51 cm; (f) plants spaced 18 and 65 cm apart along rows separated by 51 cm. The shading represents the area per plant that is incompletely exploited.

Jaggard (1979) analysed two experiments in which plant population was fixed at 74 000/ha and the plants were arranged in arrays in which the between-row and within-row spacing varied in five steps from a ratio of 1:1–1:6. Yield was reduced when row spacing exceeded 51 cm. When the circles are drawn for the treatment where density was 75 000/ha and the row spacing was 51 cm, i.e. the minimum density and maximum row spacing that gave maximum yield, only 5% of the land area is not 'enclosed' by circles (Fig. 7.17b). In practice, this area would be partially exploited and so yield would be expected to be very close to potential. Where rows were further, i.e. 71 cm apart, the 'circles of influence' do not span the ground area and a ribbon of land is left incompletely exploited (Fig. 7.17c). Thus yield declines progressively as the inter-row distance increases because the partially exploited area increases pro rata with row spacing. With very few exceptions around the world, row spacings for maximum yields of sugar beet are 50 cm or less: where larger spaces are used it is usually because another crop on the farm is dictating the distance between tractor wheels.

What is the influence of irregular spacing along the row? To explore this Jaggard (1979) grew plants in rows 51 cm apart and alternated long and short spaces along the row. The ratios of the long to short were 1:1, 2:1 and 4:1 and the length of the longest space ranged in 12 steps from 20 to 125 cm. Treatment effects on yield were reconciled by a critical gap length of 40 cm; wherever inter-plant distances exceeded this, yield was lost (Fig. 7.18). Figure 7.17 shows circles drawn for four of the treatments. Where the spaces were 18 and 36 cm long (Fig. 7.17d) 10% of the land area was outside the circles and the yield loss was only 0.9%. This is very close to the critical point at which real yield losses occur: the critical gap length of 40 cm coincides with 12% of the land being outside the circles (Fig. 7.17e). The effect of large gaps on the unencircled area is clearly shown in Fig. 7.17f. The gap length at which yield loss occurs is dependent on the inter-row distance. Rows 50 cm apart are certainly at the limit, so in this configuration yield is lost with gaps of 40 cm; were the rows 45 cm apart then in all probability yield loss would not occur until the gaps were 50 cm.

The percentages of the land area outside the 'circles' were calculated for all of the treatments in these population density experiments, and the values were plotted against the percentage yield loss, i.e. taking yields from treatments where all the land area was encircled as 100. The results are shown in Fig. 7.18, where a curve has been fitted to the data by eye. The fitted line is displaced from the 1:1 line because the area outside the circles is in practice partially exploited. For example, in a closed canopy

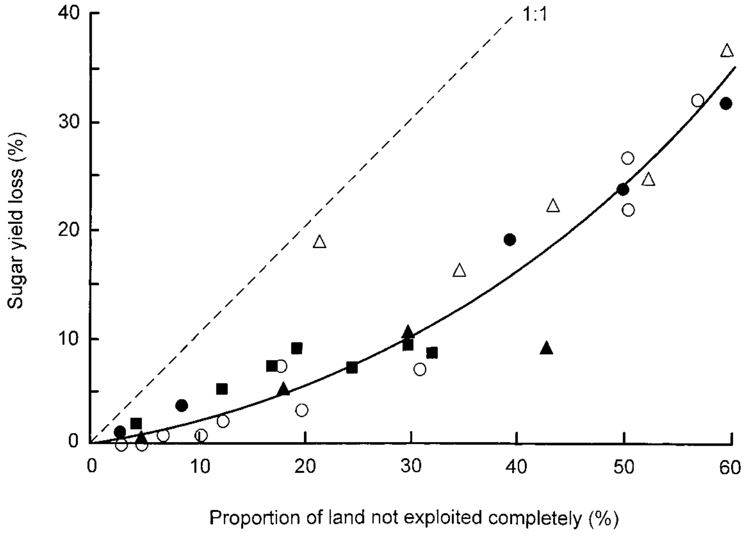


Fig. 7.18 Relationship between yield loss and the proportion of land estimated as not fully exploited on the basis of circles of influence. Data sources: ●, Fig. 7.17; △▲, rectangular arrays of 37 000 and 74 000 plants/ha respectively, Jaggard (1979); ○, irregular spacing, Jaggard (1979); ■, Norfolk Agricultural Station (1971).

only the plan area of the foliage will intercept solar radiation; however, where a plant is adjacent to a long gap the side elevation will also intercept light and it will produce additional dry matter to partially compensate for the gap. This effect becomes immaterial if the gaps are large and numerous, and at this point (about 40% of the area outside the circles) the fitted line on Fig. 7.18 runs parallel to the 1:1 line. Results from row width experiments (Norfolk Agricultural Station, 1971) were added to the plot to see if the relationship still held: the data fitted well. It seems that, for mineral soils in the UK at least, the limit, from the seedling position, of the area of complete interception extends to approximately 25 cm when the plant is fully grown. Beyond this distance sunlight falls on the soil surface and exploitation of the soil profile by roots may also be incomplete.

There are some fertile, organic soils where maximum yield is often produced with densities as low as 60 000 plants/ha (Knott *et al.*, 1976). On such soils the enlarged circles of influence are associated with much more luxurious foliage than on mineral soils. These sparse populations can produce very large roots and in organic soils they are poorly anchored in the soil so that large harvesting losses ensue.

Sowing to a stand and yield

When crops are sowed to a stand the spacing and arrangement of the plants is constrained by the requirements of the harvester and controlled by the proportion of seeds that become established. The relationship between sugar yield and the arrangement of the plants has been modelled in order to predict the seedling establishment needed to produce maximum potential yield, given the range of inter-seed distances that practicalities allow. The seeds have to be spaced far enough apart for efficient harvesting of fully grown plants. Topping is the most critical part of the procedure; plants, and therefore seeds, need to be at least 15 cm apart to allow space for the topping mechanism to readjust to varying crown heights of adjacent plants (O'Dogherty, 1976). At the other extreme Jaggard's (1979) experiments showed that gaps of more than 40 cm must be avoided. Given the minimum acceptable seed spacing and the maximum gap length tolerable, it is possible to determine the target seedling establishment percentage necessary to ensure maximum yield in crops that are sowed to a stand.

Ehnrot (1965) demonstrated that the proportion of gaps of various lengths between beet plants could be predicted on the basis of the binomial theorem. Jaggard (1979) showed that the way these gaps combine to provide a growing space for each plant could be predicted from expansion of the polynomial theorem. This information, combined with knowledge of the relationship between the weight of the individual plant and population density (Bleasdale & Nelder, 1960), allowed predictions to be made of the effect of seed spacing and plant establishment on sugar yield. This work, based on yields achieved in the early 1970s, showed that at practical seed spacings, maximum yield would only be achieved if more than 70% of seeds produced established plants (Fig. 7.19). The accuracy of this simple model was checked in an experiment when seedling establishment was contrived (by mixing known proportions of live and dead seed) to be 33, 50 and 77% and where seeds were spaced 15 or 22 cm apart. Average sugar yields of these treatments ranged from 7–10 t/ha and were always within 3% of the values predicted by the model

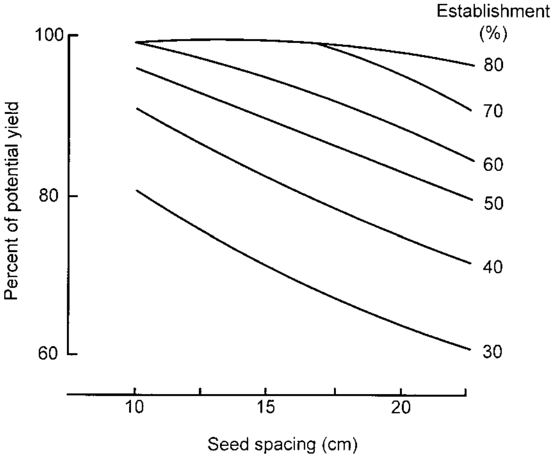


Fig. 7.19 Predicted effects of combinations of seed spacing and plant establishment on sugar yield of crops sown in rows 50 cm apart.

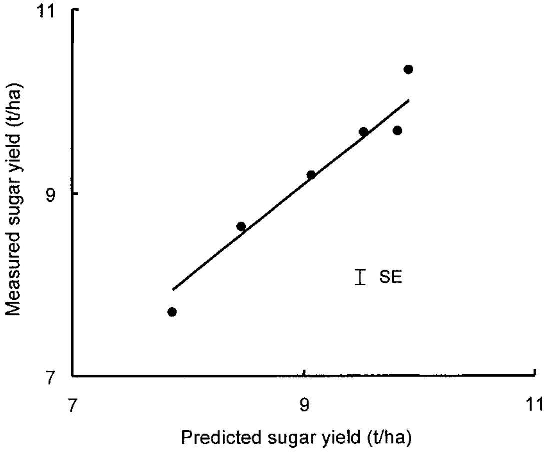


Fig. 7.20 Relationship between measured sugar yields and yields predicted on the basis of a model which describes plant arrangement and yield. The 1:1 line is shown.

(Fig. 7.20). This agreement was good enough for both the model, and its target of 70% establishment, to be widely accepted.

Minimizing the effects of poor establishment in many circumstances, for example where soil pests are present or the seedbed is prone to capping, it may prove impossible to achieve consistently the target that 70% of seeds should give established plants. In these conditions, and where sowing to a stand is practised, there is a benefit from having rows closer than 50 cm apart. If rows are 45 cm apart, as is commonplace in France, then 50 cm gaps down the row can just be tolerated without loss of yield since only 11% of the area falls outside the 'circles'. These crops can tolerate slightly less than 70% establishment and still produce maximum yield. Where establishment is really poor (< 50%) the ability of the surviving plants to grow rapidly is probably compromised by the factors that have killed the neighbouring seedlings, and no juggling with the plant arrangement will produce the potential yield.

There has long been a conflict between the need for close row spacing to intercept light and wide spacing to allow the passage of tyres on tractors. As implements have become larger, the number of passageways has reduced so that many farmers are now using 'tramlines' in their beet crops, as they have done in cereals for many years. Tyres on tractors and sprayers are now typically 500–600 mm wide, and so growers are deliberately not sowing two rows out of every sprayer pass. This may mean that there are two 1 m-wide spaces approximately every 24 m.

The yield lost as a consequence is trivial, one extra metre of bare ground represents about 4% of the land area. This represents much less than 4% yield loss because (a) the plants in the adjacent rows partially compensate for the extra width and (b) because any soil compaction from spray operations is now confined to the tramways and is not reducing yield elsewhere. The improvements made to the speed and timeliness of spraying and the saving in seed cost more than compensates for any yield reduction.

Nutrient application

It is clear from the foregoing that farmers fertilizing their crops efficiently should aim to maximize the interception of light and maintain the efficiency of its conversion to dry matter and sugar. Of the nutrients that the farmer applies, nitrogen has the most profound effect on growth. Milford *et al.* (1985a) showed that the rate of leaf expansion per unit thermal time was positively related and very sensitive to the nitrogen concentration of the leaves – see Chapter 3. The change in L per 100°C days doubled from only 0.4 when the lamina dry matter contained about 3.6% nitrogen, to 0.8 when the concentration was close to 4.5.

A prerequisite to large yields is that beet crops intercept as much as possible of May and June sunlight. To this end, beet plants should have ready access to available sources of nitrogen in the soil because, if the weather is warm and there is potential for rapid leaf expansion, the plants might need to take up as much as 5 kg N/ha/day if they are to suffer no restriction (Armstrong *et al.*, 1986). The period of rapid uptake of nitrogen extends from the time when the plants have four or five leaves until the canopy is complete. Thus, fertilizer policy should be such that nitrogen is available to meet this demand.

The effect of a farmer's nitrogen fertilizer additions on the ability of the crop to intercept sun-

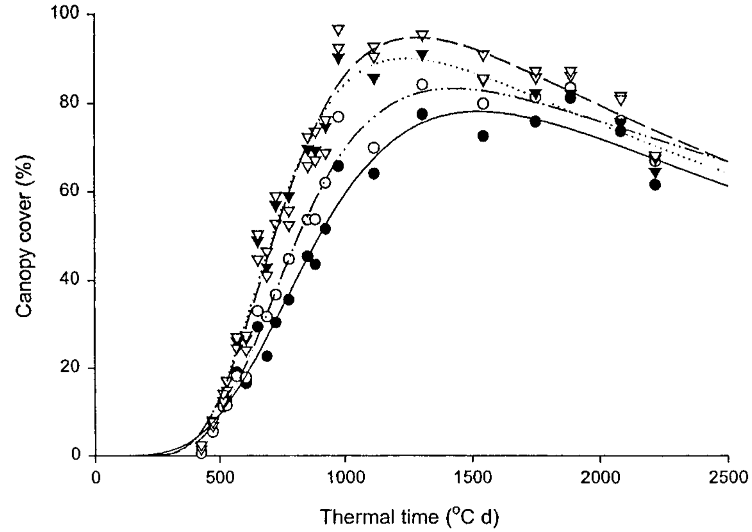


Fig. 7.21 Changes in light interception by the foliage of a sugar beet crop during summer and autumn, as influenced by the application of nitrogen fertilizer: unfertilized, o—··—o, 40 kg N/ha, ▼····▼, 80 kg N/ha, ▽—▽, 120 and 160 kg N/ha, ●—● (after Malnou *et al.*, 2003).

light is shown in Fig. 7.21. The measurements were made at Broom's Barn, where the soil contains little organic matter and where the recommended fertilizer addition would be 120 kg N/ha. On plots where smaller amounts were added, leaves grew slowly during June and July and throughout the summer much of the sun's energy fell on bare soil.

Canopy growth was rapid where 120 kg N/ha was applied, and a complete canopy, which intercepted more than 85% of the sunlight, was produced by the end of July. Although fertilizer in excess of 120 kg N/ha resulted in more prolific leaf growth, it led to only trivial increases in radiation interception and failed to increase yield (Table 7.2) despite making the leaves appear darker green.

Table 7.2 The outcome, in terms of total dry matter and sugar yields, of the various patterns of light interception (Fig. 7.21) created by different nitrogen fertilizer amounts at Broom's Barn in 2000.

	Fertilizer nitrogen (kg/ha)					
Yield t/ha	0	40	80	120	160	SED
Dry matter	22.5	24.1	26.7	27.9	27.1	1.03
Sugar	12.8	13.3	14.7	15.5	14.6	0.38

The colour range in response to nitrogen is from pale, yellowy-green deficient leaves to dark green leaves that are abundantly supplied, a change that is indicative of increased chlorophyll concentration. Are the leaves of nitrogen-deficient crops with small chlorophyll concentrations capable of efficiently using the sunlight which they intercept? Experiments at Broom's Barn between 2000 and 2002 show that, while nitrogen fertilizer had large effects on the amount of light intercepted and on the colour of the leaves, it did not change the conversion coefficient (Malnou, 2003). This is shown by reference to the 2000 data in Fig. 7.22; the data in Figs 7.21 and 7.22 come from adjacent experiments in the same field. The beet plots received 0, 80 or 160 kg N/ha at sowing or soon after seedling emergence: thereafter the plots were split to receive either 0 or 60 kg N/ha of additional fertilizer in early July. In general, the late nitrogen application increased leaf chlorophyll concentration and, in some cases, the amount of light energy intercepted. However, the extra nitrogen never increased the efficiency of the foliage at converting light to dry matter, which was 1.8 g/MJ in all cases. Overall, the results indicate that the principal role of nitrogen fertilizer is to allow the beet canopy to grow as rapidly as possible: thereafter the crop seems to be able to acquire sufficient nitrogen to maintain its

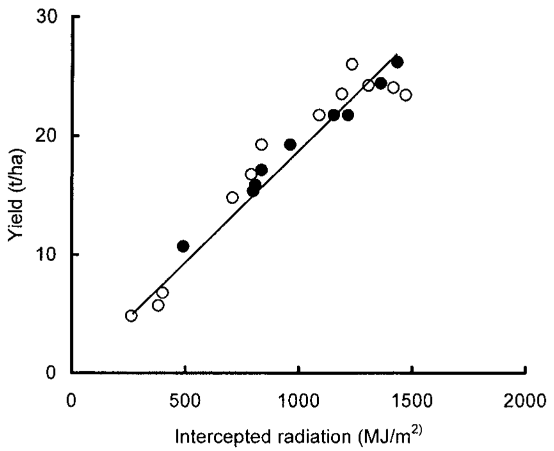


Fig. 7.22 Relationship between total dry matter yield throughout the season and the amounts of solar radiation intercepted by crops with (○) and without (●) a late application of nitrogen fertilizer (60 kg N/ha).

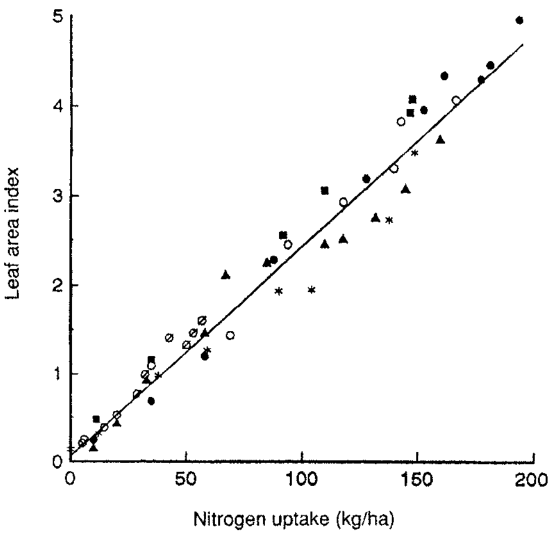


Fig. 7.23 The relationship between the leaf area index (*L*) of expanding canopies and the amounts of nitrogen which crops at Broom's Barn contained each year from 1978 to 1982 (*, ○ ,▲, ●, ■ respectively). One of the crops in 1979 (ø) was not given nitrogen fertilizer.

growth rate at the potential set by solar radiation receipts.

In many crop species, particularly those whose yield is mainly foliage or protein-rich seeds, there are direct relationships between the yield and the amount of nitrogen that crop contains: then relationships sometimes form the basis of the nitrogen fertilizers recommendation policy. Figure 7.23 shows that in beet over the period when the canopy is expanding, *L* is directly related to the amount of nitrogen in the crop. There is, however, no direct relationship between uptake and sugar yield and there are several reasons why the link is tenuous. First, there is a lack of direct proportionality between leaf area and light interception; secondly, nitrogen has an adverse effect on harvest index. While a certain amount of nitrogen uptake is required to produce and maintain a full canopy, the light that the canopy intercepts and the amount of sugar that it produces is then determined by the incident sunlight, the level of disease and the degree of drought. Over periods when the crop is growing at full potential the nitrogen concentration of the storage root can be as little as 5 kg/t dry matter. Thus, a healthy crop growing in a long, bright autumn might produce 3 t/ha more root dry matter than if the autumn is short and dull. This might represent 20% of the yield for less than 10% increase in nitrogen uptake.

A properly fertilized crop can reduce the available nitrogen concentration of the top metre of soil to only 20–30 kg/ha by late summer. In these circumstances much of the nitrogen to sustain the growth of storage roots and new leaves during autumn has to come from nitrogen mobilized from old leaves. Armstrong *et al.* (1986) showed that nitrogen started to be lost from leaves as soon as, or just before, they reached full size and Burcky and Biscoe (1983) calculated that from August onwards as much as 75 kg N/ha could be mobilized from old leaves to support the growth of new leaves and the storage root.

In circumstances where the nitrogen supply during late summer and autumn is abundant, i.e. on organic soils and where large dressings of organic manures have been applied, the crop continues to take up nitrogen. This results in less nitrogen being mobilized from old leaves, old leaves being retained longer, and the production of large, late-formed leaves. These effects combine to produce crops which, at harvest, have heavy tops. However, these tops are of little benefit for intercepting extra light or producing extra dry matter so at harvest the plants also have a poor harvest index and small roots. Thus, there are large penalties when the crop has access to too much nitrogen during late summer and autumn. However, these effects are not usually created by over-generous use of inorganic fertilizer but by growing crops in conditions where large amounts of nitrogen are continuously being mineralized either from soils inherently rich in organic matter or from recently added manures. These are also the conditions that lead to large concentrations of nitrogenous impurities in the roots. By the time the canopy of a well-grown beet crop closes in July, the crop contains 150–170 kg/ha of nitrogen. Thereafter, the content needs to rise only slowly, at less than 1 kg/ha/day, until at harvest the nitrogen uptake is approximately 200 kg/ha. When uptake exceeds this value the concentration of nitrogenous impurities, particularly the α-amino acids, rises rapidly to the point where they impair the crystallization of sugar in the factory process (Armstrong & Milford, 1985).

Like nitrogen, the presence of sodium fertilizer in the seedbed can cause the osmotic potential of the soil solution to become increasingly negative, thereby inhibiting water uptake by seeds, slowing germination and emergence and resulting in fewer, smaller plants at the early stages of growth. However, if the fertilizer is applied sufficiently early to avoid affecting seedbed water potential, then it can accelerate expansion of the leaf surface during the critical early period (Farley & Draycott, 1974; Durrant *et al.*, 1978). In 1986 at Broom's Barn, an application of sodium increased light interception by the beet canopy from 75 to 95% in early July and at the same time it increased crop dry weight from 276 to 339 g/m^2 (24%). Differences persisted so that, at the end of the season, biomass yields were 19.7 and 20.4 t/ha and sugar yields 10.9 and 11.5 t/ha, respectively. These responses were achieved with standard basal amounts of potash and in a season when the crop experienced little water stress. Durrant *et al.* (1978) detected that responses to sodium were greater in dry years because the added sodium increased leaf relative water content so that leaves remained turgid for longer. This extended the period when they intercepted more light and used it with maintained efficiency. These responses were obtained on mineral soils that naturally contain little sodium; similar responses would not be obtained on many alluvial soils that are rich in sodium (see Chapter 9).

Harvest date

Unlike wheat and barley, the sugar beet crop does not have to die before the economically important part of the plant can be harvested; therefore the sugar industry has scope to manipulate harvest date. In this section we describe the factors that limit the range of harvest dates, and examine how yield might change throughout this period.

At what stage is the quality of the root acceptable for processing? There has been a school of thought (Ulrich, 1955) that sugar beet undergoes a specific ripening phase known as 'sugaring-up'. Our observations are that this is not so; sugar as a proportion of the root's dry matter reaches a maximum by early August (Milford, 1973), and thereafter sugar and non-sugar dry matter are accumulated in parallel (Fig. 7.1). However, it is usual for sugar concentration on a fresh-weight basis to increase progressively through summer and early autumn, but its maximum value and the time when it is achieved can fluctuate widely from season to season and place to place, mainly in response to changes in soil moisture deficit and rainfall. In practice this means that sugar beet can be harvested any time after mid-August by which time the sugar concentration on a fresh-weight basis reaches about 14% in many seasons; this is the lowest concentration at which a processor would *plan* to operate a factory. The crop actually keeps growing as long as the environment allows although, of course, the environment becomes progressively less favourable for growth. For example, in beet growing areas of the UK the monthly radiation receipts diminish in the sequence approximately 5:4:3:2:1:0.5 from July until December and therefore the potential for photosynthesis declines rapidly during autumn. During the same period, mean air temperatures decline from 16.3 to 4.6°C.

Glauert (1983) made gas exchange measurements during autumn and until December; he demonstrated that the light response curve of the canopy remained constant until September; thereafter the ageing tops became less responsive to all but dull light. Nevertheless, the crop continued to photosynthesise at temperatures as low as 1°C (Fig. 7.5). However, when the days were very short and dull, as often occurs in November, and the nights were long and warm, there were certain 24-hour periods during which the carbohydrate respired overnight exceeded the amount fixed during the day. Therefore there are a few winter days when crop weight decreases and clearly there are many days in late November and December when yield does not increase, even if the canopy is healthy and capable of photosynthesis.

In many years sharp frosts occur in the UK in November and December, which kill the leaves at the top of the canopy, although the heart leaves usually survive. This effectively curtails photosynthesis and growth and the recommendation is that beet should be lifted by mid-December. This is to guard against the increasing risk that severe and prolonged frosts will freeze the roots in the ground and make them unsuitable for processing. In climates that are more continental, the critical date is considerably earlier (for example, it is in October in the Red River Valley of the USA).

In most UK experiments in which the harvest period was subdivided there was no detectable gain in sugar yield after mid-November. Over the period 1963–1967, Hull and Webb (1970) measured average yield increases of 30 kg/ha/day during October and 10 kg/ha/day in November. Scott *et al.* (1973) recorded similar gains in 1971 and observed that there was broad agreement between the increments in yield and the amount of radiation intercepted during the inter-harvest period. During autumn there were also changes in the processing quality of the roots: generally the sugar concentration on a fresh-weight basis tended to increase throughout October then to stabilize, but this was by no means universal. The norm was for the juice purity to increase until severe frosts occurred.

Crops with a sparse stand or diseased foliage either intercept little radiation or use inefficiently that which is intercepted, and the gain in sugar yield through autumn is small. Jaggard *et al.* (1983) compared the yield gains of crops that were bolter-free and healthy with those from crops with gappy stands and more than 5% of bolters. Over the harvest period the sugar yield of the 'good' crops increased significantly more (+ 0.43 t/ha) than the yield of the 'poor' crops. This contrasts strongly with the popular belief that poor crops compensate for early disadvantages if they are left to grow. In practice, yields of the farm as a whole are maximized if gappy or disease-infected crops are harvested first, and well-established, healthy crops with effective canopies are lifted last.

A question commonly asked is whether, for crops planned for late harvest, it is desirable to supply additional nitrogen and to irrigate late. The answer is that more nitrogen is not required (Draycott *et al.*, 1973). The essential function of nitrogenous fertilizer is to provide a complete canopy in early summer, and only a small amount of nitrate is needed to maintain beet growth throughout autumn. This can usually be obtained from mineralization of reserves of organic nitrogen in the soil and by retranslocation from old leaves (Armstrong *et al.*, 1986). The need for irrigation depends, as always, on the rainfall and on the evaporative demand. In arid regions where it is dry and bright throughout the harvest period it is often advisable to irrigate until a fixed period (6 or 7 weeks) before harvest (Howell *et al.*, 1987; Davidoff & Hanks, 1989). However, in north-west Europe the autumn is usually moist and the evaporative demand small and diminishing, so crops scheduled for late harvest do not need more and later irrigation. The extent of yield increase is determined mostly by the declining radiation intensity and shortening days. In practice, the capacity of crops to realize the limited potential offered by the aerial environment is rarely, if ever, restricted at this late stage by inherent shortage of nitrogen or water; if extra nitrogen were supplied the effect would be solely to produce more tops, probably at the expense of sugar yield and root purity.

There is a desire on the part of the processor to extend the period over which the factories operate in order to spread overhead costs. In practice, the earliest harvesting date is often determined by the dryness and hence the strength of the soil, the direct result of the water-extracting ability of the crop. When the soil is baked hard, losses due to root breakage and wear and tear on machinery become excessive and farmers are either unwilling or unable to harvest beet. In some exceptional circumstances it has been necessary to irrigate to commence harvest, but this is very expensive. Thus, irrespective of the processing quality of the beet, it would be foolhardy to plan to operate factories before about mid-September in north-west Europe because too often the soil is too dry for efficient lifting.

ANALYSING THE EFFECTS OF WEEDS AND VIRUS YELLOWS ON GROWTH AND YIELD

If the target for agronomy is to maximize radiation interception, how do pests, weeds and diseases create their marked effects on yield? Chapter 13 deals with the way in which pests restrict yield, first by killing seedlings and causing gappiness, and secondly by non-lethal defoliation. Here we examine the effects of weeds, which decrease radiation interception, and foliar diseases (as illustrated by virus yellows) that affect the coefficient of conversion of light to dry matter.

Weeds

Weeds compete with crops for light, water and nutrients. Generally, those weeds that grow above the crop canopy and shade the crop plants are most detrimental to yield (see Chapter 14). It should be possible to analyse the effects of such species on their ability to intercept radiation that would otherwise fall on the foliage of the crop, but few such studies have been made with sugar beet. There have been few attempts to measure how beet and weeds compete, and for which resource. Scott and Wilcockson (1976) examined competition between beet and a selection of common weed species that either tended to grow above the beet canopy (*Chenopodium album*) or which ramified within the canopy (*Polygonum aviculare* and *Tripleurospermum inodorum*). They found a close relationship: for every 100 g of above-ground weed dry weight the crop dry weight declined by about 250 g (Fig. 7.24). As weed species that grew above the crop canopy became heavier, they shaded the crop, reduced photosynthesis and shifted the distribution of beet dry matter in favour of the foliage and away from sugar production. The shorter weeds simply smothered the beet plants if allowed to grow undisturbed from the time when the crop was sown. Later emerging weeds of these types ramified within the canopy and never had a serious impact on yield. In crops sown in March, Scott *et al.* (1979) showed that weeds could be present until the beet had four to six leaves without depressing yield and it was unnecessary, as far as crop growth was concerned, to continue to control weeds beyond the time when the crop had L of 0.5. The few weeds that established thereafter had to be controlled only if they created difficulties at harvest – *Polygonum aviculare* could fall into this category. These results indicate that the serious crop/weed competition is for light. This is demonstrated by the good agreement obtained by Kropff and Spitters (1992) and Kropff *et al.* (1992) between observed yields of beet and *Chenopodium album* and yields simulated by a mathematical model that distributed incoming light between the two species.

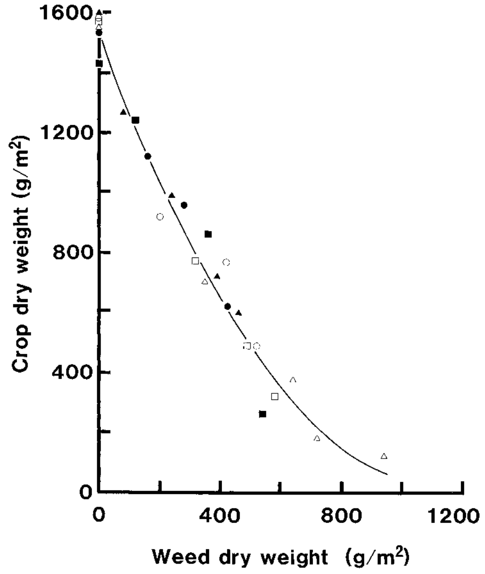


Fig. 7.24 Relationship between crop dry weight and the dry weight of weeds of three species: *T. inodorum*, △▲; *P. aviculare*, ○ ●; *C. album*, □■. Weeds were either sown at the same time as the crop (open symbols) or one week after the crop emerged (closed symbols) (after Scott & Wilcockson, 1976).

Thus, weeds affect growth of beet in two basic ways. First, tall weeds can shade beet plants, reducing photosynthesis and adversely affecting harvest index. Secondly, short weeds become very competitive if allowed to grow undisturbed when the crop plants are still small, and they affect dry matter distribution so that little is apportioned to canopy growth; the beet are then unable to intercept much of the available light. These contrasting weed types both affect yield by reducing the amount of light intercepted by the crop canopy.

Virus yellows

In the scientific literature there are very few detailed analyses of the effects of foliar diseases on the physiology of crop growth. Of the experiments that have been published, almost all are concerned with virus yellows. Hall and Loomis (1972) showed that infection of sugar beet leaves with beet yellowing viruses diminishes net photosynthesis per unit leaf area. Scott and Jaggard (1985) demonstrated that infection with a mixture of *Beet yellows virus* (BYV) and *Beet mild yellowing virus* (BMYV) restricted both the amount of radiation intercepted and the efficiency with which intercepted radiation was converted to plant material. The experiment was done in 1983 in the absence of irrigation; both infected and non-infected crops suffered water stress although the diseased crop wilted much less.

De Koeijer and Van der Werf (1995) measured the effects of yellowing viruses on light interception and light use efficiency in beet crops, using a scoring technique to differentiate between the light intercepted by green, apparently healthy foliage and that intercepted by yellow leaf. Infection with BMYV alone had no effect on the proportion of light energy intercepted. In an experiment sown very late, infection with BYV (and probably BMYV too) caused only 5% reduction in light interception in mid and late summer. However, about 20% of the sunlight was intercepted by yellow foliage in the BMYV plots and 30% in the BYV plots. They then calculated the light-use efficiency, ε, on the basis that only the green foliage was productive and showed that ε for healthy plants was the same as for those with BMYV. The green leaf in plots with BYV infection and probably a natural infection of BMYV as well, appeared to be less efficient (Fig. 7.25). The strong indication of their work is that BMYV decreases yield because it causes leaves to turn yellow and these leaves produce little dry matter with the light that they intercept, while the green areas of the leaves are unaffected. Infection with BYV causes a small reduction in the amount of light intercepted, the yellow leaf is non-productive and the efficiency of the green portion is impaired as well.

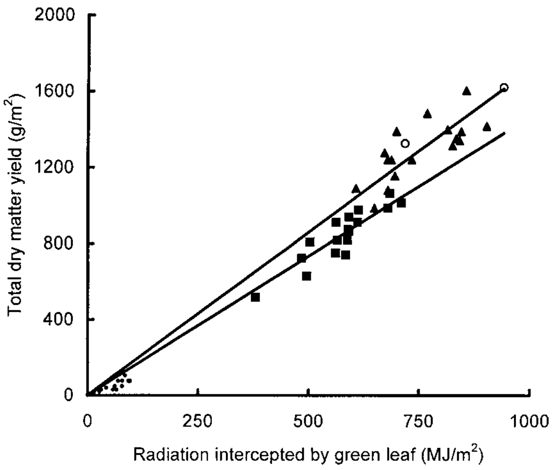


Fig. 7.25 Relationships between total dry matter yield and cumulative solar radiation intercepted by green leaves in crops infected with beet mild yellowing virus (BMYV) (▲) or beet yellows virus (BYV) (■). Radiation conversion coefficients were 1.72 and 1.43 g/MJ for BMYV and BYV respectively. Data from the uninfected controls (○) were not included in the regressions, but are close to the BMYV line (after De Koeijer & Van der Werf, 1995).

Clover *et al.* (1999a,b) studied drought-affected and irrigated plants that had been either inoculated with BYV or were kept disease free. They did this to distinguish effects of disease from those of drought (in practice the two tend to occur in the same season because warm, dry years also favour the activity of aphids). There was no interaction between the effects of drought and disease, perhaps because the large impacts of drought occurred later in the year than the large impacts of the disease. Like De Koeijer and Van der Werf (1995) they found that the disease hardly affected ground cover and light interception, but that much of the interception was by inefficient yellow leaves with poor rates of net photosynthesis. However, many of these yellow leaves were shed by the plant by late summer and they were replaced by new leaves that remained green. The green leaf, although infected, had net photosynthesis rates close to, but less than those of healthy plants. This was demonstrated again by Jaggard *et al.* (2002) who showed that the effects of nitrogen fertilizer on yield were almost exclusively due to changes in foliage cover and light interception, but that effects of virus yellows were due to changes in light use efficiency. The virus-infected leaves were less efficient, even when the yellow symptoms of infection were masked by applying large doses of fertilizer that kept the foliage green.

MATHEMATICAL MODELS AND THEIR USES

Some of the physiological reactions of the beet crop to environmental conditions have been described in previous sections of this chapter. In order to understand how these reactions interact to determine the rate of growth and eventual yield of the crop it is appropriate to consider mathematical models that simulate growth. The models are equations, each describing a physiological reaction, which are interlinked to simulate the growth of the whole crop.

In 1965, Monteith and De Wit both published sets of equations to describe hour by hour the photosynthesis of canopies of field crops, including sugar beet. These models were extended by others (Patefield & Austin, 1971; Spitters *et al.,* 1989) to simulate how crops develop and grow throughout the season. Fick *et al.* (1975) used similar principles of gross photosynthesis to estimate the supply of dry material for growth of the beet crop, and then used a series of relationships to estimate respiration and the distribution of dry matter between the main organs of the plant. These models depended on parameters that describe the architecture and size of the foliage canopy, but these values were often difficult to estimate, particularly because they changed with time, certainly over the season and sometimes during the day.

A huge simplification to crop growth modelling was stimulated by Monteith's (1977) paper, in which he related growth to the fraction of solar energy intercepted by the crop canopy, so that

$$\mathrm{d}w/\mathrm{d}t = \varepsilon f S \qquad (7.1)$$

where ε is the coefficient of conversion of solar energy to biomass and f is the fraction of incident solar radiation, S, which is intercepted by the foliage. The productivity (W) at the end of the season is given by integrating (7.1) over the period from sowing until harvest so that

$$W = \varepsilon \int f S \,\mathrm{d}t \qquad (7.2)$$

This is now used as the basis for many crop growth models, although most derive the value for f from measurement of leaf area index (L). Making measurements of L in sugar beet crops is both tedious and expensive. At Broom's Barn f was measured instead, and a yield forecasting system built (Steven *et al.*, 1983) and a beet crop growth simulation model was based on these measures. The remainder of this section of the chapter is a description of this model (which has been reported in detail by Jaggard & Werker, 1999; Qi *et al.*, 2005) in an attempt to illustrate the interactions of crop development and growth processes. The model is depicted diagrammatically in Fig. 7.26.

In the model, germination of seeds, emergence of 75 000 seedlings through the surface of each hectare and development of the foliage canopy is driven by temperature above a base temperature of 3°C (Milford & Riley, 1980). The canopy grows from cotyledons, each 2 mm^2, to a maximum size, where it intercepts about 90% of the available light, and then tends to decrease in size as the large leaves die and are replaced by new leaves, each of which has a progressively smaller maximum size. This foliage cover decrease is marked in crops growing in soils where water stress is experienced, and is hardly noticeable on the sites where water remains plentiful. Figure 7.27 illustrates foliage canopy growth and decay in contrasting soil types. At the same time, development of the fibrous root system down through the soil profile is also driven by the temperature above a base of 3°C (Fig. 7.28).

The equations describing these growth processes are solved for every day in the growing season, and the simulated foliage cover is used to intercept solar radiation on a daily basis. Solar radiation is converted to dry matter using the equation (7.1). However, the conversion coefficient, ε, is conditioned to allow for three factors not included in Monteith's (1977) paper. The first is a variable that

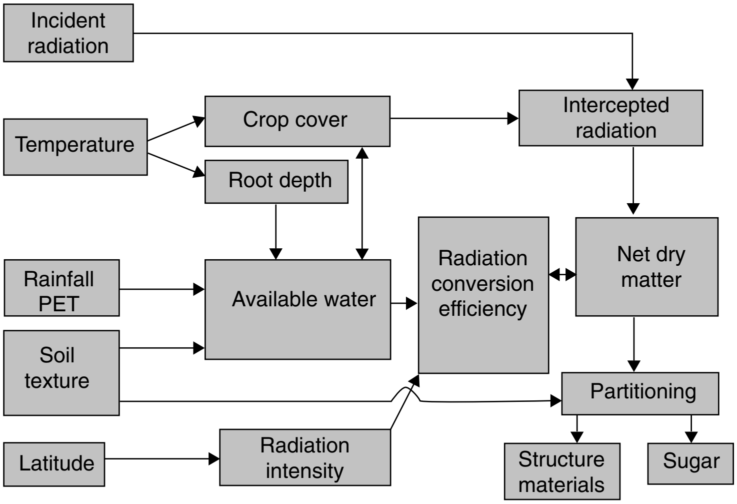


Fig. 7.26 Schematic representation of a crop growth model (Qi *et al.*, 2005).

describes the decreasing photosynthetic efficiency of the whole canopy as it ages. We do not have a direct measure of canopy age; instead we use plant weight and assume that the heavier the plant, the older its canopy. The second factor is an estimate of the fraction of solar radiation that is received as bright sunshine (Richter *et al.*, 2001). This can be simply used in the model as the fraction of diffuse radiation, but these data are rarely available. Instead, knowing the latitude of the site and the day of the year, it is possible to calculate the solar radiation that would be received in the absence of cloud and dust in the atmosphere. Knowing this value and the measured value of solar radiation we can calculate a 'brightness' index. The brighter the conditions, the smaller the radiation conversion coefficient. This is clearly shown by the shape of the photosynthesis/light response curve (Fig. 7.3). The effect of brightness on this coefficient is shown in Fig. 7.29, using data collected by Glauert (1983). He found that young foliage on dull days produced dry matter at the rate of 2.2 g/MJ, whereas old foliage on bright days in autumn could only produce about 1.4 g/MJ.

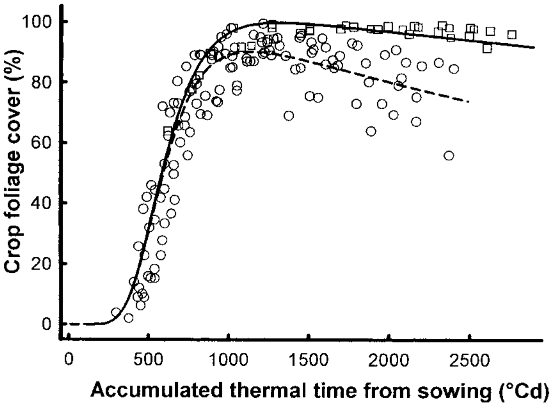


Fig. 7.27 Contrasting patterns of development of foliage cover and thermal time in late summer and autumn between crops growing on soils with available water capacity of 14% (○) or 20% (□). The lines represent the model's development patterns.

The third and most important factor controlling ε is water stress. Stress is defined as the actual evapotranspiration of the crop divided by the potential evapotranspiration. Potential evapotranspiration is calculated from the Penman-Monteith equation (Allen *et al.*, 1998), modified by a crop specific coefficient to allow for the roughness of the beet crop surface (Brown *et al.*, 1987). Actual evapotranspiration is calculated on the basis of soil water availability. Each day the model estimates how much water can be removed from the depth of the soil that contains roots. The amount to be removed today is either the potential evapotranspiration, or a lesser amount determined by the difference in water potential between the soil and the foliage. The minimum water potential of the foliage was set at -1500 kPa (Lawlor & Milford, 1975). The soil

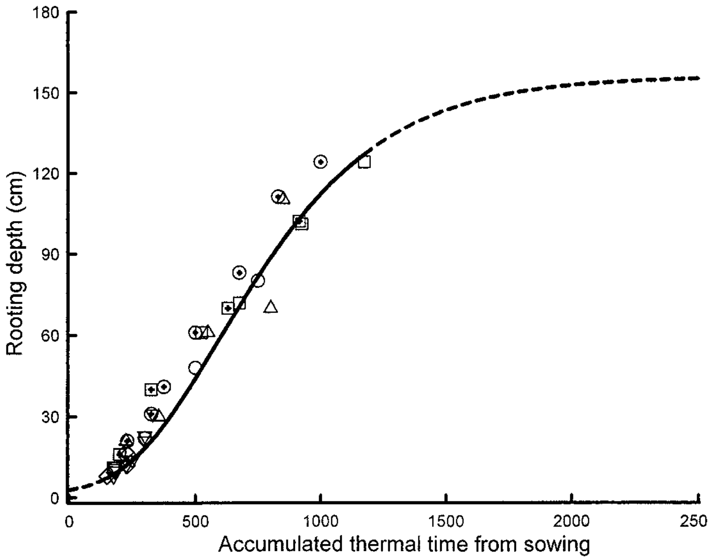


Fig. 7.28 The relationship between rooting depth and thermal time after sowing at Broom's Barn. The different symbols represent different years.

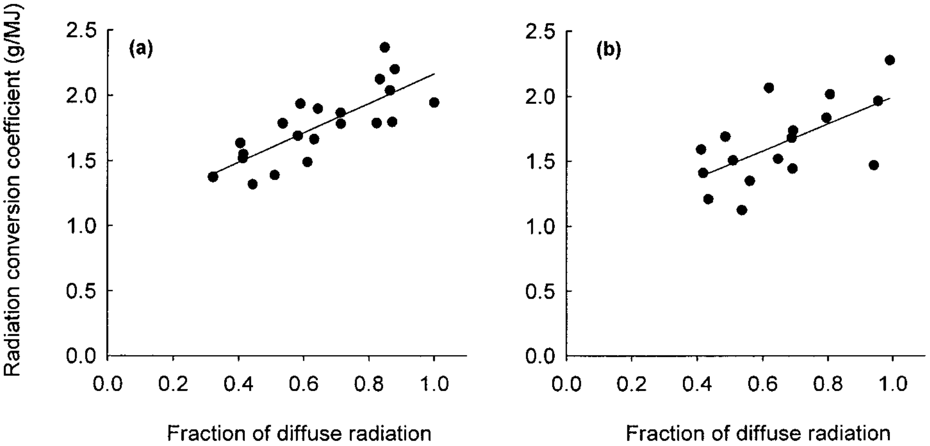


Fig. 7.29 Relationships between estimates of whole day radiation conversion coefficient and the fraction of the day's global solar radiation that was diffuse. The radiation conversion coefficients were estimated by Glauert (1983) from gas exchange measurements made in beet crop growing at Broom's Barn. The relationships are for days during (a) June to August and (b) September to October when the foliage was older.

water potential varies and is calculated from the soil water potential at field capacity and the soil water content relative to field capacity. This balance is defined relative to the water release characteristics of the soil, described by a parameter, b (Gregson *et al.*, 1987). This parameter varies with soil texture type, and this information has to be put into the model before it can run. Various constants in the soil water balance of the model could not be experimentally determined and had to be defined by fitting the model to data. Water stress during any day affects growth of the modelled crop by reducing the coefficient of converting light to dry matter. If water availability restricts water consumption on any day by, for example, 50%, then ε is reduced to 50% too.

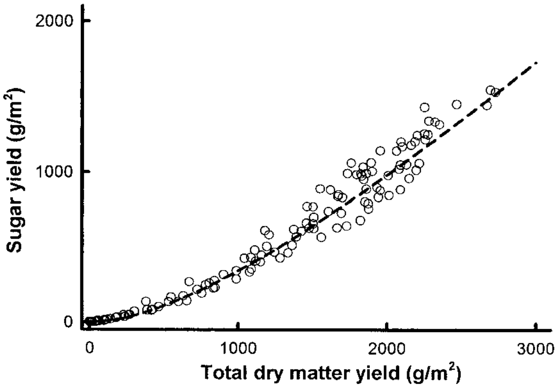


Fig. 7.30 Relationship between sugar and total dry matter yield throughout the development of beet crops grown at Broom's Barn.

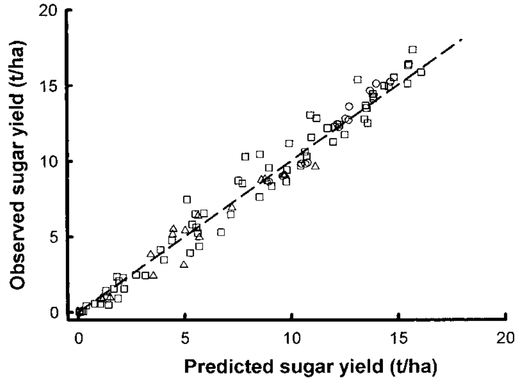


Fig. 7.31 A relationship between sugar yields observed by sampling a range of crops during the growing season and sugar yields simulated by the Broom's Barn crop growth model using daily weather data and a soil texture description. The crops were grown in the period between 2000 and 2004 in 13 experiments in the UK (○), in 10 experiments in Germany (□) and in 6 experiments in USA (△). The 1.1 line is shown for comparison.

These components of the model largely determine how much dry matter is produced. The distribution of the dry matter is determined by a partition coefficient, κ, which allocates material to plant structure or to stored sugar. This coefficient is not a constant, but changes as the plants increase in weight (Fig. 7.30). It also changes in relation to the water-holding capacity of the soil in which the crop is being grown. Plants that have a history of water stress allocate less of their dry matter to foliage growth (only producing small leaves so that *f* declines in late summer) and more to stored sugar. Crops grown on very water-retentive soils are less likely to suffer these long-term stresses and so have a smaller κ value (Werker *et al.*, 1999). The nitrogen supply to crop in late summer and throughout the autumn also has large effects on dry matter allocation, but as yet the model makes no allowance for this.

The fact that models built on these principles do describe realistically how beet crops grow, in part at least, is demonstrated by comparing their predictions with independent observations. This is illustrated (Fig. 7.31) for crops grown in the UK, Germany and in the Midwest of America. The model, supplied with data for sowing date, harvest date and local weather, accounts for 96% of the variance in sugar yield observed in crops that were treated to ensure that they did not suffer from weed competition or from diseases.

Models like this, allied to databases of weather, soil type, crop area, sowing date and use of irrigation are now being used to produce local yield forecasts in England. Similar forecasts, although made on a less detailed scale, are made with the SUMO model in the Netherlands, (Van Swaaij *et al.*, 2003). Research has been done to train the models with estimates of foliage cover made either from aircraft (Jaggard & Clark, 1990) or from satellites (Guérif & Duke, 2000). They have been used to forecast the possible impacts of climate change in sugar production throughout Europe (Jones *et al.*, 2003).

These models predict yield as if it were measured in an experiment where: the crop area is accurately established; everything is done to minimize harvest and storage losses; pests, diseases and weeds have little impact on production; and crops that fail are not harvested nor accounted for. The commercial, whole-field situation is very different (Jaggard *et al.*, 1984) and allowance has to be made for these discrepancies so that the forecasts are realistic. In the UK it is common to find that only about 70% of the predicted yield is actually delivered to the factory, and Scott and Jaggard (1992) attempted to explain this 'loss' by allocating it to a range of possible causes. Harvesting losses, the inappropriate reporting of cropped area and harvesting earlier than assumed for the model all made large contributions. Van Swaaij *et al.* (2003) make a smaller correction because about 80% of their predicted yield is delivered to the factories in the Netherlands. Possible reasons for the closer agreement are that (a) the post harvest losses may be smaller there, where the processing campaign finishes soon after Christmas and (b) there may be closer agreement between the reported and actual area because fields in the Netherlands tend to be more regular and rectangular than in England.

Many beet farmers around the world, and certainly those within the European Union have a contract with the sugar manufacturer to produce a specified tonnage of beet. The price for this beet is usually stable and is sufficient for production to be profitable. In many cases any beet produced in excess of the contract has a very low value. Therefore growers need advisory systems to help them to make good decisions about the area of beet to sow and about the use of expensive, yield enhancing inputs in the latter part of the growing season. Crop growth models have the potential to be developed to provide individual growers with these decision support tools, but as yet none are widely used in this way.

REFERENCES

Allen, R.G., Pereira, L.S., Raes, D. & Smith, M. (1998) *Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements.* FAO Irrigation and Drainage Paper No. 56, Food and Agriculture Organisation, Rome.

Armstrong, M. & Milford, G. (1985) The nitrogen nutrition of sugar beet: the background to the requirement for sugar yield and amino-N accumulation. *British Sugar Beet Review* **53** (4), 42–44.

Armstrong, M.J., Milford, G.F.J., Pocock, T.O, Last, P.J. & Day, W. (1986) The dynamics of nitrogen uptake and its re-mobilization during the growth of sugar beet. *Journal of Agricultural Science, Cambridge* **107**, 145–154.

Bleasdale, J.K.A. & Nelder, J.A. (1960) Plant population and crop yield. *Nature* **168**, 324.

Brown, K.F. & Biscoe, P.V. (1985) Fibrous root growth and water use of sugar beet. *Journal of Agricultural Science, Cambridge* **105**, 679–691.

Brown, K.F. & Dunham, R.J. (1986) The fibrous root system: the forgotten roots of the sugar beet crop. *British Sugar Beet Review* **54** (3), 22–24.

Brown, K.F., Messem, A.B., Dunham, R.J. & Biscoe, P.V. (1987) Effect of drought on growth and water use of sugar beet. *Journal of Agricultural Science, Cambridge* **109**, 421–435.

Burcky, K. & Biscoe, P.V. (1983) Stickstoff im rubenblatt und N-translokation aus alternden bliittern. *IIRB Symposium 'Nitrogen and Sugar Beet'.* pp. 63–75.

Chroboczek, E. (1934) A study of some ecological factors influencing seed-stalk development in beets (*Beta vulgaris* L.). *Cornell University Agricultural Experimental Station, Memoir* 154.

Clark, E.A. & Loomis, R.S. (1978) Dynamics of leaf growth and development in sugar beet. *Journal of American Society of Sugar Beet Technologists* **20**, 91–112.

Clover, G.R.G., Smith, H.G., Azam-Ali, S.N. & Jaggard, K.W. (1999a) The effects of drought on sugar beet growth in isolation and in combination with beet yellows virus infection. *Journal of Agricultural Science, Cambridge* **133**, 251–261.

Clover, G.R.G., Azam-Ali, S.N., Jaggard, K.W. & Smith, H.G. (1999b) The effects of beet yellows virus on the growth and physiology of sugar beet (*Beta vulgaris*). *Plant Pathology* **48**, 129–138.

Davidoff, B. & Hanks, R.J. (1989) Sugar beet production as influenced by limited irrigation. *Irrigation Science* **10**, 1–17.

De Koeijer, K.J. & Van der Werf, W. (1995) Effect of beet yellowing viruses on light interception and light use efficiency of the sugar beet crop. *Crop Protection* **14**, 291–297.

De Wit, C.T. (1965) *Photosynthesis of Leaf Canopies.* Agricultural Research Report No. 663, Pudoc, Wageningen.

Draycott, A.P., Webb, D.J. & Wright, E.M. (1973) The effect of time of sowing and harvesting on growth, yield and nitrogen fertilizer requirement of sugar beet. *Journal of Agricultural Science, Cambridge* **81**, 267–275.

Durrant, M.J., Draycott, A.P. & Milford, G.F.J. (1978) Effect of sodium fertilizer on water status and yield of sugar beet. *Annals of Applied Biology* **88**, 321–328.

Durrant, M.J., Payne, P.A. & McLaren, J.S. (1983) The use of water and some inorganic salt solutions to advance sugar beet seed. II: Experiments under controlled and field conditions. *Annals of Applied Biology* **103**, 517–526.

Durrant, M.J., Mash, S.J. & Jaggard, K.W. (1993) Effects of seed advancement and sowing date on establishment, bolting and yield of sugar beet. *Journal of Agricultural Science, Cambridge* **121**, 333–341.

Ehnrot, B. (1965) Field properties of sugar beet seed and considerations on the mechanisation of the thinning. *Socker* **20**, 19–38.

Farazdaghi, H. (1968) Some aspects of the interaction between irrigation and plant density in sugar beets. PhD thesis, University of Reading.

Farley, R.F. & Draycott, A.P. (1974) Growth and yield of sugar beet in relation to potassium and sodium supply. *Journal of* *the Science of Food and Agriculture* **26**, 385–392.

Fauchere, J., Richard-Molard, M., Souverain, F., Prats, S., Perarnaud, V. & Decquiedt, B. (2003) Cartographie des risques de montées en France en relation avec les température de printemps et d'été-Consequences sur l'experimentation et le conseil. *Proceedings of the 1st Joint IIRB-ASSBT Congress.* San Antonio, USA, pp. 189–205.

Fick, G., Loomis, R.S. & Williams, W.A. (1975) Sugar beet. In: Evans, L.T. (ed.) *Crop Physiology – Some Case Histories.* Cambridge University Press, UK, pp. 259–298.

Ghariani, S.A. (1981) Impact of variable irrigation water supply on yield determining parameters and seasonal water-use efficiency of sugar beets. PhD thesis, University of California, Davis.

Glauert, W. (1983) Carbon exchange of a sugar beet crop through a season. PhD thesis, University of Nottingham.

Goodman, P.J. (1966) Effect of varying plant populations on growth and yield of sugar beet. *Agricultural Progress* **41**, 82–100.

Green, C.F., Vaidyanatham, L.V. & Ivins, J.D. (1986) Growth of sugar-beet crops including the influence of synthetic plant growth regulators. *Journal of Agricultural Science, Cambridge* **107**, 285–297.

Gregson, K., Hector, D.J. & McGowan, M. (1987) A one-parameter model for the soil water characteristic. *Journal of Soil Science* **38**, 483–486.

Guérif, M. & Duke, C. (2000) Adjustment procedures of a crop model to the site specific characteristics of soil and crop using remote sensing data assimilation. *Agriculture, Ecosystems and Environment* **81**, 57–69.

Gummerson, R.J. (1986) The effect of constant temperatures and osmotic potentials on the germination of sugar beet. *Journal of Experimental Botany* **37**, 729–741.

Guyot, G. (1990) Optical properties of vegetation canopies. In: Steven, M.D. & Clark, J.A. (eds) *Applications of Remote Sensing in Agriculture.* Butterworths, London, pp. 19–43.

Hall, A.E. & Loomis, R.S. (1972) Photosynthesis and respiration by healthy and beet yellows virus-infected sugar beets (*Beta vulgaris* L.). *Crop Science* **12**, 566–572.

Hodanova, D. (1981) Photosynthetic capacity, irradiance and sequential senescence of sugar beet leaves. *Biologica Plantarum* **23**, 58–67.

Houba, V.J.G. (1973) Effect of nitrogen dressings on growth and development of sugar beet. *Agricultural Research Reports* 791, Pudoc, Wageningen.

Howell, T.A., Ziska, L.H., McCormick, R.L., Burtch, L.M. & Fischer, B.B. (1987) Response of sugar beets to irrigation frequency and cut off on a clay loam soil. *Irrigation Science* **8**, 1–11.

Hull, R. & Webb, D.J. (1970) The effect of sowing date and harvesting date on the yield of sugar beet. *Journal of Agricultural Science, Cambridge* **75**, 223–229.

Jaggard, K.W. (1977) Effects of soil density on yield and fertilizer requirement of sugar beet. *Annals of Applied Biology* **86**, 301–312.

Jaggard, K.W. (1979) The effect of plant distribution on yield of sugar beet. PhD thesis, University of Nottingham.

Jaggard, K.W. & Clark, C.J.A. (1990) Remote sensing to predict the yield of sugar beet in England. In: Steven, M.D. & Clark, J.A. (eds) *Applications of Remote Sensing in Agriculture.* Butterworths, London, pp. 201–206.

Jaggard, K.W. & Werker, A.R. (1999) An evaluation of the potential benefits and costs of autumn-sown sugar beet in NW Europe. *Journal of Agricultural Science, Cambridge* **132**, 91–102.

Jaggard, K.W., Wickens, R., Webb, D.J. & Scott, R.K. (1983) Effects of sowing date on plant establishment and bolting and the influence of these factors on yields of sugar beet. *Journal of Agricultural Science, Cambridge* **101**, 147–161.

Jaggard, K.W., Clark, C.J.A. & Bell, S. (1984) An analysis of yield from fields of sugar beet. *British Sugar Beet Review* **52** (3), 67–69.

Jaggard, K.W., Dunham, R.J., Brown, K.F. & Werker, A.R. (1996) Season and soil-type effects on sugar-beet root development. *Proceedings of the 59th IIRB Congress.* Brussels, pp. 213–228.

Jaggard, K.W., Allison, M.F., Clark, C.J.A., Todd, A.D. & Smith, H.G. (2002) The effect of nitrogen supply and virus yellows infection on the growth, yield and processing quality of sugarbeet (*Beta vulgaris*). *Journal of Agricultural Science* **139**, 129–138.

Jones, P.D., Lister, D.H., Jaggard, K.W. & Pidgeon, J.D. (2003) Future climate impact on the productivity of sugar beet (*Beta vulgaris* L.) in Europe. *Climatic Change* **58**, 93–108.

Knott, C., Palmer, G. & Mundy, E.J. (1976) The effect of row width and plant population on the yield of sugar beet grown on silt and black fen soils. *Experimental Husbandry* **31**, 91–99.

Kropff, M.J. & Spitters, C.J.T. (1992) An eco-physiological model for interspecific competition, applied to the influence of *Chenopodium album* L. on sugar beet. I. Model description and parameterization. *Weed Research* **32**, 437–450.

Kropff, M.J., Spitters, C.J.T., Schnieders, B.J., Joenje, W. & De Groot, W. (1992) An eco-physiological model for interspecific competition applied to the influence of *Chenopodium album* L. on sugarbeet. II. Model evaluation. *Weed Research* **32**, 451–463.

Lawlor, D.W. & Milford, G.F.J. (1975) The control of water and carbon dioxide flux in water stressed sugar beet. *Journal of Experimental Botany* **26**, 657–665.

Lexander, K (1969) Increase in bolting as an effect of low temperature on unripe sugar beet seed. *Proceedings of the 32nd IIRB Congress.* Brussels, Report no. 2.4.

Malnou, C.S. (2003) A canopy approach to nitrogen recommendation for the sugar beet crop. PhD Thesis, University of Nottingham.

Malnou, C.S., Jaggard, K.W. & Sparkes, D.L. (2003) A canopy approach to nitrogen recommendations for the sugar beet crop. *Proceedings of the 1st Joint IIRB-ASSBT Congress.* San Antonio, USA, pp. 37–50.

Milford, G.F.J. (1973) The growth and development of the storage root of sugar beet. *Annals of Applied Biology* **75**, 427–438.

Milford, G.F.J. & Riley, J. (1980) The effects of temperature on leaf growth of sugar beet varieties. *Annals of Applied*

Biology **94**, 431–443.

Milford, G.F.J., Pocock, T.O., Jaggard, K.W., Biscoe, P.V., Armstrong, M.J., Last, P.J. & Goodman P.J. (1985a) An analysis of leaf growth in sugar beet. IV: The expansion of the leaf canopy in relation to temperature and nitrogen. *Annals of Applied Biology* **107**, 335–347.

Milford, G.F.J., Pocock, T.O. & Riley, J. (1985b) An analysis of leaf growth in sugar beet. I: Leaf appearance and expansion in relation to temperature under controlled conditions. *Annals of Applied Biology* **106**, 163–172.

Milford, G.F.J., Pocock, T.O. & Riley, J. (1985c) An analysis of leaf growth in sugar beet. II: Leaf appearance in field crops. *Annals of Applied Biology* **106**, 173–185.

Milford, G.F.J., Pocock, T.O., Riley, J. & Messem, A.B. (1985d) An analysis of leaf growth in sugar beet. III: Leaf expansion in field crops. *Annals of Applied Biology* **106**, 187–203.

Milford, G.F.J., Travis, K.Z., Pocock, T.O., Jaggard, K.W. & Day, W. (1988) Growth and dry-matter partitioning in sugar beet. *Journal of Agricultural Science, Cambridge* **110**, 301–308.

Monteith, J.L. (1965) Light distribution and photosynthesis in field crops. *Annals of Botany* NS **29**, 17–37.

Monteith, J.L. (1977) Climate and the efficiency of crop production in Britain. *Philosophical Transactions of the Royal Society*. London, **B281**, 277–294.

Monteith, J.L. (1986) How do crops manipulate water supply and demand? *Philosophical Transactions of the Royal Society*. London, **A316**, 245–259.

Norfolk Agricultural Station (1971) Sugar beet – the effect of row width, 1968–1970. *Report of Norfolk Agricultural Station*. 1970–1971, **63**, 22–44.

O'Dogherty, M.J. (1976) The mechanics of a sugar beet topping mechanism. PhD thesis, University of Reading.

Patefield, W.M. & Austin, R.B. (1971) A model for the simulation of the growth of *Beta vulgaris* L. *Annals of Botany* **35**, 1227–1250.

Qi, A., Keuter, C., Hoffmann, C. & Jaggard, K.W. (2005) The Broom's Barn sugar beet growth model and its adaptation to soils with varied available water content. *European Journal of Agronomy*.

Richter, G.M., Jaggard, K.W. & Mitchell, R.A.C. (2001) Modelling radiation interception and radiation use efficiency for sugar beet under variable climatic stress. *Agricultural and Forest Meteorology* **109**, 13–25.

Scott, R.K. (1964) The relationship between leaf growth and yield of sugar beet. PhD thesis, University of Nottingham.

Scott, R.K. & Bremner, P.M. (1966) The effects on growth, development and yield of sugar beet of extension of the growth period by transplantation. *Journal of Agricultural Science, Cambridge* **66**, 379–388.

Scott, R.K. & Jaggard, K.W. (1985) The effects of pests and diseases on growth and yield of sugar beet. *Proceedings of the 48th IIRB Congress*. Brussels, pp. 153–169.

Scott, R.K. & Jaggard, K.W. (1992) Crop growth and the weather: can yield forecasts be reliable? *Proceedings of the 55th IIRB Congress*. Brussels, pp. 169–187.

Scott, R.K. & Jaggard, K.W. (2000) Impacts of weather, agronomy and breeding on yields of sugar beet grown in the UK since 1970. *Journal of Agricultural Science, Cambridge* **134**, 341–352.

Scott, R.K. & Wilcockson, S.J. (1976) Weed biology and the growth of sugarbeet. *Annals of Applied Biology* **83**, 331–335.

Scott, R.K., English, S.D., Wood, D.W. & Unsworth, M.H. (1973) The yield of sugar beet in relation to weather and length of growing season. *Journal of Agricultural Science, Cambridge* **81**, 339–347.

Scott, R.K., Wilcockson, S.J. & Moisey, F.R. (1979) Effects of weed removal on growth and yield of sugar beet. *Journal of Agricultural Science, Cambridge* **93**, 693–709.

Smit, A.L. (1983) Influence of external factors on growth and development in sugar beet (*Beta vulgaris* L.). PhD Thesis, Wageningen, Netherlands.

Spitters, C.J.T., Van Keulen, H. & Van Kraalingen, D.W.G. (1989) A simple universal crop growth simulator: SUCROS87. In: Rabbinge, R., Ward, S.A. & Van Laar, H.H. (eds) *Simulation and Systems Management in Crop Production*. Simulation Monographs, 32, Pudoc, Wageningen, pp. 147–181.

Squire, G.R. (1990) *The Physiology of Tropical Crop Production*. CABI Publishing, Wallingford.

Steven, M.D., Biscoe, P.V. & Jaggard, K.W. (1983) Estimation of sugar beet productivity from reflection in the red and infra-red spectral bands. *International Journal of Remote Sensing* **4**, 325–334.

Steven, M.D., Biscoe, P.V., Jaggard, K.W. & Paruntu, J. (1986) Foliage cover and radiation interception. *Field Crops Research* **13**, 75–87.

Stout, M. (1946) Relation of temperature to reproduction in sugar beets. *Journal of Agricultural Research* **72**, 49–68.

Sylvester-Bradley, R., Scott, R.K. & Wright, C.E. (1990) *Physiology in the Production and Improvement of Cereals*. Research Review No. 18, Home Grown Cereals Authority, London.

Szeicz, G. (1974) Solar radiation in crop canopies. *Journal of Applied Ecology* **I**, 1117–1156.

Ulrich, A. (1955) Influence of night temperature and nitrogen deficiency on the growth, sucrose accumulation and leaf minerals of sugar beet plants. *Plant Physiology* **30**, 250–257.

Van Swaaij, A.C.P.M., Withagen, L.M., Schiphouwer, T. & Smit, A.B. (2003) SUMO: a growth model for predicting the yield and quality of sugar beet. In: *Sugar Beet Growth and Modelling: Advances in Sugar Beet Research*. International Institute of Sugar Beet Research, Brussels, 5, pp. 123–133.

Watson, D.J. (1956) Leaf growth in relation to crop yield. In: Milthorpe, F.D. (ed.) *The Growth of Leaves*. Proceedings of the Third Easter School in Agricultural Science, University of Nottingham, pp. 178–190.

Weaver, J.E. (1926) *Root Development of Field Crops*. McGraw-Hill, London.

Werker, A.R. & Jaggard, K.W. (1998) Dependence of sugar beet yield on light interception and evapotranspiration. *Agricultural and Forest Meteorology* **89**, 229–240.

Werker, A.R., Jaggard, K.W. & Allison, M.F. (1999) Modelling partitioning between structure and storage in sugar beet: effects of drought and soil nitrogen. *Plant and Soil* **207**, 97–106.

Windt, A. (1995) *Entwicklung des faserwurzel systems der zuckerrübe sowie dessen beziehung zum wachstum der gesuntpflauze und der Nährstoffaufuahime.* Cullivier Verlag, Göttingen.

Windt, A. & Märländer, B. (1994) Root growth of sugar beet under special consideration of water relations. *Zuckerindustrie* **119**, 659–663.

Chapter 8
Nutrition – Nitrogen

Michel Cariolle and Rémy Duval

IMPORTANCE

Nitrogen is a vital element for sugar beet growth. It is provided through the mineralization of organic matter derived from soil and crop residues, as well as by mineral fertilizers and organic manures. In many cases nitrogen is a limiting factor because few soils contain sufficient nitrogen in an available form, i.e. as nitrate or ammonium, to provide for maximum growth at each stage of the crop. Where the element is in short supply, even temporarily, yields can be drastically reduced and may even be halved on some soils. This shortage can be compensated for by fertilizers that provide sugar beet with the required nitrogen in its early stages and throughout active leaf canopy growth. Because the fertilizer has a remarkable effect on the appearance of the crop, most noticeably by improving colour and vigour of the leaf canopy, it has led to a widespread over-use of nitrogen. In many cases, this over-use decreases both sugar percentage and sugar extractability.

Since 1945 there has been rapid annual increase in the average application in many countries, reaching amounts that were clearly excessive in the 1960s and 1970s (Van Burg *et al.*, 1983). In the 1980s, progress was made towards optimizing the use of nitrogen through a better understanding of the crop's requirement under varying conditions of soil and climate. Since the 1990s, largely as a result of detailed research and development work, there has been a change to more realistic quantities, which is to the advantage of producers and processors alike. The decrease in nitrogen use, observed in most beet growing countries, has not affected yields on a national level (Fig. 8.1).

Progress has been achieved on the dynamics of nitrogen in soil, and modelling the soil–plant system in terms of growth as well as nitrogen flow is now possible. These mechanistic approaches are used mainly to calculate the optimal nitrogen supply for a specific plot and to evaluate nitrogen leaching outside the root zone. It is still necessary to make further progress on knowledge of environmental impact, in particular for a better appreciation of the processes that govern ammonia volatilization and nitrous oxide emissions from sugar beet fields.

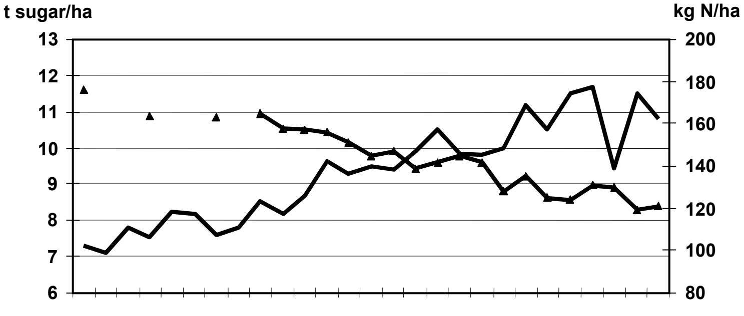


Fig. 8.1 Improvement in sugar yield and decreased use of nitrogen fertilizers in France, 1977–2004.

NITROGEN UPTAKE AND CONCENTRATION

The maximum quantity of nitrogen absorbed by the crop during its vegetative growth to achieve maximum root yield is extremely variable and correlated to the availability of nitrogen: from 3 to 6 kg N/t roots (Guiraud *et al.*, 1986). It is therefore difficult to identify an average need. In tests carried out in France between 1980 and 2000 (Duval, 2001), the 'envelope curve' of uptake for maximum sugar yield suggests a total uptake of 250 kg/ha is the non-limiting value for sugar yield (Fig. 8.2). In the early growth stages, nitrogen is absorbed mainly to produce the leaf canopy, so in spring, young plants contain up to 5% nitrogen in top dry matter and 3% in roots, concentrations that decrease progressively towards harvest.

The critical curve proposed by Duval *et al.* (2003) gives a synthetic and simple representation of the physiological links between nitrogen and growth (Fig. 8.3). During canopy growth the increase in leaf surface is associated with development of supporting structures (stems, petioles, ribs). These are made up of weakly photosynthetic, low nitrogen content tissues, whose growth leads to an overall decrease in the nitrogen percentage of the whole canopy. As successive leaves appear and create a self-shading effect in the plant, the new leaves are enriched in chlorophyll at the expense of the lower, contributing to the phenomenon of nitrogen 'dilution'.

The critical curve for sugar beet shown in Fig. 8.3 is based on maximum sugar production. An increase in nitrogen supply generates more foliar and root growth and new leaves, but no extra storage of nitrogen, either in canopy or root. This

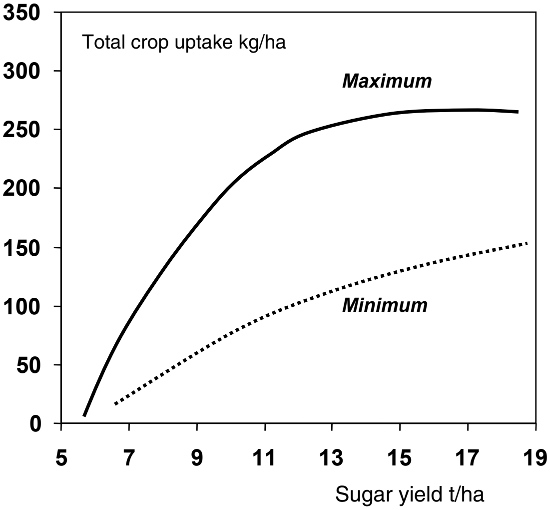


Fig. 8.2 Relationship between sugar yield and nitrogen uptake by the crop.

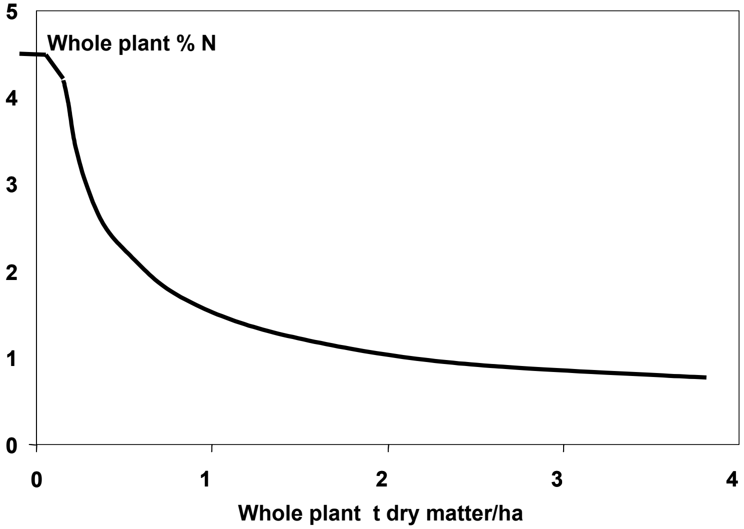


Fig. 8.3 Decrease in plant nitrogen concentration with increase in dry matter yield.

curve makes it possible to diagnose the nitrogen status (deficiency or excess) in the crop. Points above the curve indicate over-fertilization, those below, deficits in absorption. This type of curve is used in models for growth simulation purposes with respect to nitrogen availability.

NITROGEN DEFICIENCY AND ITS DETECTION

Leaf canopy observations allow detection of nitrogen deficiency as, unlike deficiency symptoms of some other elements, nitrogen deficiency shows on sugar beet leaves at almost any developmental stage. The seed contains much of the nitrogen needed by the cotyledons as they first emerge, but very soon nitrogen must be taken up by the plant. In soils containing little nitrogen, symptoms commonly appear on the first two true leaves and subsequent ones. There are no symptoms that completely characterize nitrogen deficiency (as there are, for example, with manganese, boron or magnesium deficiency). However, leaves of affected plants turn an even, light green colour, turning yellow later. Loomis and Nevins (1963) showed that nitrogen deficiency decreases chlorophyll concentration and photosynthetic rate of older leaves. These older leaves often wilt and die prematurely, and new leaves typically have long narrow blades and long petioles (Draycott & Christenson, 2003 and the following chapter).

Besides leaf colour being an indicator of nitrogen deficiency, the general aspect of the crop is also very symptomatic. The leaf canopy takes longer to form and very often remains incomplete. Leaves show a characteristic erect aspect, and leaf area index does not reach the minimal value to give complete interception of radiation (see Chapter 3). Finally, sugar yield may be greatly decreased. Numerous experiments have been carried out to use leaf colour measured colorimetrically, to characterize nitrogen status, which in turn is closely correlated with chlorophyll content. Such techniques are based on measuring the modification in the light spectrum due to the uptake of part of the spectrum through photosynthesis, either by reflection (remote sensing) or absorption (chlorophyll meter, N-tester). There are difficulties, both in sampling leaves and in the imperfect correlation between these measurements and plant production during summer and autumn.

Measurements of nitrogen concentration could be used as a way of indicating deficiency. Usually, nitrogen-deficient leaves contain 1.9–2.3% nitrogen in dry matter. In California, Ulrich and Hills (1969) developed tissue-testing techniques, in which the petiole was usually the part of the plant sampled, to determine when nitrogen was in short supply. They found that dried petioles from plants with deficiency symptoms contained 70–200 p.p.m. nitrate-nitrogen, whereas those from plants without symptoms contained 350–35 000 p.p.m.

As with techniques used for wheat, several authors attempt to link nitrogen status of sugar beet with the nitrate concentration in the petiole juice. There are the same difficulties as encountered with colorimetric measures, and these studies have not led to development of usable tools. Considering the complex phenomena of growth and redistribution of nitrogen between senescent and new leaves, as well as between top and root in the course of time, it seems that only the nitrogen concentration of the entire plant is capable of quantifying the nitrogen status of the crop (see dilution curve) throughout the vegetation period.

EFFECT OF NITROGEN ON GERMINATION, EMERGENCE AND ESTABLISHMENT

Uptake of nitrogen starts as early as the emergence of the seedling radicle (Dürr & Mary, 1998). Nitrogen is preferentially present in both radicle and hypocotyl (Fig. 8.4), which contributes to rapid growth of these organs and their elongation. This phenomenon can have a direct effect on emergence rate. It matches field observations on emergence and weaker initial stands when the crop is short of nitrogen. An excess of nitrogen is no advantage either: with increased nitrogen application, a decrease in final population has frequently been observed in trials. For example in France, increasing nitrogen fertilizer decreased population by up to 10% (Fig. 8.5). Delay in sowing after nitrogen ap-

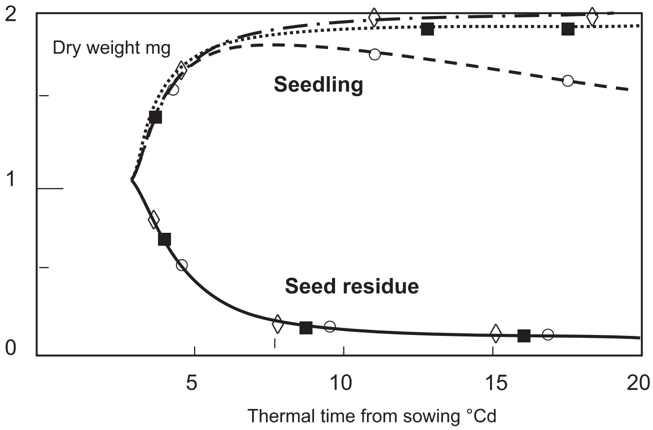


Fig. 8.4 Changes in dry matter of sugar beet seeds and seedlings with thermal time in the dark with nutrient solution containing 0 (○), 0.7 (■) and 10.5 (◇) mol N/m^3 (after Dürr & Mary, 1998).

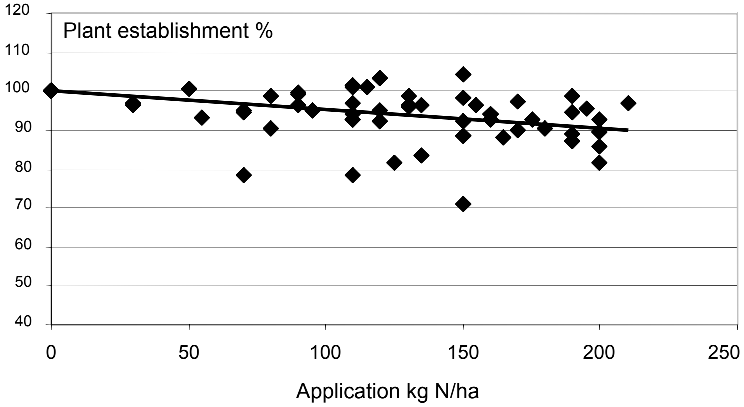


Fig. 8.5 Effect of nitrogen application on sugar beet emergence in French trials, 1992–1996.

plications did not seem to affect toxicity, and there were variations between years. The proportion of trials in which nitrogen caused a decrease in population varied between 7 and 14%, depending on year, during the period considered. Figure 8.6 shows serious loss of plants due to nitrogen fertilizer toxicity.

In practice, slight toxicity often passes unnoticed, because growers usually apply only one dose of nitrogen. It is only when a drastic drop in population is noticed that toxicity of nitrogen is suspected, although in trials, even a low dosage is potentially toxic. One cannot completely exclude an accumulation or even a synergy of toxicities related to nitrogen fertilizer, as well as to pre-emergence herbicide applications, particularly in dry conditions.

Many experiments have investigated possible solutions to this problem. Initially, various forms of placement were tested, but these involved the use of more sophisticated and expensive equipment than was already present on most farms, e.g. equipment allowing localized nitrogen application parallel to the seed row, which does not cause toxicity, however high the applied nitrogen dosage (see Figs 8.7 and 8.8).

Later work showed that a small initial broadcast dose permits full establishment and gives optimum early growth. Once the crop is established, the required balance of nitrogen fertilizer can be applied with impunity at the two to four true leaf stage. This has become universal practice in the UK since the 1970s. However, such application may result in insufficient nitrogen being absorbed, particularly

Fig. 8.6 Serious loss of plant resulting from nitrogen fertilizer toxicity in a dry spring.

in a dry spring, as is often the case in continental or southern Europe with no irrigation. Delayed application could also trigger late nitrogen uptake, which would result in increased α-amino nitrogen in the juice and degradation of root quality.

EFFECT OF NITROGEN ON GROWTH AND YIELD

Growth

Figure 8.9 illustrates the pattern of uptake and distribution of nitrogen in sugar beet. In the early growth stages, nitrogen is preferentially distributed to the tops, and increases dry matter production per unit area, mostly from leaves and petioles. Armstrong *et al.* (1983) showed that nitrogen fertilizer did not affect conversion of intercepted radiation to dry matter, but greatly increased amount intercepted, as a result of increased leaf canopy. This increase in amount intercepted is observed up to a leaf area index of 3–4. During summer, the nitrogen absorbed helps maintain the top and even triggers an increase of leaf area index to more than 3–4. However, this does not result in increased efficiency of radiation interception.

Fig. 8.7 Sowing sugar beet with placed liquid nitrogen fertilizer.

Fig. 8.8 Liquid nitrogen fertilizer being injected through a coulter a few cm to the side and below the seed.

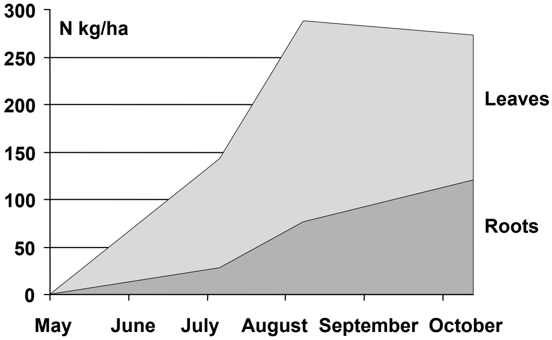


Fig. 8.9 Distribution of nitrogen to tops and roots during growth period (Iverny, France, 1987).

The amount of nitrogen present in the root steadily increases from emergence to harvest and corresponds to the quantity of dry matter produced. In autumn, leaf senescence accompanies a re-distribution of assimilates, as well as nitrogen present in the foliar system, towards the roots. As already explained above, an increase of nitrogen fertilization essentially results in increased top dry matter production with no proportional increase in root dry matter. Root quality is decreased through increased α-amino nitrogen concentration. Excess nitrogen application also enhances production of top dry matter to the detriment of root dry matter.

Yield

The impact of nitrogen fertilization on yield parameters is one of the most important topics discussed in all sugar beet growing countries. The primary effect of nitrogen fertilizer is on root and top dry matter production, much of which is eventually stored in the form of sugar. Figure 8.10 represents the typical response to nitrogen of root yield, sugar content and sugar yield at harvest. Root yield increases, then stabilizes with increased nitrogen. Sugar content first decreases slowly then rapidly as more and more nitrogen is applied (much of the effect on sugar percentage results from increased water retention by the taproot). Consequently, sugar yield obtained from nitrogen application reaches an optimum value. This type of curve corresponds to situations in which nitrogen supplied by soil and plant residues is fairly small and where nitrogen fertilizer is needed. However, when the supply in the soil is large, in extensive animal breeding farms for example where slurry is applied, maximum sugar yield can be achieved without any mineral fertilizer.

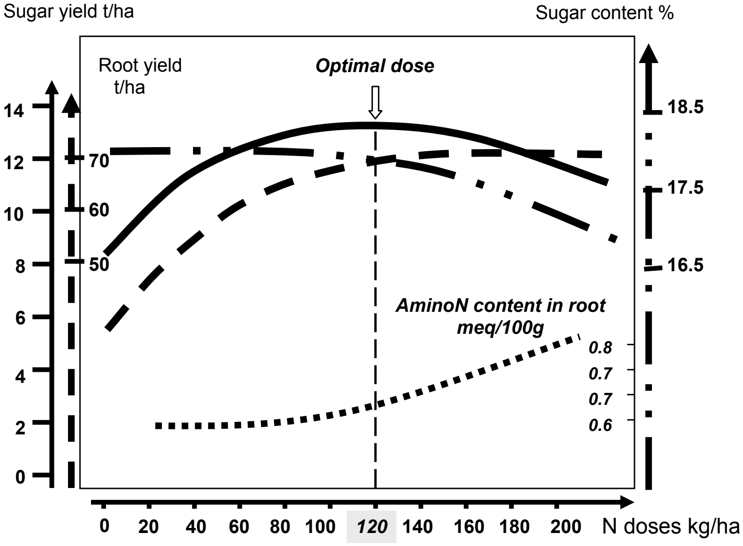


Fig. 8.10 Response of sugar beet to increasing nitrogen fertilizer amounts. Example for a 120 kg N/ha optimum application.

Winter (1984) mentions sugar beet fields in the USA with huge amounts of residual nitrogen and where sugar yield is maximum with no additional fertilizer. Experiments have even been carried out to discover whether yield is increased by growing a preceding crop to remove some of the residual nitrogen!

In the UK, Draycott (1972) emphasized the primary influence of soil type, particularly its organic matter content, on juice purity and sugar content. In France, in trials carried out between 1988 and 1997, situations where optimum sugar yield was obtained without additional mineral fertilization, represented 9% of fields, generally those that benefit from slurry or irrigated plots favouring mineralization and an early nitrogen supply to the beet.

EFFECT OF NITROGEN ON ROOT QUALITY

Figure 8.10 also shows the typical effect of nitrogen fertilizer on α-amino nitrogen, which greatly decreases root quality. Juice purity, which shows the proportion of extractable sugar, can only be accurately measured in the laboratory using a combination of refractometer and polarisation measurements. In order to simplify this approach, various formulae from regression calculations are used to establish juice purity. These all give α-amino nitrogen a leading position in the calculation e.g. Carruthers *et al.* (1962): Juice purity = 97.0–0.0008 (2.5 K + 3.5 Na + 10 α-N), with K, Na and α-N expressed as mg/100g sugar, or that used in France which expresses the non-extractable sugar in relation to sugar content SM/Pol = 100(0.14(Na + K) + 0.25 α-N + 0.5)/%S with K, Na and α-N content expressed as meq/100g, %S: sugar content.

This increasing concentration of amino compounds is mainly caused by excessive uptake of nitrate late in the season and the phenomenon was studied very early because of the enormous economic consequences for the industry. Work began in the 1950s and 1960s, (Carruthers *et al.*, 1962) and the next decade witnessed a multiplication of fertilization field trials. They showed amongst other things, the deleterious effect of nitrogen supply on internal quality of sugar beet, even at low doses, and regardless of its form, mineral or organic. These trials were carried out in the whole of Europe, in the UK (Adams, 1962; Collier, 1967; Boyd *et al.*, 1970), in Germany (Von Lüdecke & Nitzsche, 1967), as well as in the USA (Ogden *et al.*, 1958). More recently, the Institut Technique Français de la Betterave Industrielle (ITB) has been measuring the average effect of increased nitrogen supplies, centred on

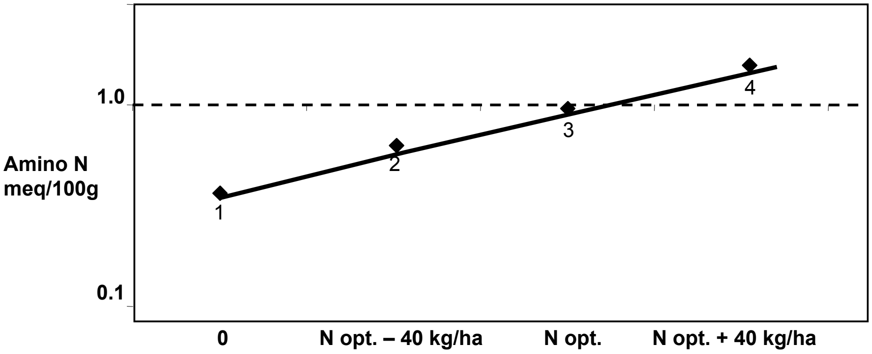


Fig. 8.11 Effect of nitrogen fertilizer application on α-amino nitrogen concentration in roots (95 trials).

an optimal dosage from an experimental network carried out in 95 trials from 1992 to 1997 (Fig. 8.11). It was shown that increased supply greatly increases α-amino nitrogen in roots and the variability of these concentrations (see Chapter 16).

At the same time, more complex studies were aimed at establishing the link between juice purity and the quantity of nitrogen taken up (Marcussen, 1985). A threshold of 200–220 kg/ha of nitrogen taken up by the crop was identified by a large number of researchers who considered it to be the value above which juice purity was severely damaged (Armstrong & Milford 1985; Pocock *et al.*, 1990). This threshold also corresponds to the maximum sugar yield achieved.

Once the effect of nitrogen application is established, other factors also play a part. The N/K_2O balance in soil was studied by Von Müller *et al.* (1962), who found that when this ratio is low, close to 1, purity is poor. The effect of water stress on internal quality has been studied by the ITB since 1997: in the case of severe drought without irrigation, with equal nitrogen fertilization, α-amino nitrogen may be tripled, increasing the proportion of non-extractable sugar by more than 50%. All these observations suggest that the availability and uptake of nitrogen plays an important part in causing high α-amino N, which could also explain the variability of measurements between various situations.

In conclusion and in practice, fertilizer nitrogen applications need to be planned to boost the early growth of the leaf canopy and to maintain it until harvest, but to avoid excess, which inevitably depresses root quality. The following sections show what progress there has been towards achieving these objectives.

SOIL SUPPLIES OF NITROGEN

Sugar beet absorbs nitrogen mainly as nitrate and partly as ammonium form. This ‘mineral’ nitrogen stems from three major sources: unstable organic matter in soil, organic manure e.g. slurry from animal breeding or non-agricultural sources, and unused nitrogen fertilizers left from previous crops. The availability of mineral nitrogen in soil depends directly on microbial processes (Fig. 8.12). These determine mineralization, which results in ammonium nitrogen production from organic matter, and ensure nitrification (transformation of ammonium nitrogen into nitrate), but microbes also consume mineral nitrogen for their own use. These processes are simultaneous and balanced, depending on physical (temperature, moisture) and trophic factors (availability of carbon and nitrogen in soil).

Many investigations have been made in the past into the nitrogen requirement of sugar beet grown on different soil types, usually classified either by texture, or by Major Soil Group or Series (Webster *et al.*, 1977). With few exceptions, the overwhelming evidence is that, for a given climatic zone, neither of these classifications is useful in predicting nitrogen requirement. Far more important are:

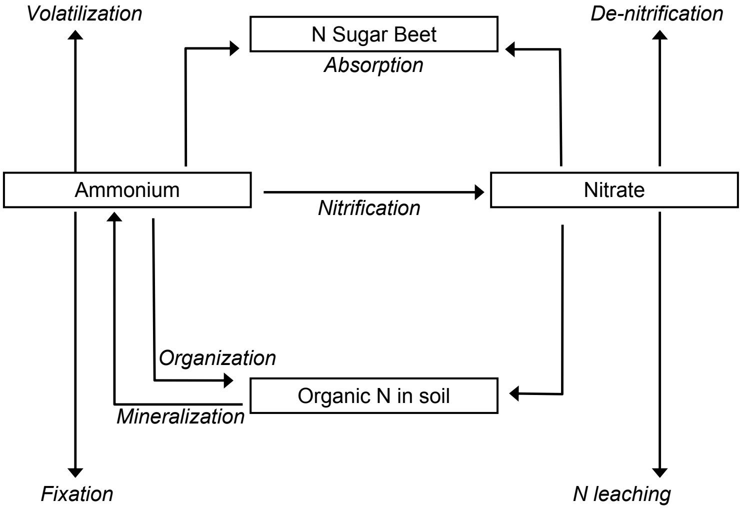


Fig. 8.12 Transformation and availability of nitrogen in soil (adapted from S. Recous, 2004).

- The amount of available nitrogen present in soil before sowing sugar beet.
- The amount mineralized during the growing period, as described in the next section.

However, these quantities depend closely on the microbial balance responsible for mineralization and nitrification, being themselves determined by climate, previous crop and its fertilizer residue, and organic supply. Soil characteristics, no matter how important, cannot be sufficient to predict the nitrogen available before and after sowing sugar beet.

The total quantity of nitrogen available to the crop varies depending on type of soil, in particular its organic matter content and cultural history. Various authors have measured these quantities. Müller (1978) indicates that, based on a 10-year experiment, sugar beet absorbs between 100 and 200 kg/ha of nitrogen from the soil. In the south of Germany, Günter (1978) found larger quantities, from 200 to 220 kg/ha.

Work carried out with ^{15}N fertilizer in several countries has helped the understanding of nitrogen uptake by sugar beet. Haunold (1983) in Austria showed that, with a normal fertilizer application, 50% of the applied ^{15}N was taken up by the crop, 20% was left in the soil and 30% disappeared, presumably by de-nitrification, change to organic form, volatilization or leaching. Similar studies by Lindemann *et al.* (1983) in France, over a 5-year period on various soils, showed that 50–80% was taken up by the crop, and that the soils themselves contributed 100–215 kg/ha, more than 60% of total nitrogen uptake. Broeshart (1983) placed ^{15}N at intervals down to 120 cm, and found that sugar beet took it up effectively from all depths, particularly during the later stages of development.

While it was long considered that most of the nitrogen taken up by sugar beet came from fertilizer, these observations indicate that mineral fertilization only provides part of the supply, complementing that supplied by the soil. They confirmed the necessity of reducing fertilizer applications that were too great. The difficulty remains to estimate the optimal dosage: not too low, risking a reduction in sugar yield, and not too high risking a decrease in sugar content and juice purity.

Most difficult of all is estimating how much nitrogen will be mineralized during the growth of the crop. In the case of humid soils, mineralization is fairly stable from year to year, but most often it is necessary to resort to an analytical approach in the laboratory. In the UK for example, the organic matter breakdown process has been simulated by incubating soil samples under controlled moisture and temperature conditions (Last & Draycott, 1971). In France, the Hénin Dupuis model (Henin & Dupuis, 1945) is being used for calculating the quantity of nitrogen produced by mineralization.

Effect of organic manures

Organic manure can benefit crops in various ways, and it is often applied before sugar beet. Much, but not all, of the benefit is as a result of the nitrogen that it provides, both early in the season and more slowly throughout the growing period, as nitrate is released when urea, amino compounds and proteins from animal and plant remains decay. Organic manures often decrease sugar percentage and increase amino nitrogen concentration, with large quantities of animal slurry, sewage sludge and poultry manure being particularly drastic in their effect on quality. Sugar beet that has been treated with these products rarely requires more than a starter dose of 40 kg N/ha as fertilizer.

The short- and medium-term effects of organic matter have been studied and work continues with the aim of improving mineralization models. In practice, there are difficulties due to the diversity of types of organic manure, whether from animal sources or urban and industrial residues. Moreover, distribution equipment does not allow an efficient control of the quantities applied. Consequently, an accurate estimation of the supply of nitrogen from organic matter to sugar beet remains a problem.

Nitrogen recommendations

Increasingly, recommendations are based on the expected supply of nitrogen from soil. In Europe, two main methods are used to estimate the quantities of nitrogen likely to be supplied by the soil. Then the complementary nitrogen fertilizer can be determined.

The first consists of an inventory of entry/exit of nitrogen in the soil/plant system, either measured or estimated. The quantities of available nitrogen from mineralization can be determined by analysis of the mineralization processes and nitrification. The method most used was developed in France – the so called 'predictive balance sheet method', which was developed by Rémy and Hébert (1977), Rémy (1981) and Machet and Hébert (1983), and then computerized by Machet *et al.* (1990). Machet (2004) has proposed a simplified version:

$$Rf - Ri = (Mn + X) - (Pf - Pi + L)$$

where Rf and Ri are the mineral nitrogen quantities in soil (kg N/ha) at the opening and closing of the inventory (i.e. after harvest and before beet sowing), Mn represents the net mineralization from organic sources, X nitrogen fertilizer, Pf and Pi absorbed nitrogen from the closing and opening of the inventory, representing the amount needed by the sugar beet (220 kg N/ha), and L losses due to leaching. Certain terms of the inventory are roughly estimated (for example the needs of the crop), others are measured (e.g. the quantity of mineral nitrogen in soil at the time of sowing), and others result from modelling (e.g. the quantity of nitrogen from mineralization of organic matter).

This method is used routinely in France for calculating the amount of nitrogen to be applied to sugar beet on more than 60% of the crop, which is analysed for the mineral nitrogen present in soil down to 90 cm depth each year before sowing (Fig. 8.13). Its generalized use since the early 1980s led to a very noticeable decrease in fertilizer use and an improvement in technological quality. In Belgium, a more simplified method is used. The estimate of optimum fertilizer requirement (N_{op}) is made on the basis of the mineral nitrogen present in soil (samples 0–60 cm depth) taken before sowing ($N_{min.}$) and the sugar beet crop requirement, expressed in kg/ha, is: $N_{op} = 220 - 1.7\ N_{min.}$.

The second, EUF method, was first developed and used in Germany and Austria, and is also used in Ireland. It includes a determination of the mineral nitrogen present in soil samples, but also estimates the quantity of nitrogen likely to mineralize during crop growth. This method extracts ions and small organic molecules, which are charged electrically by electrostatic forces. The fraction of organic matter extracted by this method is supposed to mineralize quickly. The applied dosage D is calculated from the results of extraction (N-NO_3-EUF, N-Org-EUF) by means of formulae such as $D = B -$ k1N-NO_3-EUF – k2N-Org-EUF – (k3F – p), where B corresponds to the requirement of the crop; k1, k2, k3, and p are coefficients adapted to local conditions and F is the relation of two fractions of N-Org extraction. In countries where this method is applied, the EUF method is used successfully on a large area, and gives considerable improvements in yield and of quality.

Fig. 8.13 Mechanized collection of soil samples to about 1 m deep prior to sugar beet.

FORM AND APPLICATION OF NITROGEN FERTILIZER

Having determined the total quantity of nitrogen fertilizer required by the crop, it is important that applications are made correctly and in the best form to achieve the desired uptake.

Form of nitrogen fertilizer

A large variety of nitrogen fertilizers are used for sugar beet e.g. urea, anhydrous ammonia, ammonium nitrate, calcium or sodium nitrate, mixture of urea and soluble ammonium nitrate, etc. Choice is essentially based on unit cost and spreading equipment available. All these fertilizers, no matter in which form, are considered to provide the same quantity of nitrogen though some authors have compared their efficiency.

Early work with urea led to the belief that it was slightly less effective than ammonium nitrate (Tomlinson, 1970), but more recent experiments have detected little difference between the two forms. Similarly, sodium nitrate (16% N) can be used with equal efficiency, provided its sodium content is taken into account. Christmann and Guiraud (1989) using ^{15}N determined the actual sugar beet intake coefficients from various types of fertilizer applied before sowing. They showed that fertilizers containing a high proportion of nitrate are of greater value to the crop (Table 8.1). On the one hand, differences between various forms are generally small in comparison to other variables of nitrogen availability to the plant in practice. On the other hand, the decrease in efficiency of a fertilizer also depends on its tendency to volatilize. Taking this criterion into account might lead to greater use of forms that are less likely to volatilize, or those that contain less ammonium or urea.

Table 8.1 Relative efficiency of uptake of nitrogen from various forms of fertilizers (%) (after Christmann & Guiraud, 1989). Comparison of real capacity coefficients of various forms of fertilizer

Form of fertilizer	1981 (1 test)	1984 (3 tests)	1985 (4 tests)
Ammonium nitrate	50	51	56
Solution 39 (⅓ urea, ⅓ NH_4, ⅓ NO_3)			42
Urea	29		49
Ammonium sulphate	28		39

Application of nitrogen fertilizer

In many countries, spinning disc fertilizer spreaders are used for solid fertilizers and sprayers for liquid fertilizers. Spreading is done either before or immediately after sowing. In regions with reliable rainfall in spring and summer the rain helps the crop to absorb nitrogen so application can be made to the growing crop. In Belgium, the Netherlands and, more recently, in France, a new spreading technique has been developed. The nitrogen fertilizer is applied at the time of sowing, parallel to the seed furrow and a few centimetres deep (Figs 8.7 and 8.8). This technique makes it possible to avoid a separate application and also allows reduction in dosage compared to that which would have been applied normally. It has been demonstrated that burying nitrogen by the seed gives better use of nitrogen by the plant. The increase in fertilizer efficiency (Real Capacity Coefficient) can reach 37%, depending on year and type of fertilizer and was measured by Cariolle *et al.* (1991). Moreover, significant yield increases are regularly observed, which can be explained by the early availability of nitrogen, favouring leaf canopy development and photosynthetic activity.

INTERACTIONS WITH THE ENVIRONMENT

The presence of nitrogen in soils, whether supplied in mineral or organic form or from mineralization, could be a cause of water or air pollution. Surface or ground water pollution is normally caused by soluble nitrate ions carried to the water resources by leaching or run-off. Air pollution is caused by nitrogen volatilization as ammonia (NH_3) or nitrous oxide (N_2O).

Leaching of nitrates

Nitrogen is lost in drainage water once soil reaches saturation; first during the intercrop phase following harvest, then further into the early stages of the next crop. During this intercrop period mineralization occurs when the soil re-wets at the end of summer and in autumn and nitrate is produced in more or less large quantities, depending on the year. Moreover, when climatic or health conditions do not allow certain crops (cereals, rape seed, maize) to achieve maximum yield, part of the available nitrogen may not be absorbed and remains in the soil at harvest. Nitrate can then be leached in autumn and during the winter when the soil starts its drainage phase until the root system of the following crop absorbs nitrate.

With beet, the following as well as the preceding intercrop could present a risk of nitrate leaching. An autumn cereal usually follows beet harvest, causing a short and late intercrop, with weak cumulated rainfall and limited mineralization which, with decreasing temperatures, reduces leaching. Moreover, the amount of mineral nitrogen present at sugar beet harvest is low, often less than 30 kg N/ha, which further decreases leaching risks.

The preceding intercrop presents a higher risk. Sugar beet is sown in spring, often more than 200 days after harvesting the preceding crop, usually a cereal. This long intercrop period allows early and extended mineralization, often together with considerable rainfall. In addition, the quantity of mineral nitrogen present at the previous crop's harvest and potentially susceptible to being leached may be considerable in the case of cereals, often above 60 kg/ha. In order to limit the risks and complement the fertilization for successive crops, different management solutions are being sought.

Despite the deep rooting system that allows sugar beet to reach part of the leached nitrogen, beyond 1 m depth, cultural practices should aim to minimize risks of leaching. Burying crop residues from the preceding crop enables mineral nitrogen to be partly immobilized, particularly if the carbon/nitrogen ratio of the residues is high, e.g. cereal straw with a C/N ratio above 80 can protect 20–30 kg N/ha from leaching. A reduction in the area of bare soil during the intercrop period can be achieved by sowing intermediate crops. These crops, generally mustard, radish, phacelia or grasses are not harvested, but incorporated after their destruction playing the role of nitrate 'traps', by absorbing mineral nitrogen present in soil and locking it up in the vegetation produced. The efficiency of intermediate crops is very much superior to burying crop residues from the preceding crop, because between 40 and 100 kg N/ha can be prevented from leaching, giving dry matter production in the intermediate crop of between 1500 and 3000 kg/ha.

After burying the trap crop, decomposition progressively releases nitrogen during spring, rendering it available to sugar beet. It is considered that a minimum of 30% of nitrogen intake of intermediate crops is returned to the next sugar beet crop. The rest is loosely bound in soil and is progressively returned over several years. The impact of intermediate crops in the long term allows a sustainable reduction of nitrogen fertilizers. It has been demonstrated in France, in a long term trial on chalky soils in the Champagne region, that cultivation of intermediate crops decreases nitrate concentration of water leaching into ground water more than the reduction of nitrogen fertilizer application (Fig. 8.14).

In practice, in many beet-growing countries, practices aimed at reducing risks of nitrate leaching are being implemented. Depending on local conditions, these aim either at a reduction of nitrogen fertilization or cultivation of intermediate crops or, whenever the level of water pollution requires it, both practices combined.

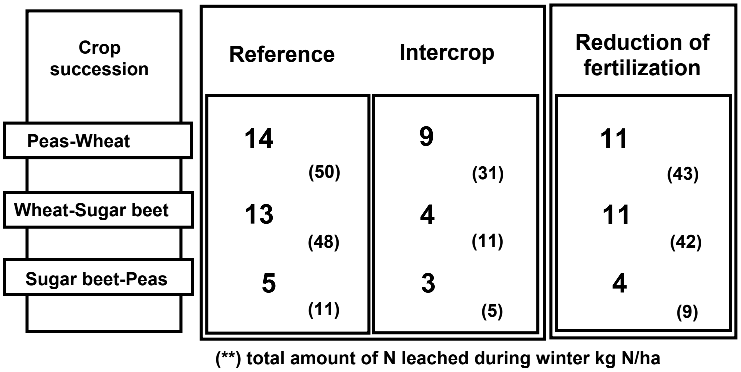
Ammonia volatilization

Atmospheric ammonia (NH_3) is essentially of agricultural origin in countries where intensive cropping and animal breeding are extensively developed. It derives from gas emission of nitrogen contained in slurry from animal breeding, or from mineral fertilizers, although animal breeding accounts for most emissions. Volatilization from mineral fertilizer applications represents less than 15% of the total emission (CORPEN, 2001).

Nitrogen deposits from the atmosphere are responsible for acidification of forests and lakes and can also be implicated in certain eutrophication processes. They contribute, either indirectly or directly, to modifications in the equilibrium of the flora. In Europe, the annual residues measured vary from 0 to 40 kg N/ha with values locally above 100 kg N/ha. These quantities are seldom taken into account when calculating the amount to be applied to crops, but they contribute to the excessive supply of nitrogen to soils and indirectly influence the leaching of nitrate. Ammonia volatilization after spreading mineral fertilizer is encouraged by its ammonium ion content (NH_4^+), and its high pH encourages volatilization. The same goes for soils: neutral or basic pH, with high cationic exchange capacity encourages volatilization of ammonia.

With regard to mineral fertilization of beet crops, ammonia volatilization depends on technical as well as meteorological factors. In the first instance, composition and form of a mineral fertilizer determines its propensity to lose nitrogen as ammonia gas. Ammonium ions or urea can rapidly change into ammonia gas. Nitrogen solution fertilizers combining urea, ammonia and ammonitrate are the most susceptible to volatilization, whereas fertilizers of the 'ammonitrate' type are less so, solid forms volatilizing more slowly than liquid.

The length of air/fertilizer contact is also important. A longer lapse between application and



Crop succession	Reference	Intercrop	Reduction of fertilization
Peas-Wheat	14 (50)	9 (31)	11 (43)
Wheat-Sugar beet	13 (48)	4 (11)	11 (42)
Sugar beet-Peas	5 (11)	3 (5)	4 (9)

(**) total amount of N leached during winter kg N/ha

Fig. 8.14 Effect of reduction of fertilization and inter-cropping on nitrate concentration (mg/l) in water at 1.10 m deep.

the period of nitrogen requirement of the crop increases the risks. Burying the fertilizer by means of cultural techniques immediately after application, or weather favourable to evaporation (high temperatures, wind) are also factors reducing volatilization. Finally, the volume of volatilized nitrogen is directly correlated to the applied dose. On average, between 5 and 15% of the nitrogen applied in the ammonium form in the spring without any precaution can volatilize.

Another possibility for ammonia volatilization is from residues of crops and organic manures rich in nitrogen, which produce ammonia when rotting. The changes in beet leaves and crowns left on the ground after harvest was studied in Sweden by Olson and Bramstorp (1994) in field trials and in the laboratory. They reported between 20 and 30% of the total nitrogen from leaves and crowns can be volatilized as ammonia during the 7 weeks after harvesting unless they are buried. They also noted an initial phase of 1 week during which no loss was measured and they therefore recommended burying leaves and crowns as soon as possible after sugar beet harvest to reduce risk of ammonia emission. Similarly, organic manures should, if possible, be ploughed in soon after spreading.

Emission of nitrous oxide

Very few field measurements have been made to quantify emission of nitrous oxide (N_2O) by crops in temperate climates. Recent results were obtained during a research programme in France (Hénault & Germon, 1995). The conclusions of this study were that emission is large and encouraged by soil when saturated with water, high organic matter content and mean high temperatures. Type of crop was more important than the amount of fertilizer. In conditions in which this study was carried out, on aerated soils, the N_2O emissions were low with an average of 1 g/ha/day as soon as the average temperature reached 10°C with highs observed in stormy weather. When applied to sugar beet cultivation under normal conditions, it is estimated that only 0.25 kg N_2O/ha are emitted each year.

Measurements made by Harrison *et al.* (2002) on a limey/sandy soil in the east of England, on an experimental plot with sugar beet, emphasize the importance of the date for burying plant residues, with a high year effect. The values measured from August to March for the 1998–1999 and 1999–2000 winters varied from 0.22 to 1.9 kg N-N_2O/ha. The emission factors (relation between amount of nitrogen released as N_2O and the total quantity of nitrogen incorporated) calculated from measured values for the entire crop residues (Table 8.2) are on average lower than the default values of the International Panel on Climatic Changes (1.25%).

Table 8.2 Average emission factors for crop residues (%).

Crop	Month incorporated	1998–1999	1999–2000	Average
Sugar beet residues	October	1.16	0.47	0.81
	January	1.20	0.17	0.69
All crops residues		1.37	0.55	0.96

SUMMARY AND CONCLUSIONS

Because of its impact on yield, sugar content and sugar extraction, nitrogen fertilization has been one of the most important topics studied in all sugar beet growing countries over the past 40 years. Better understanding of the crop's behaviour and requirements under varying conditions of soil and climate has led to significant progress in nitrogen management. Since the 1990s, mainly as a result of detailed research and development work, progress has been made in adjusting nitrogen fertilization in order to optimize sugar yield and juice quality.

Nowadays, applications aim to allow rapid expansion of the leaf canopy and to maintain it until harvest, giving better sugar yield and avoiding excess. Nitrogen fertilizer applications now take into account nitrogen coming from all sources. This contributes to higher farmers' income and greater efficiency of processing as a result of reduced inputs. However, some aspects of nitrogen fertilization, such as improvement of use of organic manure in combination with mineral fertilizers, need further investigation.

Progress has been made, but a better understanding of the dynamics of nitrogen in soil would help in modelling the soil–plant system in terms of growth as well as nitrogen flow. It is also necessary now to better assess environmental risks in terms of nitrate leaching, ammonia volatilization and nitrous oxide emissions in order to improve sugar beet cultivation in relation to other crops in the rotation.

REFERENCES

Adams, S.N. (1962) The response of sugar beet to fertilizer and the effect of farmyard manure. *Journal of Agricultural Science, Cambridge* **58**, 219–226.

Armstrong, M.J. & Milford, G.F.J. (1985) The nitrogen nutrition of sugar beet. *British Sugar Beet Review* **53** (4), 42–44.

Armstrong, M.J., Milford, G.F.J., Biscoe, P.V. & Last, P.J. (1983) Influences of nitrogen on physiological aspects of sugar beet productivity. *Proceedings of the IIRB Congress*. pp. 53–61.

Boyd, D.A., Tinker, P.B.H., Draycott, A.P. & Last, P.J. (1970) Nitrogen requirement of sugar beet grown on minerals soils. *Journal of Agricultural Science, Cambridge* **74**, 37–46.

Broeshart, H. (1983) ^{15}N tracer techniques for the determination of active root distribution and nitrogen uptake by sugar beets. *Proceedings of the IIRB Congress*. pp. 121–124.

Cariolle, M., Duval, R. & Guiraud, G. (1991) French experiments on localized ploughing in of N during drilling: experimental results, estimate of the real capacity coefficient using nitrogen N15. *Proceedings of the IIRB Congress*. pp. 319–346.

Carruthers, A., Oldfield, J.F.T. & Teague, H.J. (1962) Assessment of beet quality. *Paper presented to the XVth annual Technical Conference of the British Sugar Corporation*. pp. 1–28.

Christmann, J. & Guiraud, G. (1989) Note interne. *Institut Technique Français de la Betterave Industrielle.*

Collier, P.A. (1967) *ICI Fertilizer Trials on Sugar Beet 1962–1965.* ICI Farming Service, London.

CORPEN (2001) Les émissions d'ammoniac d'origine agricole dans l'atmosphère. Etat des connaissances et perspectives de réductions des émissions, p. 64.

Draycott, A.P. (1972) *Sugar Beet Nutrition.* Applied Science Publishers Limited, London.

Draycott, A.P. & Christenson, D.R. (2003) *Nutrients for Sugar Beet Production: Soil-Plant Relationships.* CABI Publishing, Wallingford, pp. 7–32, 123–138, 180–181.

Dürr, C. & Mary, B. (1998) Effect of nutrient supply on pre-emergence growth and nutrient absorption in wheat (*Triticum aestivum* L.) and sugar beet (*Beta vulgaris* L.). *Annals of Botany* **81**, 665–672.

Duval, R. (2001) Note interne. *Institut Technique Français de la Betterave Industrielle.*

Duval, R., Machet, J.M. & Maupas, F. (2003) Critical curve for the dilution of nitrogen under sugar beet. Institut International de Recherches Betteravières. 'Sugar Beet Growth and Growth Modelling'. *Advances in Sugar Beet Research*, Vol. 5, pp. 47–62.

Guiraud, G., Christmann, J., Lindemann, Y. & Marol, C. (1986) Utilisation de l'azote 15 dans les études de fertilisation sur betterave sucrière. *Comptes Rendus de l'Acadamie d'Agriculture de France*, **72** (5), 439–446.

Günter, L. (1978) Seasonal changes of mineral nitrogen in beet soils. *Proceedings of the IIRB Congress*. pp. 23–34.

Harrison, R., Ellis, S., Cross, R. & Hodgson, J.H. (2002) Emissions of nitrous oxide and nitric oxide associated with the decomposition of arable crop residues on a sandy loam soil in Eastern England. *Agronomie* **22**, 731–738.

Haunold, E. (1983) Isotopostudie über die Nutzung von Dünger und Bodenstickstoff durch die Zuckerrübe. *Proceedings of the IIRB Congress*. pp. 136–144.

Hénault, C. & Germon, J.C. (1995) Quantification de la dénitrification et des émissions de protoxyde d'azote (N2O) par les sols. *Agronomie* **15**, 321–355

Henin, S. & Dupuis, M. (1945) Essai de bilan de la matière organique des sols. *Annales Agronomiques* **15**, 161–162.

Last, P.J. & Draycott, A.P. (1971) Predicting the amount of nitrogen fertilizer needed for sugar beet by soil analysis. *Journal of the Science of Food and Agriculture* **22**, 215–220.

Lindemann, Y., Guiraud, G., Chabouis, C., Christmann. J. & Mariotti, A. (1983) Cinq années d'utilisation de l'isotope 15 de l'azote sur betteraves sucrières en plein champ. *Proceedings of the IIRB Congress*. pp. 99–115.

Loomis, R.S. & Nevins, D.J. (1963) Interrupted nitrogen nutrition effects on growth, sucrose accumulation and foliar development of the sugar beet plant. *Journal of the American Society of Sugar Beet Technologists* **12**, 309–322.

Machet, J.M. (2004) Outils pour la préconisation de la fertilisation azotée des cultures. Gestion de l'azote. *Colloque national Académie d'Agriculture* – Comifer – CORPEN. à paraître.

Machet, J.M. & Hébert, J. (1983) Résultats de six années d'essais sur la prévision de la fumure azotée de la betterave sucrière. *Proceedings of the IIRB Congress*. pp. 493–507.

Machet, J.M., Dubrulle, P. & Louis, P. (1990) AZOBIL: a computer program for fertilizer N recommendations based on predictive balance sheet method. *Proceedings 1st Congress of European Society of Agronomy.*

Marcussen, C. (1985) Amino N figures as used in Denmark. *British Sugar Beet Review* **53** (4), 46–48.

Müller, H.J. (1978) Soluble nitrogen in soil at drilling in relation to soil characteristics and climatological factors. *Proceedings of the IIRB Congress*. pp. 45–52.

Ogden, D.B., Fincker, R.F., Olson, R.F. & Hanzas, P.C. (1958) The effect of fertilizer treatment upon three different varieties in the Red River Valley of Minnesota. 1. Stand, yield, sugar purity and non sugar. *Journal of the American Society of Sugar Beet Technologists* **10**, 265–271.

Olson, R. & Bramstorp, A. (1994) Fate of nitrogen from sugar beet tops. *Proceedings of the IIRB Congress*. pp. 189–212.

Pocock, T.O., Milford, G.F.J. & Armstrong, M.J. (1990) Storage root quality in sugar beet in relation to nitrogen uptake. *Journal of Agricultural Science, Cambridge* **115**, 355–362.

Rémy, J.C. (1981) Etat actuel et perspectives de la mise en œuvre des techniques de prévision de la fumure azotée.

Comptes Rendus de l'Acadamie d'Agriculture de France **67**, 859–874.

Rémy, J.C. & Hébert, J. (1977) Le devenir des engrais azotés dans le sol. *Comptes Rendus de l'Acadamie d'Agriculture de France* **11**, 700–714.

Tomlinson, T.E. (1970) Urea – agronomic applications. *Proceedings of the Fertilizer Society, London*, no. 112.

Ulrich, A. & Hills, F.J. (1969) *Sugar Beet Nutrient Deficiency Symptoms.* University of California, Division of Agriculture Science Bulletin.

Van Burg, P.F.J., Holmes, M.R.J. & Dilz, K. (1983) Nitrogen supply from fertilizers and manure; its effect on yield and quality of sugar beet. *Proceedings of the IIRB Congress*. pp. 189–282.

Von Lüdecke, H. & Nitzsche, M. (1967) Influence of excessive amounts of minerals fertilizers on yield and quality of sugar beets. *Zucker* **20**, 461–466.

Von Müller, K., Niemann, A. & Werner, W. (1962) Influence of nitrogen: potassium ratio on yield and quality of sugar beet. *Zucker* **15**, 142–147.

Webster, R., Hodge, C.A.H., Draycott, A.P. & Durrant, M.J. (1977) The effect of soil type and related factors on sugar yield. *Journal of Agricultural Science, Cambridge* **88**, 455–569.

Winter, S.R. (1984) Cropping systems to remove excess soil nitrate in advance of sugar beet production. *Journal of the American Society of Sugar Beet Technologists* **22**, 285–290.

Chapter 9

Nutrition – Phosphorus, Sulphur, Potassium, Sodium, Calcium, Magnesium and Micronutrients – Liming and Nutrient Deficiencies

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INTRODUCTION

Past reviews

Previous reviews on sugar beet nutrition summarized research mainly from Europe and the USA (Draycott, 1972; 1993). A more recent review (Draycott & Christenson, 2003) brought together nearly a century of research from across the world. This chapter highlights the more important points from that review with some updating. Nitrogen is covered in Chapter 8 and macronutrients (phosphorus, potassium, sodium, sulphur, calcium, magnesium) together with micronutrients (boron, chlorine, copper, iron, manganese, molybdenum and zinc) are considered here. In this chapter, we also include liming practices and nutrient deficiencies. Generally accepted values for the concentration of macronutrients are in excess of 500 mg/kg of plant tissue while those of micronutrients are less than 100 mg/kg (Anon., 2001).

Importance of nutrition research

High priority has been placed on nutrition research wherever sugar beet is grown because of demonstrated yield increases and control of cost by growers. Initially attention was paid to increasing yield; however, the effect of nutrition on processing quality has received more attention since the 1960s. More recently, research has been refocused on strategies aimed at reducing polluting effects of agriculture. Reducing nitrate contamination of ground water has been a focal point of much of this research. In addition, reduction of soil erosion (both wind and water), control of airborne dust and odours along with noise abatement are also receiving attention.

Determining nutrient needs

In common with other crops, only part of the nutrient needs of sugar beet come from the soil. The remainder must be obtained from fertilizers, both mineral and organic, applied in a number of ways including broadcast on the soil surface, banded to the side and below the seed, and foliar spray. Not surprisingly, most of the questions asked of scientists and advisors concern which elements need to be applied in a given soil situation and how much of each is required for optimum yield. The need to answer these questions has led to literally thousands of field experiments worldwide. The amount of work has been considered necessary largely because of the wide range of climate and soil in which the crop is grown.

Efficient use of nutrients

Several developments markedly aided in making more specific nutrient applications, allowing for conservation of resources as well as creating better environmental practices in sugar beet fertilization. Firstly, developments in fertilizer technology to enable bulk blending have revolutionized the fertilizer industry. These include compatibility among sources, correct sizing and density of particles, blending and field application equipment and education programmes (public and private) concerning correct use of these materials. Di-ammonium and mono-ammonium phosphates along with urea are the main materials used in the blending operations. Muriate of potash (KCl) is also used with sodium, calcium, magnesium, sulphur and micronutrients.

Secondly, soil analysis (soil testing) supporting fertilizer recommendations has gained acceptance in many countries. Methodology has been developed over a period of 80 years with much attention paid to analysis for phosphorus. Methods giving repeatable results and correlated with plant response are now commonly used in most laboratories. Procedures developed for phosphorus include Bray and Kurtz P_1 (1945) and Olsen bicarbonate extractable phosphorus (Olsen *et al.*, 1954). Draycott and Durrant (1970a) worked out a procedure for magnesium specifically for sugar beet. Development of methods for micronutrients was aided by improvement in analytical instruments making analysis more easily done. Brown (1998) presents procedures adaptable to a wide range of soils in temperate regions, where most of the sugar beet crop is produced. Specific recommendations are available from agricultural universities in the USA, governmental agencies in many countries and private sources as well.

A combination of proper sampling, utilizing well-developed methods and fertilizer recommendations combined with the fertilizer technology provides a system for making judicious use of fertilizer in the production of sugar beet. The system promotes a saving in cost of unwarranted fertilizer on fields with adequate nutrients and correct application on fields deficient in nutrients. In addition to reducing expenses for the producer, protection of the environment from incorrect use of nutrients is promoted.

Thirdly, strides have been made in the use of plant analysis as an aide in fertilizer use. Critical values for nutrient concentration have been determined. Such information can be used to assess the fertilizer programme along with making corrections during the growing season. However, timely sampling and rapid return of the results are necessary for this tool to be effective for 'in season' adjustments of plant nutrition.

Variability of nutrient status of soils

Concentration of plant-available nutrients present in soils varies widely both between regions, but also within regions as a result of a number of factors. Some soils in parts of Spain, North Africa, the Middle East and the USA have grown sugar beet for relatively short periods of time. The soil test values of these areas are generally low. In other areas of the USA and northern Europe with more intensive cropping and fertilizer use, the soil test values for available nutrients have increased. Many of these soils have major nutrients in nearly adequate amounts needed by sugar beet and other crops. By eliminating supply of macronutrients as a limiting factor, micronutrient additions are needed more frequently. Nutrient variability within fields requires a careful programme for sampling soil. It is essential that such sampling and analysis lead to the best use of fertilizer resources for production of sugar beet.

PHOSPHORUS

Considerable attention was paid to the phosphorus needs of sugar beet during the twentieth century as the nutrient was in short supply in many soils. During the first 60 years of the century, fertilizer sources contained only a small ($< 10\%$ P_2O_5) concentration of available nutrient. In addition, fertilizer was comparatively expensive, limiting amounts applied at any one time. Consequently, available reserves in the soil did not increase. In the latter half of the twentieth century higher analysis phosphorus sources ($> 30\%$ P_2O_5) coupled with lower relative cost led to greater amounts applied. In turn accumulation of available reserves supplied crop needs with no further additions. Consequently, less attention was paid to phosphorus, nutrition research shifting to environmental issues and needs for micronutrients and sulphur.

Total phosphorus in soils

Total phosphorus (400–4000 mg P/kg) in the soil generally reflects the low concentration in parent materials. Much of the phosphorus in rocks is in the form of apatite ($Ca_{10}(PO_4)_6X_2$ (where: X may be OH^-, Cl^- or F^-). During weathering, phosphorus is released as the soluble ions $H_2PO_4^-$ and HPO_4^{2-}, to be either taken up by roots or rendered insoluble again through precipitation or adsorption. Fertilizer additions have increased the total phosphorus in soils in some cases. At Rothamsted, where plots have received a moderate amount annually since the beginning of the twentieth century, total concentration has increased threefold, nearly all of the change being in the surface 25 cm of soil. Additional inputs from farmyard and other organic manures may also increase phosphorus in soils.

Fate of applied phosphorus

Phosphorus applied in commercial fertilizers or organic manures add directly to labile (available) and non-labile forms. In soils with high pH (above 7.3) added phosphorus reverts through a series of calcium phosphates ultimately becoming apatite. The intermediate forms contribute to the labile phosphorus pool, which is why sugar beet often yields well on these soils.

In slightly acid to neutral soils (pH 6.1–7.3) calcium phosphates mentioned above may exist, but in the presence of K^+ and NH_4^+ from fertilizers or manures, compounds similar to taranakites [$Al_5(X_3)H_8(PO_4)_6$, where X may be K^+ and/or NH_4^+] are also formed. In addition aluminium phosphates form in this pH range, and all contribute to the labile pool.

Available phosphorus in soils

Phosphorus is present in solution as HPO_4^{2-} or $H_2PO_4^-$ at the pH range of crop production. Since concentration in solution is usually < 0.1 mg P/kg, rate of replenishment to solution is critical during rapid growth of the crop, coming from labile phosphorus mentioned earlier. Allison and Chapman (1995) found the topsoil (0–30 cm) of a typical sugar beet field contained less than 2 kg P_2O_5/ha in the immediately available form. Labile phosphorus amounted to 50 kg P_2O_5/ha or about 1% of the total in the top soil. Unavailable fractions predominated with that bound in the organic matter accounting for most (3.5 t P_2O_5/ha or 70%) and iron, calcium and aluminium phosphates accounting for 1.5 t P_2O_5/ha, or about 30% of the total.

Mycorrhiza

While many plant species have association with mycorrhiza (mycorrhizal symbiosis), this mutually beneficial relationship is absent in sugar beet. Tinker *et al.* (1992) reported in mycorrhizal plants external hyphae absorb and translocate nutrients from non-depleted zones, effectively increasing root length by up to threefold. Practical implications of the absence of mycorrhizas in sugar beet have received little attention. Some evidence suggests larger amounts of fertilizer phosphorus need to be applied for sugar beet as compared to 'mycorrhizal crops' including cereals, maize, soya and lucerne. Draycott and Christenson (2003) suggested correlations between crop response to fertilizer phosphorus and soil analysis are closer in sugar beet because uneven amounts of colonization may cause variability in mycorrhizal crops.

Phosphorus in sugar beet

Physiological roles of phosphorus are summarized in Table 9.1. While the structural roles of this element are indeed important, the role played in energy transfer mediated by adenosine triphosphate (ATP) is better known. These reactions occur in respiration, photosynthesis and sugar production. Other reviews in addition to Marschner (1995) include Kirkby *et al.* (1987) and Terry and Ulrich (1973).

Draycott and Christenson (2003) summarized existing data concerning phosphorus concentration in sugar beet. The average (Table 9.2) suggests 0.34% in tops and 0.15% phosphorus in roots is adequate for optimum growth. Concentrations less than these values represent conditions where deficiency is likely.

Range in uptake varies from as little as 5 kg P_2O_5/ha as a result of low yields and restricted soil

Table 9.1 The physiological role of macronutrients in sugar beet growth (after Marschner, 1995).

Nutrient	Role
Phosphorus	Structural: Nucleic acids (DNA, RNA), Phospholipids, Phytic acid Energy Transfer: ATP, ADP
Sulphur	Amino acid constituent: Cysteine and methionine Coenzyme and prosthetic groups: Ferredoxin, biotin, thiamine, pyrophosphate, coenzyme A, APS sulfotransferase Structural: Sulfolipids
Potassium	Enzyme activation: More than 50 enzymes are affected by potassium Protein synthesis Photosynthesis: CO_2 fixation Osmoregulation: Cell extension, stomatal movement, nyctinastic and seismonastic movements, phloem transport, cation–anion balance
Sodium	Substitution for potassium: Sparing effect Cell expansion and water balance Stomata numbers and function
Calcium	Cell wall stabilization: Polygalacturonic acids (pectins) Osmoregulation: Cell extension, cation–anion balance Membrane stabilizaton Enzyme modulation
Magnesium	Chlorophyll synthesis: Central atom of molecule Cellular pH control Protein synthesis: Aggregation of ribosome subunits, RNA formation Enzyme activation: Phosphatases, ATPases, carbosylases

Table 9.2 Concentration and uptake of phosphorus by sugar beet at harvest (after Draycott & Christenson, 2003).

P concentration (% dry weight)			Uptake (kg P_2O_5/ha)		
Roots	Tops	Rating	Roots	Tops	Total
0.13 or less	0.29 or less	Deficient			
0.15 or more	0.34 or more	Adequate	45	35	80

reserves to exceeding 100 kg/ha. However, much data suggest total uptake of 80 kg P_2O_5/ha is adequate for high yields (Table 9.2). Excessive nitrogen availability, producing top growth greater than needed for optimum growth, causes values exceeding this amount.

Response to applied phosphorus

Under conditions of low supply of phosphorus, seedlings lack vigour, grow slowly and produce small plants resulting in loss of stand due to susceptibility to physical damage. A supply of phosphorus fertilizer around the roots has a visible effect on vigour, size and plant number (Davis *et al.*, 1961; 1962; Romsdal & Schmehl, 1963; Sipitanos & Ulrich, 1969). Sims and Smith (2001) showed that a reduction in yield because of insufficient phosphorus is initiated very early and is maintained throughout the growing season. Even though the above-ground sugar beet growth appears to return to near normal as the growing season progresses, root yield potential may already have been reduced.

Olsen *et al.* (1954) proposed using sodium bicarbonate as an extractant for available phosphorus from soils. Draycott and co-workers (Draycott *et al.*, 1971; Draycott, 1972; Draycott & Durrant, 1976; Draycott, 1993) worked out and reported correlation and calibration data leading to fertilizer recommendations based on soil analysis. Analogides *et al.* (1987b) and Sanz Saez (1985) con-

Table 9.3 Recommended amounts of fertilizer phosphorus for economic optimum based on sodium bicarbonate extractable concentration (Draycott & Durrant, 1976; MAFF, 2000).

	Extracted phosphorus (mg P/l)			
	0–9	10–15	16–25	25 and above
Amount recommended (kg P_2O_5/ha)	100	75	50	0

firmed the merits of this procedure in Greece and Spain, respectively. This method is widely adopted as a guide for phosphorus fertilization of sugar beet (Table 9.3).

Time, form and method of application

Early work by Adams (1961a), Larson (1954) and Schmehl *et al.* (1952; 1954) showed no important differences between autumn and spring application. More recently, Allison *et al.* (1994) confirmed that time of application had no effect on sugar yield, providing no soil compaction occurred from the application equipment. Some success was obtained by applying 10 kg P_2O_5/ha directly with the seed on low testing soils in the Red River Valley, USA (Sims & Smith, 2003). However, more work is needed to detail the conditions where this method is advantageous.

Water solubility is an important property of phosphorus fertilizer materials (Olsen *et al.*, 1950; Engelstad & Terman, 1980). Those used in the market today are nearly 100% water soluble and include di-ammonium phosphate, mono-ammonium phosphate and mono-calcium phosphate (triple super phosphate). Also ammonium polyphosphates, in both liquid and solid forms are utilized in some fertilizer programmes. It is expected these sources perform equally (Murphy, 1979). Siegenthaler (1987) reported phosphorus from sewage sludge is similar in availability to growing plants as concentrated super phosphate.

Early reports from experiments conducted on soils with low concentrations of phosphorus showed benefits of placement of fertilizer to the side and below the seed (Millar *et al.*, 1938; 1940; 1945; Haddock, 1952; Lawton *et al.*, 1954; Davis *et al.*, 1962; Moraghan & Etchevers, 1981; Papanicolaou *et al.*, 1982; Yerokun & Christenson, 1989). Other reports showed no difference between such placement and broadcast phosphorus, but on soils with higher concentrations of phosphorus (Romsdal & Schmehl, 1963; Christenson *et al.*, 1975; Dunham, 1991a,b). However, there may be added efficiency of micronutrients (manganese, iron, zinc, copper) applied in a band containing an acidic source of phosphorus (Murphy & Walsh, 1972; Voth & Christenson, 1980).

SULPHUR

Sulphur in soil

Sulphur, like phosphorus, is taken up as an anion (SO_4^{-2}) by the sugar beet crop. Both elements are taken up in similar quantities, but sulphur is not bound to soils as is phosphorus.

The concentration of sulphur ranges from 200 mg S/kg soil on sandy soils to as much as 3 g S/kg on saline soils with little leaching (Syers *et al.*, 1987). The sulphate form is usually regarded as plant available and comprises less than 5% of the total while the remaining 95% is in the organic form (Scherer, 2001). Inorganic forms are derived from parent material, atmospheric deposition and from oxidation/reduction of soil organic sulphur. Organic forms include plant residues, organic manures, microorganisms and humified organic matter.

Decomposition of organic matter in the soils oxidizes organic sulphur to the sulphate form. In this manner sulphur behaves more like nitrogen than any other element. Generally oxidation occurs when the C:N ratio is less than 20, corresponding to a C:S ratio of 200:3. Sulphate ions are weakly held by the soil, move to the roots by mass flow in response to the transpiration stream and are subject to leaching. However, sulphate ions are adsorbed by sesquioxides present in subsoils as a result of soil forming processes. Sparse information is at hand addressing the availability of sulphate bound in this manner.

Little evidence is available relating soil test values for sulphate and response to applied sulphur by sugar beet. Ions that replace sulphate ions (OH^-, $H_2PO_4^{-1}$ and HCO_3^{-1}) are often used to extract sulphate. Sodium bicarbonate extraction has produced results that correlate with uptake by some crops. However, several studies have also shown the amount extracted with phosphate solutions predict soils that are sulphur deficient (Syers *et al.*, 1987). Armstrong (1985) showed available sulphur concentrations range from 8 to 41 mg SO_4^{2-}/l soil.

Sulphur in plants

The functions sulphur plays in higher plants include structural roles (amino acids, coenzymes, enzymes, sulfolipids in membranes and in polysaccharides) and supplying functional groups in metabolic reactions (Table 9.1). A ratio of nitrogen to sulphur is usually about 15:1 by weight in healthy plants. Where the ratio is greater, a shortage of sulphur might be the cause. There may also be unusual concentrations of certain amino acids (e.g. arginine, as suggested by Hocking (1995)) when the balance between nitrogen and sulphur is upset. When sulphur is deficient, the concentration of the sulphur-containing amino acids is decreased, but glutamine may be greatly increased (Sexton, 1996). McGrath (2000) found that the ratio of malate to sulphate was affected in sulphur-deficient plants and proposed that the ratio could be used as an indicator of deficiency.

There is a paucity of information on the range of concentrations expected in healthy and deficient sugar beet crops and the quantity taken up by roots and tops (Draycott & Christenson, 2003). Data compiled in Table 9.4 suggests that either (a) sugar beet concentrations vary widely in both top and root dry matter; or (b) there are discrepancies in the analytical techniques employed.

Data for uptake of sulphur by the sugar beet crop shows similar variability (Table 9.5). There is no clear relationship between yield and uptake of sulphur. Clearly, more work is needed to determine accurately the expected concentration and its range in healthy and deficient crops along with the amount of sulphur taken up by the sugar beet crop.

Studies measuring yield response from applied sulphur

There are very few reports of clear evidence of shortage of sulphur on sugar beet anywhere in the world. The earliest was that of Ulrich and Hills (1969), who illustrated response to sulphur fertilizer in California. However, there were no further reports from California concerning needs for supplemental sulphur fertilizer. Later trials in the USA showed no response to applied sulphur (Robertson *et al.*, 1976a; D.R. Christenson, 1986 unpublished

Table 9.4 Concentration of sulphur in healthy and deficient sugar beet plant parts (after Draycott & Christenson, 2003).

	% S in dry matter		
Portion of plant	Healthy	Deficient	Reference
Leaf blades	0.05–1.4	0.005–0.02	Ulrich & Hills, 1969
Leaf blades	0.4–0.7	–	Bravo *et al.*, 1989
Petioles	0.1–0.3	–	
Crowns	0.08–0.28	–	
Roots	0.01–0.15	–	
Whole leaves (solution culture)	0.4–0.5	0.1–0.2	Hocking, 1995
Tops	0.8–1.1	0.6	Sexton, 1996
Roots (field-grown)	0.2	0.1	
Recent fully expanded leaves (field-grown)	> 0.3	< 0.3	Connors, 2000
Tops	0.30–0.35	–	F. Zhao, UK, 2002, personal communication
Roots	0.03–0.04	–	

Table 9.5 Uptake of sulphur by field-grown sugar beet (after Draycott & Christenson, 2003).

Tops (kg S/ha)	Roots (kg S/ha)	Total (kg S/ha)	Yields	Reference
7–23	8–16	15–39	Low	Syers *et al.*, 1987
		50–70	Average	Armstrong, 1985
8	5	13	Average	Bravo *et al.*, 1989
	20–50	100	High	Armstrong, 1985
10	6	16	Very high	Jourdan *et al.*, 1992

data; Lamb, 1989). No other reports concerning work with sulphur in the USA were found.

Armstrong (1985) in the UK noticed slight paling of leaves in some of his experiments where sugar beet was grown on soils containing a small concentration of available sulphur but there was no response.

Atmospheric deposition

In a survey by Sexton (1996), deposition from the atmosphere ranged from 10 to 40 kg S/ha. Sulphur concentration in leaves taken in July ranged from 0.6 to 1.1%, concentration reflecting the amount of atmospheric deposition. However, this concentration is well above the 0.35% critical value suggested by Hocking (1995) based on solution culture work.

There is no doubt that atmospheric deposition now is only a fraction of what it was in 1980. This would suggest the need for sulphur application on field crops including sugar beet in the future. If this is the case, there is a range of inexpensive materials that could be used – gypsum, 15–18% S; kieserite, 20% S; ammonium sulphate 24% S – all fitting into sugar beet production practices. In addition, elemental sulphur may be used as it is currently on other crops.

New experiments are needed to establish the need for supplemental sulphur. This work should include studies on the concentration and uptake of sulphur, availability of sulphur from subsoil sesquioxides and further evaluation of methods for predicting needs.

POTASSIUM

Potassium and sodium (see following section) are two important monovalent cations in sugar beet nutrition. Both are macronutrients, being taken up and utilized in large quantities by sugar beet crops, particularly when producing optimum yield. Potassium has been shown to greatly improve early vigour and growth, often with an increase in sugar yield. When sugar beet tops are removed, large quantities of potassium are also removed from the soil. Such fields need additions of potassium in fertilizers and/or manures because few soils release sufficient to maintain yield.

Potassium in soil

Potassium concentration in soils of the USA and UK range from 0.3 to 2.5% on a dry weight basis giving a range of 9–75 t/ha for a soil weighing 3000 t/ha (Whitehead, 2000). Figure 9.1 shows the dynamics of potassium in a typical soil from the UK and probably other soils in humid temperate sugar beet producing areas. Available potassium is made up of water soluble and exchangeable, the latter comprising the majority of this fraction. Release of fixed potassium to available forms from primary minerals such as feldspars is very slow (years) while being reasonably rapid (weeks to months) from clay minerals such as illite and vermiculite. Potassium added from mineral or organic sources readily enters the available pool in Fig. 9.1.

Potassium in sugar beet

Potassium is a monovalent ion highly mobile in the sugar beet plant, not entering into physical structures within the plant. A listing of these functions is given in Table 9.1. Läuchli and Pflüger (1978) also give a comprehensive discussion of potassium in plants.

Potassium concentration declines over the course of the growing season from 7% in leaf and 6% root in April to 3% and 1%, respectively, in August. The average concentration of potassium in top dry matter at harvest is about 3%, whereas

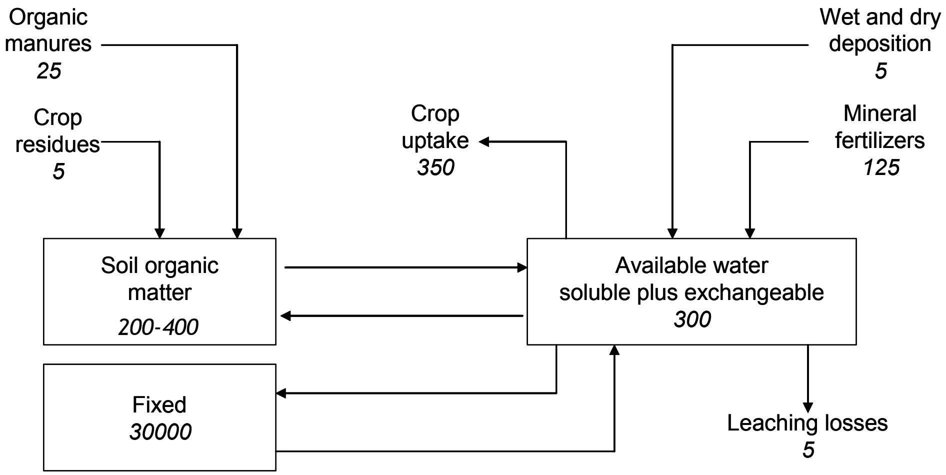

Fig. 9.1 Potassium dynamics of a typical soil where sugar beet is produced (kg K_2O/ha) (after Draycott & Christenson, 2003).

the concentration in root dry matter is about 0.8%, although values frequently range from 2.0–3.5% for tops and 0.6–1.0% for roots (Table 9.6).

As pointed out before, sugar beet takes up large quantities of potassium, tops containing greater amounts than roots. Draycott (1993) suggested tops contained 1.5 times the amount of roots. However, limited data appear in the literature measuring quantity of potassium taken up by sugar beet. What data exist show wide variability ranging from 168 to 660 kg K_2O/ha corresponding to 3.5–8.2 kg K_2O/t of sugar beet (Table 9.7).

Table 9.6 Potassium concentration in roots and tops of sugar beet at harvest (after Draycott & Christenson, 2003).

Concentration (% of dry matter)			
Roots		Tops	Reference
0.77		3.0	Draycott, 1972
–		3.5	Moraghan & Ananth, 1985
0.98	Laminae	3.6	Analogides, 1987a
	Petioles	5.0	
0.79		2.6	Bravo *et al.*, 1989

Table 9.7 Quantity of potassium in sugar beet at harvest (after Draycott & Christenson, 2003).

Tops (kg K_2O/ha)	Roots (kg K_2O/ha)	Total (kg K_2O/ha)	Root yield (t/ha)	Total crop uptake (kg K_2O/t roots)	Reference
204	132	336	50	6.72	Durrant & Draycott, 1971
144	112	256	42	6.40	Draycott, 1972
		306			Beringer, 1987
	134		63		Frankinet *et al.*, 1987
		308	50	6.16	Jansson, 1987
		660	81	8.15	Kirkby *et al.*, 1987
		350	94	3.72	Kirkby *et al.*, 1987
140					Vanstallen & Vandergeten, 1987
290	190	480	86	5.58	Analogides, 1987a
74	94	168	48	3.50	Bravo *et al.*, 1989
	70–170		70		Armstrong *et al.*, 1999
	25–230		20–100		Milford *et al.*, 2000
	70–240		60–105		Hollies *et al.*, 2001

Assessing the removal of potassium in the harvest of roots is useful in formulating fertilization guidelines. Hollies *at al.* (2001) from 72 fields found that 60 t of beet removed 100 kg K_2O and this increased linearly to 170 kg for 100 t of beet. Previously Hollies (2000) proposed a value of 1.7 kg K_2O removed per tonne of beet. This value has been adopted in commercial practice (MAFF, 2000).

In separate studies in France and the UK, results showed the pattern of uptake was similar, 400–500 kg K_2O/ha (Fig. 9.2). Initially slower in the UK due to cooler weather, a period of rapid growth occurred in both countries averaging an uptake of 8.5 kg K_2O/day with a maximum of 15 kg K_2O/day.

Response to applied potassium

Durrant *et al.* (1974a,b; 1978) assessed some 200 experiments in Europe, testing the effect of potassium and sodium on yield of sugar. There was a marked response to increasing quantities of applied potassium without sodium. However, in the presence of sodium, the response was not as great and the apparent optimum amount may be less than without sodium.

Draycott (1993) showed response to applied potassium alone is directly related to extractable soil potassium concentration (Table 9.8). Jarvis and Bee (1996) in later trials found less response to applied potassium than seen before. Large concentration of potassium in many soils where sugar beet is produced probably contributes to the limited response to potassium.

Application recommendations based on soil test

As pointed out in Table 9.8, there appears to be a good relationship between extractable potassium and amount needed by the crop. Table 9.9 compiles information from numerous field trials into the best advice on quantities of potassium needed for sugar beet (MAFF, 2000). The amounts are based on a yield of 60 t roots/ha. It is assumed that the crop is supplied with sufficient sodium either from fertilizer or from that already present in soil (as is the case with some organic, silt and arid soils).

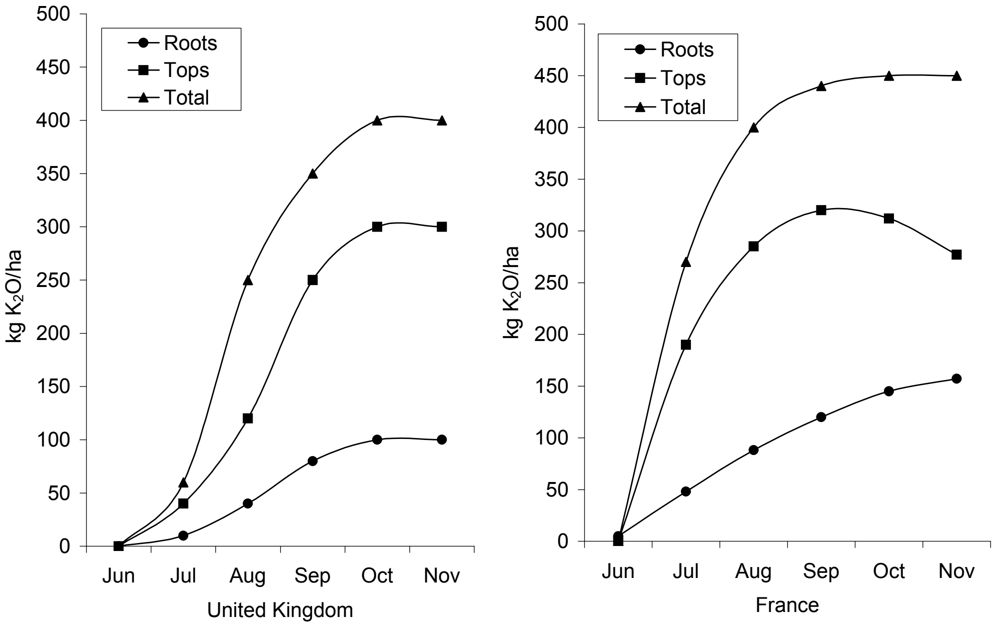

Fig. 9.2 Uptake pattern of potassium by high-yielding sugar beet in the UK and France (after Draycott & Christenson, 2003).

	Soil potassium concentration in ammonium nitrate extract (mg/l of soil)			
	0–60	61–120	121–240	241–400
Increase in sugar yield (t/ha)	+1.13	+0.70	+0.60	+0.40

Table 9.8 Soil potassium concentration and the effect of potassium fertilizer on yield in 100 fields (Draycott, 1993).

Table 9.9 Amounts of potassium fertilizer recommended for sugar beet in the UK (MAFF, 2000) and USA (Hills *et al.*, 1982; Christenson *et al.*, 1992; Lichthardt & Jacobsen, 1992; Blaylock *et al.*, 1996; Franzen & Cihacek, 1996; Mortvedt *et al.*, 1996; Binford *et al.*, 2000; Blumenthal, 2001; Lamb *et al.*, 2001).

	(mg K/l soil)				
UK	0–60	61–120	121–180	181–240	241+
Index	0	1	2–	2+	3 and above
Category	Deficient	Low	Moderate	High	
Amount of potassium advised (kg K_2O/ha)	150	125	100	75	0
	(mg K/kg soil)				
USA	0–60	61–120	121–180	181–240	241+
Range of amount of potassium advised (kg K_2O/ha)	166–285	50–151	0–65	0–31	0

Recommendations taken from various sources for sugar beet growing regions in the USA are also in Table 9.9. There is a very large range in amount of potassium recommended, particularly when the soil test value is less than 60 mg K/kg. However, few soils where sugar beet is produced would test less than 60 mg. Even though further work would be needed to reconcile these data, the similarities of the median values are striking between the two continents.

SODIUM

Sodium in soil

Soils developed from igneous rock will have 1–2% sodium and sedimentary material, 0.02–0.1%. In many sandy soils where sugar beet is grown, concentration will be less than 0.02%. Thus, the average furrow slice may contain between 0.6 and 60 t Na/ha. While sodium may be released from primary minerals such as feldspars, most of the readily available sodium will be held as exchangeable. Soils in arid regions may contain sodium as soluble chlorides and sulphates, at times in excessive amounts.

When annual precipitation exceeds evaporation, sodium does not accumulate in soils. Warren and Johnston (1962) found where sodium had been applied annually for a century the increase in exchangeable was only 10 mg/kg (0.04 cmol/kg soil). Tinker (1967) suggested that sodium applied in fertilizer was leached from soils, showing in conclusion no risk from annual application of sodium. Atmospheric deposition of sodium appears to be directly related to the distance from the seashore. Results summarized by Draycott and Christenson (2003) suggest this amounts to less than sugar beet needs; response to applied sodium occurs even in areas of greatest deposition.

Sodium in sugar beet

Sugar beet is unique amongst plants produced for food in that sodium is taken up and utilized. Many plant species have exclusion mechanisms rejecting

Table 9.10 Concentration and quantity of sodium in sugar beet at harvest (after Draycott & Christenson, 2003).

Na concentration (% dry matter)		Quantity Na in crop (kg Na/ha)			
Tops	Roots	Tops	Roots	Total	Reference
3.0	0.05	50	10	60	Draycott & Farley, 1971
1.2	0.08	50	8	58	Draycott, 1972 – average of early work
3.9	–	195	–	–	Moraghan & Ananth, 1985
2.0	0.10	90	10	100	Bravo *et al.*, 1989

sodium. Sugar beet is a halophyte originating in shoreline habitats absorbing and utilizing sodium, which partly replaces potassium.

Evidence for replacement of potassium by sodium comes from several studies. Hawker *et al.* (1974) showed an increase in dry weight of plants grown in 0.05 mM potassium plus 4.95 mM sodium compared to 5.00 mM potassium. Marschner *et al.* (1981) showed marked increases in dry weight, percentage sucrose and grams of sucrose per root with 2.5 mM potassium plus 2.5 mM sodium compared to 5.0 mM potassium in nutrient solutions. More recently, Subbarao *et al.* (1999) suggested sodium could safely replace 95% of the normal tissue potassium without decreasing production of some red beet cultivars. A listing of the role of sodium in sugar beet is given in Table 9.1.

Concentration of sodium in sugar beet tops ranges from 1.2 to 3.9% and in roots, 0.05 to 0.10% (Table 9.10). Total uptake ranges from 60 to 100 kg/ha, the lower values associated with low yields. Generally the amount in tops ranges from 5–10 times that in roots.

Response to applied sodium

Early on, it was thought sodium applied mobilized soil potassium reserves, enhancing the potassium status of the plant. However, Adams (1961b) evaluated analyses done by Hale at Rothamsted showing sodium application increased sodium uptake, not potassium. Sodium and potassium were distributed differently in the plant at harvest; only 6% of the total sodium was in the root compared with 33% of the potassium. The conclusion was that sodium was an essential nutrient for sugar beet and not a potassium substitute. Additional work by Draycott and co-workers (Draycott, 1969; Draycott *et al.*, 1970; Draycott & Farley, 1971) confirmed the need for sodium in sugar beet production on soils containing little exchangeable sodium. Results from over 200 experiments (Durrant *et al.*, 1974a) are presented in Fig. 9.3 showing the additive effect of sodium plus potassium on root yield.

Sodium increases sugar yield by several independent effects. Early in the year, coinciding with maximum solar radiation and day length, sodium increased leaf area index (as a result of increased leaf size, not number). Another mechanism by which sodium increased sugar yield was by increasing the proportion of total dry matter parti-

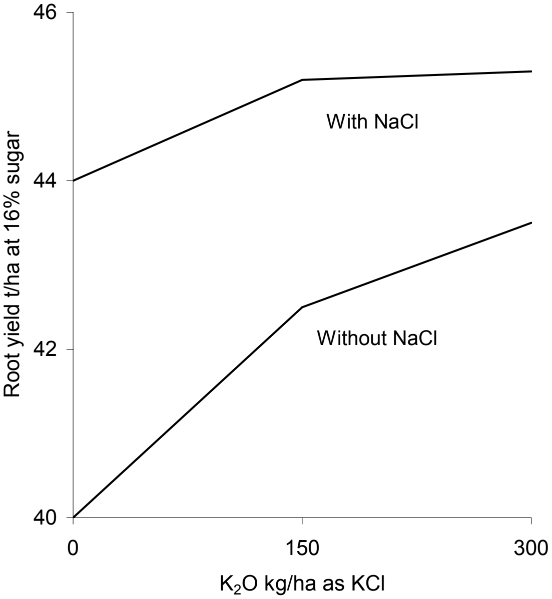

Fig. 9.3 Interaction of potassium and sodium chloride fertilizers on sugar beet yield (Durrant *et al.*, 1974a).

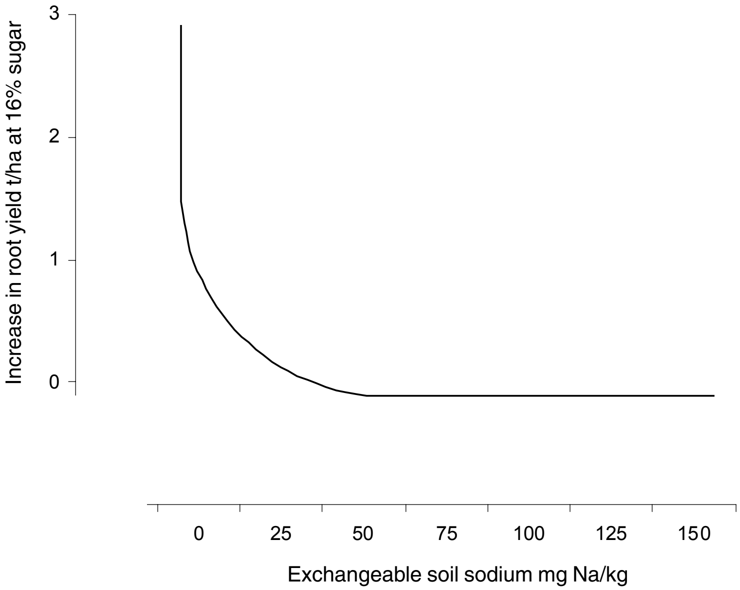

Fig. 9.4 Root yield response to applied sodium (150 kg Na/ha) at increasing concentration of exchangeable sodium (after Draycott, 1993).

tioned to roots. Sodium also improved the sugar percentage of fresh roots (Farley & Draycott, 1974; Durrant *et al.*, 1978).

Predicting sodium need by soil analysis

Predicting sodium needs by soil testing has been worked out by a number of authors (Durrant *et al.*, 1974a,b; Draycott *et al.*, 1976; Draycott & Bugg, 1982). This work is summarized in Fig. 9.4 and shows when exchangeable sodium is in excess of 75 mg/l soil there is no response to applied sodium.

CALCIUM

Calcium in soil

Calcium concentration in soils ranges from 0.1 to over 3%, derived from the primary minerals anorthite, pyroxene and amphibole, and is present in calcitic and dolomitic limestone, chalk, apatite (calcium phosphate) and gypsum (calcium sulphate, $CaSO_4\ 2H_2O$). Old soils, soils derived from acidic parent material and those highly weathered and leached have the smallest calcium content. Soils formed from alkaline or calcareous materials contain large quantities of calcium and those containing greater than 3% Ca are defined as calcareous (Anon., 2001). These are easily identified by effervescence with addition of a few drops of molar mineral acid. Such soils are widely used for sugar beet production.

The amount of calcium is usually greater in soils containing clay since that released from minerals into soil solution is quickly adsorbed on the exchange complex. Robertson *et al.* (1976b) reported that fine-textured soils contained from 1700 to 3600 mg Ca/kg soil while coarser soils ranged from 625 to 2400 mg Ca/kg. Calcium in soil solution ranges from 30 to 300 mg/l for non-calcareous soils and up to 700 mg/l in calcareous soils.

Calcium in sugar beet

Calcium plays two roles in the production of sugar beet crops. It is an essential plant nutrient and is a major factor in controlling pH of soils, covered in a later section. Deficiency symptoms of calcium are rarely seen in the field because production is done on neutral and alkaline soils. Even in soils with pH as low as 5.5, there is often sufficient calcium to support crop growth.

An important role of calcium in plants is to provide stability to cell walls by the formation of calcium pectate in the middle lamella and in some plants calcium polysaccharides in cell walls (Table 9.1). More recently, Kauss (1987) reported that a number of enzymes require calcium for activation. Bush (1995) reported that calcium regulates ionic balance, mobility, gene expression, carbohydrate metabolism, mitosis and secretion. Furthermore, calcium appears to 'detoxify' other ions and counteracts the effect of low pH on nutrient uptake. Since calcium is translocated in the xylem but not in the phloem, it is rather immobile and not readily redistributed within the plant.

Healthy sugar beet leaves were reported to contain 2.65%, whereas deficient leaves contained 0.66% calcium (Wallace, 1945). More recently, Ulrich and Hills (1969) suggested deficient leaf blades contained less than 0.4% Ca; non-deficient leaves greater than 0.4%. In a 5-year study, Draycott (1972) reported the mean concentration for tops to be 1.00% and roots 0.24% calcium.

The same study showed that sugar beet contained 12–31 kg Ca/ha in roots and 18–67 kg Ca/ha in tops. The mean was 22, 41 and 63 kg/ha for roots, tops and total, respectively. A summary of reports on amount of calcium taken up is quite variable (Table 9.11). A close relationship exists between the growth pattern and calcium uptake, and therefore plants need a good supply over the course of the season. Variability in the amount of calcium contained in a sugar beet crop may be related to the variety grown (Finkner *et al.*, 1958) but there is a paucity of information on varietal differences.

Table 9.11 Uptake of calcium by sugar beet (after Draycott & Christenson, 2003).

Range (kg Ca/ha)	Mean (kg Ca/ha)	Yield (t/ha)	References
80–100	–	33	Cooke, 1967
40–220	–	60	Viets & Robertson, 1971
30–98	63	–	Draycott, 1972
–	80	–	Robertson *et al.*, 1976b
–	120	60	Bravo *et al.*, 1989

Dynamics of calcium in sugar beet

As suggested previously, sugar beet needs a continuous supply of calcium for growth and development. Ulrich and Mostafa (1976) showed that when sugar beet plants were transferred to nutrient solutions minus calcium, deficiencies developed regardless of growth stage when transferred. Addition of calcium corrected deficiency on new growth, but did not eliminate symptoms on old growth.

Plants do not compete for calcium as well as for other cations. Calcium is absorbed only where the cell walls of the endodermis in young root tips are unsuberized, whereas other cations are absorbed along the entire length of the root (Clarkson *et al.*, 1968; 1971). As a result sugar beet plants grown in nutrient culture depleted the concentration of potassium, sodium and magnesium in solution to 1 mg/l before deficiency symptoms appeared, whereas calcium deficiency symptoms occurred when the concentration in solution was 50 mg Ca/l (Berry & Ulrich, 1968).

Berry and Ulrich (1970), in a nutrient culture study, found calcium deficiency symptoms developed progressively as potassium concentration was increased at a given calcium concentration. An adequate concentration of both elements was necessary for translocation of calcium throughout the plant and an absence of deficiency symptoms. Sugar beet roots absorbed calcium when potassium was limiting, but it was not translocated to the leaves.

There is a mutually inhibiting effect on absorption between calcium and magnesium. Mostafa and Ulrich (1976) and Ulrich and Mostafa (1976) found sugar beet did not grow well when the calcium:magnesium ratio was 0.33 or less. This was true regardless of concentration of the respective ions. Their conclusion was that the ratio of calcium:magnesium in the nutrient solutions might limit calcium uptake by sugar beet.

Cation ratios in soils

The effect of cation ratios on crop growth and yield has been the subject of numerous studies on a range of crops over the past 70 or more years. McLean *et al.* (1983) showed that a specific cation ratio for optimum production of maize, soybean, wheat and lucerne does not exist. Rather cations should be supplied in adequate, but not excessive amounts. We suggest the same to be true for sugar beet. Supply of adequate but not excessive amounts of potassium, sodium and magnesium are given in respective sections in this chapter. Calcium is adequately supplied for sugar beet production on well-limed or alkaline soils.

MAGNESIUM

Magnesium in soil

Magnesium is present in primary minerals such as biotite, serpentine, hornblende and olivine, and as a structural component of the clay minerals chlorite, vermiculite, illite and smectite. The usual range in concentration of total magnesium in soils is 0.7–1.0%. However, soils formed from dolomitic limestone may contain up to 10% magnesium. Also in arid regions the element may be present in quantity as epsomite ($MgSO_4\ 7H_2O$). Generally, these minerals and clays release sufficient quantities for most crops.

Available magnesium is that in soil solution plus exchangeable and is taken up as Mg^{2+}. This exchangeable or 'available' concentration in soils usually ranges from 10 to 500 mg Mg/l soil. A simple extraction procedure with an aqueous salt solution (commonly ammonium nitrate or acetate) reflects the amount readily available to sugar beet and other crops.

The amount of exchangeable magnesium in soils is directly related to the amount of clay-sized material. For example, Robertson *et al.* (1979) noted that clay and clay loam soils ranged from 250 to 500 mg Mg/kg, loam and sandy loam from 150 to 450 mg Mg/kg and loamy sand and sands from 30 to 175 mg Mg/kg. Consequently, deficiencies occur more frequently on coarser textured soils.

Magnesium in sugar beet

Magnesium is the central atom of chlorophyll, playing a vital role in plant growth. Major involvement in energy transfer involves enzymes referred to as ATPases that use magnesium ATP as a substrate. Consequently, magnesium also plays an extensive role in reactions associated with respiration and photosynthesis. General roles of magnesium in plants are given in Table 9.1.

A generally accepted concentration of magnesium in leaf blades, below which deficiencies occur, is 0.20% (Ulrich & Hills, 1969). A survey of literature showed when leaf blades exhibited deficiency symptoms concentration ranged from 0.010 to 0.219 with a mean of 0.120 while those without symptoms ranged from 0.100 to 0.700 with a mean of 0.444 (Draycott & Christenson, 2003). Magnesium concentration in leaf blades reaches a maximum in August followed by a decline until harvest (Bravo *et al.*, 1989; Draycott, 1993). Uptake of magnesium is related to amount supplied by fertilizer (Table 9.12). Average total uptake is of the order of 23 kg/ha with 70% in the tops.

Table 9.12 Uptake of magnesium by sugar beet.

Mg applied (kg Mg/ha)	Tops (kg Mg/ha)	Roots (kg Mg/ha)	Total (kg Mg/ha)	Reference
0	–	–	22	Bolton & Penny, 1968
44	–	–	37	
88	–	–	46	
0	8	9	17	Durrant & Draycott, 1971
100	10	11	21	
0	8	4	12	Draycott & Durrant, 1972a
50	11	6	17	
100	15	6	21	
0	–	–	15	Draycott & Durrant, 1972b
100	–	–	19	
0	28	8	36	Bravo *et al.*, 1989

Table 9.13 Magnesium fertilizer requirement as determined by the amount of exchangeable soil magnesium extracted with ammonium nitrate solution (Draycott & Allison, 1998).

Concentration in soil (mg Mg/kg)	Fertilizer (kg Mg/ha)
0–15	100
15–25	75
25–50	50
50+	0

Predicting magnesium needs by soil testing

Table 9.13 from Draycott and Allison (1998) shows the relationship between exchangeable soil magnesium and the recommended magnesium application. Soil containing less than 50 mg/kg should have magnesium applied.

In the USA, recommendations developed for other crops are used, based on extraction with molar ammonium acetate solution adjusted to pH 7.0. In Michigan, magnesium is recommended when the extractable concentration is less than 35 mg/kg of soil (Christenson *et al.*, 1992). On non-acidic soils, 10–20 kg Mg/ha is recommended for a band placement near the seed and 50–100 kg Mg/ha for broadcast material. Periodic application is needed to maintain magnesium supply for sugar beet when soluble sources are used. Dolomitic limestone is preferred on magnesium-deficient soils needing lime in the USA, as in the UK.

Fertilizer sources of magnesium

Kieserite (17% Mg), Epsom salt (10%), kainit (4.5%), calcined magnesite (48%) and dolomitic limestone (11%) are common sources available for application. Draycott and Durrant (1969a,b; 1970a,b) evaluated the effectiveness of these sources. All were effective (limestone on acidic soils) in correcting the deficiency.

MICRONUTRIENTS OR TRACE ELEMENTS

Table 9.14 shows the concentration of micronutrients in healthy sugar beet and approximate amounts taken up by tops and roots at harvest. Sugar beet is not equally susceptible to a shortage of all micronutrients. Under conditions of low supply, the crop is most responsive to boron, iron and manganese, moderately responsive to copper, molybdenum and zinc and least responsive to chlorine. Occasionally copper or zinc deficiency may be found but molybdenum deficiency is rare. To the best of our knowledge, there has never been a case of chlorine deficiency reported from the field. Draycott and Christenson (2003) outlined soil and climate conditions exacerbating deficiencies of micronutrients. Nutrient deficiencies can be prevented and/or corrected by addition of fertilizer materials as shown in Table 9.15.

Table 9.14 Average concentration of micronutrients in tops and roots of healthy sugar beet and quantity in the crop at harvest (after Draycott & Christenson, 2003).

	Concentration in dry matter (mg/kg)		Quantity in crop (g/ha)
	Tops	Roots	Tops plus roots
Boron	40	15	335
Chlorine	2000	1000	19 000
Copper	7	1	44
Iron	200	100	1 900
Manganese	50	30	520
Molybdenum	7	5	80
Zinc	20	10	190

The physiological role of micronutrients in sugar beet is outlined in Table 9.16. In many cases micronutrients serve as cofactors in enzymatic reactions, but are always unique in their role.

BORON

Boron in soil

Archer and Hodgson (1987) measured total boron in a large number of UK soils and found it ranged from 7 to 119 mg/kg with a mean of 33 mg/kg. In other studies, sandy soils contain less while finer textured soils contain greater amounts (Gupta, 1979; Adriano, 2001). Boron is a constituent of tourmaline (a silicate mineral), may be adsorbed

Table 9.15 Sources of micronutrient fertilizers used on sugar beet.

Nutrient	Chemical formula	Concentration (%)	Method of application
Boron			
Sodium borate	Various	11–17	Soil
Boric acid	H_3BO_3	17	Soil or foliar
Solubor	$Na_2B_{10}O_{10}.10H_2O$	20	Foliar
Copper			
Copper sulphates	Various	13–53	Soil or foliar
Copper chelates	Various	9–13	Soil or foliar
Copper oxychloride	$CuOCl_2$	42	Soil or foliar
Copper oxide	CuO	80	Soil
Iron			
Ferrous sulphate	$FeSO_4.7H_2O$	19	Soil or foliar
Iron chelates	Various	5–14	Soil or foliar
Manganese			
Manganese sulphate	$MnSO_4.3H_2O$	26–28	Soil or foliar
Manganese nitrate	$Mn(NO_3)_2$	22	Foliar
Manganous oxide	MnO	41–68	Soil
Manganese EDTA	MnEDTA*	12	Soil and foliar
Molybdenum			
Sodium molybdate	$Na_2MoO_4.2H_2O$	39	Soil or foliar
Ammonium molybdate	$(NH_4)_6Mo_7O_{24}.4H_2O$	54	Soil or foliar
Frits	Various	Various	Soil
Zinc			
Zinc sulphate	$ZnSO_4.H_2O$	35	Soil or foliar
Zinc oxide	ZnO	78	Soil
Zinc chelate	Various	9–14	Soil or foliar

*EDTA, ethylenediaminetetraacetic acid

on clay minerals and iron and aluminium oxides/hydroxides, and is present in organic matter.

Boron available for uptake by sugar beet is present in soil solution as H_3BO_3 in acid and neutral soil and $H(BO)_4^-$ in alkaline soils. Both easily leach in climates where precipitation exceeds evapotranspiration. Consequently there does not appear to be any accumulation of boron in soils under these conditions. Deficiencies are most often seen on sandy alkaline soils.

Additions to soils

Atmospheric deposition of boron amounts to less than 1 g/ha/yr (Wadsworth & Webber, 1980) while some irrigation water may add quantities creating toxic conditions. Hanson *et al.* (1999) suggest a threshold concentration of 4.9 mg B/l in irrigation water. On a hectare basis, this would amount to 49 kg B/m of irrigation water. Sugar beet is generally tolerant of boron, perhaps because it can sequester the element in cell walls (Rozema *et al.*, 1992). On the other hand, field bean (*Vicia faba* and *Phaseolus vulgaris*), soybean (*Glycine max*) and cereals such as wheat and barley are less tolerant of high boron levels. Careful management of irrigation when boron concentration is high is critical so boron does not accumulate to toxic proportions in the soil. The critical toxicity concentration in wheat is about 100–250 mg B/kg dry matter (Paull *et al.*, 1988).

Boron in sugar beet

Sugar beet, in common with other dicotyledon plants, has a high boron requirement. This is related to higher proportions of compounds associated with the hemicullulose fraction and in lignin precursors. It must be able to take up sufficient quantities of the element to maintain a minimum concentration in tissue or growth is disrupted. De-

Table 9.16 Physiological role of micronutrients in sugar beet growth (after Marschner, 1995).

Nutrient	Role
Boron	Boron complexes: mono- and diester complexes with *cis*-diols Structural: hemicellulose and lignin Growth: cell elongation and division, tissue differentiation Metabolism: carbohydrate, protein Growth regulation: auxin and phenol metabolism Membrane permeability Reproduction: pollen germination and pollen tube growth
Chlorine	Regulation: photosynthesis and stomatal Ion transport: membrane bound proton pumping ATPase
Copper	Structural: copper proteins, plastocyanin, superoxide dimutase, cytochrome oxidase Enzyme activation: phenolase, amine oxidases Metabolism: carbohydrate and nitrogen Cell wall: lignification Reproduction: pollen formation and fertilization
Iron	Structural: hemoproteins, iron-sulphur proteins, enzymes Protein synthesis Chloroplast development
Manganese	Growth: photosynthesis, oxygen evolution, cell division and extension Structural: enzymes Co-factor of some enzyme activity Synthesis: proteins, carbohydrates and lipids
Molybdenum	Structural: enzymes Co-factor: nitrogenase, nitrate reductase
Zinc	Structural: enzymes Enzyme activation: dehydrogenases, aldolases, isomerases, trans-phosphorylases, RNA and DNA polymerases Metabolism: carbohydrate Synthesis: protein, tryptophan and indoleacetic acid

ficiency symptoms are pictured later in this chapter. The physiological role of boron is outlined in Table 9.16.

Boron concentration in leaf tissue is most useful for diagnosis of deficiency and closely reflects both supply and symptoms. Root boron is not a good guide. Ideally leaf concentration should exceed 30 mg B/kg and deficiency symptoms can be expected below 20 mg B/kg. Uptake and concentration in sugar beet are given in Table 9.14.

Prediction of needs by soil analysis

Boron availability is determined by a widely used soil test first introduced by Berger and Truog (1939) and slightly improved by Offiah and Axley (1988). Soil is boiled with water under reflux and boron may be determined on a colourless extract using colorimetric methods or one of the plasma emission techniques.

Smilde (1970) showed a close relationship between hot water soluble soil boron and leaf boron over a wide range of soil pH and organic matter conditions. There was no loss in yield of tops, roots or sugar from inadequate boron supply when soil boron exceeded 0.50 mg B/kg of soil. Table 9.17 summarizes information concerning hot water soluble boron along with incidence of deficiency, and amount to apply. This table was constructed to take into account patchy within-field occurrence of boron deficiency where mean soil concentration ranges from 0.50 to 1.00 mg B/kg soil.

Boron deficiency seems to be widespread. Between 50 and 90% of half a million soils analysed in southern Germany needed boron application (Fürstenfeld & Bürcky, 2000). Similarly, Rodriguez

Soil B (mg/kg)	Symptoms expected	Application required (kg B/ha)
0–0.25	Very severe in most conditions	3
0.26–0.50	Severe at high pH	2
0.51–1.00	Some plants may be deficient	1
1.10–2.00	None deficient	0
2.10–4.00	High concentration	0
> 4.00	May be toxic	0

Table 9.17 Relationship between hot-water-soluble boron, expression of deficiency by sugar beet and amount required (after Draycott & Christenson, 2003).

and Tomic (1984) analysed soils in Chile and also classified over half as boron-deficient.

Supplying boron to sugar beet

The standard application became 20 or 25 kg sodium borate/ha furnishing 2.0–2.5 kg B/ha (Draycott, 1972). A general conclusion is that liquid applied to soil or foliage or solid applied to soil are equally effective provided the application is before June. Response to foliar application may be smaller than soil application, but was equal if two foliar sprays were made (Narayan *et al.*, 1989). Applications made in autumn or winter or before ploughing on sandy soils are effective. Borated fertilizers containing NPK may be used in the seedbed at planting.

Residual effects of boron application

As pointed out earlier field beans, soybeans and cereals are sensitive to an excessive supply of boron. Consequently there have been several investigations to determine the carry-over from boron applications given to sugar beet. Leaching experiments made by Krügel *et al.* (1938) in Germany showed that 75% of this was leached out of the soil during the first winter, and by the third year after application little remained. In the climate of western Europe, they concluded there was no evidence of boron accumulation in the soil. Robertson *et al.* (1975) showed that cropped soils had two-thirds as much extractable boron as uncropped soils. Hamence and Oram (1964), Van Luit and Smilde (1969) and Chabannes (1959) in England, Holland and France, respectively, have investigated the fate of boron applied for sugar beet. These reports indicated that little boron remains 2 years after application, presumably because it is subject to rapid leaching during winter. Evidence for accumulation of boron in soils is scant. However, Ødelein (1963) reported that 1 kg B/ha/year injured some of the crops grown after a few years, especially on unlimed soil.

Incidence of boron deficiency

Incidence of boron deficiency appearing on sugar beet in the Great Lakes and Red River Valley is quite low (Cattanach, 1991; Christenson *et al.*, 1991; Giles *et al.*, 1991). However, two decades earlier Voth *et al.* (1979) showed a significant yield response to applied boron. The reason for the difference is not clear. Earlier Tandon (1979) had shown a differential response to boron in solution culture among four varieties. The role that genetics plays in boron needs for sugar beet is in need of further research.

In summary, yield of roots, tops and sugar are all increased by boron application where soil supplies are low (Draycott, 1972; Allison, 1996). Sugar percentage is often improved, but surprisingly juice purity does not appear to be affected.

MANGANESE

Manganese in soil

Temperate-zone soils on which sugar beet is grown can be expected to contain 50–500 mg Mn/kg (Whitehead, 2000; Adriano, 2001). Since these soils are not highly leached, manganese remains in the root zone, some in clays (smectite), some as oxides and hydroxides, and some in plant-available forms. Insoluble MnO_2 may be seen in some subsoils in the UK as black granules, 0.5–2 mm diameter. It is thought that these nodules were formed by precipitation reactions during periglacial conditions following melting of ice sheets that covered the region. Unfortunately, such manganese is not in a plant-available form. Small additions of manganese to soils are through atmospheric deposition (50–300 g Mn/ha/year), as impurities in NPK fertilizers (from a few grams to 1 kg Mn/t), farmyard manure (1–2 kg Mn/25 t manure) and where sewage sludges are used.

In common with other nutrients, available manganese is present in the soil solution. Solubility is governed by pH, redox condition and other soil characteristics. It may be present in more than one oxidation state, Mn^{2+} (reduced) and Mn^{4+} (oxidized) being the most common (Brady & Weil, 1999). Reduction is brought about by metabolic reducing agents produced by plants and micro-organisms in soil in addition to the reducing conditions (exclusion of oxygen). The Mn^{2+} state is most soluble and therefore most available to plants.

The effect of soil pH on manganese solubility is marked, increasing concentration in solution 100-fold for each pH unit decrease (Lindsay, 1972). Generally sugar beet on mineral soils does not show deficiency below soil pH 6.5 and toxicity may occur below pH 5.5. In contrast, on highly organic soils sugar beet is prone to deficiency over a wide range of pH.

Manganese in sugar beet

Manganese enters into the structure of at least two enzymes in plants and is required by a large number of enzymes as an activator (Table 9.16). Most of these enzymes are associated with oxidation–reduction, decarboxylation and hydrolytic reactions. Deficient leaves usually contain 10–30 mg Mn/kg of dry matter and healthy leaves 40–100 mg Mn/kg (Table 9.18), while the concentration tends to decrease over the course of the season (Last & Bean, 1990). Manganese concentration is reduced by the dilution effect of growth without additional translocation of manganese to the tissue. Uptake by the sugar beet crop is in the range of 520 g/ha (Table 9.12). Manganese is not translocated from leaf to leaf, deficiency symptoms appearing on new leaves as they emerge and expand.

Manganese deficiency

In some situations, sugar beet during the early stages of growth often shows mild symptoms of deficiency during periods of wet weather in spring. Often these conditions cause a reduction of manganese, which increases its solubility. However, slow growth reduces the amount of manganese moving to the roots by mass flow. Warm weather favours increased growth causing greater mass flow carrying manganese ions to the root surface.

Sugar beet production is best on soils that are kept near the neutral point (pH 7.0). Often production is on mineral soils and fenland, peat or 'muck'

Table 9.18 Manganese concentration in sugar beet plants with and without deficiency symptoms (after Draycott & Christenson, 2003).

Plant part	With symptoms (mg Mn/kg dry matter)	Without symptoms (mg Mn/kg dry matter)	References
Leaf: Range	12–17	46–110	Summary of early work, Draycott, 1972
Leaf: Mean	14	70	
Leaf	20–30	Above 30	MAFF, 1976
Leaf	16–22	60–76	Farley, 1980
Leaf: May	30	162	Last & Bean, 1990
Leaf: June	20	58	
Leaf: July	23	76	
Leaf: October	32	35	
Leaf	20	74	Last & Bean, 1991
Root	8	11	

soils, which are naturally alkaline. The solubility of manganese is lower on these soils increasing the incidence of deficiency. Many times these soils show severe forms of deficiency every year without suitable applications of manganese.

On soils more acid in nature, application of lime results in manganese deficiency particularly where there is also a large amount of organic matter present (Farley & Draycott, 1973). A major factor seems to be an interaction with sesquioxides (iron-aluminium oxides/hydroxides) as pH increases above 5.8, which reduces the solubility of manganese in the soil (Mehlich, 1957). This occurs less often on less acid soils since the activity of the sesquioxides is very low. Christenson *et al.* (2000) showed that liming soils with pH above 6.8 had no effect on manganese concentration in sugar beet and other crops grown in rotation.

Methods of soil analysis and response to manganese

Soil testing for predicting manganese needs for sugar beet and other crops is only moderately successful. Draycott and Farley (1973) found soil extracted with ammonium acetate/hydroquinone (10–300 mg Mn/kg) was moderately correlated with manganese concentration in sugar beet leaves in the range of 10–50 mg Mn/kg. Robertson and Lucas (1981) found manganese deficiency likely on soils with less than 5 mg Mn/kg extracted with 0.1 M HCl on mineral and certain organic soils. Salcedo *et al.* (1979) reported correlation (r^2) between manganese from soil with 0.3 M H_3PO_4 and plant uptake was 0.92. Other extractants correlated less well. Reisenauer (1988) found soil analysis had limited ability to predict plant available manganese. Germida *et al.* (1985) had more success using a simple microbial bioassay to determine plant-available manganese in soil.

Correction of deficiency and response to applied manganese

Field experiments generally show that only where symptoms appear on leaves does the sugar beet crop respond to treatment. This is of great value since in the absence of symptoms it can be safely assumed the crop had sufficient supply of manganese. Correction of manganese deficiency can be by soil and foliar application of suitable manganese fertilizers. Generally, foliar application is used when deficiencies occur after the crop emerges. One or more applications may be needed to completely eliminate the deficiency; new leaves should be examined since manganese is not translocated from leaf to leaf (Henkens & Jongman, 1965). Broadcast application of manganese fertilizer is not considered to be an effective method. Banding with starter fertilizer to the side and below the seed is effective and in some studies a combination of both banded and foliar has been shown necessary to completely eliminate symptoms. Fertilizer materials are listed in Table 9.15. Farley and Draycott (1978) explored the use of manganese pelleted with seed. This method met with limited success. Our experience suggests that, in addition to soil analysis, history of manganese deficiency and soil type should be used to predict future problems.

COPPER

Copper in soil

Copper concentration in soil ranges from 2 to 100 mg Cu/kg. Copper may be present as divalent cupric (Cu^{2+}) or monovalent cuprous (Cu^+), both forming complexes with organic matter. The cupric form is adsorbed on surfaces of iron and manganese oxides.

In some soils where sugar beet is grown, copper may accumulate from sewage sludge, poultry manures and where pigs are reared outdoors. Smaller inputs are from farmyard manure (0.3 kg Cu/25 t manure), fertilizers (1–20 g Cu/t) and atmospheric deposition (0.5 g Cu/ha/year in parts of Europe). Significant amounts are also applied where copper-based fungicides are applied to vegetable crops and where applied as a nutrient for sensitive crops, such as cereals, grown in rotation with sugar beet. Where cropping is intensive, a running total of copper inputs should be maintained since toxicities may occur as the element accumulates in surface soils.

In most soils, provided they are not waterlogged, copper available or potentially available to the crop is in the divalent form, most (76–99%) being held in complexes by organic matter (Hodgson *et al*., 1965; 1966). Some of the copper may be in an adsorbed form, but only minute amounts in an entirely inorganic form. Extraction is usually with a chelating agent such as ethylene diamine tetracetic acid (EDTA). Usefulness of such results may be improved by also taking into account pH and/or soil organic matter concentration.

Copper in sugar beet plants

Essential roles for copper in plants include a component of proteins and enzymes, lignification during formation of cell walls, and pollen formation and fertilization (Table 9.16). Draycott (1972) suggested deficiency might be expected when dried leaves contained less than 6 or 7 mg Cu/kg. Plants well supplied with copper contained up to 20 mg Cu/kg in leaves. In more recent field experiments, Allison *et al.* (1996) found 6 mg Cu/kg in dried leaves at harvest and 3 mg Cu/kg in dried roots on sites where deficiencies were likely to occur. However, applying copper had little effect on these concentrations. Pizer *et al.* (1966) reported a total uptake of 40 g Cu/ha in tops plus roots. The value given in Table 9.14 suggests 44 g Cu/ha.

Effects of copper on sugar beet yield

Copper applied to foliage can control fungal diseases, making it important to separate the nutritional and fungicidal effects, particularly where *Cercospora beticola* infections occur. In these cases, fungicidal effects of a copper spray will greatly outweigh its nutritional value. In addition to suppression of fungal diseases, foliar application of copper has been reported to suppress nematode activity (Graham & Webb, 1991).

The incidence of copper deficiency is rare as a result of adequate reserves in soils, application to sugar beet for control of *Cercospora beticola*, and application to sensitive crops in rotation. In early experiments responses to applied copper were usually small, but not consistent across all fields (Van Schreven, 1936; Lachowski, 1961; Pizer *et al.*, 1966; MAFF, 1976; Tills & Alloway, 1981; Alloway & Tills, 1984). More recently, Allison *et al.* (1996) conducted a survey and suggested 15% of the fields in the UK were deficient. McGrath and Loveland (1992) considered that less than 10% of UK soils were likely to be deficient.

ZINC

Zinc in soil

Berrow and Burridge (1980) reported total zinc present in soil is of the order 10–300 mg/kg dry soil, originating mainly from parent materials. Atmospheric deposition, fertilizers, organic manures, sewage sludges, industrial wastes and zinc-based fungicides all add to the total zinc in soils. The effluents from many industrial processes contain significant concentrations of zinc. If sludge from these processes is deposited on land, toxic amounts of zinc may accumulate.

Sugar beet takes up zinc as Zn^{2+}. No other oxidation states exist in soils of this element, making it unique among the metal ions iron, manganese and copper. The main sources of available zinc are water-soluble and exchangeable forms, but some is adsorbed on hydrous oxides, clays and organic matter. Consequently a chelating agent or a dilute mineral acid (Brown, 1998) are used as extracting agents for determining the amount of available zinc in soils.

Zinc in sugar beet

Zinc is necessary as a structural component of some enzymes and proteins, and as a cofactor for the activity of several enzymes (Table 9.16). It is also essential for the formation of phytohormomes such as indole-3-acetic acid. Concentration in healthy leaves is about 20 mg Zn/kg and in roots 10 mg Zn/kg (Boawn & Viets, 1956; Boawn *et al.*, 1960; 1961; Draycott, 1972). Leaves containing less than 10 mg Zn/kg showed deficiency symptoms (Ulrich & Hills, 1969). Roots contain about 4 mg Zn/kg at harvest (Bravo *et al.*, 1992). Total uptake by leaves and roots was reported to be of the order of 200 g Zn/ha (Table 9.14). However, Bravo *et al.* (1992) reported a total uptake of 100 g/ha, Boawn *et al.* (1960), 200–300 g/ha and Robertson and Lucas

(1981), 600 g/ha. Bravo *et al.* (1992) showed a decline in zinc concentration in roots and leaf blades over the course of the growing season.

Field experiments with zinc

There are many reports of zinc deficiency on a wide range of crops across the world. While zinc deficiency on sugar beet has been reported, it is not widespread. The limited amount of trial work with zinc is summarized below. In the state of Washington, USA, Boawn and Viets (1956) and Boawn *et al.* (1960; 1961) conducted a study on a fine sandy loam soil with low zinc supply. Even though the soil was low in zinc, and leaves showed deficiency symptoms there was a small increase (5–6%) in yield. Without zinc, tops contained 12 mg Zn/kg in dry matter and 22 mg/kg with 18 kg $ZnSO_4$/ha.

There seems to be little likelihood of response by sugar beet to applied zinc in either Michigan or the Red River Valley. Judy *et al.* (1964) reported no effect on yield or quality of sugar beet roots on a site where yield response to applied zinc was evident on field bean. Lamb and Cattanach (1990) found no response to applied zinc in the Red River Valley on soils testing low in zinc and which would have zinc recommended for some other crops. Generally sugar beet does not respond to applied zinc on sites where maize and field bean will show deficiencies. More recently, Bakhsh Kelarestaghi *et al.* (2002) in Iran, showed that zinc sulphate (40 kg/ha) before sowing gave a 10% increase in sugar yield. No other reports of response to zinc were found.

IRON

Iron in soil

Iron is by far the most abundant of the metals ranging from 12 to 100 g Fe/kg soil (Whitehead, 2000). Both ferric (Fe^{3+}) and ferrous (Fe^{2+}) forms are present, reflecting amount of aeration during soil formation. Ferrous iron forms under reducing conditions giving waterlogged soils the characteristic greyish-blue colour. Iron may be deposited from the atmosphere (1 kg Fe/ha/year), or applied as impurities in fertilizers (particularly triple superphosphate) and organic manures. Incidence of iron deficiency is low and few cases of deficiency symptoms have been reported on sugar beet leaves. More experimental evidence is needed to show when the crop needs treatment.

Iron in plants

The role of iron is similar to other micronutrients, entering into the structure of proteins, as a cofactor in enzymatic reactions and is required for photosynthesis (Table 9.14). The most unique role is that involving redox reactions in cytochromes. Winder and Nishio (1995) found a shortage of iron caused marked reduction in leaf chlorophyll and this decreased carbon dioxide fixation linearly. RNA synthesis was halved in iron-deficient leaves.

Concentration in leaf tissue ranges from less than 20 to more than 300 mg/kg dry weight. Leaf yield was decreased when the concentration of iron in laminae was less than 55 mg/kg. Symptoms ranged from yellowing and necrosis to a light green in leaves containing 20–50 mg/kg (Nagarajah & Ulrich, 1966). Normal laminae contained between 60 and 150 mg/kg. Uptake by sugar beet is in the range of 1900 g/ha (Table 9.14).

Response to iron in the field

There is a paucity of information concerning response to applied iron in the field. In Poland, Lachowski and Wesolowski (1964) found that 40 kg $FeSO_4$/ha increased yield of roots by 10% and tops by 5%. Yield was increased on leached sandy soils containing less than 4.5 g Fe/kg in the plough layer. No other reports were found where iron produced a response on sugar beet.

CHLORINE

Chlorine in soils

Most of the chlorine in soils is present in soil solution as the chloride ion (Cl^{-1}). Small amounts are derived from mineral and organic fractions. Large quantities may be present in soils of arid regions as part of the soluble salt content. Chlorine may be derived from parent materials, but much more from atmospheric and agricultural inputs. In maritime climates where sugar beet is grown, atmospheric inputs are often large. Deposition in the UK near the coast is of the order of 100 kg Cl/ha/year but at 200 km inland it may be 20 kg/ha. In the Midwest of the USA, only about 1 kg Cl/ha/year may be deposited (Fixen, 1993). Fertilizers used in sugar beet and other arable crops supply large quantities of chlorine. Potassium chloride (KCl) supplies 80 kg Cl for every 100 kg K_2O applied. Similarly, where NaCl is used for sugar beet, relatively large quantities of chlorine are supplied, far in excess of the plant's requirement.

Chlorine in plants

Draycott and Christenson (2003) provided the following development of information showing chlorine to be needed for plants. Warburg and Lüttgens (1946) first showed that chlorine was necessary for the evolution of O_2 from isolated chloroplast fragments during photosynthesis. It was noted that the rate of photosynthesis was depressed by the absence of chlorine, but could be restored by the addition of the element. Arnon and Whatley (1949) considered it unlikely that chlorine was a cofactor for photosynthesis since chlorine had not been proved to be essential. However, Broyer *et al.* (1954) published a study confirming that chlorine met the criteria for essentiality. Ulrich and Ohki (1956b) demonstrated the essentiality of chlorine for sugar beet. Terry (1977) demonstrated that the principal effect of chlorine deficiency was to lower the cell multiplication rates in leaves. Using sugar beet as the test crop, Findenegg *et al.* (1989) noted huge growth reductions in chlorine-deficient plants. Deficient leaves contained 0.01 to 0.04% while healthy leaves contained 0.8–8.5% Cl. Uptake of chlorine by a sugar beet crop has been shown to be 19 kg/ha (Table 9.14). There have been no cases of response to applied chlorine on sugar beet, probably because of the use of potassium and sodium chloride as fertilizers.

MOLYBDENUM

Molybdenum in soils

The element is present in soils in minerals, adsorbed onto iron and aluminium oxides, and in organic matter (Whitehead, 2000). Plants take up the element as the molybdate anion (MoO_4^{2-}) from soil solution. The solubility of molybdenum in soils increases with increasing pH, probably explaining the infrequency of molybdenum deficiencies in the field. Since the quantity is very small, available molybdenum is difficult to measure in soils.

Molybdenum in plants

Molybdenum is a constituent of several plant enzymes involved in oxidation and reduction (Table 9.16). Ulrich and Hills (1969) described the symptoms of deficiency and found that healthy leaves contained 0.2–20.0 mg Mo/kg of dry matter, whereas deficient leaves contained 0.01–0.15 mg Mo/kg. Bravo *et al.* (1992) suggested that leaves contain 0.2 mg Mo/kg to avoid deficiencies throughout the growing season. Uptake of molybdenum by a sugar beet crop is of the order of 18 g/ha (Table 9.14).

Response to applied molybdenum

There have been few investigations of the molybdenum nutrition of sugar beet. Henkens and Smilde (1966) found increased yields in pot experiments from molybdenum given to sugar beet plants grown in molybdenum-deficient soil (previous sugar beet plants grown in the same soil showed distinct symptoms of molybdenum deficiency). Dry-matter production was increased considerably by molybdenum and there was a negative relationship between dry-matter yield and severity of molybdenum deficiency. Sodium molybdate gave the largest yield and plants receiving the equivalent of 0.6 or 0.8 kg Mo/ha had no symptoms of the deficiency. Glassy frits varied in ability to correct deficiency but had a greater residual effect than the molybdate, as shown by further cropping. Nowicki (1969) found applied molybdenum had no effect on yield but showed some tendency to decrease incidence of disease and increase quality of roots.

SOIL ACIDITY AND LIMING

General effects of acidity on plants

The primary reason for liming soils is to adjust pH to a favourable range. While it is mistakenly assumed that the primary purpose of liming is to provide calcium, and in some cases magnesium, the action of liming provides hydroxyl to neutralize acidity:

$$CaCO_3 + H_2O = Ca^{2+} + HCO_3^- + OH^-$$

The provision of calcium (and magnesium in the case of dolomitic lime) is secondary to the reduction in acidity.

Under acid conditions some nutrients, particularly phosphorus, become less available. Reduction of the effects of manganese toxicity is also important since the solubility of manganese increases 100-fold for each unit of pH decrease. (The reverse is also true making the incidence of manganese deficiency greater on alkaline soils.) In addition, the concentration of soluble aluminium increases rapidly below pH 5.5 saturating the exchange complex with Al^{3+} at pH 4. Foy (1984) points out few plants can tolerate such metal concentrations.

Effects of soil pH on sugar beet

Sugar beet is sensitive to low pH even though germination and emergence are often satisfactory on moderately acid soils. However, seedlings grow slowly and stands will be uneven owing to death of beet plants. 'Good' beets interspersed with stunted or missing beets and remaining roots are often 'stubby' and spatulated. Full yield will not be obtained unless soil pH is near the neutral point.

Symptoms of acid injury show cotyledons with red margins and are unusually erect. Blades and petioles become uniformly pale yellowish green and leaf margins roll inwards (Hale *et al.*, 1946). Cases of very high manganese concentration in leaf tissue have been reported in association with acid soil effects (Brown *et al.*, 1968). Terry *et al.* (1975) showed that manganese toxicity reduced the numbers of cells per leaf and the average leaf cell volume. Plants also had smaller leaf and root weight in acid conditions. While manganese toxicity appears mainly on the leaves, aluminium toxicity affects roots as described above. Aluminium toxicity may also induce phosphorus, calcium, magnesium and molybdenum deficiencies (Foy, 1984).

Optimum pH

Ulrich and Ohki (1956a) showed in solution culture that sugar beet grew best at pH 7.0 (Fig. 9.5). At pH 4.0 leaves were small, dark green and smaller in number than at higher pH. At pH 9.0 yields of roots and tops were reduced. Leaf colour and nitrogen status of the plants were not affected by pH. Increasing pH decreased phosphorus concentration, but even at 9.0 there was adequate phosphorus in the tops. Based on our many observations in the UK and USA, the crop grows best on soils of pH between pH 6.5 and 8.0. Viets and Robertson (1971) reported that sugar beet grew well on soil with pH 6.5, grew poorly at pH 5.5 and had virtually no growth at pH 4.5. In both field and controlled environment experiments, sugar beet performed best when the soil or root medium is near pH 7.0 (P. Wilting, the Netherlands, 2002, and O. Hellgren, Sweden, 2002, personal communications).

Response to lime

In spite of few thorough investigations to determine optimum pH for sugar beet (Draycott 1972), there are some observations and studies giving some guidelines concerning response to applied lime. Morley Davies (1939) reported a striking increase in yield and percentage of sugar from applied lime on a sandy soil (Table 9.19). McEnroe and Coulter (1964) surveyed over 3000 farms in Eire and showed an increase in both sugar concentration and yield with increasing pH.

Liming materials

Calcitic limestone ($CaCO_3$), dolomitic limestone ($Ca.MgCO_3$) and chalk ($CaCO_3$) are common liming materials taken from natural deposits. In addi-

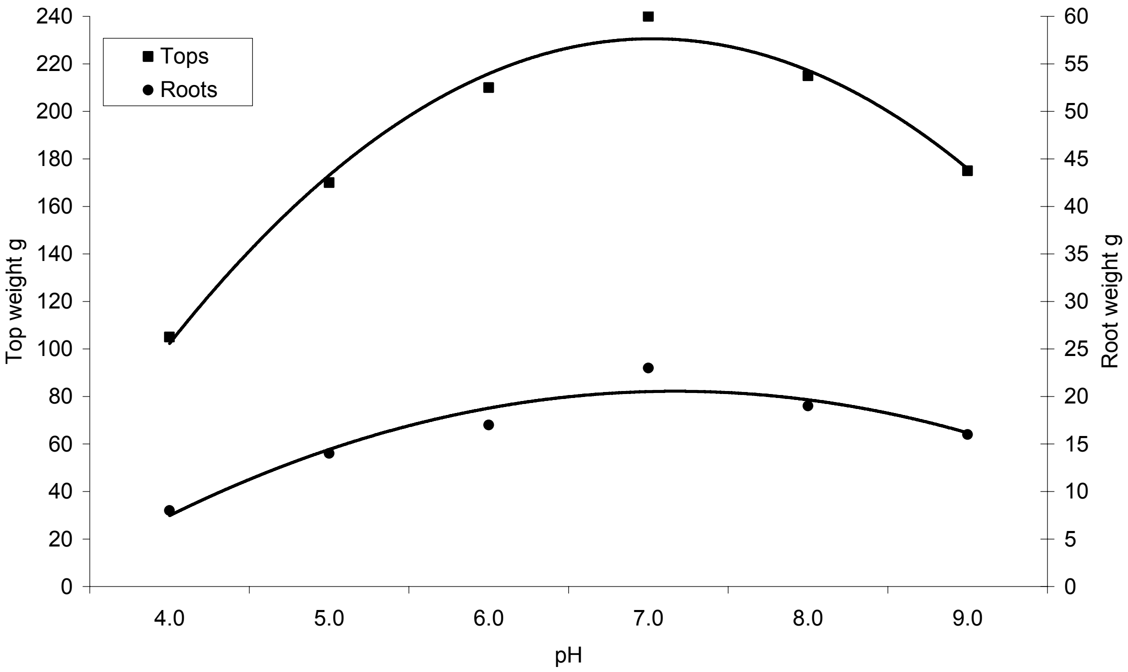

Fig. 9.5 Effect of pH on solution culture on weight of sugar beet tops and roots (after Ulrich & Ohki, 1956a).

Table 9.19 Effect of calcium carbonate on yield of sugar beet and soil pH 24 months after lime application on very acid soil (McEnroe & Coulter, 1964).

Amount of $CaCO_3$ (t/ha)	Yield of roots (t/ha)	Sugar (%)	Soil pH
0	11.3	16.7	4.9
2.8	22.9	17.1	5.3
5.6	25.9	17.1	5.5
11.2	25.4	17.2	5.9

tion, refuse liming materials from various chemical processes are also used. One of the latter, factory lime from sugar beet processing, is a good quality material since it is both fine and has a good neutralizing value.

Neutralizing value and particle size are two major factors affecting quality of liming materials. In the USA, calcium carbonate equivalent is a measure of the capacity of the material to neutralize acidity and is calculated as if all of the carbonate is in the form of $CaCO_3$ (Anon., 2001). In the UK, the neutralizing value is calculated as calcium oxide equivalent. The effectiveness of lime is also controlled by particle size. Watson and Brown (1998) suggest particle size be such that 40% passes a 0.15 mm, 50% passes a 0.25 mm, 70% passes a 0.85 mm, and 95% passes a 2.36 mm sieve. Other factors influencing rate of dissolution include crystalline make-up, density, surface area, porosity and surface coatings on the particles.

Methods of determining lime requirement

A considerable amount of research has been done developing methods for determining lime requirement of soils. An early method bases lime requirement on soil pH and texture. The basic premise of this procedure is that total acidity is related to the amount of clay and organic matter in the soil. This method gave unsatisfactory results on groups of dissimilar soils. Buffering systems that measure total acidity have been adopted over much of the USA (Shoemaker *et al.*, 1961; Adams & Evans,

Table 9.20 Amount of calcium carbonate needed to increase soil pH from measured pH to pH 7.0 (from Christenson *et al.*, 1988; Draycott, 1993).

Soil pH	CaCO$_3$ required for 20 cm soil depth (t/ha)			
	Soil texture			
After Draycott	Light	Medium	Organic	Peats
4.0	9	15	23	39
4.5	8	12	19	26
5.0	7	9	10	14
5.5	5	7	5	8
6.0	3	4	0	0
After Christenson *et al.*	Loamy sand	Sandy loam	Loam and clay loam	Organic
4.5–4.9	9	12	15	11
5.0–5.4	8	9	12	7
5.5–5.9	7	8	9	2
6.0–6.4	4	5	7	0

1962); the former on soils of the mid-western USA, the latter on more highly weathered soils of south-eastern USA.

Draycott and Messem (1979) and Draycott (1993) outlined a procedure for determining lime requirement of sugar beet fields by pH and soil texture. This method holds for groups of similar soils such as in the sugar beet producing regions of the UK. Relationship between pH and texture (Table 9.20) show remarkable similarity between the UK and USA. The reader is referred to Shoemaker *et al.* (1961), Adams and Evans, (1962) and Watson and Brown (1998) for further information concerning buffer systems.

Liming in practice

In commercial sugar beet production on soils inherently acidic, maintaining pH at 6.5–7.0 is required. Lime needs to be mixed thoroughly with soil since surface application without tillage is ineffective just before sugar beet. Soil pH should be checked at least 18 months before sowing the crop, applying lime to bring the pH within the desired range. Tillage (preferably ploughing) should be used to incorporate the lime. To be absolutely sure that the sugar beet show no acidity problems, soil needs to be checked and limed again if necessary 6 months before sowing and ploughed again.

The amount of lime applied effectively in one application is also limited by the amount that can be mixed with the soil plough layer. Research shows a range of 6–12 t/ha may be applied and mixed by harrowing and ploughing. When greater quantities of material are required, half should be applied before ploughing with the remainder applied after ploughing.

NUTRIENT DEFICIENCIES

Separating deficiencies

Chlorosis (yellowing), mottling, stunting and deterioration of the growing point and leaf necrosis are amongst the signs observed. While symptoms are somewhat unique for each nutrient, care is needed evaluating symptoms, since weather conditions, herbicide, insect damage or disease may mask, confuse or exacerbate symptoms. Identification of deficiency becomes increasingly difficult when there is more than one cause of abnormal growth or appearance.

Separation of the various symptoms may be aided by the following categories:

- Uniform yellowing – nitrogen, sulphur, molybdenum
- Stunted greening – phosphorus

- Leaf scorch – potassium, magnesium
- Growing-point damage – boron, calcium
- Yellowing with green veining – manganese, iron, chlorine, copper, zinc

Some nutrients deficiency examples are included in this chapter. For more detailed, complete descriptions and examples, the reader is referred to Ulrich and Hills (1969) and Draycott and Christenson (2003).

Nitrogen

Nitrogen-deficiency symptoms appear on older leaves first since nitrogen is mobile in the plant. At the onset, there is a general light green colour (yellowing) and often leaves grow horizontally from the crown. Leaves are smaller in size with new leaves in the centre of the plant dark green in colour. Chlorosis continues to develop as the plant grows. Deficiency is often in patches in the field, due to differences in mineral nitrogen supply caused by soil variability. Plate 3 shows the effect of prolonged nitrogen deficiency on leaves of the same age.

Phosphorus

Phosphorus deficiency causes reduction in leaf size and stunting owing to slow growth. There is a gradual development of a deep green colour followed by red and purple coloration of the leaves (Plate 4). Seedlings have yellow cotyledons when severely deficient, often with a green first pair of leaves. Leaves may develop brown veining and a metallic lustre from greyish green to blue-green. In long-term experiments where phosphorus fertilizer has been withheld for many years, leaves have a purple coloration. However, purple colouring may not substantiate phosphorus deficiency since other environmental factors may also cause the plant to produce the coloured anthocyanins (Ulrich & Hills, 1969), particularly herbicide toxicities.

Potassium

An early report by Hale *et al.* (1946) described potassium deficiency as 'scorch' on the margins of the leaf blade. This scorch is a leathery tan colour accompanied by a smooth leaf surface and in more severe conditions extends all the way to the midrib, but does not involve the veins of the leaf (Plate 5). Youngest leaves may be hooded, similar to those with calcium deficiency. Draycott (1972) observed: 'Scorch symptoms develop after chlorosis or may develop independently of it. Necrosis generally follows, both forming an unbroken border around the leaf and lobes between the veins. The necrotic tissue is dull or reddish brown; it is tough but soft to handle and it does not crumble or disintegrate like the necrosis associated with magnesium deficiency.' Cook and Millar (1953) reported that the scorch moves toward the centre of the leaf. It primarily affects the recently mature leaves on the plant. The centre leaves remain green and may have a hooded appearance. Dark, longitudinal lesions may form on petioles of the older leaves (Ulrich & Hills, 1969). Potassium deficiency is most likely to develop on sandy soils, those with high organic matter and organic soils.

Sodium

There are no known symptoms associated with a low supply of sodium. However, there are examples of sodium reducing the severity of potassium deficiency.

Magnesium

Draycott and Christenson (2003) described magnesium deficiency symptoms as follows, suggesting they are not easily mistaken for any other deficiency. 'Deficiency first develops as small, pale yellow areas near the outside margins of recently mature leaves. The youngest mature leaves are affected. These lemon-yellow areas spread between the veins towards the midrib. Necrosis starts near the edge of the leaf and gradually expands to include most of the interveinal tissue except for the triangular area near the base of the leaf (Plate 6). Leaves in the final stages of magnesium deficiency show black necrotic tissue between the veins. Late-season deficiency often shows a "washing out" of necrotic tissue resulting in holes in the leaves.'

Magnesium deficiency (as well as potassium) should not be mistaken for virus yellows. Virus yellows shows vein clearing or vein yellowing in younger leaves of the plant. Older leaves on plants with virus yellows have a characteristic thickened and brittle feel. Deficiency usually appears in July and August, but may not be seen until September. Coarse-textured soils, particularly those with subsoils as coarse as or coarser than the surface soil, are most prone to magnesium deficiency. These coarse-textured soils, when heavily fertilized with potassium, may show magnesium deficiencies since potassium suppresses magnesium uptake. Deficiencies are likely when extractable potassium plus fertilizer potassium (kg/ha) are more than three times greater than extractable magnesium (Christenson *et al.*, 1992).

Calcium

Calcium deficiency affects the growing point of sugar beet. Ulrich and Hills (1969) reported that centre leaves have severe tip burn and the blades of the older leaves are crinkled, deformed and fail to expand. Young leaf blades are also hooded (downward cupping) and have a crinkled appearance. As deficiency progresses, the leaf blades may be reduced in size to a mere stub of blackened tissue at the end of the petiole (Plate 7).

Mengel and Kirkby (1978) suggest that calcium deficiency is seldom seen on most mineral soils. The supply of calcium is usually adequate in soils where sugar beet thrives best. Mass flow carries more calcium to the root surface than is needed by the growing sugar beet in most soils with pH values above 5.5. An exception is where sea-water flooding has left a large residue of sodium, which antagonizes the uptake of calcium.

Sulphur

Ulrich and Hills (1969) and more recently Connors (2000) state that initial sulphur deficiency symptoms for sugar beet are very similar to nitrogen deficiency. There is a general yellowing across the entire leaf and no veining is present with either nitrogen or sulphur deficiency (Plate 8). Since sulphur is not as mobile as nitrogen, the new centre leaves become light green to yellow rather than dark green as in nitrogen deficiency. As the deficiency progresses, leaves of the entire plant turn from green to light green and then to light yellow with a faint tinge of green remaining. Leaves remain erect, the petioles and blades are brittle, breaking readily when compressed by the hand. With severe sulphur deficiency the petioles develop brown, longitudinal lesions. In the field there is a general yellowing in patches, similar to nitrogen deficiency.

Boron

Prior to 1931, boron deficiency was thought to be a disease. Brandenburg (1931) first showed that boron deficiency was the cause of ‘heart rot’ and ‘dry rot’ observed in sugar beet. Rowe (1936) gave one of the best descriptions of the anatomical effects of boron deficiency on sugar beet. She reported ‘the apical meristem of the shoot, the youngest leaves and the newly developed cambia were most sensitive to boron deficiency and these were the first to degenerate. Cells of the vascular rings in the process of differentiating and sporadic groups of parenchyma cells adjacent to conducting elements were also sensitive to deficiency. Later stages of the deficiency were characterized by decay of cambial and adjacent parenchyma cells, together with complete disintegration of the phloem. The root tip did not degenerate but merely ceased to grow.’ A concentration of 0.17 mg/kg in the culture solution was enough for normal growth and development. Recovery in boron-starved plants involved the activation of axillary buds at the top of the beet, each of which developed its own system of secondary vascular rings.

Boron deficiency can be identified without supporting soil and plant tissue analysis because of unique symptoms on the leaves, petioles, crowns and roots (Plate 9). Symptoms may appear on either or both the roots and above-ground growth. Boron is relatively immobile in plants and symptoms appear on growing points and in meristematic tissues. Boron deficiency not only decreases yield, but also damages the roots, decreasing their value and keeping qualities. In seed production, the main flowering stem is stunted and the growing point dies (Stoker & Tolman, 1941). The growing points of laterals along these stems also give rise to stunted growths, which appear as small rosettes of discoloured bracts, and eventually these growing points also die. Deficiencies are associated with alkaline soils. The symptoms are often greater on sandy soils than on finer textured soils.

Manganese

Symptoms of manganese deficiency are unique and easily recognized. In the absence of such symptoms, it can be assumed the crop has sufficient manganese. This is of great practical value since foliar treatment can be made when symptoms occur without need for soil or plant analysis.

Manganese deficiency, known as 'speckled yellows', is characteristically interveinal, not affecting the veins. Further development of the speckling results in a translucent nature to the spots. The yellow spots become necrotic and holes develop as a result of loss of tissue (Plate 10). In the field, leaves have a characteristic upright posture due to the petioles growing nearly vertically and the laminae rolling inwards. Symptoms appear most commonly on plants from May onwards and disappear in August, although they may appear and disappear at any time. The severity of symptoms fluctuates during this period but, on average, declines from June to September.

Deficiencies are usually found on neutral and alkaline soils that are usually dark at the surface and have a grey subsoil colour. Organic soils and dark-coloured sandy loam and loam soil are also very prone to manganese deficiency. Deficiencies usually occur on these soils at pH values as low as 5.8, while on other mineral soils they occur at pH values above 6.5 (Vitosh *et al.*, 1998). In glaciated regions, the deficiency is seldom found on soils formed from glacial till and moraine materials. Manganese deficiency may be exacerbated by soils with elevated iron, copper and zinc concentrations. Dry weather, low light intensity and low soil temperature will also promote the deficiency (Lucas & Knezek, 1972).

Iron

In the UK, iron deficiency symptoms occur sporadically, usually in May or June, on sandy calcareous soils (Plate 11). Iron chlorosis on sugar beet has not been observed under field conditions in the USA. The deficiency would be expected to occur on both calcareous and non-calcareous soils. Cool, wet weather may accentuate chlorosis and the deficiency may be aggravated by irrigation with water containing a high concentration of HCO_3. Iron deficiency is not widespread in the USA and is rarely seen in the UK.

Ulrich and Hills (1969) reported that symptoms appear very quickly when young seedlings are transferred to iron-free solutions, or when iron is withheld from older plants. The veins remain green, standing out against the yellow interveinal areas. Eventually, the bleached blades become necrotic, which causes them to cup upward. If iron is reabsorbed before the blade tissues become permanently damaged, the fine veins become green and prominently netted. This symptom is normally associated with iron deficiency but is actually associated with recovery from iron deficiency.

Zinc

Ulrich and Hills (1969) reported from their solution culture work that in early stages, zinc deficiency appears as light green coloration of the larger leaves near the centre of the plant. Small pits develop between the veins on the upper surface of the blades as chlorosis becomes more intense. The small pits enlarge in an irregular pattern as more tissue collapses (Plate 12). The entire area between the veins gradually becomes dry, leaving the primary veins prominently outlined, turgid and green. The light green colour of the larger leaves is in the centre of the plant, along with the development of chlorosis and necrosis. The entire leaf blade becomes necrotic except the main veins. The petioles exhibit an upright growth habit in advanced stages of deficiency.

Zinc deficiencies appear on alkaline soils, both calcareous and non-calcareous parent materials. Often deficiencies appear when the subsoil is exposed as in where tile drainage has been installed. High concentrations of phosphorus in plants have been shown to restrict zinc movement within the plant, resulting in accumulation in the roots and deficiency in the top. However, sugar beet appears to be a very good 'forager' for zinc and deficiency symptoms are not very common. Field bean (*Phaseolus vulgaris*) and maize (*Zea mays*) may show zinc deficiency while sugar beet will not when grown on the same soil.

Copper

Van Schreven (1936) first described copper deficiency symptoms on sugar beet after growing plants in purified nutrient solutions. Symptoms developed after the plants had grown without copper for 3 weeks. Ulrich and Hills (1969) repeated this work and were able to produce symptoms only after purification of salts and water, confirming that sugar beet needed only small amounts of copper. They showed that deficiency develops as a mild chlorosis of the young centre leaves, similar to the effects observed in iron, chlorine and manganese deficiency. The symptoms progress from this mild chlorosis to a fine, green, netted veining, contrasting with light yellow areas. Further development of copper deficiency is a bleached appearance of the leaf blade (Plate 13).

Copper deficiencies on sugar beet are generally not observed in the field. Such deficiencies would first be expected on organic soils and sandy soils derived from quartzite.

REFERENCES

Adams, S.N. (1961a) The effect of sodium and potassium fertilizer on the mineral composition of the sugar beet. *Journal of Agricultural Science, Cambridge* **56**, 383–388.

Adams, S.N. (1961b) The effect of time of application of phosphate and potash on sugar beet. *Journal of Agricultural Science, Cambridge* **56**, 127–130.

Adams, F. & Evans, C.E. (1962) A rapid method for measuring lime requirement of red-yellow podzolic soils. *Soil Science Society of America Proceedings*. 26, pp. 355–357.

Adriano, D.C. (2001) *Trace Elements in Terrestrial Environments – Biogeochemistry, Bioavailability, and Risks of Metals*. Springer-Verlag, New York.

Allison, M.F. (1996) Micronutrient needs of sugar beet. *British Sugar Beet Review* **64** (4), 26–29.

Allison, M.F. & Chapman, J. (1995) Role of phosphate in beet crop nutrition. *British Sugar Beet Review* **63** (4), 12–14.

Allison, M.F., Jaggard, K.W. & Armstrong, M.J. (1994) Time of application and chemical form of potassium, phosphorus, magnesium and sodium fertilizers and effects on the growth, yield and quality of sugar beet. *Journal of Agricultural Science, Cambridge* **123**, 61–70.

Allison, M.F., Last, P.J. & Bean, K.M.R. (1996) Response by sugar beet to foliar sprays of copper. *Journal of the Science of Food and Agriculture* **72**, 219–225.

Alloway, B.J. & Tills, A.R. (1984) Copper deficiency in world crops. *Outlook on Agriculture* **13**, 32–34.

Analogides, D.A. (1987a) Seasonal uptake of P, K and Na by irrigated sugar beet as related to growth and soil nutrient supply. *Proceedings of the IIRB Congress*. pp. 305–324.

Analogides, D.A. (1987b) Estimating response by irrigated sugar beet to P and K fertilization in relation to soil fertility variables. *Proceedings of the IIRB Congress*. pp. 325–340.

Anon. (2001) *Glossary of Soil Science Terms*. Soil Science Society of America, Madison, WI

Archer, F.C. & Hodgson, I.H. (1987) Total and extractable trace element contents of soils in England and Wales. *Journal of Soil Science* **38**, 421–431.

Armstrong, M.J. (1985) Sulphur nutrition. *Rothamsted Experimental Station Report for 1984*, p. 47.

Armstrong, M.J., Milford, G.F.J. & Hollies, J. (1999) Potassium requirement of sugar beet. *British Sugar Beet Review* **67** (3), 4–6.

Arnon, D.E. & Whatley, F.R. (1949) Is chloride a coenzyme of photosynthesis? *Science* **110**, 554–556.

Bakhsh Kelarestaghi, K., Khalili, A. & Ahmadi, G. (2002) Effect of micro nutrients on sugar beet in Djovain area of Iran. *Proceedings of the IIRB Congress*. pp. 389–395.

Berger, K.C. & Truog, E.C. (1939) Boron determination in soils and plants. *Industrial and Engineering Chemistry, Analytical Edition* **11**, 540–545.

Beringer, H. (1987) Recent data about P, K and Na fertilizer application to sugar beet in Central Europe. *Proceedings of the IIRB Congress*. pp. 103–133.

Berrow, M.L. & Burridge, J.C. (1980) Trace element levels in soils: effects of sewage sludge. In: *Inorganic Pollution and Agriculture* MAFF Reference Book 326. HMSO, London, pp. 159–183.

Berry, W.L. & Ulrich, A. (1968) Cation absorption from culture solution by sugar beets. *Soil Science* **106**, 303–308.

Berry, W.L. & Ulrich, A. (1970) Calcium nutrition of sugar beets as affected by potassium. *Soil Science* **110**, 389–394.

Binford, G.G., Hergert, G.W. & Blumenthal, J.M. (2000) Sugar beets. In: Ferguson, R.B. (ed.) *Nutrient Management for Agronomic Crops in Nebraska*. University of Nebraska Extension Circular EC 155, Lincoln, NB, pp. 127–130.

Blaylock, A.D., Belden, K. & Hough, H.W. (1996) Guide to Wyoming fertilizer recommendations. *University of Wyoming Cooperative Extension Service Bulletin* B-1045, Laramie, WY.

Blumenthal, J.M. (2001) Fertilizing sugarbeet. In: Wilson, R.G., Smith, J.A. & Miller, S.D. (eds) *Sugarbeet Production Guide*. University of Nebraska Cooperative Extension EC01–156, Lincoln, NB, pp. 75–80.

Boawn, L.C. & Viets Jr, F.G. (1956) Zinc fertilizer tests on sugar beets in Washington. *Journal of American Society of Sugar Beet Technologists* **9**, 212–216.

Boawn, L.C., Viets Jr, F.G., Crawford, C.L. & Nelson, J.L. (1960) Effect of nitrogen carrier, nitrogen rate, zinc rate and induced soil changes on zinc uptake by sorghum, potatoes and sugar beets. *Soil Science* **90**, 329–337.

Boawn, L.C., Viets Jr, F.G., Nelson, C.E. & Crawford, C.L. (1961) Yield and zinc content of sugar beets as affected by nitrogen source, rate of nitrogen and zinc application. *Journal of American Society of Sugar Beet Technologists* **11**, 279–286.

Bolton, J. & Penny, A. (1968) The effects of potassium and magnesium fertilizers on yield and composition of successive crops of ryegrass, clover, sugar beet, potatoes, kale and barley on sandy soil at Woburn. *Journal of Agricultural Science, Cambridge* **70**, 303–311.

Brady, N.C. & Weil, A.R. (1999) *The Nature and Properties of Soils*, 12th edn. Prentice Hall, NJ.

Brandenburg, E. (1931) Die Herz- und Trockenfäule der Rüben als Bormangelerscheinung. *Phytopathologische Zeitschrift* **3**, 499–517.

Bravo, S., Lee, G.S. & Schmehl, W.R. (1989) The effect of planting date, nitrogen fertilizer rate and harvest date on seasonal concentration and total content of six macronutrients in sugar beet. *Journal of American Society of Sugar Beet Technologists* **26**, 34–49.

Bravo, S., Lee, G.S. & Schmehl, W.R. (1992) Effect of planting date, nitrogen fertilizer and harvest date on seasonal concentrations and total content of five micronutrients in sugar beet. *Journal of American Society of Sugar Beet Technologists* **29**, 45–57.

Bray, R.H. & Kurtz, L.T. (1945) Determination of total, organic, and available forms of phosphorus in soils. *Soil Science* **59**, 39–45.

Brown, J.R. (1998) *Recommended Chemical Soil Test Procedures for the North Central Region*. North Central Research Publication No. 221. University of Missouri, Columbia.

Brown, A.L., Hills, F.J. & Krantz, B.A. (1968) Lime, P, K and Mn interactions in sugar beets and sweet corn. *Agronomy Journal* **60**, 427–429.

Broyer, T.C., Carlton, A.B., Johnson, C.M. & Stout, P.R. (1954) Chlorine – a micronutrient element for higher plants. *Plant Physiology* **29**, 526–532.

Bush, D.S. (1995) Calcium regulation in plant cells and its role in signaling. *Annual Review of Plant Physiology* **46**, 95–122.

Cattanach, A. (1991) Boron fertilization of sugarbeets in the Red River Valley. *1990 Sugarbeet Research and Extension Reports* 21, North Dakota State University, Fargo.

Chabannes, J. (1959) Long-term effects of repeated additions of borates. *Belgian Industrial Chemistry*, Supplement No. 2, 697–698.

Christenson, D.R., Bricker, C., Reisen, J., Voth, R., Mertz, M., Mezoghi, M., Almustafa, W., Oaks, J. & Kestner, R. (1975) Soil fertility and management for the production of sugar beets, navy beans and corn. In: *Saginaw Valley Bean and Beet Research Farm Report*. Michigan State University, East Lansing, pp. 3–28.

Christenson, D.R., Warncke, D.D. & Leep, R. (1988) Lime for Michigan Soils. *Cooperative Extension Service Extension Bulletin* E-471, Michigan State University, East Lansing.

Christenson, D.R., Bricker, C.E. & Hubbell, L. (1991) Yield and quality of sugar beets as affected by applied boron. *Michigan State University Agricultural Experiment Station Research Report* 51, East Lansing.

Christenson, D.R., Warncke, D.D., Vitosh, M.L., Jacobs, L.W. & Dahl, J.G. (1992) Fertilizer recommendations for field crops in Michigan. *Cooperative Extension Service Extension Bulletin* E-550A, Michigan State University, East Lansing.

Christenson, D.R., Brimhall, P.B., Hubbell, L. & Bricker, C.E. (2000) Yield of sugar beet, soybean, corn, field bean and wheat as affected by lime application on alkaline soils. *Communications in Soil Science and Plant Analysis* **31**, 1145–1154.

Clarkson, D.T., Sanderson, J. & Russell, R.S. (1968) Ion uptake and root age. *Nature* **220**, 805–806.

Clarkson, D.T., Robards, A.W. & Sanderson, J. (1971) The tertiary endodermis in barley roots: fine structure in relation to radial transport of ions and water. *Planta* **96**, 292–305.

Connors, G. (2000) Kieserite – the superior magnesium and sulphur fertilizer. *Kali und salz*. Brochure for Potash Limited, Hertford, England, pp. 1–14.

Cook, R.L. & Millar, C.E. (1953) Plant nutrient deficiencies diagnosed by plant symptoms, tissue tests, soil tests. *Michigan State College Agricultural Experiment Station Special Bulletin* 353, East Lansing.

Cooke, G.W. (1967) *The Control of Soil Fertility*. Crosby Lockwood & Son Ltd, London.

Davis, J.F., Nichol, G. & Thurlow, D. (1961) The effect of phosphorus fertilization and time of application on chemical composition and on yield, sucrose content and percent purity of sugar beet roots. *Journal of American Society of Sugar Beet Technologists* **11**, 406–412.

Davis, J.F., Nichol, G. & Thurlow, D. (1962) The interaction of rates of phosphate application with fertilizer placement and fertilizer applied at planting time on the chemical composition of sugar beet tissue, yield, percent sucrose and apparent purity of sugar beet roots. *Journal of American Society of Sugar Beet Technologists* **12**, 259–267.

Draycott, A.P. (1969) The effect of farm yard manure on the fertilizer requirement of sugar beet. *Journal of Agriculture Science, Cambridge* **73**, 119–124.

Draycott, A.P. (1972) *Sugar Beet Nutrition*. Applied Science Publishers Limited, London.

Draycott, A.P. (1993) Nutrition. In: Cooke, D.A. & Scott, R.K. (eds) *The Sugar Beet Crop – Science into Practice*. Chapman and Hall, London, pp. 239–278.

Draycott, A.P. & Allison, M.F. (1998) Magnesium fertilizers in soil and plants: comparisons and usage. *Proceedings of Fertilizer Society, London*. No. 412, pp. 1–28.

Draycott, A.P. & Bugg, S.M. (1982) Response by sugar beet to various amounts and times of application of sodium chloride fertilizer in relation to soil type. *Journal of Agricultural Science, Cambridge* **98**, 579–592.

Draycott, A.P. & Christenson, D.R. (2003) *Nutrients for Sugar Beet Production: Soil Plant Relationships*. CABI Publishing, Wallingford.

Draycott, A.P. & Durrant, M.J. (1969a) The effects of magnesium fertilizers on the yield and chemical composition of sugar beet. *Journal of Agricultural Science*, *Cambridge* **72**, 319–324.

Draycott, A.P. & Durrant, M.J. (1969b) Magnesium fertilizers for sugar beet (Part I). *British Sugar Beet Review* **37**, 175–179.

Draycott, A.P. & Durrant, M.J. (1970a) The relationship between exchangeable soil magnesium and response by sugar beet to magnesium sulphate. *Journal of Agricultural Science, Cambridge* **75**, 137–143.

Draycott, A.P. & Durrant, M.J. (1970b) Magnesium fertilizers for sugar beet (Part II). *British Sugar Beet Review* **38**, 175–180.

Draycott, A.P. & Durrant, M.J. (1972a) Comparisons of kieserite and calcined magnesite for sugar beet grown on sandy soils. *Journal of Agricultural Science, Cambridge* **79**, 455–461.

Draycott, A.P. & Durrant, M.J. (1972b) The immediate and long-term value of some magnesium fertilizers for sugar beet. *Journal of Agricultural Science*, *Cambridge* **79**, 463–471.

Draycott, A.P. & Durrant, M.J. (1976) Response by sugar beet to superphosphate, particularly in relation to soils containing little available phosphorus. *Journal of Agricultural Science, Cambridge* **86**, 181–187.

Draycott, A.P. & Farley, R.F. (1971) The effect of sodium and magnesium fertilizers, and irrigation on growth, composition and yield of sugar beet. *Journal of the Science of Food and Agriculture* **22**, 559–563.

Draycott, A.P. & Farley, R.F. (1973) Response by sugar beet to soil dressings and foliar sprays of manganese. *Journal of the Science of Food and Agriculture* **24**, 675–685.

Draycott, A.P. & Messem, A.B. (1979) Soil acidity. The need for a systematic approach to liming. *British Sugar Beet Review* **47** (2), 21–23.

Draycott, A.P., Marsh, J.A.P. & Tinker, P.B.H. (1970) Sodium and potassium relationships in sugar beet. *Journal of Agricultural Science, Cambridge* **74**, 568–573.

Draycott, A.P., Durrant, M.J. & Boyd, D.A. (1971) The relationship between soil phosphorus and response by sugar beet to phosphate fertilizer on mineral soils. *Journal of Agricultural Science, Cambridge* **77**, 117–121.

Draycott, A.P., Durrant, M.J. & Webb, D.J. (1972) Long term effects of fertilizers at Broom's Barn 1965–70. *Rothamsted Experimental Station Report for* 1971, Part 2, 155–164.

Draycott, A.P., Durrant, M.J., Davies, D.B. & Vaidyanathan, L.V. (1976) Sodium and potassium fertilizers in relation to soil physical properties and sugar beet yield. *Journal of Agricultural Science, Cambridge* **87**, 633–642.

Dunham, R.J. (1991a) Effect of starter fertilizers close to seeds. *Proceedings of the IIRB Congress*. pp. 369–384.

Dunham, R.J. (1991b) Fertilizer placement. *British Sugar Beet Review* **59** (2), 21–25.

Durrant, M.J. & Draycott, A.P. (1971) Uptake of magnesium and other fertilizer elements by sugar beet grown on sandy soils. *Journal of Agricultural Science, Cambridge* **77**, 61–68.

Durrant, M.J., Draycott, A.P. & Boyd, D.A. (1974a) The response of sugar beet to potassium and sodium fertilizers. *Journal of Agricultural Science, Cambridge* **83**, 427–434.

Durrant, M.J., Draycott, A.P. & Payne, P.A. (1974b) Some effects of sodium chloride on germination and seedling growth of sugar beet. *Annals of Botany* **38**, 1045–1051.

Durrant, M.J., Draycott, A.P. & Milford, G.F.J. (1978) Effect of sodium fertilizer on water status and yield of sugar beet. *Annals of Applied Biology* **88**, 321–328.

Engelstad, O.P. & Terman, G.L. (1980) Agronomic effectiveness of phosphate fertilizers. In: Khasawneh, F.E., Sample, E.C. & Kamprath, E.J. (eds) *The Role of Phosphorus in Agriculture*. American Society of Agronomy, Madison, WI, pp. 311–332.

Farley, R.F. (1980) Manganous oxide as a seed pellet additive for controlling manganese deficiency in sugar beet seedlings. *Plant and Soil* **54**, 451–459.

Farley, R.F. & Draycott, A.P. (1973) Manganese deficiency of sugar beet in organic soils. *Plant and Soil* **38**, 235–244.

Farley, R.F. & Draycott, A.P. (1974) Growth and yield of sugar beet in relation to potassium and sodium supply. *Journal of the Science of Food and Agriculture* **26**, 385–392.

Farley, R.F. & Draycott, A.P. (1978) Manganese deficiency in sugar beet and the incorporation of manganese in the coating of pelleted seed. *Plant and Soil* **49**, 71–83.

Findenegg, G.R., Nelemans, J.A. & Arnozis, P.A. (1989) Effect of external pH and Cl^- on the accumulation of NH_4^+ ions in the leaves of sugar beet. *Journal of Plant Nutrition* **12**, 593–601.

Finkner, R.E., Ogden, D.B., Hanzas, P.C. & Olson, R.F. (1958) The effect of fertilizer treatment on the calcium, sodium, potassium, raffinose, galactinol, nine amino acids, and total amino acid content of three varieties of sugar beets grown in the Red River Valley of Minnesota. *Journal of American Society of Sugar Beet Technologists* **10**, 272–280.

Fixen, P.E. (1993) Crop responses to chloride. *Advances in Agronomy* **50**, 107–150.

Foy, C.D. (1984) Effects of aluminium on plant growth. In: Carson, E.W. (ed.) *The Plant Root and its Environment*. University Press of Virginia, Charlottesville, pp. 601–642.

Frankinet, M., Raimond, Y., Destain, J.P. & Rixhon, L. (1987) Influence of organic manures and incorporation of harvest residues on mineral PK fertilization in large scale cropping. *Proceedings of the IIRB Congress*. pp. 163–176.

Franzen, D.W. & Cihacek, L.J. (1996) North Dakota fertilizer recommendation: tables and equations. *Extension Service SF-882*, North Dakota State University, Fargo.

Fürstenfeld, F. & Bürcky, K. (2000) Current results concerning boron supplies for sugar beet in Southern Germany. *Proceedings of the IIRB Congress*. pp. 415–417.

Germida, J.J., Karamanos, R.E. & Stewart, J.W.B. (1985) A simple microbial bioassay for plant available manganese. *Soil Science Society of America Journal* **49**, 1411–1415.

Giles, J.F., Cattanach, A.W. & Cattanach, N.R. (1991) Effect of boron and Triggrr on sugarbeet yield and quality. *1990 Sugarbeet Research and Extension Reports* 21, North Dakota State University, Fargo, pp. 119–121.

Graham, R.D. & Webb, M.J. (1991) Micronutrients and disease resistance and tolerance in plants. In: Mortvedt, J.J., Cox, F.R., Shuman, L.M. & Welch, R.M. (eds) *Micronutrients in Agriculture*. 2nd edn. Soil Science Society of America, Madison, WI, pp. 329–370.

Gupta, U.C. (1979) Boron nutrition of crops. *Advances in Agronomy* **31**, 273–307.

Haddock, J.L. (1952) The influence of soil moisture condition on the uptake of phosphorus from calcareous soils by sugar beets. *Soil Science Society of America Proceedings*. 16, pp. 235–238.

Hale, J.B., Watson, M.A. & Hull, R. (1946) Some causes of chlorosis and necrosis of sugar beet foliage. *Annals of Applied Biology* **33**, 13–28.

Hamence, J.H. & Oram, P.A. (1964) Effects of soil and foliar applications of sodium borate to sugar beet. *Journal of the Science of Food and Agriculture* **15**, 565–579.

Hanson, B., Grattan, S.R. & Fulton, A. (1999) *Agricultural Salinity and Drainage.* Division of Agriculture and Natural Resources Publication 3375, University of California, Davis.

Hawker, J.S., Marschner, H. & Downton, W.J.S. (1974) Effect of sodium and potassium on starch synthesis in leaves. *Austrian Journal Plant Physiology* **1**, 491–501.

Henkens, C.H. & Jongman, E. (1965) The movement of manganese in the plant and the practical consequences. *Netherlands Journal of Agricultural Science* **13**, 392–407.

Henkens, C.H. & Smilde, K.W. (1966) Evaluation of glassy frits as micronutrient fertilizers. I. Copper and molybdenum frits. *Netherlands Journal of Agricultural Science* **14**, 165–177.

Hills, F.J., Sailsbery, R. & Ulrich, A. (1982) Sugarbeet fertilization. *University of California Cooperative Extension Bulletin 1891*, Davis.

Hocking, T. (1995) The role of sulphur in sugar beet. *British Sugar Beet Review* **63** (1), 10–13.

Hodgson, J.F., Gerring, H.R. & Norvell W.A. (1965) Micronutrient cation complexing in soil solution: I. Partitioning between complexed forms by solvent extraction. *Soil Science Society of America Proceedings.* 29, pp. 665–669.

Hodgson, J.F., Lindsay, W.L. & Trierweiler, J.F. (1966) Micronutrient cation complexing in soil solution: II. Complexing zinc and copper in displaced solution from calcareous soils. *Soil Science Society of America Proceedings.* 30, pp. 723–726.

Hollies, J. (2000) Phosphate and potash removal by crops. *Potash Development Association*, Revision Leaflet 10/00, 1–4.

Hollies, J., Draycott, A.P. & Chambers, B.J. (2001) Beet nutrition. *The Agronomist* **1**, 5–6.

Jansson, S.L. (1987) Optimum supply of P, K and Na to sugar beet in North West Europe. *Proceedings of the IIRB Congress.* pp. 85–101.

Jarvis, P. & Bee, P. (1996) Influence of potassium and sodium fertilizer on beet yields and quality. *British Sugar Beet Review* **64** (3), 25–27.

Jourdan, O., Bourrié, B. & Etourneaud, F. (1992) Elaboration of curves of absorption of mineral elements. 'La betterave'. *Ministère de l'Agriculture et de la Pêche*, Aspach-le-Bas, France, pp. 1–8.

Judy, W., Melton, J., Lessman, G., Ellis, B. & Davis, J. (1964) Zinc fertilization of pea beans, corn and sugar beets in 1964. *Michigan State University Agricultural Experiment Station Research Report* 33, East Lansing.

Kauss, H. (1987) Some aspects of calcium dependent regulation in plant metabolism. *Annual Review of Plant Physiology* **38**, 47–72.

Kirkby, E.A., Armstrong, M.J. & Milford, G.F.J. (1987) Absorption and physiological roles of P and K in the sugar beet plant with reference to the functions of Na and Mg. *Proceedings of the IIRB Congress.* pp. 1–23.

Krügel, C., Dreyspring, C. & Kittganner, R. (1938) Leaching experiments with borates. *Superphosphate* 8 and 9, 141–150, 161–166.

Lachowski, J. (1961) The effect of boron, manganese and copper on the production value of sugar beet in Poland. *Roczniki Nauk Rolniczych* **84A**, 63–88.

Lachowski, J. & Wesolowski, F. (1964) The influence of iron sulphate on yield of sugar beets in Poland. *Roczniki Nauk Rolniczych* **89A**, 547–564.

Lamb, J.A. (1989) Sulfur for sugarbeet in Minnesota and North Dakota. *Sugarbeet Research and Extension Report* 19, North Dakota State University, Fargo, pp. 98–99.

Lamb, J.A. & Cattanach, A.W. (1990) Zinc application on sugarbeet. *1989 Sugarbeet Research and Extension Reports* 20, North Dakota State University, Fargo, pp. 84–86.

Lamb, J.A., Sims, A.L., Smith, L.J. & Rehm, G.W. (2001) *Fertilizing Sugar Beet in Minnesota and North Dakota.* University of Minnesota Extension Service FO-07715-C. St Paul.

Larson, W.E. (1954) Response of sugar beets to potassium fertilization in relation to soil physical and moisture conditions. *Soil Science Society of American Proceedings.* 18, pp. 313–317.

Last, P.J. & Bean, K. (1990) Manganese deficiency and the adjuvant connection. *British Sugar Beet Review* **58** (3), 15–16.

Last, P.J. & Bean, K.M.R. (1991) Controlling manganese deficiency in sugar beet with foliar sprays. *Journal of Agricultural Science, Cambridge* **116**, 351–358.

Läuchli, A. & Pflüger, R. (1978) Potassium transport through plant cell membranes and metabolic role of potassium in plants. *Proceedings 11th Congress International Potash Institute.* Bern, pp. 111–163.

Lawton, K., Erickson, A.E. & Robertson, L.S. (1954) Utilization of phosphorus by sugar beets as affected by fertilizer placement. *Agronomy Journal* **46**, 262–264.

Lichthardt, J.J. & Jacobsen, J.S. (1992) Fertilizer Guidelines for Montana, *Montana State University Extension Service* EB 104, Bozeman.

Lindsay, W.L. (1972) Inorganic phase equilibria of micronutrients in soils. In: Mortvedt, J.J., Giordano, P.M. & Lindsay, W.L. (eds) *Micronutrients in Agriculture.* Soil Science Society of America, Madison, WI, pp. 41–57.

Lucas, R.E. & Knezek, B.D. (1972) Climatic and soil conditions promoting micronutrient deficiencies in plants. In: Mortvedt, J.J., Giordano, P.M. & Lindsay, W.L. (eds) *Micronutrients in Agriculture.* Soil Science Society of America, Madison, WI, pp. 265–288.

MAFF (1976) Trace element deficiencies in crops. *Advisory Paper* **17**, 1–34.

MAFF (2000) Fertilizer recommendations for agricultural and horticultural crops. *Ministry of Agriculture, Fisheries and Food UK RB209*, 1–175.

Marschner, H. (1995) *Mineral Nutrition of Higher Plants.* 2nd edn. Academic Press, London.

Marschner, H., Kylin, A. & Kuiper, P.J.C. (1981) Genotypic differences in response of sugar beet plants to replacement of potassium by sodium. *Physiology Plant* **51**, 239–244.

McEnroe, P. & Coulter, B. (1964) Effect of soil pH on sugar content and yield of sugar beet. *Ireland Journal of Agriculture Research* **3**, 63–69.

McGrath, S.P. (2000) Practical field test for sulphur deficiency. *Arable Farming*, 8th July, p. 6.

McGrath, S.P. & Loveland, P.J. (1992) *The Soil Geochemical Atlas of England and Wales*. Blackie, Glasgow.

McLean, E.O, Hartwig, R.C., Eckert, D.J. & Triplett, G.B. (1983) Basic cation saturation ratios as a basis for fertilizing and liming agronomic crops. II. Field studies. *Agronomy Journal* **75**, 635–639.

Mehlich, A. (1957) Aluminum, iron and pH in relation to lime induced manganese deficiencies. *Soil Science Society of America Proceedings*. 21, pp. 625–628.

Mengel, K. & Kirkby, E.A. (1978) *Principles of Plant Nutrition*. International Potash Institute, Worblaufen-Bern, Switzerland.

Milford, G.F.J., Armstrong, M.J., Jarvis, P.J., Houghton, B.J., Bellett-Travers, D.M., Jones, J. & Leigh, R.A. (2000) Effect of potassium fertilizer on the yield, quality and potassium offtake of sugar beet crops grown on soils of different potassium status. *Journal of Agricultural Science, Cambridge* **135**, 1–10.

Millar, C.E., Cook, R.L. & Davis, J.F. (1938) The effect of fertilizer placement on the yield and stand of sugar beets at the Michigan Experiment Station in 1938. *Proceedings of Annual Meeting National Joint Committee on Fertilizer Application*. 14, pp. 129–131.

Millar, C.E., Cook, R.L. & Davis, J.F. (1940) The effect of fertilizer placement on the yield and stand of sugar beets at the Michigan Experiment Station. *Proceedings of the Annual Meeting National Joint Committee on Fertilizer Application*. 16, pp. 115–116.

Millar, C.E., Cook, R.L., Rood, P.J. & Robertson, L.S. (1945) A comparison of methods of applying fertilizer plough under versus deep planting time placement for corn and plough under versus row application for corn, sugar beets and potatoes. *Proceedings of Annual Meeting National Joint Committee on Fertilizer Application*. 21, pp. 99–104.

Moraghan, J.T. & Ananth, S. (1985) Return of sugar beet tops and the accumulation of certain chemical constituents in soil. *Journal of American Society of Sugar Beet Technologists* **23**, 72–79.

Moraghan, J.T. & Etchevers. J.D. (1981) Method of phosphorus fertilization for sugar beets in the Red River Valley. *Journal of American Society of Sugar Beet Technologists* **21**, 103–111.

Morley Davies, W. (1939) Acidity and manganese deficiency problems in connexion with sugar beet growing. *Annals of Applied Biology* **26**, 285–392.

Mortvedt, J.J., Westfall, D.G. & Croissant, R.L. (1996) Fertilizing sugar beets. *Colorado State University Cooperative Extension Bulletin* No. 0542, Fort Collins.

Mostafa, M.A.E. & Ulrich, A. (1976) Interaction of calcium and magnesium in nutrition of intact sugarbeets. *Soil Science* **121**, 16–20.

Murphy, L.S. (1979) MAP, DAP, poly and rock. *North Central Extension-Industry Soil Fertility Workshop*. Potash and Phosphate Institute, Norcross, GA, p. 35.

Murphy, L.S. & Walsh, L.M. (1972) Correction of micronutrient deficiencies with fertilizers. In: Mortvedt, J.J., Giordano, P.M. & Lindsay, W.L. (eds) *Micronutrients in Agriculture*. Soil Science Society of America. Madison, WI, pp. 347–388.

Nagarajah, S. & Ulrich, A. (1966) Iron nutrition of the sugar beet plant in relation to growth, mineral balance, and riboflavin formation. *Soil Science* **102**, 399–407.

Narayan, D., Chandel, A.S. & Singh, G.R. (1989) Effect of boron fertilization on yield and quality of sugar beet. *Indian Journal of Plant Physiology* **32**, 164–168.

Nowicki, A. (1969) The effect of molybdenum upon yield, health and processing quality of sugar beet. *Roczniki Nauk Rolniczych* **95**, 55–74.

Ødelein, M. (1963) Long-term field experiments with small applications of boron. *Soil Science* **95**, 60–62.

Offiah, O. & Axley, J.H. (1988) Improvement of boron soil test. *Communications in Soil Science and Plant Analysis* **19**, 1527–1542.

Olsen, S.R., Gardner, R., Schmehl, W.R., Watanabe, F.S. & Scott, C.O. (1950) Utilization of phosphorus from various fertilizer materials by sugar beets in Colorado. *Proceedings of American Society of Sugar Beet Technologists*. 6, pp. 317–331.

Olsen, S.R., Cole, C.V., Watanabe, F.S. & Dean, L.A. (1954) Estimation of available phosphorus in soils by extraction with sodium bicarbonate. *USDA Circular 939*, US Government Printing Office, Washington, DC.

Papanicolaou, E.P., Analogides, D.A., Apostolakis, C.G., Skarlou, V. & Nobeli, C. (1982) Effectiveness of P fertilizer placement methods and N fertilizer sources on fertilizer utilization and yield characteristics of sugarbeets. *Journal of American Society of Sugar Beet Technologists* **21**, 247–259.

Paull, J.G., Rathjen, A.J. & Cartwright, B. (1988) Genetic control of tolerance to high concentrations of soil boron in wheat. *Proceedings of 7th International Wheat Genetics Symposium*. Cambridge, pp. 871–877.

Pizer, N.H., Caldwell, T.H., Burgess, G.R. & Jones J.L.O. (1966) Investigations into copper deficiency in crops in East Anglia. *Journal of Agricultural Science, Cambridge* **66**, 303–314.

Reisenauer, H.M. (1988) Determination of plant available soil manganese. In: *Manganese in Soils and Plants, Proceedings of an International Symposium*. University of Adelaide, August 1988, pp. 87–98.

Robertson, L.S. & Lucas, R.E. (1981) Essential micronutrients: manganese. *Michigan State University Cooperative Extension Service Extension Bulletin* E-1031, Michigan State University, East Lansing.

Robertson, L.S., Knezek, B.D. & Belo, J.O. (1975) A survey of Michigan soils as related to possible boron toxicities. *Communications in Soil Science and Plant Analysis* **6**, 359–373.

Robertson, L.S., Cook, R.L. & Davis, J.F. (1976a) The Ferden Farm Report: Part II, Soil management for sugar beets 1940–1970. *Michigan State University Agricultural Experiment Station Research Report* 324, East Lansing.

Robertson, L.S., Christenson, D.R. & Warncke D.D. (1976b) Essential secondary elements: calcium. *Cooperative Extension Service Extension Bulletin* E-996, Michigan State University, East Lansing.

Robertson, L.S., Christenson, D.R. & Warncke D.D. (1979) Essential secondary elements: magnesium. *Cooperative Extension Service Extension Bulletin* E-994, Michigan State University, East Lansing.

Rodriguez, J. & Tomic, Y.M.T. (1984) Micronutrient availability in andisols and ultisols of Los Lagos region. *Ciencia e Investigacion Agrararia* **11**, 169–178.

Romsdal, S.D. & Schmehl, W.R. (1963) The effect of method and rate of phosphate application on yield and quality of sugar beets. *Journal of American Society of Sugar Beet Technologists* **12**, 603–607.

Rowe, E.A. (1936) A study of heart-rot of young sugar beet plants grown in culture solutions. *Annals of Botany* **50**, 735–746.

Rozema, J., De Bruin, J. & Brockman, R.A. (1992) Effect of boron on the growth and mineral economy of some halophytes and non halophytes. *New Phytologist* **121**, 249–256.

Salcedo, I.H., Ellis, B.G. & Lucas, R.E. (1979) Studies in soil manganese: II. Extractable manganese and plant uptake. *Soil Science Society of America Journal* **43**, 138–141.

Sanz Saez, A. (1985) Fertilizer trial results with phosphorus and potassium in Central and Northern Spain. *Proceedings of the IIRB Congress*. pp. 341–355.

Scherer, H.W. (2001) Sulphur in crop production. *European Journal of Agronomy* **14**, 81–111.

Schmehl, W.R., Olsen, S.R. & Gardner, R. (1952) Effect of type of phosphate material and method of application on phosphate uptake and yield of sugar beets. *Proceedings of American Society of Sugar Beet Technologists*. 7, pp. 153–158.

Schmehl, W.R., Olsen, S.R. & Gardner, R. (1954) Effect of method of application on the availability of phosphate for sugar beets. *Proceedings of American Society of Sugar Beet Technologists*. 8, No. 2, pp. 363–369.

Sexton, J.J. (1996) Sulphur survey of the sugar beet crop in England 1995. *British Sugar Beet Review* **64** (2), 50–53.

Shoemaker, H.E., McLean, E.O. & Pratt, P.F. (1961) Buffer methods of determining lime requirement of soils with appreciable amounts of extractable aluminium. *Soil Science of America Proceedings*. 25, pp. 274–277.

Siegenthaler, A. (1987) Influence of phosphorus fertilizer on yield and sugar content of sugar beet in field experiments. *Proceedings of the IIRB Congress*. pp. 271–279.

Sims, A.L. & Smith, L.J. (2001) Early growth response of sugar beet to fertilizer phosphorus in phosphorus deficient soils of the Red River Valley. *Journal of American Society of Sugar Beet Technologists* **38**, 1–17.

Sims, A.L. & Smith, L.J. (2003) Broadcast applications of phosphorus fertilizer in low P testing soils. *Proceedings of the 1st Joint IIRB-ASSBT Congress*. San Antonio.

Sipitanos, K.M. & Ulrich, A. (1969) Phosphorus nutrition of sugarbeet seedlings. *Journal of American Society of Sugar Beet Technologists* **15**, 332–346.

Smilde, K.W. (1970) Soil analysis as a basis for boron fertilisation of sugar beets. *Zeitschrift fuer Pflanzenernachrunk Enähr und Bodenkunde* **125**, 130–143.

Stoker, G.L. & Tolman, B. (1941) Boron deficiency relations in sugar beets grown for seed in Oregon. *Journal of the American Society of Agronomy* **33**, 657–665.

Subbarao, G.V., Wheeler, R.M., Stutte, G.W. & Levine, L.H. (1999) How far can sodium substitute for potassium in red beet? *Journal of Plant Nutrition* **22** (11), 1745–1761.

Syers, J.K., Skinner, R.J. & Curtin, D. (1987) Soil and fertilizer sulphur in UK agriculture. *Fertilizer Society Proceedings*. No. 264, pp. 1–43.

Tandon, P.K. (1979) Relative susceptibility of four varieties of sugar beet to boron deficiency. *Indian Journal of Agricultural Research* **13**, 55–56.

Terry, N. (1977) Photosynthesis, growth and the role of chloride. *Plant Physiology* **60**, 69–75.

Terry, N. & Ulrich, A. (1973) Effects of phosphorus deficiency on the photosynthesis and respiration of leaves in sugar beet. *Plant Physiology* **51**, 43–47.

Terry, N., Evans, P.S. & Thomas, D.E. (1975) Manganese toxicity effects on leaf cell multiplication and expansion and on dry matter in sugar beets. *Crop Science* **15**, 205–208.

Tills, A.R. & Alloway, B.J. (1981) Subclinical copper deficiency in crops on the Breckland in East Anglia. *Journal of Agricultural Science, Cambridge* **97**, 473–476.

Tinker, P.B.H. (1967) The relationship of sodium in the soil to uptake of sodium by sugar beet in the greenhouse and to yield responses in the field. *Proceedings of International Soil Science Society*. pp. 223–231.

Tinker, P.B., Jones, M.D. & Durall, D.M. (1992) A functional comparison of ecto- and endomycorrhizas. In: Read, D.J., Lewis, D.H., Fitter, A.H. & Alexander, I.J. (eds) *Mycorrhizas in Ecosystems*. CABI Publishing, Wallingford, pp. 303–310.

Ulrich, A. & Hills, F.J. (1969) Sugar beet nutrient deficiency symptoms – a color atlas and chemical guide. *Division of Agriculture Sciences*, University of California, Davis.

Ulrich, A. & Mostafa, M.A.E. (1976) Calcium nutrition of the sugarbeet. *Communication in Soil Science and Plant Analysis* **7**, 483–495.

Ulrich, A. & Ohki, K. (1956a) Hydrogen ion effects on early growth of sugar beet plants in culture solution. *Journal of American Society of Sugar Beet Technologists* **9**, 265–274.

Ulrich, A. & Ohki, K. (1956b) Chlorine, bromine and sodium as nutrients for sugar beet plants. *Plant Physiology* **31**, 181–191.

Van Luit, B. & Smilde, K.W. (1969) Boron fertilisation of sugar beets based on soil analysis. *Rapport Insituut voor Bodemvruchtbaarheed Haren* **9**, 1–48.

Van Schreven, D.A. (1936) Copper deficiency in sugar beets. *Phytopathology* **26**, 1106–1117.

Vanstallen, R. & Vandergeten, J.P. (1987) Quantitative and qualitative study of nutrient elements in crop residues in the course of long term trials. *Proceedings of the IIRB Congress*. pp. 25–41.

Viets Jr, F.G. & Robertson, L.S. (1971) Secondary nutrients and micronutrients. In: Johnson, R.T., Alexander, J.T., Rush, G.E. & Hawkes, G.R. (eds) *Advances in Sugar Beet Production: Principles and Practices*. The Iowa State University Press, Ames, pp. 171–187.

Vitosh, M.L., Warncke, D.D. & Lucas, R.E. (1998) Secondary- and micro-nutrients. *Michigan State University Extension Service Bulletin* E-486, East Lansing.

Voth, R.D & Christenson, D.R. (1980) Effect of fertilizer reaction and placement on availability of manganese. *Agronomy Journal* **72**, 769–773.

Voth, R.D., Reisen, J. & Christenson, D.R. (1979) Effect of applied boron on yield of sugarbeets. *Michigan State University Agricultural Experiment Station Research Report* 376, East Lansing.

Wadsworth, G.A & Webber, J. (1980) Deposition of minerals and trace elements in rainfall. In: *Inorganic Pollution and Agriculture*. MAFF Reference Book 326, HMSO, London, pp. 47–55.

Wallace, T. (1945) Some aspects of mineral deficiencies in farm crops. *Agricultural Progress* **20**, 20–25.

Warburg, O & Lüttgens, W. (1946) Photochemiche Reduction des Chinons in grünen Zellen und Granual. *Biochemia* **11**, 321–322.

Warren, R.G & Johnston, A.E. (1962) Barnfield. *Rothamsted Experimental Station Report for 1961*, pp. 58–59.

Watson, M.E & Brown J.R. (1998) pH and lime requirement. In: Brown, J.R. (ed.) Recommended chemical soil test procedures for the North Central Region. *Missouri Agricultural Experiment Station* SB 1001, University of Missouri, Columbia.

Whitehead, D.C. (2000) *Nutrient Elements in Grassland*. CABI Publishing, Wallingford.

Winder, T.L & Nishio, J.N. (1995) Early iron deficiency stress response in leaves of sugar beet. *Plant Physiology* **108**, 1487–1494.

Yerokun, O.A & Christenson, D.R. (1989) Use of urea and ammonium phosphates as starter fertilizers. *Journal of Fertilizer Issues* **6**, 12–16.

Chapter 10
Water Use and Irrigation

Rodrigo Morillo-Velarde and Eric S. Ober

INTRODUCTION

Water is the basis of life and an important constituent in plants. Sugar beet, like all plants, require a certain amount of water for cellular functions and turgor pressure, which supports the structure of the plant. This amount of water, however, is far exceeded by the quantity of water that passes through roots, stems and leaves as it moves from the soil to the atmosphere during the life of the plant. This transpirational water loss is an inevitable consequence of life on dry land and the fact that plant leaves must be open to gas exchange in order to survive. Plants require uptake of carbon dioxide from the air for photosynthesis (and sugar production), but cannot at the same time prevent water from escaping through the same pores (stomata) that permit the entry of carbon dioxide. Understanding and managing this balance of growth and water consumption is the crux of profitable and environmentally sustainable use of water resources.

WATER AS A RESOURCE

The availability of fresh water for human use is a worldwide problem, and predictions are that as populations increase, the pressure on limited resources will magnify the many already existent crises (Postel, 1998; Qadir *et al.*, 2003; Araus, 2004). On a global scale, agriculture consumes more water than any other sector. Where water supplies are limited, there are constant political and environmental discussions over the distribution of water between urban, industrial and agricultural water needs. Agricultural users, therefore, are increasingly being asked to justify water inputs, and demonstrate that it is used efficiently. Examples of this can be found in the water directives issued by the European Union in 2000.

THE SUGAR BEET CROP AND WATER

Sugar beet is currently grown on four continents, and if the commercial introduction of this crop prospers in Australia (Weeden, 2000), soon there will be five. This means that sugar beet can be grown profitably in very different climatic and edaphic environments. The wild relative of sugar beet (*Beta vulgaris* ssp. *maritima*), from which sugar beet was originally developed, also thrives from Scandinavia to North Africa (Doney, 1989). Populations of *maritima* beet are often established in niches where other plant species cannot survive, such as beaches, rocky cliffs exposed to sea spray, and other sites with shallow, sandy soil. Because of this background, modern sugar beet varieties also show remarkable tolerance to salinity and drought compared to many other crop species. However, unlike wild plants that need only survive to produce seed for the next generation, plants cultivated for profit need to show much greater levels of productivity. In most arid and semi-arid areas where water availability limits growth, irrigation is a necessity. This chapter reviews current understanding of how water affects the growth and yield of sugar beet, and how water inputs are best applied when the natural supply is insufficient.

WATER AND PHYSIOLOGY

Water has several important roles in plants:

- Water is the solvent for cytoplasmic and extracellular constituents.
- Water participates in many biochemical reactions.
- Water is the primary electron donor in photosynthesis and the source of photosynthetically produced oxygen.
- It provides the hydrostatic pressure (turgor) that drives growth and maintains plant structure and posture.
- The cooling effect as water evaporates from leaf surfaces is important for temperature control.
- Nutrients and hormones are carried through the plant by mass flow of water through vascular elements.

Water moves from the soil through the plant in one continuous liquid phase until it evaporates from the stomatal pores of leaves. This is commonly described as the 'soil–plant–atmosphere continuum' (SPAC). The term emphasizes the idea that the cohesion of water between cells, through the conducting elements (xylem), and at the root–soil interface is essential for the movement of water through the plant. Along the SPAC, there is natural resistance to water flow, which causes tension (negative pressure) to develop in the xylem. This resistance is greater at some points within the plant than at others. For instance, the complex weave of vascular elements as xylem vessels pass through the crown may be one place in which hydraulic conductivity is limited (Stieber & Beringer, 1984; Cavazza *et al.*, 1992). When the atmospheric demand is high (a large leaf-to-air vapour pressure difference [VPD]), and water is being pulled through the plant causing a large tension in the xylem, the water column can actually break, causing an embolism. This cavitation prevents further water movement until it is repaired by refilling xylem vessels during the night (McCully, 1999). During the day, the rate of water loss from the leaf is controlled mostly by the aperture of the stomatal pores. Closed stomata limit water loss, but also restrict the uptake of carbon dioxide, inhibit photosynthesis and ultimately decrease yield.

DEFINING THE WATER STATUS OF PLANTS AND SOILS

The water status of plants and soils can be expressed in terms of water potential (ψ_w), which is defined as the difference in free energy per unit volume between water at one location and pure water at the same temperature and atmospheric pressure. Water potential is expressed in units of pressure and has several components:

$$\psi_w = \psi_s + \psi_p + \psi_m + \psi_g$$

where the subscripts s, p, m and g refer to the effect of dissolved solutes, pressure, matric forces and gravity, respectively. (Except in tall trees, differences due to gravity are negligible, and for most purposes ψ_m is adequately described by ψ_s and ψ_p.) The ψ_s decreases the value of ψ_w, while ψ_p usually has a positive influence. Since the ψ_w of pure water is set at 0, the ψ_w of plant cells and soil solutions are negative. Despite the complexity of this thermodynamic nomenclature, the utility of ψ_w is that it chemically defines each compartment within the SPAC and describes how water moves between these compartments. Within a defined system, water always moves from a region of greater ψ_w to smaller (more negative) ψ_w.

To illustrate: the ψ_w of soil solution at field capacity is usually near –0.005 MPa, a root epidermal cell may have a ψ_w equal to –0.5 MPa, the leaf –0.8 MPa, and the air surrounding the leaf (at 90% relative humidity and 20ºC), –14 MPa. Note the steep gradient in ψ_w from leaf to air; the ψ_w of air at 50% humidity decreases to –94 MPa! Similarly, even though root cells have a positive ψ_p (turgor), which would tend to force water out of the root, water flows into the root because these cells accumulate enough solutes to make ψ_s more negative than ψ_p, and hence the ψ_w of the root more negative than the soil solution. The accumulation and compartmentalization of solutes is a regulated process in plant cells, and determines not only water influx, but maintenance of turgor and it also influences sucrose accumulation in root cells. The ψ_w of leaves and soils are used in modelling crop growth (Jaggard & Werker, 1999) and programming irrigation (see below).

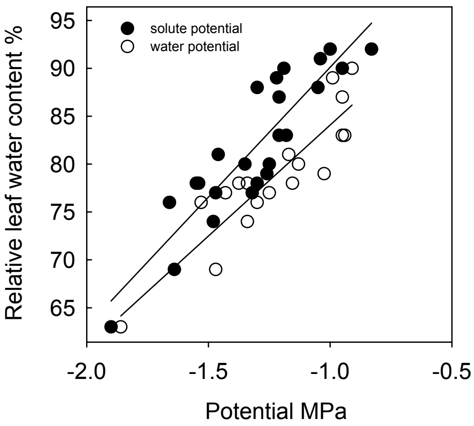

Fig. 10.1 The relationship between leaf relative water content and components of leaf water potential. Redrawn from Milford *et al.*, 1977.

Another indicator of the water status of plants is the relative water content (RWC). This parameter, which relates the water content of tissues to a fully hydrated state, often correlates with the level of physiological activity. Leaf ψ_w and RWC are related in a simple fashion, but the nature of the relationship depends on many factors including plant species (Fig. 10.1). Note that leaf turgor pressure is the arithmetic difference between the lines for ψ_w and ψ_s, and that it is possible to maintain some turgor even at ψ_w as low as –1.5 MPa.

How plants regulate their water economy

Plants respond to a decrease in the availability of water, measured in terms of soil ψ_w, by limiting transpiration rate (Fig. 10.2a). Correspondingly, leaf ψ_w also decreases (Fig. 10.2b). This behaviour characterizes sugar beet as an 'anisohydric' species, in contrast to 'isohydric' species such as maize that maintains leaf ψ_w even as soil ψ_w decreases (Tardieu & Simonneau, 1998). The VPD has a large effect on transpiration rate, with drier air pulling more water out of the leaf. The lines converge as stomata increasingly restrict water loss as the soil dries (Fig. 10.2a). A consequence of incomplete stomatal control of transpiration at high VPD under irrigated conditions is that leaf ψ_w decreases. Thus, it is not surprising that in hot, dry climates more irrigation water is required to maintain the same soil water status as in cooler, humid areas.

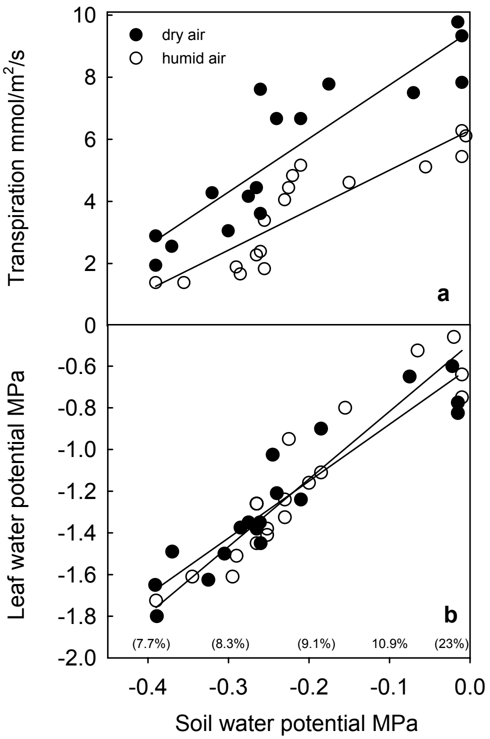

Fig. 10.2 The relationships between soil water potential and transpiration rate (a) and leaf water potential (b) under conditions of high vapour pressure deficit (dry air) or humid air obtained using mist irrigation. Values in parentheses are approximate volumetric soil water contents for the corresponding soil water potentials in this experiment. Redrawn from Lawlor and Milford (1975).

Interestingly, in pot-grown plants in the glasshouse, leaf ψ_w is insensitive to changes in VPD over a range of soil ψ_w (Fig. 10.2b). Under these conditions, the flux of water through the plant is adjusted in response to supply and demand, such that leaf ψ_w is maintained. In field experiments, a different behaviour is often observed: leaf water potential is sensitive to VPD and decreases even in the absence of soil water deficit (Fig. 10.3). This suggests that when evaporative demand is high (perhaps greater than can be achieved in artificial conditions) the hydraulic resistance of the water conduction pathway limits the flux of water to leaves (Brown *et al.*, 1987; Cavazza & Patruno, 1993) and leaves can

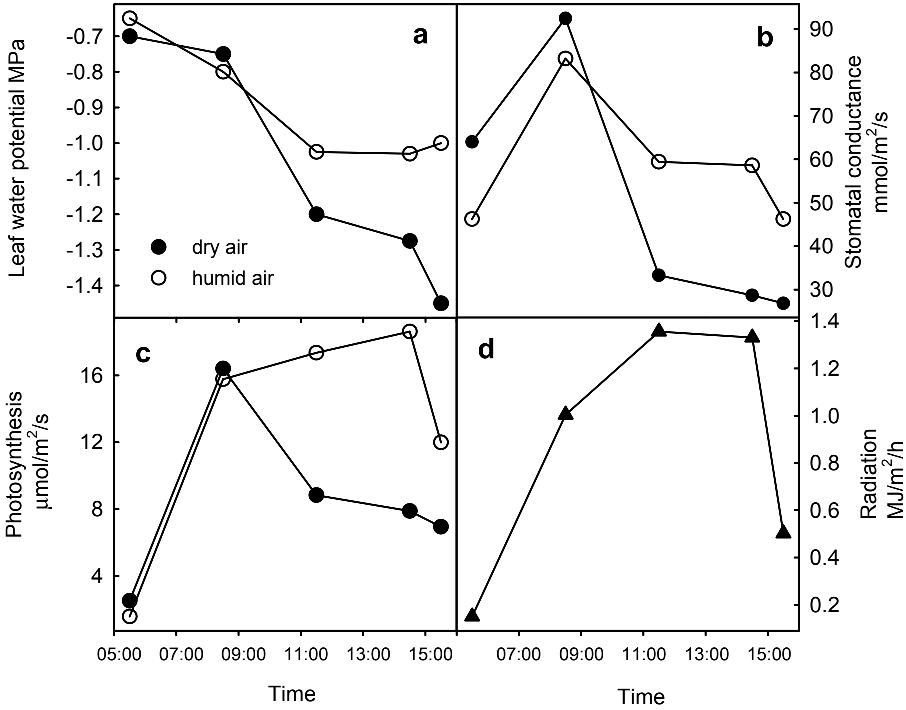

Fig. 10.3 Diurnal changes in leaf water potential (a), stomatal conductance (b), photosynthetic rate (c) and solar radiation above the crop (d) for an experiment conducted 21 August, 1974. The crop was irrigated with trickle irrigation to avoid soil moisture deficits greater than 15 mm. Supplemental mist irrigation was applied to humidify the air and decrease VPD compared to plots growing in relatively dry air. Redrawn from Milford (1975).

temporarily wilt. Some data suggest that it is the number and size of functional xylem elements that keep water from reaching the leaves fast enough to prevent a decline in leaf ψ_w (Fernandez & McCree, 1991). Stomata begin to close in response to the declining water status of the plant, keeping further loss of water in check. The consequence is that photosynthetic rate is far from the potential rate for the amount of light and water available, and therefore growth and sugar accumulation are also affected. However, other studies show that when irrigated plants wilt at midday, stomatal conductance and photosynthetic rates are less affected (Kohl & Cary, 1969; Brown & Rosenberg, 1971; Cavazza & Patruno, 1993). In these circumstances, the loss of turgor affects the posture of the canopy more than physiological activity, with little effect on yield.

Two processes that are critical for sugar production are leaf expansion (important for the interception of solar radiation) and photosynthetic rate. Photosynthetic rate is regulated mostly by stomatal conductance, which decreases as leaf ψ_w decreases (Fig. 10.4a,b). Growth is more sensitive to changes in water supply than is photosynthesis (compare the slopes of Figs 10.4b and 10.4c). Stomata respond to a number of environmental cues such as light, carbon dioxide, transpiration rate, and the water status of the plant and soil. These factors are integrated into chemical and hydraulic messages that communicate environmental conditions to the stomata.

There is substantial evidence from several species that chemical signals produced by roots in drying soil inhibit leaf growth or stomatal conductance before there is any noticeable change in leaf ψ_w (Ghariani, 1981; Davies *et al.*, 2002). Increased concentration of abscisic acid (ABA) in xylem sap and changes in xylem sap pH are two widely studied root-sourced messages to leaves. Increased sap pH modulates the sensitivity to ABA, which in-

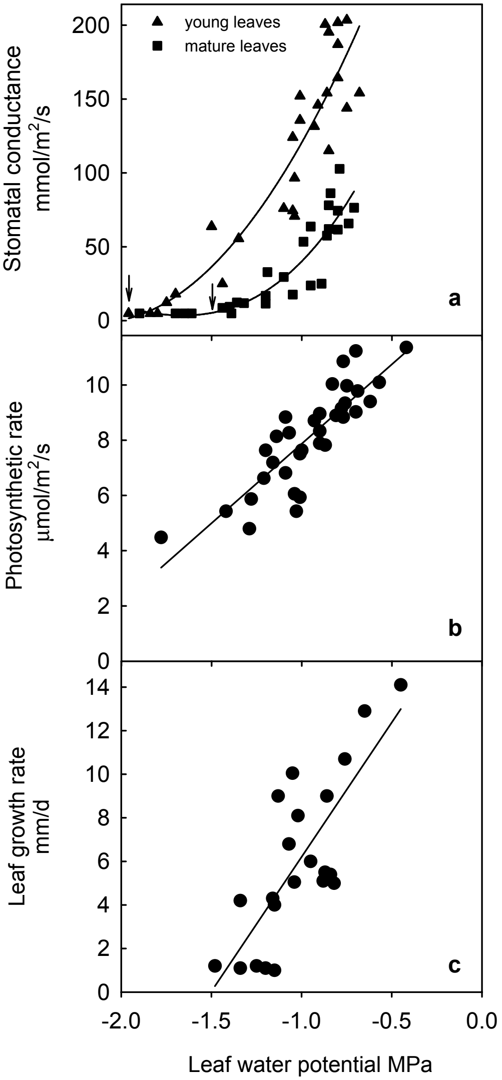

Fig. 10.4 Relationships between leaf water potential and stomatal conductance (a), photosynthetic rate (b) and leaf growth rate (c). In (a), arrows next to the curves indicate the leaf water potentials at which the first signs of wilting were observed in young and mature leaves. Redrawn from Lawlor and Milford, 1975.

duces stomata to close. The concentration of ABA at the stomatal guard cell is also affected by the delivery rate of ABA via xylem sap, determined by the rate of transpiration.

Stomata also respond to hydraulic signals (Sperry *et al.*, 2002). Leaf ψ_w (or leaf RWC), xylem resistance (Sperry *et al.*, 2003) and cellular conductance to water via the expression of membrane-integrated aquaporins (Maurel, 1997; Amodeo *et al.*, 1999) are forms of hydraulic signals. Information on the nature of chemical and hydraulic signals and how they operate in sugar beet is required.

Young leaves can maintain greater stomatal conductance than older leaves at the same leaf ψ_w (Fig. 10.4a). Young leaves also wilt at lower leaf ψ_w than mature leaves (Fig. 10.4a; Fig. 10.5). Some of the processes that decrease with leaf age may be hydraulic conductivity, the ratio of xylem capacity to leaf area and the ability to accumulate solutes for turgor maintenance. As leaves grow there is an increase in the size of stomata and a decrease in stomatal density. Sugar beet has stomata on both surfaces of the leaf (amphistomatic), but with greater frequencies on the lower (abaxial) side (Burrows, 1969; Tognetti *et al.*, 2003). Ploidy level affects leaf


(a)

Fig. 10.5 Drought-stressed sugar beet plants in the field. (a) Note the loss of turgor in petioles, which changes leaf angle and allows leaves to touch the soil. (*Continued.*)


(b)


(c)

Fig. 10.5 (*Continued*.) (b) Stressed plants in the UK, showing the differential sensitivity of the smaller, younger leaves compared with older, mature leaves. (c) Stressed plants in Spain. Note the large amount of leaf area that has senesced in response to the drought, and the differences between the UK and Spain. Responses to water shortage are also connected to heat stress.

size and stomatal density. It is unlikely that differences in stomatal density have a sizeable effect on transpiration rate since stomatal size and aperture compensate for changes in density (Jones, 1977), and plants regulate water flux regardless of how water leaves the plant.

Plant responses to water deficit

Plants experience water deficit when water supply to the foliage cannot keep pace with the rate of water loss. This can occur on a daily basis when the evaporative demand is high, with recovery as soon as the demand decreases. Limited periods of water deficit often have no measurable effect on final yield. Prolonged water deficit (drought), however, diminishes photosynthetic capacity, hastens leaf death and takes a significant toll on yield. In the UK and Iran, for instance, drought causes more annual yield losses than pests and diseases (Jaggard *et al.*, 1998; Abdollahian-Noghabi, 2000). If enough water is removed from the plant, including the storage root, the entire plant dies. In temperate climates this rarely, if ever, happens to established plants.

Plant function is affected in several ways as soil ψ_w decreases, in general order of occurrence:

- Leaf expansion slows (Milford *et al*., 1985, Morillo-Velarde, 1991). If drought occurs before full ground cover (while the canopy is still enlarging), slow leaf expansion means that valuable radiation is not intercepted by the plant and yield suffers accordingly. The rate of production of new leaves is less sensitive to water deficits than the expansion of leaves already formed (Morton & Watson, 1948; Milford *et al*., 1985; Velicia, 1998). There are genotypic differences in the sensitivity of leaf expansion to drought (Ober & Luterbacher, 2002). Water deficit hastens the senescence of leaves (Fig. 10.5), which reduces the photosynthetic efficiency of the leaves and the amount of light intercepted by the canopy as leaves die. Leaf growth recovers quickly after removal of the water deficit, and in some cases recovered leaves temporarily grow faster than those on irrigated plants (Owen & Watson, 1956; Milford *et al*., 1985). However, the yield of crops that have suffered from drought cannot match that of irrigated crops because the radiation use efficiency was low during the time the leaves were stressed (Ober *et al*., 2004), and this time cannot be recovered.
- Leaf ψ_w and stomatal conductance decrease, limiting photosynthesis by decreasing carbon dioxide uptake. Smaller transpiration rates provide less leaf cooling, and high temperatures, too, can damage leaves and accelerate senescence. Only at very low leaf RWC is the photosynthetic apparatus itself damaged. Decreased production of assimilate slows root growth and sugar storage.
- Plants accumulate solutes in a process called osmotic adjustment. The decrease in cellular ψ_s increases the driving force for water uptake and counteracts the loss of turgor as tissues dehydrate during drought or salinity stress. Osmotic adjustment is usually differentiated from the passive concentration of solutes that occurs as water is withdrawn from the cells. The principle solutes in sugar beet are sucrose, glycine betaine, proline and inorganic ions such as Na^+ (Hanson & Wyse, 1982; Heuer & Plaut, 1989; Gzik, 1996; Ghoulam *et al.*, 2002). In wheat, a single recessive gene conditions osmotic adjustment, and drought tolerant varieties have been selected on this basis (Morgan, 2000). In sugar beet, genotypes differ in osmotic adjustment, but it is not yet clear if this trait contributes to better yields under drought conditions (Ober *et al*., 2005b).
- The industrial quality of roots is diminished by drought, principally by increased levels of α-amino N compounds (Bazza, 1993; Röver & Büttner, 1999; Kenter & Hoffmann, 2002). Irrigation often improves beet quality mostly by decreasing α-amino N compounds (Winter, 1988; Morillo-Velarde, 1990; Dunham *et al*., 1993). The effect of water deficit on other quality parameters is less clear and varies from year to year (Mambelli *et al*., 1992; Tugnoli *et al*., 1999; Fabeiro *et al*., 2003; Ober *et al*., 2005a).

The root system and water uptake

From the day of germination, the root system of the plant grows and enlarges, exploring the soil and absorbing water and nutrients. The rate of root growth is determined by the ability of the leaves to supply energy to the roots, and by the soil environment. Abiotic factors of the rhizosphere include temperature, soil ψ_w, pH, soil NO_3^- and PO_4^- concentration, penetration resistance, salinity, etc. Organisms in the soil can be harmful (e.g. nematodes) or beneficial (certain bacteria) to growth. Initially, the root system grows at a rate of approximately 10 mm/day (which is temperature dependent), and later it increases to 15 mm/day (Brown & Dunham, 1989; Wright *et al*., 1994).

The roots of sugar beet are divided into the main storage (tap) root and the system of lateral roots emanating from the grooves and branching from the tip of the main root axis. These lateral roots are collectively called the 'fibrous' root system, which are responsible for the majority of water and nutrient uptake. The ratio of fibrous roots to total dry matter decreases from 0.3 in young plants to 0.04 in mature plants (Brown & Biscoe, 1985). The root system of beet can reach 2 m from the surface, given time and the absence of physical barriers. In most soils, however, the majority of root activity takes place within the upper 30–50 cm where root density is the greatest. The root density of sugar beets is sparse compared to the root system of grain crops (Brown *et al.*, 1987; Windt & Märländer, 1994; Camposeo & Rubino, 2003). Within the upper 30 cm of a fully irrigated soil profile, a typical value for sugar beet is 2.0 cm root per cm^3 soil volume compared with approximately 8.0 in wheat or maize. Sugar beet apparently compensates for the lack in root proliferation by high rates of water absorption. Water inflow rates for sugar beet roots are typically 5–15 μl/cm/d compared to 0.2–2.0 in wheat. Although there are many kilometres of roots in 1 m^3 of soil, perhaps only limited sections of root contribute to the bulk of water uptake. In maize, there have been extensive studies of root anatomy and water uptake (McCully, 1995), but similar work in sugar beet is lacking.

The distribution or architecture of the root system also depends on genetic and environmental factors. For instance, a root system growing in dry conditions can reach deeper into the soil profile, but has fewer live roots in more shallow soil layers (Brown *et al.*, 1987; Smith, 2002). Irrigated crops preferentially extract water near the soil surface, while withholding irrigation eight weeks prior to harvest resulted in significant changes in the proportion of water removed from deep soil layers (Fig. 10.6).

WATER USE BY SUGAR BEET

Calculating evapotranspiration

The establishment of an environmental 'baseline' is vital to estimating crop water use and is essential for crop growth models and scheduling irrigation. The standard baseline is the evapotranspiration rate (*ET*), which is simple in concept, but slightly more complicated to measure or estimate. As the term indicates, *ET* combines evaporation from bare soil and transpiration from the crop canopy. The relative contributions of evaporation and transpiration depend on the proportion of bare soil covered by the crop, which changes as the crop grows. The movement of water from a crop into the atmosphere depends on the energy balance of the system, driven by the incident solar radiation, wind, humidity, air temperature, etc.

At first, when the plant is small, 85% of *ET* is evaporation from soil, but this decreases as the canopy develops and transpiration increases. *ET* and leaf area index (LAI) are highly correlated. An increase in LAI of 15% causes a 5–7% increase in estimated *ET* according to the model of Rosenberg

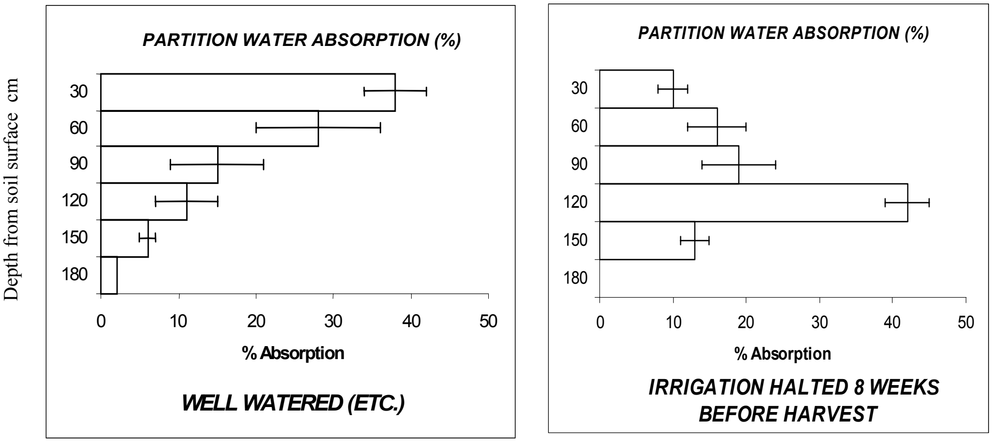

Fig. 10.6 The partitioning of total soil water absorption according to depth from the soil surface under irrigated conditions or water deficit. Data from Velicia, 1998.

et al. (1990). When LAI reaches 3, soil evaporation is already less than 10%, and at full ground cover (LAI 4–6), transpiration is 90–95% of *ET*. Even at this stage, if the soil is wet evaporation can be a considerable fraction of *ET*. When the soil surface is dry, however, evaporation rates are low compared with rates of transpiration.

Thornthwaite (1944; 1948), defined *ET* as 'the maximum amount of water which will be lost by a surface covered in vegetation actively growing if at all times there is moisture in the soil'. The concept of *ET* was formalized by Penman, working at Rothamsted, who used sugar beet as one of his test crops (Penman, 1952). The original Penman equation has been modified over the years to include additional terms, first by Monteith (1965) who included a canopy resistance function. In 1977, Doorenbos and Pruitt introduced the term 'reference evapotranspiration' (ET_o). More recently, the FAO has defined ET_o, using the modified Penman-Monteith equation, as the rate of evapotranspiration from a 'hypothetical grass reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s/m and an albedo of 0.23. The reference surface closely resembles an extensive surface of green, well-watered grass of uniform height, actively growing and completely shading the ground' (Allen *et al.*, 1998). A slight disadvantage to this derivation of ET_o is that detailed weather data are required. Quite often, these data are not available for every location, and even more often some values are missing. The FAO recommends procedures to estimate the missing data in order to then use the Penman-Monteith equation (Allen *et al.*, 1998).

The actual evapotranspiration from a crop (ET_c) can be obtained by direct measurements, or by multiplying ET_o by a crop coefficient (K_c). There are a number of methods to measure or infer ET_c: weighing lysimeters, micrometeorological measurements (Bowen ratio-energy balance or eddy covariance methods), measurements of sap flow, and scintillometry. The Bowen ratio method can be very accurate in the estimation of *ET*. Lysimeters are also accurate, provided that they are surrounded by crop at the same height, and wide and deep enough to mimic a field situation (Anda, 1994; Prueger *et al.*, 1996).

Alternatively, ET_c can be calculated from estimates of ET_o and K_c, following FAO recommendations (Doorenbos & Pruitt, 1977). K_c is determined empirically as a function of crop growth and coverage of the soil surface by foliage. Since the development of the canopy is a continuous process in sugar beet, four crop stages were proposed to facilitate use of K_c (Table 10.1). An example of the K_c values for spring-sown sugar beet in Spain is shown in Fig. 10.7. At full canopy cover, the maximum value of K_c reported for the UK was 1.26 (Draycott & Messem, 1977), with similar values proposed for Germany (Roth & Guenther, 1992) and the USA (Doorenbos & Pruitt, 1977). A slightly lower value (1.11) was obtained for spring-sown beet in Spain (Morillo-Velarde, 1996). These values are similar to those reported for maize (1.2) and other crops such as tomato, cotton, sunflower and alfalfa (1.15; Allen *et al.*, 1998).

An alternative method is to determine the value of K_c based on measurements of LAI (Ritchie & Johnson, 1990), or the proportion of soil covered by foliage assessed by remote sensing (Dunham & Brown, 1987). Since the growth stages in Table 10.1 are not discrete in practice, and the duration of each stage is subject to husbandry and environmental conditions, actual measurements of canopy cover improves the accuracy of using the correct value of K_c.

Table 10.1 Approximate duration of crop growth stages under different cultivations in different regions (Allen *et al.*, 1998). Growth stage 1 = ≤ 10% crop cover; stage 2 = 10–100% cover (or LAI = 3); stage 3 = 100% cover until beginning of leaf senescence; stage 4 = late season to harvesting. The range of reported K_c values for each stage are given.

		Growth stage (days)			
Region	Sowing date	1	2	3	4
Northern Europe	Spring	25–30	35–60	50–70	30–50
California	Spring	30	45	90	15
Mediterranean	Autumn	45	75	80	30
Mediterranean	Spring	25	35	50	50
Arid		35	60	70	40
K_c		0.4–0.5	0.75–0.85	1.05–1.20	1.0–0.9

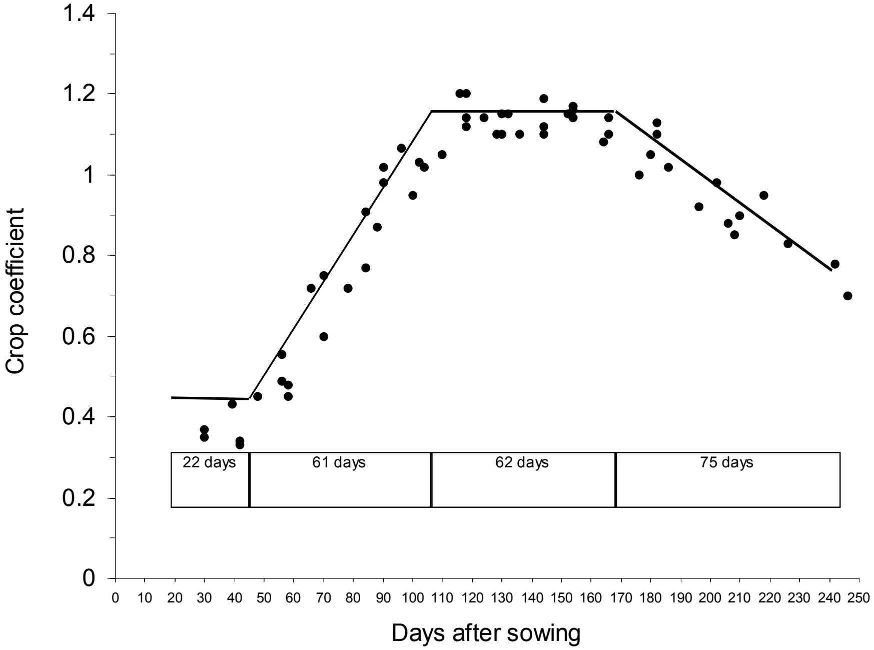

Fig. 10.7 Seasonal changes in the crop coefficient relating to four stages of canopy development. Data from Morillo-Velarde, 1996.

Rates of water consumption

A range of ET_c values for sugar beet have been reported (Table 10.2). These measurements should be of a crop that is managed using best practice (well-fertilized, disease-free, minimal soil water deficit). Additional values of water consumption have been published previously (Dunham, 1993). The broad range of climatic conditions under which sugar beet is grown results in an equally broad range of water demand and water consumption. *ET* generally decreases with increasing lati-

Table 10.2 Water consumption by sugar beet crops in different regions. Length of growing season and measurement methods differed between studies.

Region	Year	Water consumption (ET_c) (mm)	Reference
UK	1967–1969	450	Draycott & Durrant, 1971
Broom's Barn, UK	1967–1991	385	Dunham *et al.*, 1993
Göttingen, Germany	1971	492	Ehlers & Goss, 2003
Skopje, Macedonia	1993	795	Cukaliev & Iljovski, 1993
Mediterranean average		680–920*	Morillo-Velarde, 2000
Doukkala, Morocco	1996	571	Belabbes, 2002
Kafr El Sheikh, Egypt	1999	627–653	El Yamani, 1999
India	1988	494	Bains & Narang, 1988
California, USA	1987	969–1043	Pruitt *et al.*, 1986
Colorado, USA	1988	781	Waskom, 1994

* Average of several Mediterranean countries. Smaller value refers to autumn-sown crops; larger value is for spring-sown crops.

Table 10.3 Typical quantities of water consumption for whole-season growth of various crops. Length of the growing season can vary within each crop.

Crop species	Total water consumption (mm)	K_y
Sugar beet (Spain)	636	0.86
Sugar cane	700–1000	1.2
Maize	559	1.25
Tomato	703	1.05
Sunflower	486	0.95
Alfalfa	1063	1.1
Cotton	717	0.85
Potato	460	1.1
Winter wheat	450	1.05

Data from FAO (Doorenbos & Kassam, 1979). The water consumption value for sugar beet is the long-term average (1969–1996) for an autumn-sown crop in the Guadalquivir valley, Andalusia, Spain (Morillo-Velarde, 2000). Sugar cane water-use value from Cock (2003). K_y is the crop yield response factor to water deficit (Doorenbos & Kassam, 1979).

tude. Sugar beet can use from 350 mm of water in temperate areas to over 1000 mm in arid areas. However, sugar beet consumes no more or less than other crops (Table 10.3).

Models of crop growth and water use

The water consumption (ET_c) by sugar beet in a certain period of time can be determined using a simple water balance equation:

$$\Delta S + \Delta V = (R + Ir + Cf) - (ET_c + Ro + D)$$

where: $\Delta S = \Theta_2 - \Theta_1$ = the change in soil water content in the root zone between time 2 and time 1; ΔV = increase in volume of water stored in plant tissues; R = rain; Ir = irrigation; Ro = surface runoff; Cf = upward capillary flow from the water table; D = drainage below the effective root zone; ET_c = crop evapotranspiration. In most cases ΔV and Cf can be ignored as ΔV is very small compared to ΔS, and the water table is well below the rooting depth. Furthermore, if runoff and drainage are negligible (i.e. the field is sufficiently level, permeable to influx, and sufficiently below field capacity to store water inputs), the equation reduces to:

$$ET_c = (R + Ir) - (\Theta_2 - \Theta_1)$$

Positive values indicate that the crop is removing water from the soil at a greater rate than it is being refilled by water inputs. Irrigation can be scheduled to ensure that inputs balance ET_c without consuming any of the water stored in the soil profile. However, a more efficient approach is to allow the crop to use stored soil water, at least up to the point when plant productivity begins to decrease in response to soil moisture deficit. This requires knowledge of the permitted depletion level (PDL); i.e. what percentage of the available soil water (ASW) can be achieved without producing any reduction in yield (Table 10.4). This value, together with other soil characteristics, determines the optimum irrigation measurement for maximum yield. (Note later that maximum net profit may not necessarily equate with maximum yield, depending on the costs of irrigation). Numerous studies have been directed towards the determination of the PDL. The average of 19 studies revealed that a PDL of 50% was desirable, but with the PDL ranging from 40–70% (Morillo-Velarde, 1992). Central to this approach, of course, is accurate knowledge of the ASW in the particular field where the beet is grown. This can be determined by taking several soil samples, determining the soil texture class and stone content, and then obtaining the appropriate ASW from published soil survey tables (e.g. Hall *et al.*, 1977).

Table 10.4 The permitted depletion level (PDL), or soil moisture deficit at which sugar beet yield losses begin to occur on different soils in the UK (BBRO, 2002).

	Coarse sand (mm)	Loamy sand (mm)	Sandy loam (mm)	Clay loam (mm)
Mid-June	25	30	35	50
Mid-July	35	40	50	100
Mid-August	50	60	75	125
Mid-September	65	75	125	150

Some specific models

WATYIELD is a simple two-stage model for predicting actual water use, which relates transpiration to soil hydraulic characteristics, rooting density and ET_o (Wright *et al.*, 1994). A version of the model tailored to sugar beet showed that a beet crop at a consumption rate of 5–6 mm/d could deplete 50–60% of the available soil water before there was a reduction in the absorption rate due to stomatal closure (Wright *et al.*, 1997). Water balance models such as this can be very useful for efficient irrigation management. However, there are limitations to models based on root growth functions. It is now clear that the physical structure of the soil must be taken into account so that the actual amount of water consumed by the crop is not under- or over-estimated (Tardieu & Katerji, 1991). Models also assume that there is no water use below the effective rooting depth, that there is uniform root distribution (roots are not clumped), and rates of root growth are steady with time. An empirical model based on actual patterns of water uptake avoids some of these assumptions, but has not yet been tested on sugar beet (Dardanelli *et al.*, 2004). These workers compared seven crop species across a range of soils and computed a single constant representing the maximum fraction of available water extractable in 1 day when root length density had reached a maximum value. The value for this generic constant was 0.096.

Modelling growth and water uptake has been reviewed (Wang & Smith, 2004). Listed here are some further examples of models that simulate crop growth and water use:

- SUBGRO relates crop growth rate to relative water content (Fick *et al.*, 1975).
- Van der Ploeg *et al.* (1978) determined the water used in a horizon as a function of the matric potential, hydraulic conductivity and root density.
- Water limitation restricted transpiration as an inverse function of the remaining available soil water in MORECS (Thompson *et al.*, 1981).
- With PLANTGRO, Davidoff and Hanks (1989) proposed a linear diminution in transpiration when the soil water content fell below a specific value.
- The PlantWaterDynamics Model allowed manipulation of stomatal conductance, osmotic adjustment and xylem conductivity to match observed increases in plant dry matter during cycles of water deficit (Fernandez & McCree, 1991).
- Soil water distribution was compared with two more recent models, SWATRER and CERES/MOD, with reference to lysimeter data. The latter agreed satisfactorily with observed values when there was no interference from ground water. Both models simulated well the accumulated ET (Vitali *et al.*, 1990).
- The ENWATBA model (Lascano *et al.*, 1987) predicts soil evaporation and transpiration.
- The Broom's Barn Crop Growth Model (Jaggard & Werker, 1999) has been modified to handle less drought-prone, water-retentive soils (Qi *et al.*, 2003) and the effects of water stress on radiation use efficiency (Richter *et al.*, 2001).

Water use efficiency

For all crops, dry matter production is directly proportional to water consumption (Tanner & Sinclair, 1983). This is basically because solar energy drives both transpiration and photosynthesis, in a constant proportion, regardless of the level of energy input (Kramer & Boyer, 1995). Thus, for maximum yields, ET_c should be maximized for the conditions. However, in semi-arid and arid areas where water is costly and in short supply, it is necessary to develop strategies to economize and optimize water use. These are discussed in the next section. The incremental gain in dry matter per unit of water taken up and transpired by the plant is termed the water use efficiency (WUE). WUE is constant across a range of water supplies for a given environment. However, there are differences between species and even between varieties. There are significant differences in WUE between C_4 and C_3 species as a result of the nature of carbon fixation in the leaf. Within C_3 crops, sugar beet has greater WUE (50 kg/ha/mm) than cereals (approx. 33 kg/ha/mm), although the figure for cereals rarely includes below-ground dry matter.

WUE can be defined at the leaf level, often termed instantaneous WUE, which is the ratio of moles of carbon dioxide fixed per mole of water transpired. Instantaneous WUE is affected by stomatal conductance and the carboxylation efficiency of the photosynthetic apparatus. Thus, C_4 crops such as maize and sugar cane demonstrate greater WUE than C_3 crops such as sugar beet and potato. Although instantaneous WUE is easy to measure, it usually has little relation to season-long WUE because a number of other factors come into play when scaling from a leaf to the whole plant. One of the environmental factors with the greatest influence on WUE is VPD (Tanner & Sinclair, 1983), which explains why WUE varies between climatic regions and even between years at the same site. When different experiments are normalized for differences in VPD, many of the apparent differences in WUE disappear. Some references on WUE values are indicated in Table 10.5.

There are several management options for increasing WUE. Since WUE is proportional to the ratio of transpiration to evaporation, cultural practices that reduce evaporation from soil will increase WUE. Preliminary evidence of genotypic differences in estimated WUE (Ober *et al*., 2005b) suggests that choice of variety eventually could be another management option for balancing water inputs and yield. The use of drip versus furrow irrigation (see below) can also improve returns on water inputs (Sharmasarkar *et al*., 2001a).

WUE can also be expressed in terms of the irrigation use efficiency, which relates how much yield increase is obtained per unit applied water (Howell, 2003). This has economic and political ramifications, particularly where water resources are limited. In many areas there is competition for water between urban, industrial and agricultural sectors. There is also concern that excessive depletion of water sources could threaten environmentally sensitive sites. In the European Union, for example, new legislation will require growers to calculate irrigation efficiency in terms of returns on water inputs, showing that the amounts were justified and water was not wasted. Some factors that improve irrigation efficiency are:

- uniformity of water distribution throughout a field;
- adequate pumps and pipes with sufficient capacity and appropriate pressurization;
- frequent checks on the system for leaks.

Pereira (1999) wrote an excellent review of methods for measuring the efficiency of irrigation systems.

IRRIGATION MANAGEMENT

The key to effective irrigation management is to balance water inputs and outputs in order to maximize yield and minimize costs. This requires good information about each of the components of the water balance equation discussed above. Crop water requirements are met by the combination of

Table 10.5 Values for water use efficiency (WUE). In the cases where the original units were non-SI units, these were converted to t/ha/mm. The variation in reported values probably reflects different methods of measuring water use rather than actual differences in WUE.

	WUE (kg/ha/mm)		
Region and year	Root	Sugar	Reference
Italy	55	8.8	Cavazza, 1976
Lhudiana, India, 1988	91.2	–	Bains & Narang, 1988
UK		6.8–18*	Dunham, 1988
UK, 1991	–	25	Dunham *et al*., 1993
France, 22 years	114	18.2	Cariolle & Ciecierski, 1993
Germany, 1992–1993	45–61†		Märländer & Windt, 1996
UK, 1980–1991	59–65††		Werker & Jaggard, 1998
Kafr-El-Sheik, 1999	133	19	El Yamani, 1999
Doukkala, 1996	145	25	Belabbes, 2002

These values are irrigation use efficiencies (per mm water applied). † These values are on a dry weight basis; other values are per unit root fresh weight. †† Total dry matter basis.

effective rain, irrigation and the water stored in the soil. The term 'effective' rainfall reflects the fact that a significant portion of rainfall may be lost as runoff or percolation. How much of the rain that becomes available to the crop depends on ET, the soil's storage capacity and permeability to infiltration (Dastane, 1974).

A shallow water table can be a source of water for the crop. Its contribution to transpiration depends on its depth from the surface, soil hydraulic conductivity, ET, and on the depth of the root system. Nevertheless, studies of numerous crops with a shallow water table have shown a better yield when ET was replaced by irrigation, although this may not be true for beet grown in the Red River Valley, USA. Water table contributions to sugar beet yields have not been studied extensively. In one study with a water table at 1 m in the spring, the largest yields were obtained when all the water used by the plant was applied by irrigation (Reichman *et al.*, 1978). Later, Cavazza (1989) found that when the water table was not very deep the largest yield was obtained by applying 70% of ET_c.

When soil water and precipitation are insufficient to meet the crop's water demand, irrigation is necessary to avoid yield losses. In general, sugar beet is not usually irrigated in northern European countries or northern USA; it is necessary to apply around 100–200 mm/year in central European countries, 300–500 mm/year in Mediterranean countries and over 600 mm/year in North Africa, Asia and southern USA.

Irrigation programming methods

Irrigation programming is a means to apply water in accordance with crop requirements in a cost effective and environmentally sustainable manner. The important management questions are how much, how often, and with what method.

Irrigation programming can be based either on indicators of plant water status, or on the water balance method discussed above. Several parameters have been used in the past to indicate when a crop should be irrigated. For instance, the crop water stress index (CWSI) is based on VPD and the difference between leaf and air temperatures, measured by infrared thermometry (Jones, 1999) or thermography (Jones *et al.*, 2002). Other methods have used leaf RWC, leaf sap ψ_s, leaf ψ_w and stomatal conductance (Dragović & Vučić, 1976; Ludlow & Muchow, 1990).

Today, the preferred and most accurate method is based on the soil water balance equation (Dunham *et al.*, 1988; De Juan *et al.*, 1993). Computer software is available to aid growers in scheduling irrigation, but the quality of data on soil moisture content is crucial to the accuracy of this approach. There are several methods available for measuring soil moisture (Table 10.6). Irrigation is carried out when the soil water content falls below the PDL.

Irrigation in northern and central European countries

In the UK, the majority of sugar beet is grown in East Anglia; the average summer rainfall is 150 mm, whereas average ET_o is 300 mm (Jaggard *et al.*, 1998). Thus, irrigation requirements are typically about 100 mm, and yield responses are usually favourable (BBRO, 2002). However, less than 5% of the national crop is irrigated because higher value crops such as potato take precedence on most farms during the irrigation season.

In Germany, irrigation is important where annual average rainfall is less than 450 mm. Irrigation is carried out on light soils when there is little summer rainfall (about 10% of the production area). Recent references indicate that irrigation increases LAI, yield and quality (Kenter & Hoffmann, 2002).

In France, around 10% of the beet production area is irrigated with an average of 160 mm. Strict rules govern the maximum amount of water that can be applied (replacing only 70% of the soil moisture deficit and stopping the irrigation by 20 August (ITB, 2003)). This procedure reduces water use without measurable effects on sugar yield.

Irrigation in the Mediterranean area

In southern Europe and North African countries, plus those with similar climatic conditions like Iran and the USA, irrigation is necessary. At present it entails a minimum of 15% of the production costs. With no irrigation, only 32% of the production potential would be generated, on average (Morillo-

Table 10.6 Methods for measuring soil moisture content.

Type	Method	Advantages	Disadvantages	Reference
Gravimetric	Take soil samples at several depths, weigh wet and dry.	Simple, no sophisticated equipment necessary.	Slow and tedious to do properly; not amenable to repeated measurements.	Holmes, 1967
Electrical resistance (gypsum) blocks	Placed at 40 or 45 cm; measure resistance with ohmmeter.	Cheap and easy to construct; accurate within prescribed range of soil ψ_w.	Only sensitive at relatively high soil ψ_w; degrade in performance over time; sensitive to changes in soil conductivity; require disturbing soil profile to install.	Neibling & Gallian, 1997
Neutron probe	Install Al access tubes. Measure absorption of neutron back-scattering by hydrogen in water.	Standard method for years; senses large soil volume.	Correct installation of tubes is critical, time consuming and difficult in hard soils; accuracy low near surface; health and safety concerns working with radioactive sources-subject to increasing level of regulatory paperwork and costs.	Bell, 1987
Soil dielectric probes	Install PVC access tubes. Measures soil modulation of emitted signal based time domain (TDR) or frequency domain reflectometry (FDR).	Relatively inexpensive; measurements rapid, safe, non-destructive.	Correct installation of tubes is critical, time consuming and difficult in hard soils. Small detection volume makes it sensitive to air gaps and stones next to access tube.	Paine & Brück, 1996
Tensiometer	Tube with porous cup placed in soil; measure suction with digital device.	Cheap and easy to construct; accurate within prescribed range of soil ψ_w.	Only sensitive at relatively high soil ψ_w; usually used only in surface soil layers.	Urbano *et al*., 1993; Arroyo, 2002
Thermocouple Psychrometer	Small probes buried at required depths, connected to instrument designed to measure vapour pressure of air in equilibrium with soil water.	Most precise technique, covers useful range of soil ψ_w.	Cannot be used near surface since small temperature fluctuations compromise data; accuracy low at high ψ_w; requires disturbing soil profile to install.	Brown & Oosterhuis, 1992

Velarde, 2001). In transition areas such as the north of Italy, around 25% of the production area is irrigated. These are usually sandy-loam soils with no surface water table. Under these conditions, irrigation significantly increases sugar yields (Mosca & Candolo, 2003). In autumn-sown crops, except for part of the south of Spain and northern Morocco, 100% of the production area is irrigated. The amount of water used depends on the environmental conditions and harvest date for each year. Typical quantities for Italy are 370 mm (31 May harvest) and 690 mm (31 July harvest) (Caliandro *et al*., 1996). In Spain, all spring-sown crops are irrigated, and autumn-sown crops require 800 mm (31 July harvest), of which 350 mm is usually supplied by rainfall. In Portugal, all that is sown in the autumn and in the spring is irrigated. In Greece, where the potential soil moisture deficit is 430 mm, all of the crop is spring-sown and irrigated with approximately 380 mm. The optimum volumes, depending on the area, range from 200 to 550 mm (Analogides, 1993). Farmers are recommended to fully replace ET_c, which has led to a large increase in yields since 1994. In Morocco, 100% of the crop (autumn-sown) is irrigated with approximately 550 mm. In California (USA), the average ET_c in 2002 was 740 mm. Some level of deficit irrigation is usually practised (Kaffka *et al*., 1997).

Irrigation in arid areas

A climate is arid if 50% of the area receives less than 200 mm of rain, and semi-arid if rainfall supplies only 25–50% of crop water requirements. In arid areas, sugar beet has a vegetative period of over 240 days. The main arid areas where sugar beet is produced are found in the southern parts of North African countries, Iran and California, USA. Irrigation is applied to meet 100% of ET_c.

One problem of arid areas is advection, i.e. the flow of sensible heat (hot air) generated by a dry surface towards a moist surface. Advection increases the water consumption of the crop considerably, up to 90% according to some estimates (Prueger *et al*., 1996). Under these conditions, many methods usually underestimate the ET_o, although the Penman-Monteith method has given an excellent estimate of the ET_o, when compared to lysimeter values (Gavilán, 2002).

RESPONSES TO IRRIGATION

Just as irrigation requirements vary, so the quantitative response of the crop to water differs from one place to another. This response depends on the soil moisture deficit, the amount of water applied and on its distribution.

Yield

In countries of central and north-eastern Europe the crop response to irrigation is usually measured in reference to dryland yields, and is determined by the soil moisture deficit, estimated as the difference between the ET_o and rainfall. Using this method, Cariolle and Ciecierski (1993) summarized the results of 22 years of experimentation in France and concluded that the average irrigation of 133 mm produced 35% greater root yields. Van der Beek and Houtman (1993) and Trybala (1979) reached similar conclusions from experiments in the Netherlands and Germany, respectively. Accurate estimates of the maximum response to irrigation depend on establishing a stress-free crop, which is sometimes difficult to achieve (Wright *et al*., 1997). Late season additions of water decrease the sugar concentration of roots by increasing root water content. For instance, Vukov (1977) found a negative correlation between the sugar concentration and the rainfall in the month of September in a non-irrigated crop. There are also reports that in semi-arid and arid areas yields decrease if irrigation is applied after a period of drought (Cavazza & Patruno, 1993). Presumably this is because rapid re-growth of foliage occurs to the detriment of sugar accumulation.

An analysis of 27 years of irrigation experiments in the UK showed that little response to irrigation was seen if soil moisture deficits were less than 75 mm, as a result of the contribution of stored soil water. With deficits greater than 75 mm, the crop response to irrigation was 2 t sugar/ha per 100 mm water. The 27-year average response to irrigation, compared with unirrigated crops, was 1.1 t sugar/ha. In many northern temperate areas, solar radiation limits yields more than water supply. However, in years with greater sunshine and greater VPD, water can quickly become the limiting factor (Arroyo, 2002).

Yield responses to applied water can range from linear to curvilinear (concave and convex) and vary from year to year. These relationships are usually called yield or production functions. The relation is generally linear (Groves & Bailey, 1994), although it often becomes curvilinear (convex) when inputs exceed crop requirements (Ghariani, 1981; Winter, 1988; Stewart & Hagan, 1990). Depending on the soil type and irrigation system, maximum yields can be achieved by applying between 80% of ET_c (e.g. Bonari *et al.*, 1992) and 100% of ET_c (Robert *et al.*, 1977; Caliandro, 1994).

Radiation use efficiency

There is a direct relationship between the amount of radiation intercepted by a crop and the subsequent yield, and the ratio of these two variables is termed the radiation use efficiency (RUE). RUE is generally greater in irrigated than in stressed, unirrigated crops because as stomata close, less carbon dioxide is fixed but the same amount of radiant energy is captured by leaf pigments. Brown *et al.* (1987) studied the effect of drought during different stages of crop development. Early season drought (June-July) led to a decrease in season-long RUE from 1.64 (irrigated) to 1.37 g dry matter/MJ. RUE with a late season drought (August-September) was 1.51 g dry matter/MJ.

Earlier studies indicated that varietal responses to irrigation were similar (Amaducci *et al.*, 1976; Van der Beek & Houtman, 1993). More recent evidence indicates that there are substantial differences between genotypes in susceptibility to drought (Sadeghian *et al.*, 2000; Ober *et al.*, 2004) and response to irrigation (Mambelli *et al.*, 1992). Sugar beet genotypes also differ in RUE, and the RUE of some genotypes is less sensitive to drought than others (Ober *et al.*, 2004).

Harvest index

The partitioning of assimilates between sugar storage, shoot and root system dry matter is heavily influenced by water and other factors, particularly nitrogen nutrition. The ratio of sugar to total dry matter (the harvest index) is typically around 0.5. Water deficit and low nitrogen reduce canopy growth to a greater extent than sugar accumulation; thus, the harvest index is often greater under these conditions (Scott *et al.*, 1994). Conversely, abundant water and nitrogen increases productivity and the mass of tops, but decreases the proportion of assimilates stored in the root (Werker *et al.*, 1999).

IRRIGATION PRACTICES

Maximum yield is achieved when irrigation ensures:

- plants achieve maximum daily ET;
- soil water deficit and leaf water potential depression are minimized;
- stomatal conductance and therefore net photosynthesis are maximized.

Good irrigation management at the beginning of the growing season encourages the development of a deep root system. An extensive root system permits greater access to stored soil water and less reliance on irrigation. In consideration of sowing and harvest dates, it is especially important to determine when irrigation should be begun and ended (the first and the last irrigation of the season).

First irrigation

The earliest research on irrigation of sugar beet recommended delaying the first irrigation so that roots would grow deeper (Foster, 1899). Subsequent studies demonstrated that these recommendations were incorrect (e.g. Nuckols, 1931). Judicious irrigation actually increases depth of root development (Draycott & Messem, 1977). Water deficits early in crop development affect the growth of fibrous roots and hasten the death of roots in upper soil layers. In autumn- and spring-sown crops, delaying the first irrigation decreased yields (Morillo-Velarde, 1993a; 1999; Velicia, 1998; Velicia & Morillo-Velarde, 2001). Leaf expansion is sensitive to water deficit and rapid establishment of the canopy is essential to capture as much radiant energy as early as possible. Therefore, any treatment that can increase initial growth (including first irrigation) should contribute to greater yields.

Withdrawal of irrigation before harvest

Stopping irrigation at a certain time before harvesting in order to increase the sugar percentage, by root dehydration, is a technique known and applied by farmers since the beginning of beet cultivation. The increase in sugar concentration must be balanced against the possibility of applying so much stress that further late season gains in sugar formation are missed.

Many studies have been carried out to determine the optimum dates for stopping irrigation before harvest. For instance, Carter *et al.* (1980) indicated that if irrigation was stopped at the beginning of August (for a spring-sown crop in Idaho, USA) and 200 mm of water was available in the soil, there was only a small reduction in yield. Hills *et al.* (1990) established that the most profitable interval between the last irrigation and harvesting depends on the climate, the texture and depth of the soil, the root distribution and the water level in the soil at the time of the last irrigation. Further information on when to schedule the last irrigation for spring-sown crops (Fig. 10.8) can be found in Howell *et al.* (1987), Cavazza (1989), Davidoff and Hanks (1989), Kaffka *et al.* (1997), Yonts (1997) and Velicia (1998). References for autumn-sown crops are Bazza (1993), Morillo-Velarde (1993b; 1999), El Messaoudi *et al.* (2002) and Zehauf *et al.* (2002).

Irrigation frequency

Irrigation frequency (the number of waterings and the time interval between them) can affect the yield response to water (Howell *et al.*, 1987). An increase in frequency permits the application of reduced doses, which results in an economization of water and increases irrigation efficiency (Sepaskhah & Kamgar-Haghighi, 1997). The main conclusion reached from many studies on irrigation frequency is that different irrigation frequencies can be used and still attain maximum yields. Salter and Goode (1967) showed that near maximum yields could be achieved provided that the water depleted between irrigations did not consume more than 25–40% of available soil water. Aastad and Miller (1973) obtained a high yield with almost daily irrigation, applying a volume less than ET and using up to 90% of the available soil water. Jensen and Erie (1971) concluded that sugar beet can be watered frequently with small amounts, using up to 70% of soil water between irrigations without any notable loss of yield.

In 1987, Howell *et al.* indicated that a 3-week irrigation frequency reduced ET_c as a result of a slight stress compared to irrigation every 1 or 2 weeks.

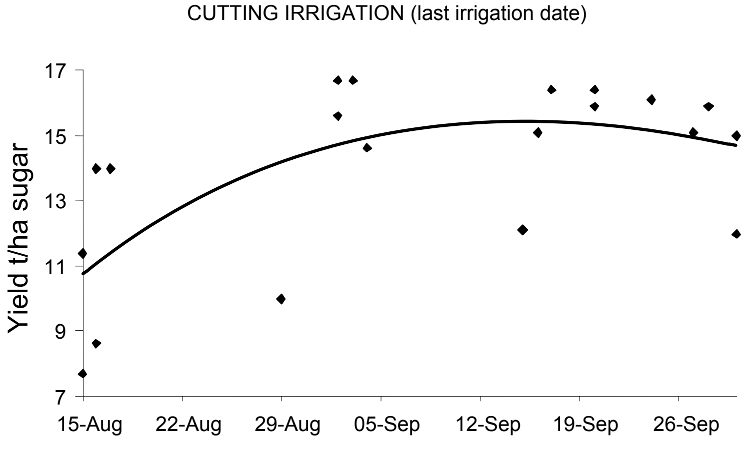

Fig. 10.8 Sugar yield response to date of last irrigation for a spring-sown crop in Spain. Data from Morillo-Velarde *et al.*, 1997.

Ezekari *et al.* (1993) found a reduction in root and sugar yields when irrigation frequency increased, but applying only 40% of the *ET.* In well-drained soils, Cavazza and Patruno (1993) concluded that sugar beet offers great flexibility in volumes and intervals of irrigation without affecting root growth. An increase in frequency from one to two irrigations per week significantly increased root development and yield (De Benito *et al.*, 2002).

In autumn-sown beet, yield was not affected if the irrigation volume required to replace *ET* was applied in larger volumes over 4 days, or smaller volumes every 12 days (Morillo-Velarde, 1993b). Changes in irrigation frequency can affect rooting patterns. When the quantity of soil water consumed was increased from 30% to 70% by increasing the frequency and decreasing the dosage, there was an 85% increase in water uptake from deep soil layers (Camposeo & Rubino, 2003). In summary, high-frequency irrigation on heavier soils starting at field capacity gives satisfactory results even if total volumes are well below *ET.*

Irrigation methods

Sugar beet can be cultivated under any irrigation system (Fig. 10.9). The method selected depends mostly on the technical and economic possibilities of the area (Dunham, 1993). Worldwide, the most prevalent irrigation system is gravity-fed furrow irrigation. This system is very common in the USA, Turkey, Egypt and Iran, whereas in most European and Mediterranean countries sprinkler irrigation is favoured.

There have been many comparisons between irrigation systems used for sugar beet. A comparison of furrow and sprinkler irrigations showed that larger tops were produced with the sprinkler system, with water savings of 20%, but there was no benefit in sugar yield (Haddock *et al.*, 1974). Vučić (1976) and Vanli (1993) also compared both systems and reported higher yields with the sprinkler system. A full sprinkler irrigation session used 36% less water than furrow irrigation in Ontario (Barnum & Clinton, 1995). Eckhoff and Bergman (1999) also recently compared flood and sprinkler systems. One drawback of flood irrigation is the leaching of nitrogen and the difficulty of maintaining soil water availability when the interval between irrigations increases (Arroyo *et al.*, 2000).

Fig. 10.9 Irrigation systems used in sugar beet. (a) Irrigation in Belgium using a rain gun. (b) Irrigating a seed beet in Spain using fixed risers. Photograph credits: (a) and (b), R. Morillo-Velarde (*Continued*.)

Management and optimization is important for any irrigation system. For instance, it is possible to

(c)

(d)

Fig. 10.9 (*Continued.*) (c) Furrow irrigation in the Imperial Valley, California, USA. (d) Centre-pivot irrigation in Montana, USA. Photograph credits: (c) and (d), USDA-ARS-Northern Plains Agricultural Research Lab, Sidney, Montana, USA.

save 23% of water in furrow irrigation by watering alternate furrows and increasing the irrigation frequency (Sepaskhah & Kamgar-Haghighi, 1997). Complete information on the optimum management of furrow irrigation can be found in Yonts and Palm (2001). Specific problems in irrigation coverage that limit efficiency (design, materials, nozzles, etc.) also have been reviewed (Morillo-Velarde & Moreno, 2002).

Sugar beet is well adapted to drip irrigation, which has been used with success in semi-arid and arid regions. In one study, drip irrigation was compared with sprinkler systems and no yield differences were found (Draycott & Messem, 1977). However, others showed an improvement in yield and efficiency with the smaller amounts of water that can be applied using drip irrigation (Hetz & Merino, 1998; Arroyo *et al.*, 2000; Sharmasarkar *et al.*, 2001b). Tognetti *et al.* (2003) showed that yields obtained with drip irrigation applied at 75% of *ET* were no less than those obtained with low-pressure sprinkler irrigation applied at 100% *ET*. Compared with furrow irrigation, localized irrigation provided a water saving of 37% and an improvement in efficiency of 86%; semi-fixed sprinklers saved 22% and improved efficiency by 65% (Hilali *et al.*, 2002). In arid areas, drip irrigation economized water by 43% in relation to sprinkler and with an increase of 16% in root yield (Amzir & Tizaoui, 2002). Drip irrigation is also useful for autumn-sown sugar beet (Caliandro *et al.*, 2000; Zuffrano *et al.*, 2001). An additional benefit of these systems over furrow irrigation is that they permit the application of fertilizers and phytosanitary products and are an alternative to control nitrate leaching. Cavazza (1976) felt that when irrigation systems are designed and managed adequately there are no important differences in yield.

DEFICIT IRRIGATION

Deficit irrigation is the deliberate under-irrigation of crops and is a common practice in many crops and areas of the world. With this technique the crop is exposed to certain levels of water stress, either during a particular period or throughout the whole growing season. Government agencies in some countries nowadays recommend deficit irrigation practices (English & Raja, 1996). The benefits of this practice are clear: an increase in irrigation-use efficiency and a reduction in irrigation costs (including water, labour and energy). Some production functions and cost analyses show the benefits of deficit irrigation under different conditions (e.g. Sharmasarkar *et al.*, 2001a). Thus, where land is abundant and water is scarce, the general strategy could be to irrigate 28–59% less than ET_c. Even under conditions in which the availability of water is not limiting, the best strategy could be a deficit irrigation of 15% (English & Raja, 1996). The motivation for deficit irrigation is greatest where irrigation costs are the greatest. In California, 30% of production costs go to irrigation, 12–21% in Spain, and in arid areas the proportion is even greater.

Sugar beet shows a complex response to deficit irrigation because of its deep root system, its ability to maintain a low leaf-water potential and maintain turgor through osmotic adjustment. Many studies show that optimum yields can be achieved using deficit irrigation (Okman, 1973; Winter 1980; Bazza, 1999; Kirda, 2002), provided that there is at least 125 mm storage capacity in the soil (Keller & Bliesner, 1990). Recently, Belabbes (2002) applied only 80% of ET_c during the whole season and Fabeiro *et al.* (2003) applied a range from 77% to 95%. In both studies, yield and quality were not affected, but irrigation use efficiency increased significantly.

In many crops, deficit irrigation often requires modification of agronomic practice, i.e. decreasing plant population, applying less fertilizer, modifying sowing dates, using earlier maturing varieties. More research in these areas is needed to optimize advice for deficit irrigation on sugar beet. Other related, emerging techniques such as Partial Root zone Drying (PRD) are promising with respect to economizing water without seriously affecting yield (Sepaskhah & Kamgar-Haghighi, 1997; Davies *et al.*, 2002). With this technique, every other furrow is irrigated (with furrow or drip irrigation), allowing half the root system to dry the soil profile in the unirrigated furrows. The principle is that half the root system supplies the necessary water for transpiration while the other roots produce and send drought-induced hormonal signals to slow leaf growth. The advantage for tomatoes and grapes is that less foliage means more assimilate supply to fruits and less shading of fruits, which develops colour and flavour. After a few weeks the alternate furrow irrigations are switched so that the intensity of the signals does not diminish in roots subjected to long-term water deficit. In sugar beet, the potential benefit lies in improving the harvest index for sugar by limiting dry matter accumulation in excessive foliage, particularly after full ground cover is achieved.

The crop response factor, K_y

Crops less sensitive to stress such as cotton, sunflower and sugar beet can adapt well to deficit irrigation practices. A method of quantifying the sensitivity of yield to imposed water deficits was developed by Doorenbos and Kassam (1979). The proportion of potential yield lost when actual ET is less than ET_c is:

$$(1 - Y_a/Y_{max.}) = K_y(1 - ET_a/ET_c)$$

where Y_a and $Y_{max.}$ are the actual yield and maximum yield (under non-limiting conditions), respectively. ET_a is the actual rate of ET, and ET_c is the maximum crop ET for local conditions as defined earlier. K_y is the crop yield response factor. $Y_{max.}$ depends on the variety, environmental conditions, and the length of the growing season. $Y_{max.}$ can be estimated under ideal conditions using a simple equation (Kassam, 1977) or by using a crop growth model (e.g. Qi *et al.*, 2003). ET_a and Y_a represent the measured water consumption and yield in a particular field trial. The yield response factor (K_y), which is the amount of yield lost per unit of ET loss, expresses the sensitivity of the crop to water deficit. A larger K_y value indicates greater yield losses due to water deficit. The accuracy of K_y depends on having a sufficient range and number of values for Y and ET, and assumes that the relationship between Y and ET is linear over this range. Values obtained from different experiments are shown in Table 10.7. Comparison of K_y among different crops (Table 10.3) shows that for a given water deficit, sugar beet is better able to produce a yield than many other crops. Part of the reason for this is that the formation of economic yield in sugar beet is simply dependent on vegetative growth and not on sensitive reproductive or tuber-forming stages.

SALINITY

The wild progenitors of present day sugar beet lived and still thrive on sea coasts around the Mediterranean and the eastern shores of the North Atlantic. Retention in sugar beet of traits necessary for adap-

Table 10.7 Crop yield response factor (K_y) to water deficit (Doorenbos & Kassam, 1979) for beet crops with different husbandry and irrigation.

Sugar beet crop details	K_y	Reference
Root	0.6–1.0	Doorenbos & Kassam, 1979
Sugar	0.7–1.1	
Root	0.8–0.9	Kassam & Smith, 2001
Root, normal frequency irrigation	0.3- 0.9	Morillo-Velarde, 1993b
Root, high frequency irrigation	0.7–1.0	
Root, first irrigation	1.14	Velicia & Morillo-Velarde, 2001
Root, last irrigation	0.95	
Root	0.7	Velicia, 1998
Sugar	0.6	
Sugar	0.95–1.07	Bazza & Tayaa, 1999
Root, whole season	0.86	
Root, late season	0.74	
Root, mid-season	0.64	

tation to saline environments is probably why this crop is better able to survive these conditions than most other crops (Hanson & Wyse, 1982). Among crop species, only cotton and barley are more tolerant than beet to saline soils (Maas, 1990; Allen *et al*., 1998). Two mechanisms employed by sugar beet for tolerance to salinity are the sequestration of Na in vacuoles (Na in high concentrations is generally toxic to plants), and osmotic adjustment (Katerji *et al*., 1997). Low levels of Na can actually increase yields by improving plant water status (Milford *et al*., 1977; Durrant *et al*., 1978) and is commonly applied as a fertilizer component in some areas. In the plant, Na can replace K to a certain extent (Marschner *et al*., 1981), although apparently not in its role in the transport of sugars (Peel & Rogers, 1982; Badraoui & Agbani, 2002).

Despite a certain level of tolerance in established plants, saline soils and saline water nevertheless reduce yield (Table 10.8). Young, germinating plants are particularly susceptible to salinity; at this stage soil electrical conductivity (ECs) should not exceed 3 dS/m (Durand, 1983). The quality of irrigation water is a serious problem in many semi-arid and arid areas. Experiments in the San Joaquin and Imperial valleys in California (USA) using sprinkler irrigation on soils with ECs up to 24 dS/m showed a larger yield than expected. The adverse effects of salinity on root yield were partly compensated by an increase in the sugar content.

Table 10.8 Effect of salinity on sugar beet yields. Salinity levels are reported in units of electrical conductivity (EC) of soil saturation extract (ECs) or irrigation water (ECw). Data are based on those published by Maas (1990). A value of 5 dS/m is equivalent to approximately only 2000 p.p.m. dissolved salts.

Ecs (dS/m)	Ecw (dS/m)	Yield reduction (%)
7.0	4.7	0
8.7	5.8	10
11.0	7.5	25
13.7	8.7	50
24.0	–	Maximum

In saline areas it is necessary to leach accumulated salts from the soil. The increased irrigation volume necessary, depending on the ECs, is called the leaching fraction (Doorenbos & Kassam, 1979). Because sugar beet is capable of absorbing some of the salts in irrigation water, beet production helps to maintain the quality of soils and the sustainable duration of production systems.

The use of saline irrigation water has a negative effect on the yield and technological quality of sugar beet, especially from the excessive absorption of sodium (Mekki & El Gazaar, 1999; Cheggour & Fares, 2002). This negative effect can be controlled by a balanced fertilization with a N/K ratio of between 0.5 and 1. Sugar beet is also tolerant to exchangeable sodium and starts to show signs of sodium toxicity at ESP (exchangeable Sodium Percentage) in the range of 40 to 60. To compensate for the effect of saline water (11.1 dS/m), the addition of compost has improved development and growth (Aylaj & Lhadi, 2002). Not surprisingly, irrigation with sea water seriously affected the growth of plants (Koyro & Huchzermeyer, 1997). With drip irrigation, saline water with an ECw of over 1 dS/m caused an accumulation of salt and eventual clogging of the irrigation system. Varietal differences in salinity tolerance have been found (Marschner *et al.*, 1981; Ghoulam *et al.*, 2002), which could be exploited by breeders to develop varieties targeted to areas with salinity problems.

A recent study carried out in Andalusia (Spain) showed that the application of two irrigations with moderately saline water (5.9–7.0 dS/m) alternated with irrigations of fresh water (0.9 dS/m) increased the soil salinity in the top layer. However, soil salinity was smaller and yields were larger than with saline irrigations alone. These two alternate irrigations signify a saving of 25% in fresh water by permitting the use of saline water for supplementary irrigation. This technique, which does not damage crops or soils, could be of great interest for arid and semi-arid areas where water quality is limited (Moreno *et al.*, 2001).

GERMINATION AND EMERGENCE

In many areas where sugar beet is grown, irrigation is necessary for the germination and emergence of the seed. Seedlings are especially sensitive to low temperatures and a lack of moisture until the two-leaf stage. The minimum threshold for germination is between 3°C (Gummerson, 1986), and temperatures over 48°C are fatal (François & Goodin, 1972). There is an important relationship between soil temperature and moisture for germination (Akenson & Henson, 1980). At a soil ψ_w of $^{-}0.7$ MPa, germination was inhibited; at soil $\psi_w = {}^{-}0.5$ MPa, germination was 71% at a temperature of 26°C; at soil $\psi_w = {}^{-}0.1$ MPa, germination was 45% at 9°C. For autumn sowing in a dry seed bed, application of 20–25 mm was required for germination (Bouzaidi, 1982; Nunes, 1983; Morillo-Velarde, 1992). Under other conditions, larger volumes (up to 60 mm) may be necessary to establish the crop (Oussible & Jbilou, 2004). The minimum soil ψ_w required for germination of sugar beet is greater for sugar beet ($^{-}0.35$ MPa) than for wheat ($^{-}1.2$ MPa), rice ($^{-}0.79$ MPa), and soybean ($^{-}0.65$ MPa) (Hunter & Erickson, 1952). Therefore, preplant irrigations are often desirable in semi-arid and arid climates. In some situations, pre-irrigation is important for preparing an optimum seed bed and promoting fast, even germination. More weed seeds also germinate, which makes pre-emergence herbicides more effective. (Oussible *et al.*, 2002). Any irrigation system, from furrow to centre pivot, can be used at this stage of the crop.

IRRIGATION AND OTHER FACTORS

Crop nutrition

The supply of N and water are key determinants of sugar beet yield and quality. There is a positive and additive interaction between irrigation and N fertilizer (Draycott, 1976; Winter, 1990; Mompin *et al.*, 1993). One study found that, under very special conditions, the interaction could be negative (Ezekari *et al.*, 1993). Optimizing the supply of nutrients can increase WUE (Ehlers & Goss, 2003). Although the availability of P and K increases with irrigation, Mannini and Venturi (1993) showed that there was no interaction between P and irrigation.

Plant density

Draycott (1976) found a slight positive interaction between irrigation and plant density. Low plant density (50 000 plants/ha) limits yield, whatever the amount of water applied. When water availability is limited, the largest plant densities produce the largest yields (AIMCRA, 1993). Since water uptake by the crop is influenced by plant spacing (Moraghan (1972), which affects the transpirational leaf area (Dragović *et al.*, 1996), the yield response to irrigation increases with plant density.

Pests and diseases

Although sprinkler irrigation can wash organisms and spores from foliage, turgid leaves and high humidity favours the development of some foliar diseases such as Cercospora (*Cercospora beticola*) and powdery mildew. Conversely, droughted plants are more susceptible to *Fusarium* root rot that enters the root where leaves have died back. Sprinkle irrigation applied to assist germination often provides ideal conditions for the development of damping off (*Aphanomyces*).

Harvesting

In rain-fed production areas, irrigation is sometimes beneficial when late-season droughts harden soils. Lifting beet from hard, dry soils increases wear on machinery and tends to break roots, leaving costly harvest losses in the field. In irrigated production, there appears to be no relation between irrigation and harvesting dates (Gucci & De Caro, 1993; Velicia, 1998).

Advisory services

In many countries crop water-use information (ET_c or ET_o) is determined by using weather stations and is made available to farmers and technicians through a variety of media (newspaper, radio, SMS messages, fax, websites on the internet). The most frequently accessed information from irrigation advisory services is that giving the water consumed by the crop during the past week, and the recommended dosages. The irrigation notices are site-specific and require a substantial extension education effort to promote their use, especially among farmers. When taken up, the results are usually excellent. A recent experiment in irrigation advice for farmers in Doukkala, Morocco, using a perimeter sprinkler, showed that water savings of 25–50% were possible (Belabbes, 2002). Advice on timing and volumes led to a net improvement in root yield and sugar concentration. The dissemination of advice usually depends on general or regional governmental administration, sugar factories, or sugar beet grower institutes. Some examples of this are the pioneer system, the CIMIS (California, USA), services provided by Broom's Barn and British Sugar (UK), ITB (France), PAR (sugar factories and AIMCRA, Spain), ADB (Portugal), and BETA (Italy).

DROUGHT TOLERANCE

Drought causes more losses to crop yields worldwide than any other single biotic or abiotic factor (Boyer, 1982). In many areas where sugar beet production is dependent solely on rainfall, drought is a major problem. These areas include the East of England, parts of France, eastern Germany and western Poland (Jaggard *et al.*, 1998; Pidgeon *et al.*, 2001). In these regions, summertime rainfall is often insufficient to meet the demands of the crop, which results in greater year-to-year yield variability than where rainfall and/or deep, water retentive soils prevent water deficits from developing (Table 5 in Jaggard *et al.*, 1998). Moreover, climate change models predict that droughts will become more frequent in the future (Jones *et al.*, 2003). In areas of the world where sugar beet is irrigated, restrictions on the availability and cost of irrigation water means that water deficits often cannot be prevented or are allowed to develop.

Faced with these restrictions, research efforts have focused on improving the productivity of sugar beet while maintaining sustainable use of resources. One important area of work concentrates on increasing irrigation efficiency through improved irrigation techniques (see above). Other work is aimed at developing genotypes better suited for water-limited environments. In both cases, a fundamental understanding of how the sugar beet crop uses water is important.

Improving sugar beet drought tolerance through plant breeding

Genotypic differences in drought tolerance can be defined in several ways, depending on the objective. One approach is to express the yield under water-limiting conditions as a function of yield potential (the yield under fully irrigated conditions). This drought tolerance index (DTI), similar in principle to the susceptiblity index developed for wheat (Fischer & Maurer, 1978), is important since yield potential can vary greatly between different genotypes. Another useful index, the yield/tolerance index (YTI) (Fernandez, 1992), combines yield potential and drought tolerance so that genotypes with high YTI express relatively good yield under irrigated conditions and can maintain a larger proportion of that yield under dry conditions than other genotypes. Both indices are based on a computation of the overall mean yield within a trial, so the particular genotypic composition of an experiment has an influence on the DTI and YTI.

Early studies that examined a small range of cultivars concluded that the genotypic differences in drought tolerance were small (Amaducci *et al.*, 1976); hence, breeding for drought tolerance would be a slow and difficult process (Van der Beek & Houtman, 1993). More recent work has shown that within diverse sets of germplasm, there are significant genotypic differences for drought tolerance (Sadeghian *et al.*, 2000; Ober & Luterbacher, 2002; Ober *et al.*, 2004). Experiments conducted in the UK under managed drought conditions using semi-permanent polythene tunnels (Figs 10.10, 10.11) showed that not all genotypes respond to water supply similarly. The correlation between yield under irrigated and droughted conditions is high, but significant deviations about the regression line indicate substantial risk involved in characterizing droughted yield based solely on yield under optimum conditions (Fig. 10.12).

Yield stability across environments is important to breeders and growers. In many regions, yield potential varies from location to location largely because of rainfall distribution and/or the water-holding capacity of the soil. In this case, desirable genotypes are those that show a smaller response to water supply, but competitive yield under optimum conditions would be desirable. There are many ways to measure yield stability, but an index that combines yield potential and low across-environment variability has been proposed as the most useful (Kang, 1993). Another index, first described by Finlay and Wilkinson (1963), measures the slope of the regression line (b_i) between individual genotype yields and the mean location yield across a range of environments. A steep slope (large b_i) indicates high sensitivity to environmental conditions. For genotypes with large b_i, the positive aspect is that these genotypes quite often are best at taking advantage of ideal growth conditions to produce large yields. On the downside, this also means large yield variability when environmental conditions change. The challenge for breeders is to develop varieties that show less sensitivity to the prevailing water supply, but without sacrificing too much yield potential when water is plentiful.

Fig. 10.10 Aerial view of polytunnels used in the UK to impose drought for field experiments. See Ober *et al.*, 2004.

Fig. 10.11 Experimental plots irrigated with drip tape adjacent to droughted, non-irrigated plots under polythene-covered tunnels (see Fig. 10.10).

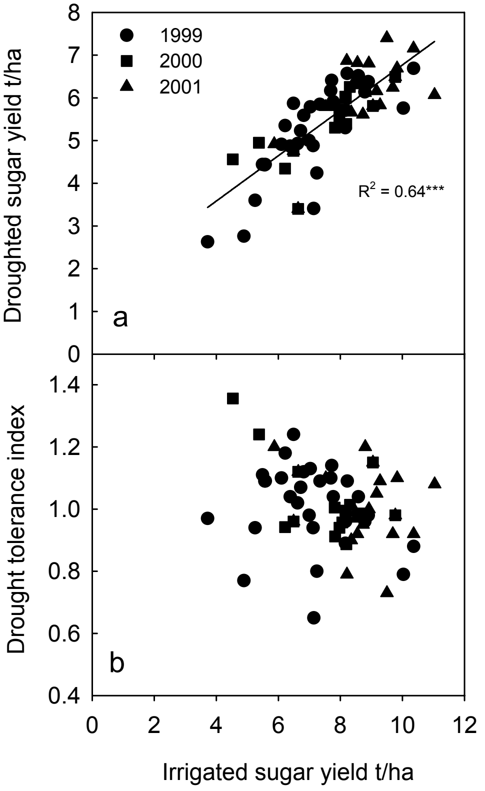

Fig. 10.12 (a) The relationship between irrigated yield potential and droughted yield for 46 different sugar beet genotypes in three experiments from 1999–2001. Drought was imposed using large polythene tunnels covering the crop. (b) The relationship between irrigated yield potential and drought tolerance index. Drought tolerance index values greater than 1 indicate genotypes with greater than average drought tolerance. Data from Ober *et al.*, 2004.

Results from research on other crops as well as sugar beet indicate that drought tolerance and yield potential are not necessarily mutually exclusive goals (Tollenaar & Lee, 2002).

In other crops, most improvements in drought tolerance have come through empirical breeding. That is, breeders select for high yield in dry locations without needing to know what specific traits confer an advantage. An alternative or complementary approach is physiology-based breeding, where genotypes are selected based on the expression of one or more morphological or physiological traits that are shown to be important for drought tolerance. Characters that proved useful were osmotic adjustment (Morgan, 2000) and carbon isotope discrimination ratio (Passioura, 2002) in wheat, and depth of rooting in rice (Babu *et al.*, 2003). In sugar beet, traits that were correlated with drought tolerance were the maintenance of green canopy cover, leaf succulence index, and scores for wilting and senescence (Ober *et al.*, 2005b; Fig. 10.13). Measurements of these traits are relatively inexpensive and quick, which makes them amenable to genotype selection on a large scale in breeding trials. One possibility is to use these traits in a screen to cull inferior genotypes in early stages of the breeding cycle. The effect may be to increase the frequency of favourable alleles for drought tolerance within the pool of germplasm drawn on by breeders for new varieties.

Another breeding approach would be to incorporate genes from wild beet (*Beta vulgaris* ssp. *maritima*), which thrives in dry and saline habitats. However, a study that compared the relative drought tolerance of three different *maritima* populations with sugar beet showed that the differences were small (Johnston, 2000). It would appear that sugar beet has managed to retain many of the essential traits for stress tolerance through the process of domestication. Biotechnological advances may someday allow selection for candidate genes that are known to confer drought tolerance. A step in this direction is the identification of up- and down-regulated proteins in sugar beet grown under droughted or irrigated conditions in the field (Hajheidari *et al.*, 2005). Several of the proteins play a role in handling reactive oxygen species, which can build up in stressed plants.

Describing drought tolerance in multi-environment variety trials

In final stages of variety development, there is no substitute for measuring sugar yield under a range of environmental conditions. One aspect of these multi-location variety trials is that the ranking of genotype performance usually depends on the location. This genotype × environment interaction slows breeding progress. However, it is possible to make use of these interactions if factors that cause the interactions are better understood. In the Finlay-Wilkinson approach to assessing yield stabil-

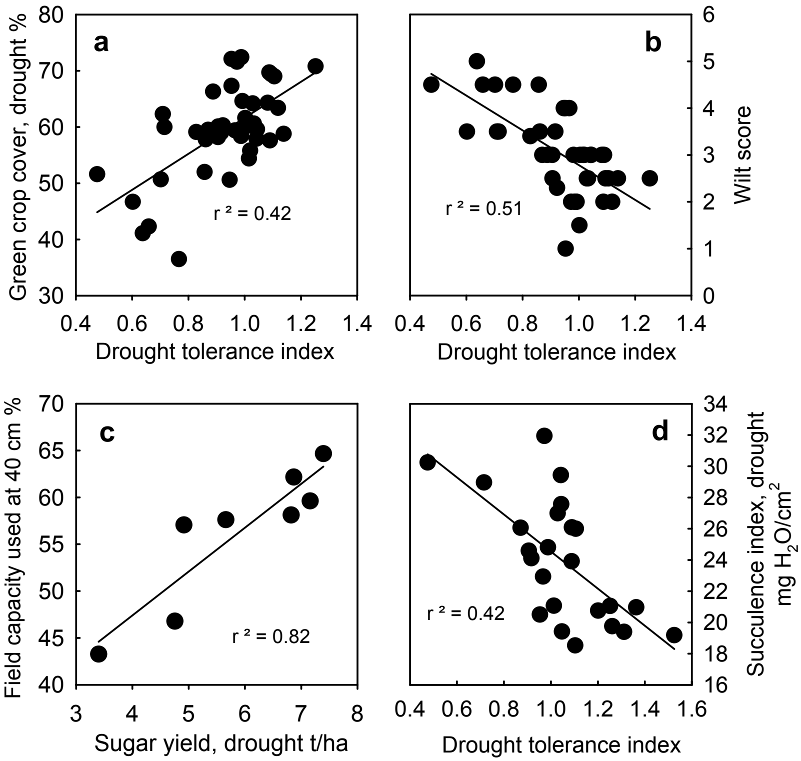

Fig. 10.13 Scatter diagrams showing the associations between secondary physiological traits and yield or drought tolerance index. Genotypes that retained more of the canopy after a season of drought (a), or extracted more water from the soil at 40 cm from the surface (c) tended to be more drought tolerant. Genotypes with greater tendency to wilt (b) or those with thicker leaves (d) were less drought tolerant. Data from Ober *et al.*, 2004.

ity described above, environments are described simply by the overall site mean yield. Quite often, breeders cannot determine why yields are greater at one site versus another. The distribution of rainfall and water holding capacity of the soil can often explain a large proportion of the site-to-site yield variation. Thus, particularly in a dry year, trial locations differ in the degree of drought stress experienced by the crop. By calculating a drought stress index (DSI) for each trial, individual sites can be given a specific environmental descriptor in terms of water availability, and the relative performance of genotypes can be compared across a range of DSI. This exercise was done on 11 years of official variety trials in the UK from 1989–1999, which comprised 533 varieties and 120 test sites (Pidgeon *et al.*, 2005). Each variety that had been tested on 10 or more sites over 1 or more years was evaluated by plotting relative sugar yield versus DSI (Fig. 10.14). The slope of this regression indicates susceptibility to drought and the intercept indicates yield potential. A positive slope indicates relative drought tolerance while a negative slope indicates relative drought susceptibility. Results showed that varieties can differ substantially in sensitivity to water supply (Fig. 10.15). With this information, and knowing the pedigree of the tolerant varieties, breeders can emphasize this genetic background for varieties targeted to drought prone areas.

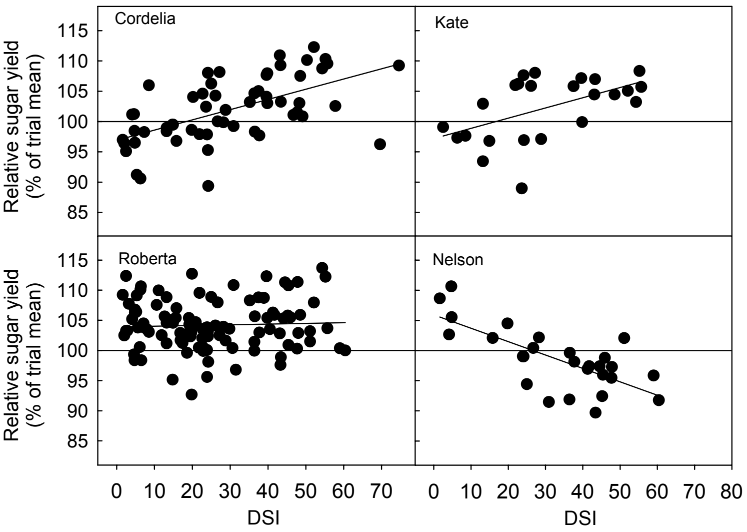

Fig. 10.14 Drought-responsiveness of selected varieties from multi-location variety trials. Each trial was assigned a drought stress index based on soil and weather conditions. Slopes and intercepts indicate that Cordelia and Kate showed near average yields with little water deficit (low DSI), but had relatively better performance under drier conditions. Nelson had good yield potential, but was susceptible to drought. Slopes were significant at P < 0.01. Roberta showed little responsiveness to water availability, and showed greater than average performance across a range of water regimes. Roberta was a highly popular variety. Data from Pidgeon *et al.*, 2005.

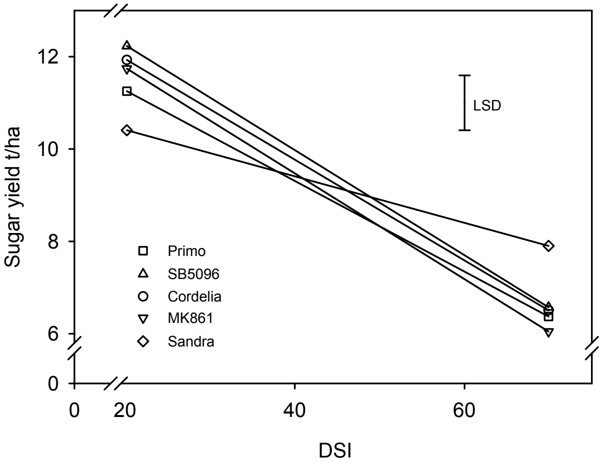

Fig. 10.15 Differential drought responsiveness of five varieties tested at two locations with contrasting levels of drought stress in 1989. SB5096 showed the best yield potential (at low DSI) was the poorest under dry conditions, while Sandra showed the opposite behaviour. The LSD (P = 0.05) is shown for the genotype x environment interaction term from ANOVA. Data from Pidgeon *et al.*, 2005.

REFERENCES

Aastad, J.S. & Miller, D.E. (1973) Soil management to reduce runoff under center pivot sprinkler system. *Journal of Soil and Water Conservation* **28**, 171–173.

Abdollahian-Noghabi, M. (2000) A review of drought stress-studies in Iran. *IIRB* info no. 7, 6–8.

AIMCRA (1993) Memoria de los trabajos realizados en siembra de primavera. In: Asociación de investigación para la mejora del cultivo de la remolacha azucarera. pp. 207–269.

Akenson, W.R. & Henson, H.A. (1980) Sugarbeet fruit germination and emergence under moisture and temperature stress. *Crops Science* **20**, 735–739.

Allen, R.G., Pereira, L.S., Raes, D. & Smith, M. (1998) Crop evapotranspiration. Guidelines for computing crop water requirements. *FAO Irrigation and Drainage Paper* 56.

Amaducci, M.T., Caliandro, A., Cavazza, L., De Caro, A. & Venturi, G. (1976) Effects of irrigation on different sugar beet varieties in different location and years. *Proceedings of the 39th IIRB Congress*. Brussels, pp. 423–448.

Amodeo, G., Dorr, R., Vallejo, A., Sutka, M. & Parisi, M. (1999) Radial and axial water transport in the sugar beet storage root. *Journal of Experimental Botany* **50**, 509–516.

Amzir, A. & Tizaoui, C. (2002) Essais de la technique d´irrigation localisee sur la culture de la betterave a sucre. *Proceedings of IIRB Congress, Mediterranean Section*. Marrakech, pp. 75–84.

Analogides, D.A. (1993) Estimating sugarbeet irrigation requirements on the basis of climatic parameters in Greece: results and conclusions from a 6 year experimental study (1980–1985). *Proceedings of the 56th IIRB Congress*. Brussels, pp. 259–269.

Anda, A. (1994) Problems in lysimeter use for water demand determination in sugar beet. *17th Regional Conference on irrigation and drainage.* Valna, Vol. 1, pp. 77–82.

Araus, J.L. (2004) The problem of sustainable water use in the Mediterranean and research requirements for agriculture. *Annals of Applied Biology* **144**, 259–272.

Arroyo, J.M. (2002) Influencia del riego sobre el crecimiento, el rendimiento, la calidad industrial y las eficiencias en el uso del agua de riego y la radiación PAR en el cultivo de la remoalcha azucarera. Tesis doctoral, Universidad Politécnica de Madrid, pp. 692.

Arroyo, J.M., Urbano, P., Rojo, C. & Gonzalez, F. (2000) Sugar beet irrigation: comparative study between trickle and sprinkler irrigation. *Agricultura* **803**, 490–493.

Aylaj, M. & Lhadi, E. (2002) Effet du compost sur l´amelioration de la tolerance de la betterave a sucre irriguee avec une eau salee. *Proceedings of IIRB Congress, Mediterranean Section.* Marrakech, pp. 114–120.

Babu, R.C., Nguyen, B.D., Chamarerk, V., Shanmugasundaram, P., Chezhian, P., Jeyaprakash, P., Ganesh, S.K., Palchamy, A., Sadasivam, S., Sarkarung, S., Wade, L.J. & Nguyen, H.T. (2003) Genetic analysis of drought resistance in rice by molecular markers: association between secondary traits and field performance. *Crop Science* **43**, 1457–1469.

Badraoui, M. & Agbani, M. (2002) Qualite de l´eau d´irrigation et qualité technologique de la betterave dans le perimetre irrigue des Doukkala, Maroc. *Proceedings of the IIRB Congress, Mediterranean Section.* Marrakech, pp. 93–99.

Bains, B.S. & Narang, R.S. (1988) Water use efficiency of sugar beet under semi-arid and sub-tropical climate. *Indian Journal of Agronomy* **33** (3), 283–286.

Barnum, J.M. & Clinton, C.S. (1995) Water use efficiency for sugarbeet production. *American Society of Sugar Beet Technologists Meeting.* New Orleans, p. 171.

Bazza, M. (1993) Effets du stress hydrique et de sa place dans le cycle sur le rendement et la qualite technologique de la betterave sucrière. *Proceedings of the 56th IIRB Congress.* Brussels, pp. 119–130.

Bazza, M. (1999) Improving irrigation management. In: Kirda, C., Moutonnet, P., Hera, C. & Nielsen, D.R. (eds). *Crop Yield Response to Deficit Irrigation.* Kluwer Academic Publisher, Dordrecht, The Netherlands.

Bazza, M. & Tayaa, M. (1999) Contribution to improve sugar beet déficit-irrigation. In: Kirda, C., Moutonnet, P., Hera, C. & Nielsen, D.R. (eds). *Crop yield response to deficit irrigation.* Kluwer Academic Publisher, Dordrecht, The Netherlands.

BBRO (2002) *Sugar Beet: A Grower's Guide*, 6th edn. British Beet and Research Organisation, Peterborough.

Belabbes, K. (2002) L´avertissement a l´irrigation de la betterave a sucre dans le contexte marocain. *Proceedings of IIRB Congress, Mediterranean Section.* Marrakech, pp. 1–9.

Bell, J.P. (1987) *Neutron Probe Practice.* Report No. 19 (3rd edn), Institute of Hydrology, Wallingford.

Bonari, E., Mazzoncini, M., Masoni, A., Bertolacci, M. & Perioli, R. (1992) Risposta produttiva di mais (*Zea mays* L.) soia (*Glycine max* L. Herr.), girasole (*Helianthus annuus* L.) e barbabietola da zuccherro (*Beta vulgaris* L.) a regimi irrigui diversi nell'Italia centro-settentrionale. *Rivista di Agronomia* **26** (4), 676–684.

Bouzaidi, A. (1982) Besoin en eau et irrigation de la betterave a sucre. *Communication Mediterraneénne.* Journeès d'Etudes en Tunisie.

Boyer, J.S. (1982) Plant productivity and environment. *Science* **218**, 443–448.

Brown, K.F. & Biscoe, P.V. (1985) Fibrous root growth and water use of sugar beet. *Journal of Agricultural Science* **105**, 679–691.

Brown, K.F. & Dunham, R.J. (1989) Recent progress on the fibrous root system of sugar beet. In: Licht, F.O. (ed.) *World Sugar and Sweetener Handbook.* GmbH, Ratzburg, pp. F5-F13.

Brown, K.F., Messem, A.B., Dunham, R.J. & Biscoe, P.V. (1987) Effect of drought on growth and water use of sugar beet. *Journal of Agricultural Science, Cambridge* **109**, 421–435.

Brown, K.W. & Rosenberg, N.J. (1971) Energy and CO_2 balance of an irrigated sugar beet (*Beta vulgaris*) field in the Great Plains. *Agronomy Journal* **63**, 207–213.

Brown, R.W. & Oosterhuis, D.M. (1992) Measuring plant and soil water potentials with thermocouple psychrometers: some concerns. *Agronomy Journal* **84**, 78–86.

Burrows, F.J. (1969) The diffusive conductivity of sugar beet and potato leaves. *Agricultural Meteorology* **6**, 211–226.

Caliandro, A. (1994) Irrigazione della barbabietola da zucchero nell´Italia Meridionale: Aspetti fisiologici di tecnica irrigua. Convegno Possibilta di sviluppo reddituale della bieticoltura meridionale. *Foggia*, Ottobre, 81–87.

Caliandro, A., Rubino, P., Catalano, M. & Mastro, M.A. (1996) Irrigation requirement variability of autumn sugar beet in different localities of the Apulian Land. *Rivista di Agronomia* **30** (3), 384–392.

Caliandro, A., Mastro, M.A. & Zuffrano, M. (2000) Irrigazione della barbabietola da zucchero con il metodo a goccia nell´Italia meridionale. *Bieticoltura associata. Giugno*, 20–22.

Camposeo, S. & Rubino, P. (2003) Effect of irrigation frequency on root water uptake in sugar beet. *Plant and Soil* **253**, 301–309.

Cariolle, M. & Ciecierski, Ch. (1993) L´irrigation des betteraves par aspersion en France. Bilan de 22 ans d´experimentation. *Proceedings of the 56th IIRB Congress.* Brussels, pp. 53–67.

Carter, J.N., Jensen, M.E. & Traveller, D.J. (1980) Effect of mid- to late-season water stress on sugar beet growth. *Agronomy Journal* **72**, 806–815.

Cavazza, L. (1976) The role of irrigation in sugarbeet growing and its problems. *Proceedings of the 39th IIRB Congress.* Brussels, pp. 83–85.

Cavazza, L. (1989) L´irrigation de la betterave a sucre en Italie. Journeés d´etudes Commission Méditerraneénne. *IIRB.* Ferrara, p.18.

Cavazza, L. & Patruno, A. (1993) Irrigation de la betterave a sucre. Aspect phisiologiques. *Proceedings of the 56th IIRB Congress.* Brussels, pp. 5–24.

Cavazza, L., Patruno, A. & Fortini, S. (1992) The hydraulic conductivity in the roots of sugarbeets. *Proceedings of 2nd ESA Congress.* Warwick, pp. 46–47.

Cheggour, M. & Fares, K. (2002) Effet de la composition de l´eau d´irrigation sur la qualité technologique de la betterave a sucre. *Proceedings of IIRB Congress, Mediterranean Section*. Marrakech, pp. 110–113.

Cock, J.H. (2003) Sugar cane growth and development. *International Sugar Journal* **105**, 540–552.

Cukaliev, I. & Iljovski, I. (1993) Micro sprinkler irrigation and its effect on sugar beet yield and sugar content. *Integrated Resource Management and Landscape Modification, International Symposium*. pp. 13–14.

Dardanelli, J.L., Ritchie, J.T., Calman, M., Andraini, J.M. & Collino, D.J. (2004) An empirical model for root water uptake. *Field Crops Research* **87**, 59–71.

Dastane, N.G. (1974) Precipitación efectiva. *Food and Agriculture Organization,* Manual no. 25, p. 68.

Davidoff, B. & Hanks, R.J. (1989) Sugar beet production as influenced by limited irrigation. *Irrigation Science* **10**, 1–17.

Davies, W.J., Wilkinson, S. & Loveys, B. (2002) Stomatal control by chemical signalling and the exploitation of this mechanism to increase water use efficiency in agriculture. *New Phytologist* **153**, 449–460.

De Benito, A., Estrada, M.A. & Sombrero, A. (2002) Fréquence de l´irrigation et dose d´apports. Deux facteurs de base sur le développement et réndement de la betterave a sucre. *Proceedings of IIRB Congress, Mediterranean Section*. Marrakech, pp. 37–47.

De Juan, J.A., Martin de Santa Olalla, F.J. & Fabeiro, C. (1993) Métodos clásicos de medida del estado hídrico de las plantas. *Riegos y Drenajes* XXI, **69**, 14–26.

Doney, D.L. (1989) The value of wild beets. In: *Research and Extension Board of Minnesota and North Dakota Report*, pp. 177–183.

Doorenbos, J. & Kassam, A.K. (1979) Yield response to water. *Food and Agriculture Organization,* Irrigation and drainage, Paper No. 33.

Doorenbos, J. & Pruitt, W.O. (1977) Crop water requirement. *Food and Agriculture Organization,* Irrigation and drainage, Paper No. 24.

Dragović, S. & Vučić, N. (1976) Comparative studies of various methods in determination of water supply timing to sugarbeet. *Proceedings of the 39th IIRB Congress*. Brussels, pp. 373–386.

Dragović, S., Maksimovic, L. & Karagic, D. (1996) Effect of stand density on formation of leaves and leaf area of sugarbeet under irrigation. *Journal of Sugar Beet Research* **33** (1–4), 45–54.

Draycott, A.P. (1976) Interaction between irrigation and other agronomic practices. *Proceedings of the 39th IIRB Congress*. Brussels, pp. 135–148.

Draycott, A.P. & Durrant, M.J. (1971) Effects of nitrogen fertilizer, plant population and irrigation on sugarbeet. Part III Water consumption. *Journal of Agricultural Science* **76**, 277–282.

Draycott, A.P. & Messem, A.B. (1977) Response by sugarbeet to irrigation 1965–1975. *Journal of Agricultural Science* **89**, 481–493.

Dunham, R. (1988) Irrigation of sugar beet: the main effect. *British Sugar Journal* **53** (3), 34–37.

Dunham, R. (1993) Water use and irrigation. In: Cooke, D.A. & Scott, R.K. (eds) *The Sugar Beet Crop. Science into Practice*. Chapman and Hall, London, pp. 279–309.

Dunham, R.J. & Brown, K. (1987) Water requirements of sugar beet. *Irrigation News* **12**, 61–72.

Dunham, R.J., Messem, A.B. & Jaggard, K.W. (1988) Scheduling irrigation for sugarbeet. *Irrigation News* **13**, 44–57.

Dunham, R.J., Draycott, A.P. & Messem, A.B. (1993) Irrigation of sugar beet in United Kingdom. *Proceedings of the 56th IIRB Congress*. Brussels, pp. 25–41.

Durand, J.H. (1983) *Les sols irrigables*. Edited Presse Université de France, pp. 272–273.

Durrant, M.J., Draycott, A.P. & Milford, G.F.J. (1978) Effect of sodium fertiliser on water status and yield of sugar beet. *Annals of Applied Biology* **88**, 321–328.

Eckhoff, J.A. & Bergman, J.W. (1999) Sugar beet production under sprinkler and flood irrigation. *Proceedings of the 30th Biennial Meeting Agriculture*. Orlando, pp. 29–281.

Ehlers, W. & Goss, M. (2003) *Water Dynamics in Plant Productions*. CABI Publishing, Wallingford.

El Messaoudi, M., Mrini, M., Adbellaoui, M. & Bazza, M. (2002) Effet du regime d´irrigation et du déficit hydrique avant l´arranchage sur le rendement et la qualité technologique de la betterave sucrière dans la region du Gharb, Maroc. *Proceedings of IIRB Congress, Mediterranean Section*. Marrakech, pp. 100–109.

El Yamani, M.S. (1999) Influence of irrigation regimes and potassium fertilization levels on yield and quality of two sugar beet varieties. *Journal of Agriculture, Mansoura Univ.*, **24** (3), 1515–1527.

English, M. & Raja, S.N. (1996) Perspectives on deficit irrigation. *Agricultural Water Management* **32**, 1–14.

Ezekari, M., Boukhal, A. & Hakim, M. (1993) Effet de la frequence d´irrigation, de la dose d´azote et son fractionnement sur le rendement et la qualite technoligique de la betterave a sucre dans la plaine du tadla. *Proceedings of the 56th IIRB Congress*. Brussels, pp. 69–83.

Fabeiro, C., Martín de Santa Olalla, F., López, R. & Domíguez, A. (2003) Production and quality of the sugar beet (*Beta vulgaris* L.) cultivated under controlled deficit irrigation conditions in a semi-arid climate. *Agricultural Water Management* **62**, 215–227.

Fernandez, G.C.J. (1992) Effective selection criteria for assessing plant stress tolerance. In: Kuo, C.G. (ed.) *Adaptation of Food Crops to Temperature and Water Stress*. Asian Vegetable Research Development Center, Shanhua, Taiwan, Publ. No. 93–410, pp. 257–270.

Fernandez, C.J. & McCree, K.J. (1991) Visualising differences in plant water dynamics with a simulation model. *Crop Science* **31**, 399–404.

Fick, G.W., Loomis, R.S. & Williams, W.A. (1975) Sugar beet. In: Evans, L.T. (ed.) *Crop Physiology*. Cambridge University Press, London, pp. 259–295.

Finlay, K.W. & Wilkinson, G.N. (1963) The analysis of adaptation in a plant breeding programme. *Australian Journal of Agriculture Research* **14**, 742–754.

Fischer, R.A. & Maurer, R. (1978) Drought resistance in spring wheat cultivars. I. Grain yield responses. *Australian Journal of Agriculture Research* **29**, 897–912.

Foster, L. (1899) Sugarbeet in Sanpete and Serier counties. *USDA Farmer Bulletin* no. 63. Citado por Jensen and Erie, 1971.

François, L.E. & Goodin, J.R. (1972) Interaction de la temperature et de la salinité sur la germination de la betterave a sucre. *Agronomy Journal* **64**, 272–273.

Gavilán, P. (2002) La advección de calor sensible en el Valle medio del Guadalquivir y su influencia en la medida y la estimación de la evapotranspiración. Tesis doctoral, ETSIAM University, Córdoba, p. 170.

Ghariani, S.A. (1981) Impact of variable irrigation water supply on yield-determining parameters and seasonal water-use efficiency of sugar beet. PhD thesis, University of California, Davis.

Ghoulam, C.H., Foursy, A. & Fares, K. (2002) Effects of salt stress on growth, inorganic ions and proline accumulation in relation to osmotic adjustment in five sugar beet cultivars. *Environmental and Experimental Botany* **47**, 39–50.

Groves, S.L. & Bailey, R.J. (1994) Strategies for the sub-optimal irrigation of sugar beet. *Aspects of Applied Biology* **38**, 201–207.

Gucci, G. & De Caro, A. (1993) Irrigation et epoque de recolte de la betterave sucriere. *Proceedings of the 56th IIRB Congress*. Brussels, pp. 97–118.

Gummerson, R.J. (1986) The effect of constant temperatures and osmotic potentials on the germination of sugar beet. *Journal of Experimental Botany* **37**, 729–741.

Gzik, A. (1996) Accumulation of proline and pattern of a-amino acids in sugar beet plants in response to osmotic, water and salt stress. *Environmental and Experimental Botany* **36** (1), 29–38.

Haddock, J.L., Taylor, S.A. & Milligan, C.H. (1974) Irrigation, fertilization and soil management of crops in rotation. *Utah Agricultural Experimental Station*, Logan, Utah State University, Bulletin 49.

Hall, D.G.M., Reeve, M.J., Thomasson, A.J. & Wright, V.F. (1977) Water retention, porosity and density of field soils. *Soil Survey, Technical Monograph* No. 9, UK Soil Survey of England and Wales, Harpenden.

Hajheidari, M.M., Abdollahian-Noghabi, M., Askari, H., Heidari, M., Sadeghian, S.Y., Ober, E.S. & Salekdeh, G.H. (2005) Proteome analysis of sugar beet leaves under drought stress. *Proteomics* 5.

Hanson, A.D. & Wyse, R. (1982) Biosynthesis, translocation and accumulation of betaine in sugar beet and its progenitors in relation to salinity. *Plant Physiology* **70**, 1191–1198.

Hetz, E.H & Merino, G.C. (1998) Energy cost of three irrigation system in sugar beet. *Agro-Ciencia* **14** (2), 371–375.

Heuer, B. & Plaut, Z. (1989) Photosynthesis and osmotic adjustment of two sugarbeet cultivars grown under saline conditions. *Journal of Experimental Botany* **40**, 437–440.

Hilali, H., Abdelwahd, R., Bennani, M. & El Antri, M. (2002) Impact de differents modes d´irrigation sur l´economie de l´eau chez la betterave a sucre. *Proceedings of IIRB Congress, Mediterranean Section*. Marrakech, pp. 19–27.

Hills, F.J., Winter, S.R. & Henderson, D.W. (1990) Sugarbeet. In: *Irrigation of Agricultural Crops*. ASA Monograph, No. 30, pp. 795–810.

Holmes, J.M. (1967) Measurement of soil water. Irrigation of agricultural land. *ASA* **11**, 275–298.

Howell, T.A. (2003) Irrigation efficiency. In: Stewart, B.A. & Howell, T.A. (eds) *Encyclopedia of Water Science*. Dekker, pp. 467–472.

Howell, T.A., Ziska, L.H., McCormick, R.L., Burtch, L.M. & Fisher, B.B. (1987) Response of sugarbeet to irrigation frequency and cutoff on a clay loam soil. *Irrigation Science* **8**, 1–17.

Hunter, J.R. & Erickson, A.E. (1952) Relation of seed germination to soil moisture tension. *Agronomy Journal* **44**, 107.

ITB (2003) Optimiser l´irrigation des betteraves. *Le Betteravier Francais* No. 805, May, p. 18.

Jaggard, K.W. & Werker, A.R. (1999) An evaluation of the potential benefits and costs of autumn-sown sugar beet in NW Europe. *Journal Agricultural Science* **132**, 91–102.

Jaggard, K.W., Dewar, A.M. & Pidgeon, J.D. (1998) The relative effects of drought stress and virus yellows on the yield of sugarbeet in the UK, 1980–95. *Journal of Agricultural Science* **130**, 337–343.

Jensen, M.E. & Erie, L.J. (1971) Irrigation and water management. In: John, R.T., Alexander, J.T., Rush, G.E. & Hawkes, G.R. (eds) *Advances in Sugarbeet Production*. Iowa State University Press, Ames, pp. 189–223.

Johnston, D. (2000) Improvement of sugar beet (*Beta vulgaris* ssp. vulgaris L.) drought tolerance: comparisons with its wild relative, *Beta vulgaris* ssp. maritima. MPhil thesis, University of Nottingham.

Jones, H.G. (1977) Transpiration in barley lines with differing stomatal frequencies. *Journal of Experimental Botany* **28**, 162–168.

Jones, H.G. (1999) Use of infrared thermometry for estimation of stomatal conductance as a possible aid to irrigation scheduling. *Agricultural and Forest Meteorology* **95**, 139–149.

Jones, H.G., Stoll, M., Santos, T., de Sousa, C., Chaves, M.M. & Grant, O.M. (2002) Use of infrared thermography for monitoring stomatal closure in the field: application to grapevine. *Journal of Experimental Botany* **53**, 2249–2260.

Jones, P.D., Lister, D.H., Jaggard, K.W. & Pidgeon, J.D. (2003) Future climate change impact on the productivity of sugar beet (*Beta vulgaris* L.) in Europe. *Climatic Change* **58**, 93–108.

Kaffka, S., Peterson, G.R. & Kirby, D. (1997) Irrigation cutoff dates for sugar beets in the Intermountain Region. *Sugar beet Research Review*, University of California, Davis, no. 4, 2.

Kang, M.S. (1993) Simultaneous selection for yield and stability in crop performance trials: consequences for growers. *Agronomy Journal* **85**, 754–757.

Kassam, A.H. (1977) Net biomass production and yield of crops. Present and potential land. Use by Agroecological Zones Project. AGL. *Food and Agriculture Organization,* Rome.

Kassam, A.H. & Smith, M. (2001) FAO methodologies on crop water use and crop water productivity. Expert meeting on crop water productivity. *Food and Agriculture Organization,* Paper no. WP-M07, Roma, p. 18.

Katerji, N., Van Hoorn, J.W., Hamdy, A., Mastrorilli, M. & Mon Karzel, E. (1997) Osmotic adjustment of sugarbeets in response to soil salinity and its influence on stomatal conductance, growth and yield. *Agricultural Water Management* **34**, 57–69.

Keller, J. & Bliesner, R.D. (1990) *Sprinkle and Trickle Irrigation*. Van Nostrand Reinhold, New York.

Kenter, C. & Hoffmann, C. (2002) Yield and quality formation of sugarbeet as affected by temperature and water supply. *Zuckerindustrie* **127** (9), 699–706.

Kirda, C. (2002) Déficit irrigation scheduling based on plant growth stages showing water stress tolerante. Deficit irrigation practices. *Food and Agriculture Organization Water Report* no. **22**, 3–10.

Kohl, R.A. & Cary, J.W. (1969) Sugarbeet yields unaffected by afternoon wilting. *Journal of the American Society of Sugar Beet Technologists* **15**, 417–421.

Koyro, H.W. & Huchzermeyer, B. (1997) The physiological response of *Beta vulgaris ssp. maritima* to sea water irrigation. Special session: salinity problems and halophyte use. Water management, salinity and pollution control towards sustainable irrigation in the Mediterranean region. *CIHEAM International Conference Valenzano.* Bari, September, pp. 29–46.

Kramer, P.J. & Boyer, J.S. (1995) *Water Relations of Plants and Soils.* Academic Press, New York.

Lascano, R.J., Van Bavel, C.H.M., Hatfield, J.L. & Upchurch, D.R. (1987) Energy and water balance of sparse crops: simulated and measured soil and crop transpiration. *Soil Science Society of America Journal* **51**, 1113–1121.

Lawlor, D.W. & Milford, G.F.J. (1975) The control of water and carbon dioxide flux in water-stressed sugar beet. *Journal of Experimental Botany* **26**, 657–665.

Ludlow, M.M. & Muchow, R.C. (1990) A critical evaluation of traits for improving crop yields in water-limited environments. *Advances in Agronomy* **43**, 107–153.

Maas, E. (1990) Crops salt tolerance. In: Tanji, K. (ed.) *Agricultural Salinity and Assessment.* ASCE Manual No. 71, New York, p. 619.

Mambelli, S., Benati, R., Amaducci, M.T. & Venturi, G. (1992) Effetti dell'irrigazione sull'accrescimiento e sulle caratteristiche qualitative della radice di barbabietola da zucchero (*Beta vulgaris* L.). *Rivista di Agronomia* **26** (4), 623–632.

Mannini, P. & Venturi, G. (1993) Effects of irrigation and fertilization on sugar beet yield and quality in northern Italy's Po Valley. In: *Proceedings of the 56th IIRB Congress.* Brussels, pp. 171–185.

Märländer, B. & Windt, A. (1996) Dévelopment du système radiculaire en relation avec l´absorption en élements nutritifs et la croissance de la betterave sucrière. *Proceedings of the 59th IIRB Congress.* Brussels, pp. 187–198.

Marschner, H., Kuiper, P.J.C. & Kylin, A. (1981) Genotypic differences in the response of sugar beet leaves to replacement of potassium by sodium. *Physiologia Plantarum* **51**, 239–244.

Maurel, C. (1997) Aquaporins and water permeability of plant membranes. *Annual Review Plant Physiology* **48**, 399–429.

McCully, M.E. (1995) How do real roots work? Some new views of root structure. *Plant Physiology* **109**, 1–6.

McCully, M.E. (1999) Root xylem embolisms and refilling. Relation to water potentials of soil, roots and leaves and osmotic potentials of root xylem sap. *Plant Physiology* **119**, 1001–1008.

Mekki, B.B. & El Gazaar, M.M. (1999) Response of root yield and quality of sugar beet to irrigation with saline water and foliar potassium fertilization. *Annals of Agricultural Science* **44** (1), 213–225.

Milford, G.F.J. (1975) Effects of mist irrigation on the physiology of sugar beet. *Annals of Applied Biology* **80**, 247–250.

Milford, G.F.J., Cormack, W.F. & Durrant, M.J. (1977) Effects of sodium chloride on water status and growth of sugar beet. *Journal of Experimental Botany* **28**, 1380–1388.

Milford, G.F.J., Pocock, T.O., Riley, J. & Messem, A.B. (1985) An analysis of leaf growth in sugar beet. III. Leaf expansion in field crops. *Annals of Applied Biology* **106**, 187–203.

Mompin, A., Lopez, T., De Benito, A. & Guirao, J. (1993) Sugar beet yield response to water and nitrogen in the Duero Valley. *Proceedings of the 56th IIRB Congress.* Brussels, pp. 131–150.

Monteith, J.L. (1965) Evaporation and environment. *Symposium of the Society for Experimental Biology* **19**, 205–234.

Moraghan, J.T. (1972) Water use by sugarbeet in a semiarid environment as influence by population and nitrogen fertilizer. *Agronomy Journal* **64**, 759–762.

Moreno, F., Cabrera, F., Fernandez-Boy, E., Girón, I.F., Fernandez, J.E. & Bellido, B. (2001) Irrigation with saline water in the reclaimed marsh soils of south-west Spain: impact on soil properties and cotton and sugar beet crops. *Agricultural Water Management* **48**, 133–150.

Morgan, J.M. (2000) Increases in grain yield of wheat by breeding for an osmoregulation gene: relationship to water supply and evaporative demand. *Australian Journal Agricultural Research* **51**, 971–978.

Morillo-Velarde, R. (1990) Effet de l´irrigation sur la qualité de la betterave sucrière en semis d´automne. *Abstract Réunion Commission Méditerraneénne.* IIRB, Mohammedia, Maroc, p. 5.

Morillo-Velarde, R. (1991) Respuesta de la remolacha de siembra otoñal al riego. Tesis Doctoral, ETSIAM, University Córdoba, p. 215.

Morillo-Velarde, R. (1992) Possibilités de réduction des coûts de l´irrigation dans la culture de la betterave sucrière. *Réunion Commission Méditerraneénne.* Brussels, February, p. 19.

Morillo-Velarde, R. (1993a) Besoins hydriques de la cultura de betteraves sucriéres. Une revue synthetique. *Proceedings of the 56th IIRB Congress.* Brussels, pp. 41–51.

Morillo-Velarde, R. (1993b) Response de la betterave de semis d´automne au deficit hydrique. *Proceedings of the 56th IIRB Congress.* Brussels, pp. 187–204.

Morillo-Velarde, R. (1996) Algunas claves de éxito en el cultivo de siembra de otoño en riego. *Revista* AIMCRA **51**, 46–47.

Morillo-Velarde, R. (1999) Conduite de l'irrigation pour le rendment maximum dans la betterave automnale. *Proceedings of the 62nd IIRB Congress.* Sevilla, pp. 37–50.

Morillo-Velarde, R. (2000) Necesidades hídricas del cultivo. ET remolacha. In: *El riego de la remolacha en Castilla y León.* Ed Caja Duero, pp. 115–134.

Morillo-Velarde, R. (2001) Les besoins hydriques de la betterave sucrière dans les règions mèditerraneénes. In: *Irrigation de la betterave sucrière en zone mediterraneenne.* Advances in Sugar Beet Research. Vol. 3. pp. 15–42.

Morillo-Velarde, R. & Moreno, A. (2002) Couvertures d'aspersion pour l'irrigation de la betterave a sucre: recommendations. *Proceedings of IIRB Congress, Mediterranean*

Section. Marrakech, pp. 67–74.

Morillo-Velarde, R., Velicia, H. & Martínez, J.C. (1997) Datos de cultivo de la remolacha azucarera en España para CROPWAT. *Revista Riegos Y Drenajes* **94**, 64–68.

Morton, A.G. & Watson, D.J. (1948) A physiological study of leaf growth. *Annals of Botany* **47**, 281–310.

Mosca, G. & Candolo, G. (2003) Irrigated beets – relation between soil and crop. *Proceedings of the 1st Joint ASSBT-IIRB Congress*. San Antonio, pp. 513–519.

Neibling, H. & Gallian, J. (1997) Sugar beet irrigation: essential in Idaho. *Irrigation Business Technology* **5**, 22–23.

Nuckols, S.B. (1931) Sugarbeet growing under irrigation in the Utah-Idaho Area. *USDA Farmer Bulletin* no. 1645. Cited in Jensen and Erie, 1971.

Nunes, A. (1983) Analise do crescimento da betterraba sacarina em cultura de outono. *Agronomia Lusitania* **42**, 5–23.

Ober, E.S. & Luterbacher, M.C. (2002) Genotypic variation for drought tolerance in *Beta vulgaris*. *Annals of Botany* **89**, 917–924.

Ober, E.S., Clark, C.J.A., Le Bloa, M., Royal, A., Jaggard, K.W. & Pidgeon, J.D. (2004) Assessing the genetic resources to improve drought tolerance in sugar beet: agronomic traits of diverse genotypes under droughted and irrigated conditions. *Field Crops Research* **90**, 213–234.

Ober, E.S., Clark, C.J.A., Le Bloa, M., Royal, A., Jaggard, K.W. & Pidgeon, J.D. (2005a) The influence of drought and genotype on sugar beet quality. *Journal of the Science of Food and Agriculture* (in review).

Ober, E.S., Le Bloa, M., Clark, C.J.A., Royal, A., Jaggard, K.W. & Pidgeon, J.D. (2005b) Evaluation of physiological traits as indirect selection criteria for drought tolerance in sugar beet. *Field Crops Research* **91**, 231–249.

Okman, C. (1973) Ankara Sartlarinda Séller Pancarinin su Instihlakinin Tayini Üzerinde bir Arastirma. PhD thesis, Ankara, Ankara University Publications.

Oussible, M. & Jbilou, M. (2004) Effet de différents enrobages à différent régimes hydriques sur la phase germination levée de la betterave monogerme. *Proceedings of the IIRB Congress*.

Oussible, M., Hilali, H. & Chokairi, A. (2002) La pre-irrigation: une technique benefique pour l´installation de la betterave a sucre au Maroc. *Proceedings of IIRB Congress, Mediterranean Section*. Marrakech, pp. 10–15.

Owen, P.C. & Watson, D.J. (1956) Effect on crop growth of rain after prolonged drought. *Nature* **177**, 847.

Paine, W.A. & Brück, H. (1996) Evapotranspiration and other soil water balance terms estimated from neutron and capacitance probe measurement. *Proceeding of the International Conference on Evapotranspiration and Irrigation Scheduling*. ASCE, San Antonio, pp. 455–460.

Passioura, J.B. (2002) Environmental biology and crop improvement. *Functional Plant Biology* **29**, 537–546.

Peel, A.J. & Rogers, S. (1982) Stimulation of sugar loading into sieve elements of willow by potassium and sodium salts. *Planta* **154**, 94–96.

Penman, H.L. (1952) Experiments on the irrigation of sugar beet. *Journal of Agricultural Science* **42**, 286–292.

Pereira, L.S. (1999) Higher performance through combined improvements in irrigation methods and scheduling: a discussion. *Agricultural Water Management* **40**, 153–169.

Pidgeon, J.D., Werker, A.R., Jaggard, K.W., Richter, G.M., Lister, D.H. & Jones, P.D. (2001) Climatic impact on the productivity of sugar beet in Europe, 1961–1995. *Agricultural and Forest Meteorology* **109**, 27–37.

Pidgeon, J.D., Ober, E.S., Qi, A., Clark, C.J.A., Royal, A. & Jaggard, K.W. (2005) Using multi-environment sugar beet variety trials to screen for drought tolerance. *Field Crops Research* (in press).

Postel, S.L. (1998) Water for food production: will there be enough in 2025? *BioScience* **48**, 629–637.

Prueger, J.H., Hipps, L.E. & Cooper, D.I. (1996) Evaporation and the development of local boundary layer over and irrigated surface in arid region. *Agricultural and Forest Meteorology* **78**, 223–237.

Pruitt, W.O., Fereres, E. & Synder, R.L. (1986) Reference evapotranspiration (Eto) for California. *Division of Agricultural and Natural Resources Bulletin* 1922. University of California.

Qadir, M., Boers, Th.M., Schubert, S., Ghafoor, A. & Murtaza, G. (2003) Agricultural water management in water-starved countries: challenges and opportunities. *Agricultural Water Management* **62**, 165–185.

Qi, A., Kenter, C., Hoffmann, C. & Jaggard, K.W. (2003) The Broom's Barn sugar beet growth model and its use to describe yield variability. In: Sugar beet growth and growth modeling. *Advances in Sugar Beet Research* **5**, 107–124.

Reichman, G.A., Doering, E.J., Benz, L.C. & Follet, R.F. (1978) Sugarbeet yield and quality as affected by water table depth and irrigation. *Sugarbeet Research and Extension Reports* **9**, 122–124.

Richter, G.M., Jaggard, K.G. & Mitchell, R.A. (2001) Modelling radiation interception and radiation use efficiency for sugar beet under variable climatic stress. *Agricultural and Forest Meteorology* **109** (1), 13–25.

Ritchie, J.T. & Johnson, S.B. (1990) Soil and plant factors affecting evaporation. Irrigation of agricultural crop. *Agronomy Monograph* no. 30, ASA, Madison, pp. 364–390.

Robert, J., Middleton, J.E. & Richard, A.W. (1977) Sugarbeet production on sandy soil with variable high frequency sprinkler irrigation and nitrogen fertilization. *Washington State University College of Agricultural Research* Circular No. 604.

Rosenberg, N.J., Kimball, B.A., Martin, P. & Cooper, C.F. (1990) From climate and CO_2 enrichment to evapotranspiration. In: *Climate Changes and US Water Resources*. J. Wiley and Sons, pp. 151–175.

Roth, D. & Guenther, R. (1992) Comparision of measured and evaluated potential evapotranspiration. *Z. Kulturtech Landentwicklung* **33** (1), 13–22.

Röver, A. & Büttner, G. (1999) Einfluß von trockenstress auf die technische qualität von Zuckerrüben. *Proceedings of the 62nd IIRB Congress*. Sevilla, pp. 97–108.

Sadeghian, S.Y., Fazli, H., Mohammadian, R., Taleghani, D.F. & Mesbah, M. (2000) Genetic variation for drought stress in sugarbeet. *Journal of Sugar Beet Research* **37**, 55–77.

Salter, P.S. & Goode, J.E. (1967) Crop responses to water at different stages of growth. *Research Review* No. 2, Bureaux. Bucks., England.

Scott, R.K., Jaggard, K.W. & Sylvester-Bradley, R. (1994) Resource capture by arable crop. In: Monteith, J.L., Scott, R.K. & Unsworth, M.H. (eds) *Resource Capture by Crops.* Nottingham University Press, pp. 279–302.

Sepaskhah, A.R. & Kamgar-Haghighi, A.A. (1997) Water use and yield of sugar beet grown under every-other-furrow irrigation with different irrigation intervals. *Agricultural Water Management* **34**, 71–79.

Sharmasarkar, F.C., Sharmasarkar, S., Held, L.J., Miller, S.D., Vance, G.F. & Zhang, R. (2001a) Agroeconomic analyses of drip irrigation for sugarbeet production. *Agronomy Journal* **93**, 517–523.

Sharmasarkar, F.C., Sharmasarkar, S., Miller, S.D., Vance, G.F. & Zhang, R. (2001b) Assessment of drip and flood irrigation on water and fertilizer use efficiencies for sugarbeets. *Agricultural Water Management* **46**, 241–251.

Smith, C.H.G. (2002) Root growth of sugar beet varieties in response to soil mechanical impedance and drought. MPhil thesis, University of Aberdeen.

Sperry, J.S., Hacke, U.G., Oren, R. & Comstock, J.P. (2002) Water deficits and hydraulic limits to leaf water supply. *Plant, Cell and Environment* **25**, 251–263.

Sperry, J.S., Stiller, V. & Hacke, U.G. (2003) Xylem hydraulics and the soil-plant -atmosphere continuum: opportunities and the unresolved issues. *Agronomy Journal* **95**, 1362–1370.

Stewart, J. & Hagan, R.M. (1990) Functions to predict effects of crop water deficits. *Journal of Irrigation and Drainage* **99**, 421–439.

Stieber, J. & Beringer, H. (1984) Dynamic and structural relationships among leaves, roots and storage tissue in the sugar beet. *Botanical Gazette* **145**, 465–473.

Tanner, C.B. & Sinclair, T.R. (1983) Efficient water use in crop production: research or re-search? In: Taylor, H.M., Jordan, W.R. & Sinclair, T.R. (eds) *Limitations to Efficient Water Use in Crop Production.* American Society of Agronomy Inc., Madison, pp. 1–27.

Tardieu, F. & Katerji, N. (1991) Plant response to the soil water reserve: consequences of the root system environment. *Irrigation Science* **12**, 145–152.

Tardieu, F. & Simonneau, T. (1998) Variability among species of stomatal control under fluctuating soil water status and evaporative demand: modeling isohydric and anisohydric behaviours. *Journal of Experimental Botany* **49**, 419–432.

Thompson, N., Barrie, I.A. & Ayles, M. (1981) *The Meteorological Office Rainfall and Evaporation Calculation System: Morecs (July 1981).* Meteorological Office, Bracknell.

Thornthwaite, C.W. (1944) Report of the Committee on Transpiration and Evaporation, 1943–1944. *Transactions of American Geophysics Union* **25**, 683–693.

Thornthwaite, C.W. (1948) An approach towards a rational classification of climate. *Geographical Review* **38**, 55–94.

Tognetti, R., Palladino, M., Minnocci, A., Delfine, S. & Alvino, A. (2003) The response of sugarbeet to drip and low-pressure sprinkler irrigation in southern Italy. *Agricultural Water Management* **60**, 135–155.

Tollenaar, M. & Lee, E.A. (2002) Yield potential, yield stability and stress tolerance in maize. *Field Crops Research* **75**, 161–169.

Trybala, M. (1979) The influence of irrigation and fertilizer on sugar beet yield. *Internationale Zeitschrift der Landwirtschaft* **5**, 452–455.

Tugnoli, V., Bettini, G., Marzi, V. & Sarli, G. (1999) Drip irrigation in Southern Italy. In: *Proceedings of the 62nd IIRB Congress.* Sevilla, pp. 217–226.

Urbano, P., Arroyo, J.M., Conde, J.R., Rojo, C. & Gonzalez, F. (1993) Gestion de l´eau en irrigation dans la culture de la betterave sucrière dans la vallee du Duero (Espagne). *Proceedings of the 56th IIRB Congress.* Brussels, pp. 85–96.

Van der Beek, M.A. & Houtman, H.J. (1993) Does interaction between varieties and drought stress exist? *Proceedings of 56th IIRB Winter Congress.* Brussels, pp. 151–169.

Van der Ploeg, R.R., Beese, F., Strebel, O. & Renger, M. (1978) The water balance of a sugar beet crop: a model and some experimental evidence. *Zeitschrift für Pflanzenrnahrung und Bodenkunde* **141**, 313–328.

Vanli, N. (1993) Comparison of different irrigation methods in sugar beet production and irrigation of sugar beet in Turkey. In: *Proceedings of the 56th IIRB Congress.* Brussels, pp. 235–236.

Velicia, H. (1998) Efectos del estrés hídrico sobre la producción y calidad de la remolacha azucarera (*Beta vulgaris* L.) de siembra primaveral en diferentes momentos del cultivo en las condiciones de la Cuenca del Duero. Tesis Doctoral, Universidad Politécnica de Madrid.

Velicia, H. & Morillo-Velarde, R. (2001) Les stratégies d´irrigation dans la culture de la betterave sucriére en semis de printemps. *IIRB Advances in Sugar Beet Research* Vol. 3, 15–42.

Vitali, G., Rossi Pisa, P., Cavazza, G., Vargas, F. & Dautrebande, S. (1990) Comparison of the SWATRER and CERES/MOD models for soil water distribution in sugarbeet. *Acta Hort* **278**, 711–720.

Vučić, N. (1976) The importance of irrigation in sugar beet production in Vojvodina and related problems. In: *Proceedings of the 39th IIRB Congress.* Brussels, pp. 365–371.

Vukov, K. (1977) *Physics and Chemistry of Sugar Beet in Sugar Manufacture.* Elsevier Scientific Publishing, Amsterdam.

Wang, E. & Smith, C.J. (2004) Modelling the growth and water uptake function of plant root systems: a review. *Australian Journal of Agriculture Research* **55**, 501–523.

Waskom, R.M. (1994) Best management practices for irrigation management. *Colorado State University Cooperative Extension Service* Bulletin XCM-173, p. 15.

Weeden, B.R. (2000) Potential of sugar beet on the Atherton Tableland. *RIDC* Publication no. 00/167, p. 48.

Werker, A.R. & Jaggard, K.W. (1998) Dependence of sugar beet yield on light interception and evapotranspiration. *Agricultural and Forest Meteorology* **89**, 229–240.

Werker, A.R, Jaggard, K.W. & Allison, M.F. (1999) Modelling partitioning between structure and storage in sugar beet: effect of drought and soil nitrogen. *Plant and Soil* **207**, 97–106.

Windt, A. & Märländer, B. (1994) Root growth of sugar beet under special consideration of water relations. *Zuckerindustrie* **119**, 659–663.

Winter, S.R. (1980) Suitability of sugarbeets for limited irrigation in a semi-arid climate. *Agronomy Journal* **72**, 118–122.

Winter, S.R. (1988) Influence of seasonal irrigation amount on sugar beet yield and quality. *Journal of Sugar Beet Research* **25**, 1–10.

Winter, S.R. (1990) Sugar beet response to nitrogen as affected by seasonal irrigation. *Agronomy Journal* **82**, 984–988.

Wright, E., Carr, M.K.V. & Hammer, P.J.C. (1994) Crop production and water-use. I. A model for estimating crop water-use with limited data. *Journal of Agricultural Science, Cambridge* **123**, 9–13.

Wright, E., Carr, M.K.V. & Hammer, P.J.C. (1997) Crop production and water-use. IV. Yield functions for sugar beet. *Journal of Agricultural Science, Cambridge* **129**, 33–42.

Yonts, C.D. (1997) Late session irrigation management for sugar beet. *Proceedings of 28th ASSBT Congress*. Phoenix, pp. 121–123.

Yonts, C.D. & Palm, K.L. (2001) Irrigation management. In: *Sugar Beet Production Guide*. University of Nebraska, pp. 161–178.

Zehauf, M., Enahari, J., El Messaoudi, M., Harrak, A. & Barraoui, D. (2002) Optimisation de la période de suspension de l´irrigation avant l´arranchage de la betterave sucriere dans la region du Gharb. Incidences sur la productivité et la qualité technologique. *Proceedings of IIRB Congress, Mediterranean Section*. Marrakech, pp. 57–66.

Zuffrano, M., Caliandro, A., Camposeo, S. & Guarini, D. (2001) Drip irrigation for the autumnal sugar beet (Italy). *Bieticoltura Associata* **6**, 16–22.

Chapter 11
Virus Diseases

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Sugar beet is susceptible to a number of different viruses that can be transmitted by insects, fungi, nematodes, seed and/or physical contact. All these viruses may decrease the potential yield of the root crop as well as (affect) the extractability of sugar by the processor. Certain viruses such as *Beet necrotic yellow vein virus* (BNYVV), the causal agent of rhizomania, have seriously damaged sugar yields in intense sugar beet producing regions of the world and this virus can dictate where beet can be grown if partially resistant varieties are not used. With the advance in molecular biology, most of the economically important sugar beet viruses have been fully characterized and their DNA or RNA genomes sequenced. This has been particularly useful in understanding how these viruses interact with plants and their vectors, and how they can be more efficiently controlled in the future. Such advances have enabled the development of highly specific and sensitive serological and molecular diagnostic methods that have helped to clarify the taxonomic position of certain viruses and their strains, such as the virus yellows complex, as well as enabling the identification of new viral species and how sugar beet viruses can interact in the same plant.

RHIZOMANIA

Beet necrotic yellow vein virus (BNYVV, *Benyvirus*), the causal agent of sugar beet rhizomania (Tamada & Baba, 1973) is transmitted by viruliferous zoospores of the soil-borne plasmodiophorid protozoa *Polymyxa betae* Keskin. Rhizomania ('root madness or beardness') is characterized by the extensive proliferation of lateral rootlets along the main taproot, necrosis of the vascular bundle and severe stunting of the plant. The disease has a worldwide distribution in most sugar beet growing areas. The potential of rhizomania to reduce yield severely and to persist almost indefinitely in soil once established, along with the difficulty of preventing its spread, has generated concern amongst growers and processors alike.

The first published reports of poorly growing sugar beet crops with symptoms very similar to those of rhizomania were from northern Italy in 1952 (Canova, 1959). In many cases the damage to these crops was so serious that cultivation had to be abandoned, this in itself implying that the disease had already been present in this area (Pô valley) for a number of years. Canova (1966) named the disease 'rhizomania' or 'root madness' on account of the abnormal proliferation of dark and necrotic lateral roots, and was the first to attribute its cause to an association between a virus and a fungus.

Discovery of rhizomania in Japan in 1965 led to intense studies culminating in the isolation, characterization and naming of the viral agent causing the disease, *Beet necrotic yellow vein virus* or BNYVV (Tamada *et al.*, 1971; Tamada & Baba, 1973). 'Paper pots' used for transplanting seedlings were the standard method of establishing the sugar beet crop in Japan and it is believed that the extensive and almost simultaneous spread of the disease over large areas was attributed to this method. Within Europe, the disease has been found in most countries except Ireland and Finland. Many of the areas affected by rhizomania are concentrated in regions of intensive sugar beet production, where crop rotations are short.

Symptoms and damage

Rhizomania occurs when viruliferous *P. betae* zoospores harbouring BNYVV virions infect the sugar beet root system. One of the symptoms, after which the virus is called (Tamada & Baba, 1973) is the yellowing and eventual necrosis of the leaf veins. However, the necrotic yellow vein symptom is relatively rare since most of the time the virus appears to be restricted to the root. Beside these virus named symptoms, leaf symptoms can be easily confused with nitrogen deficiency (Plate 14). More usually, the symptoms that appear in the shoots of affected plants result from the altered metabolism or morphology of the infected root. Premature wilting (Plate 15) may occur in affected patches as a result of insufficient water uptake by damaged roots.

Upon infection profound changes occur in the roots. Following early and severe infection, roots remain small with a constricted turnip-like shape, growth of the main taproots ceases and a proliferation of small laterals, the root 'beard', develops instead (Plate 16). In root sections a reddish-brown discoloration of the central stele can occur along with tumour-like symptoms from where the root proliferation appears (Plate 16). Microscopic observations of the small tertiary rootlets reveal the presence of numerous cystosori or resting spores of *P. betae* (Plate 17). Over time severely infected sugar beet can eventually die. Very slight or late infections may produce no obvious symptoms despite the presence of detectable virus in the root.

Severe infection can result in a high reduction of yield, sugar content and purity (Tamada, 1999; Scholten & Lange, 2000), depending on the sugar beet genotype, inoculum level in the soil, the pathotype of BNYVV, the weather conditions during the growing season and the timing of infection. Improvements in sugar yield from 3.9 t/ha in susceptible cultivars to 13.1 t/ha in resistant cultivars have been reported (M. Richard-Molard, Institut Technique de la Betterave (ITB), 1990, personal communication). However, this method may underestimate the amount of yield loss since the resistance is known to be only partial. More generally, yield losses estimated from samples taken from within and outside rhizomania patches in sugar beet crops indicate that a 50–60% reduction in sugar yield is not uncommon. As disease severity increases, for example in successive crops on infested land, sugar content appears to be the first yield parameter to be affected; root weight is reduced when inoculum reaches high levels or infection occurs early in the season. Indeed, unusually low sugar content values have been used as an early indicator of rhizomania infection in the Netherlands (Heijbroek, 1989) particularly when accompanied by a reduction in the level of amino nitrogen.

Development and spread

Polymyxa betae zoospores require high soil moisture for maximum activity; water is essential to enable cysts to germinate and the bi-flagellate zoospores to swim towards roots. Gerik *et al.* (1990) found that in naturally infested soils *P. betae* infection began at an initial matrix potential of > 400 mbar; infection appeared to be more frequent in coarse-textured soils and is influenced by factors such as poor soil structure, inadequate drainage, frequent heavy rainfall and the use of irrigation (particularly excessive irrigation) in some countries. Once introduced, BNYVV viruliferous *P. betae* displays a remarkable ability to amplify its infectious potential, with up to a 10 000-fold increase after a single growing season. Displacement of infested soil is a very efficient means to spread the disease. When adding 50 kg/ha of infested soil to a trial plot, the yield reduction was 57% in the second beet crop (Tuitert & Hofmeester, 1994). The risk of recycling beet soil from sugar factories on fields where sugar beet is the crop rotation has been evaluated and BNYVV was readily detected in the following beet crops after tare soil application, but without increase of beet cyst nematodes or fungal root pathogens (Schaufele & Buttner, 2002).

Temperatures around 25°C are optimum for *P. betae* germination and development; the minimum temperature for cyst germination and infection appeared to be between 10 and 15°C. It has been demonstrated that the effect of sowing date on infection was greater than that of year-to-year variation in temperatures associated with a fixed sowing date in a temperate climate (Webb *et al.*, 2000). These biological requirements for *P. betae* development explain why in countries experiencing a Mediterranean or continental type climate, rhizomania incidence and spread is important, whereas the more northern sugar beet growing regions of the world, such as the UK, Ireland and the Scandinavian countries, have not been affected much by the disease yet.

The association of severe rhizomania with neutral or alkaline soils has been attributed to the preference of the fungal vector for such conditions (Abe, 1974). Surveys in the northern Italian Pô valley, where rhizomania was first detected, showed that wild beets near the Pô estuary did not exhibit virus infection. The absence of BNYVV in the wild *Beta maritima* population was thought to be due to the saline conditions in the coastal ecosystem (Bartsch & Brand, 1998).

The disease is essentially restricted to *Beta* species within the *Chenopodiaceae*, which includes sugar beet, the various types of fodder beet (e.g. mangolds), red beet and leaf beets such as Swiss chard. However, spinach (*Spinacia oleracea*) is also a natural and experimental (systemic) host (Lemaire *et al.*, 1988). It is now generally believed that two or three subsequent beet crops following the primary introduction of viruliferous *P. betae*, particularly in more temperate climates, are necessary before inoculum levels build up sufficiently to generate disease symptoms (Heijbroek, 1989). However, severe yield reductions have been observed following a 10–15 year break from susceptible crops (Schlosser, 1988).

The appearance of rhizomania in so many widely separated countries of the world since the 1960s has generated considerable speculation as to how the soil-borne disease could be so rapidly and extensively disseminated. In the USA, it was first detected in 1983, and probably introduced from Europe (Wisler & Duffus, 2000) with the Great Lakes region being the latest area to be diagnosed in 2002 (Wintermantel *et al.*, 2003), in 1984 in Belgium (Schmit *et al.*, 2002), in 1988 in Spain with a unique strain over 80 000 ha (Suarez *et al.*, 1999), in Syria in 1997 (Mouhanna *et al.*, 2002) and lately in autumn 2000 in Denmark (Nielsen *et al.*, 2001). The disease is now present in Denmark and Poland, Ireland being the last country where no outbreaks have been recorded. In 2004, there has been significant spread in many countries and especially in the UK and a strong expression of the symptoms on the leaves including unusual foliage symptoms of yellow veins in Germany and France (ITB, France, 2004, personal communication).

Causal agents

The virus

Within the plasmodiophorid-transmitted virus group, the genus *Benyvirus*, which was accepted as a new genus by the International Committee on Taxonomy of Viruses (ICTV) in 1997, (previously, BNYVV was classified within the *Furovirus* genus) (Torrance & Mayo, 1997; Tamada, 1999) comprises of two members, *Beet necrotic yellow vein virus* (BNYVV) and *Beet soil borne mosaic virus* (BSBMV) plus a tentative member (*Burdock mottle virus*) BdMV (Sherwood & Rush, 1999). In Europe, two tentative members of the *Pomovirus* genus, *Beet soil-borne virus* (BSBV) and *Beet virus Q* (BVQ) are found associated with BNYVV and widespread in the sugar beet growing areas, especially in the UK and in Belgium (Stas *et al.*, 2001a,b). Pre-infection with BSBV can reduce the titer and the severity of the symptoms of challenging BNYVV (Prillwitz & Schlosser, 1993a).

The type species of the genus *Benyvirus*, BNYVV consists of rod-shaped particles (20 nm in diameter, Plate 18) of four different size classes (390, 265, 100 and 85 nm in length) (Putz, 1977; Putz *et al.*, 1988). BNYVV is composed of four genomic messenger-like RNAs of 6.8, 4.7, 1.8 and 1.5 kb with an additional fifth RNA found frequently in Asia (Tamada *et al.*, 1989) varying from 1.34 to 1.35 kb according to the geographic origin. All four RNAs possess nucleotide homologies at the 5′ and 3′ ends (60 nt for the 5 RNA species), a cap structure at the 5′ and a poly A tail at the 3′ terminus.

The use of molecular methods such as RFLP and SSCP (within the CP encoding RNA2) has shown the existence of three major pathotypes in Europe, called A, B and P type (Kruse *et al.*, 1994; Koenig *et al.*, 1995) that cannot be distinguished serologically. The A type is found in most European countries, North America, China and Japan, whereas the B type is detected frequently in France, Germany and in some cases in China (Saito *et al*., 1996; Miyanishi *et al*., 1999). BNYVV RNA-5 containing isolates (P-type) have been identified in the French Pithiviers area (Koenig *et al*., 1997; Plate 19), in East Anglia (UK) (Harju *et al*., 2002), Kazakhstan, Japan and China (Koenig & Lennefors, 2000). Some authors have indicated that P-type should be considered as an A type with an additional RNA5 corresponding to the RNA5 Pithiviers sequence (Miyanishi *et al*., 1999). BNYVV isolates harbouring RNA5 are common in Japan, and molecular epidemiology and phylo-geographic studies have been conducted to characterize correlations between RNA5 variability and the geographic origin or virulence. It has been suggested from these studies that RNA5 was probably originally associated with an A-like type ancestor in France, Kazakhstan, China and Japan (Miyanishi *et al*., 1999). B types appear to be less damaging than A or P types, the latter giving higher virus titers compared to A or B types (Heijbroek *et al*., 1999).

BNYVV isolates harbouring RNA-5 seem to be more pathogenic toward sugar beet and *Chenopodium quinoa* than A and B types (Miyanishi *et al*., 1999). Koenig *et al.* (1991) and Jupin *et al.* (1992) have shown that the RNA-3 encoded protein (P25) increased greatly the virus titer and spread of BNYVV in sugar beet taproots without induction of root symptoms.

The natural host range of the virus is clearly very much determined by that of its vector; it is therefore restricted mainly to *Beta* spp. (see below) although spinach (*Spinacia oleracea*) and some species of *Chenopodium* can also be infected by viruliferous *P. betae.* Recent studies showed that the common weed species *Amaranthus retroflexus, Capsella bursa-pastoris, Chenopodium album, Raphanus raphanastrum, Solanum nigrum, Stellaria media* and *Xanthium italicum* did not contain BNYVV (Dikova, 1997), whereas the following were recorded as hosts of BNYVV and its vector: *Polygonum aviculare, Sonchus asper* and *Descurainia sophia*, *Circium arvense, Chamomilla recutita, Xanthium strumarium, Convolvulus arvensis, Veronica hederifolia, Datura stramonium* and *Tribulus terrestris* (Kutluk *et al*., 2000). There is no evidence to date of strains of the virus that differ in their host range.

The vector

Polymyxa betae was first identified, named and described as a fungus and initially classified in the *Plasmodiophoromycetes* family (Keskin, 1964). It was observed to be consistently associated with plants showing symptoms of rhizomania in Italy (Canova, 1966). More direct evidence for its role as the vector of BNYVV was obtained from transmission experiments (Tamada & Baba, 1973; Abe & Tamada, 1986), and virus particles have been detected within zoospores by enzyme-linked immunosorbant assay (ELISA) and electron microscopy by immunogold labelling.

The correct taxonomy of the Plasmodiophoromycetes, which includes *Plasmodiophora brassicae*, the cause of club-root disease of brassicas, *Spongospora subterranea*, the cause of powdery scab and the vector of potato mop-top virus in the genus *Pomovirus* in potatoes, and *Polymyxa graminis*, the vector of several soil-borne viruses in many graminaceous crops worldwide, has been debated for years. All of them are intracellular obligate parasites, which spread and infect by anterior biflagellate zoospores and have highly resistant and long-living resting spores (cystosporus) clustered together to form a cystosorus. It is now accepted by most taxonomists, that Plasmodiophorids are recognized as a distinct valid taxonomic group, being closer to the protozoa or protists rather than to the fungus phylum *Plasmodiophoromycota* and unrelated to the other fungus taxa. Currently 20 viruses, sharing numerous properties, are known to be transmitted by these vectors. There is no consistent morphological distinction between *P. betae* and *P. graminis*; *P. betae*, being previously considered as a *forma specialis* of *P. graminis.* Recently, phylogenetic analyses have been performed on the nuclear ribosomal 5.8S DNA (nr DNA) and internal transcribed spacers (ITS) within the nr DNA of different isolates of *Polymyxa* spp. The results showed that it was possible to separate *P. betae* from *P. graminis* (Legreve *et al*., 2002).

Viruliferous resting spores of *P. betae* can survive many decades in the field. The life cycle and infection process have been well documented (Keskin, 1964). Estimates of inoculum levels in soils have been made in several countries by serially diluting soil samples and using a seedling bioassay to bait

P. betae and, in some cases, BNYVV. A statistical technique, the 'Most Probable Number' method (MPN), is commonly used to estimate the number of infective propagules in the soil from the incidence of infected seedlings at each dilution. This technique has been used extensively in ecological and epidemiological studies. Values of 16–48 infective units of *P. betae* per ml of soil were obtained in samples from rhizomania-infested fields in the Netherlands (Tuitert & Hofmeester, 1994), more or less similar to values reported in other European countries but somewhat higher than those from rhizomania-free UK soils (Blunt, 1989). This method should be considered as a relative and not absolute reference requiring statistical analysis and consistent repeats (Adams & Welham, 1995).

The possibility that the fungal vector multiplies more rapidly in the presence of the virus should not be overlooked. Gerik and Duffus (1988) have suggested that the plant's susceptibility to the vector is increased by viral infection. Whether or not this occurs, however, the morphological changes accompanying rhizomania, in particular the proliferation of fibrous roots that are the main sites of fungal activity, are likely to increase greatly the reproductive rate of viruliferous vector populations. In spite of this, the proportion of the fungal resting spores that contain infective virus may be relatively low, as indicated by the 10–15% detected in soil samples in the Netherlands (Tuitert, 1990).

Control

Agronomic measures

Since the appearance of rhizomania a number of agronomic measures have been used to reduce the impact of the disease. For example, in Japan, partially sterilized soil was used in the paper pots in which beet are grown prior to transplantation in the field. However, this method was too costly to be maintained.

The principle of establishing healthy plants in the field also underlies the recommendation for early sowing, at least in those countries where soil temperatures are sufficiently low at the time the crop is sown. The minimum temperature at which *P. betae* becomes active, and is therefore able to transmit the virus, is around 12°C (Blunt *et al.*, 1991) whereas the germination and growth of sugar beet takes place at temperatures down to 3°C. Early sowing can therefore reduce yield losses from the disease, since multiplication of the virus in roots may be significantly reduced where infection by its fungal vector is delayed or slowed (Blunt *et al.*, 1992). Other improving measures recommended in areas where rhizomania is endemic relate to the avoidance of excessively high soil moisture conditions, which stimulates release of secondary zoospores and root infection. Maintaining good soil structure and adequate drainage is of particular importance in areas of high rainfall (e.g. Atlantic maritime regions) or frequent heavy summer showers (e.g. the north-east of France). Where irrigation is essential for crop development, growers are advised to apply water sparingly. Even more important than these, however, at least in countries where 'bolting' is a problem, may be 'weed beet' arising from seed shed by bolted plants. Such self-sown plants could continue to multiply the virus in intervening crops. Nevertheless, in most non-beet crops these species are readily controlled by selective herbicides and are not perceived to be a major factor in the epidemiology of the disease.

Chemical

There are no fungicides available against *Polymyxa* spp.; the only chemicals used to control the disease have been soil fumigants. The resting spores of *P. betae* are very resistant to chemical action and to microbial degradation, though they are sensitive to heat treatment (60°C for 10 minutes is lethal (Abe, 1987)) and to some soil sterilants, and virus particles survive within the spores probably for as long as they remain viable. Fungicides that have been reported as having been tested against rhizomania have been extensively reviewed, and several organic compounds with proven fungicidal or fungistatic activity have been tested for their ability to control *P. betae* in pot tests or to reduce the symptoms and yield loss due to rhizomania in field trials (Asher, 1988).

All partial soil sterilants tested, when applied in the autumn to rhizomania-infested fields, have given considerable yield benefits in subsequent sugar-beet crops. An alternative approach is the use of fumigants such as methyl bromide or dichloropropene/dichloropropane to eradicate the virus and its vector from at least the upper soil layer of plots within fields heavily infested with the disease. Sugar yields have been increased from 2.1 to 6.9 t/ha in France (Richard-Molard, 1984) and from 1.3 to 7.9 t/ha in California (Martin & Whitney, 1990) by such treatments. However, apart from environmental concerns and economic considerations, reinfestation from lower layers can occur during the growing season and treatments must be repeated each time a crop is grown.

Biological

Seed treatments incorporating the soil rhizobacterium *Pseudomonas fluorescens* to control *P. betae* have been studied for a number of years but without convincing efficacy. Recently, a genetically modified *P. fluorescens* strain has been developed to enhance production of an antimicrobial metabolite, 2, 4-diacetylphloroglucinol and although its colonization ability on the sugar beet root system was satisfactory without subsequent detrimental effect on the native microbial population, control of rhizomania was not achieved (Resca *et al.*, 2001).

Species of *Trichoderma* spp. have been found which were able to parasitize and completely degrade the cystosori of *P. betae in vitro*. Commercial formulation composed of *T. atroviridae*, *T. asperellum* and *T. hamatum* applied as a seed treatment or by irrigation increased the sugar yield of a susceptible cultivar (Grondona *et al.*, 2001). Also, three strains of *Streptomyces* spp. were found that inhibited the germination of resting spores and the movement of zoospores of *P. betae*. ELISA showed a decrease of the virus titre in such treated plants compared to the mock inoculated beets (Wang *et al.*, 2003). Such integrated approaches, however, are many years from large scale practical application.

Genetical resistance

Selection for resistance to the vector as well as breeding programmes examining efficiencies of partial resistance or tolerance to the virus were initiated in the 1970s. Indeed, genetical resistance is the most promising approach for the control of rhizomania in the long term, and the selection of lines resistant or tolerant for the disease has become a major objective in sugar beet breeding programmes in Europe, the USA and Japan. Sources of resistance have included wild species as well as better adapted breeding material that has undergone artificial or natural selection. The history of rhizomania breeding has been well documented and reviewed (Scholten *et al.*, 1996; Scholten *et al.*, 1999; Scholten & Lange, 2000; Biancardi *et al.*, 2002), with the recent use of molecular genetics and development of molecular markers (Pelsy & Merdinoglu, 1996; Francis *et al.*, 1998; Weber *et al.*, 2000). Eleven lines of *Corollinae* and *Patellaris* appeared fully resistant to *P. betae* whereas most members of the section *Vulgaris* were susceptible to the fungus, and rhizomania symptoms such as root necrosis were observed. The genetical control of vector resistance in the section *Patellaris* has been explored. On the one hand, transferring such resistance from the *Patellaris* group is likely to be extremely difficult because successful hybridization with *B. vulgaris* is rare (Mesbah *et al.*, 1997). The wild beet, *B. maritima* (a member of the section *Vulgaris*), on the other hand, is fully compatible with sugar beet and has been used as a source of genetic improvement (Van Geyt *et al.*, 1990; Scholten *et al.*, 1999; Stevanato *et al.*, 2001; Reza *et al.*, 2003).

Breeding lines with partial resistance to the virus derived from the 'Holly' Rz resistance gene have been extensively developed by breeders, and have proven their suitability to control the disease. This gene induces strong resistance to BNYVV multiplication and translocation within the root system, but not immunity. However, using such varieties growers find that rhizomania still spreads efficiently and in the case of high inoculum density, virus titres in resistant cultivars can equal those of susceptible ones. There have been some concerns about these tolerant varieties suffering significant yield penalty in rhizomania-free areas compared to high yield susceptible ones. Resistance derived from the Rz gene is monogenic and easy to manipulate. Since the 1990s, this resistance has been introduced in sugar beet cultivars throughout Europe and the USA. In Europe, almost 700 000 ha were grown in 2001 (Richard-Molard & Cariolle, 2001). Virus titres in the roots of the most resistant lines were reduced to 1/10 compared to susceptible cultivars, and the infection levels could be reduced by up to 97% when an additional resistance gene derived from *Beta vulgaris* spp. *maritima* was introgressed into the Rz gene genotypes. Further progresses improving the level and durability of resistance should be possible in the forthcoming years, by, for example, expression of the Rz through homozygosity. However, cultivars with partial resistance allowing a virus multiplication may exert a selective pressure on the BNYVV quasi-species, with the possible emergence of BNYVV variants overcoming the resistance conferred by the Rz gene, either through mutation of the putative viral avirulence gene (RNA3) or selection of a virulent variant already present. Another concern about 'Holly' resistance is its breakdown via the emergence of new virus species, such as the appearance of a recombinant virus through recombination between BNYVV and BSBMV (in the USA), since the Rz gene does not confer any resistance toward BSBMV (Rush, 2003). In the longer term, the availability of resistance to *P. betae* from wild beet species offers the prospect of combining virus and vector resistance to gain enhanced and durable resistance to rhizomania (Asher *et al.*, 2002). Alternatively, pathogen derived resistance (PDR) provides an alternative method to confer resistance to BNYVV (Mannerlof *et al.*, 1996; Lauber *et al.*, 2001).

OTHER SOIL-BORNE VIRUSES

Beet soil-borne

Beet soil-borne virus (BSBV) was first identified in sugar beet roots from the UK in 1982 (Ivanovic & Macfarlane, 1982) and has since been reported in Belgium, Bulgaria, Denmark, Finland, France, Germany, Hungary, Iran, Sweden, Syria, Turkey, and the Netherlands (Danielsen *et al.*, 1992; Hutchinson *et al.*, 1992; Farzadfar *et al.*, 2002; Mouhanna *et al.*, 2002; Meunier *et al.*, 2003). In the USA, BSBV has not been reported from field-grown beets but has been identified by baiting the virus from soil (Lindsten & Rush, 1994).

Symptoms

BSBV causes no obvious symptoms on sugar beet, but Ivanovic and Macfarlane (1982) described that the proportion of fibrious roots was two to three times greater on BSBV infected than on healthy plants. Heavily infected sugar beet plants can exhibit browning and necrosis of vascular bundles. Additionally, Kaufmann *et al.* (1993) reported that BSBV reduced seedling growth in greenhouse studies. Mechanical inoculation of BSBV on *Chenopodium quinoa* caused chlorotic lesions. After 7–10 days, these lesions enlarged and turned into large brown necrotic patches. *C. amaranticolor* developed local lesions after 10–14 days. These lesions were large, round and yellow in colour with a necrotic centre, but did not coalesce (Danielsen *et al.*, 1992).

Causal agent

BSBV is tripartite. The virions are rod-shaped, 19 nm long with three modal lengths (65, 150, and 300 nm in diameter), with an obvious axial canal around 4.5 nm in diameter. The tripartite genome consists of three RNA species with sizes ranging in different strains between 6.1–6.4 kb, 3.0–3.6 kb, and 2.6–3.3 kb, respectively (Hutchinson *et al.*, 1992; Kaufmann *et al.*, 1992). The BSBV RNAs are not polyadenylated. Lesemann *et al.* (1989) described two serotypes for BSBV, Ahlum and Wierthe. Recent data revealed that serotype Wierthe should be considered a distinct virus species (Koenig *et al.*, 1998).

Epidemiology

BSBV is transmitted by the *Polymyxa betae* Keskin and is also transmitted by mechanical inoculation. The virus has a host range limited to the *Chenopodiaceae*. BSBV has been found associated with BNYVV. It was also present in fields free of BNYVV. Preinfection with BSBV reduced the BNYVV levels to less than half. Also, the damage due to the BNYVV was reduced (Prillwitz &

Schlosser, 1993b). Environmental conditions that favour BNYVV are also ideal for BSBV development.

Control

BSBV is transmitted mainly by its fungal vector *P. betae*. The control measures that are useful for BNYVV will limit the spread of BSBV.

Beet soil-borne mosaic

Beet soil-borne mosaic virus (BSBMV) is a member of the genus *Benyvirus* (Koenig & Lesemann, 2000b). BSBMV was first described in Texas in 1988. The particle morphology was similar to BNYVV but serologically was distinct (Liu & Duffus, 1988). BSBMV is not established in California, and is found primarily on the eastern slope of the Rocky Mountains and in the Midwestern beet growing states (Wisler *et al.*, 1996; 1997). Thus far, BSBMV has not been identified outside the USA.

Symptoms

Foliar symptoms in beet caused by BSBMV include slight leaf distortion, light green or yellow blotches, faint overall mottling, and light yellow vein banding (Plate 20). Foliar symptoms caused by BSBMV appear in field-grown sugar beets more frequently than those caused by BNYVV (Heidel *et al.*, 1997). The roots of BSBMV-infected sugar beets are generally asymptomatic. BSBMV produced diffused, pale yellow blotches with small necrotic spots on *C. quinoa*, easily differentiated from the bright yellow local lesions produced by BNYVV.

Causal agent

BSBMV is a rigid rod-shaped virus. Particles were 20 nm wide and the length ranged from 50 to over 400 nm, but no consistent modal lengths could be determined (Heidel *et al.*, 1997). BSBMV consists of four RNA species. The genomic organization of BSBMV is identical to BNYVV. BSBMV RNA 1 encodes a single large open reading frame (ORF) with similar replicase-associated motifs identified for BNYVV. RNA 2 has six potential ORFs with an organization resembling BNYVV RNA 2. RNA 3 and RNA 4 resemble the analogous BNYVV RNAs, which encode proteins associated with symptom development and fungal transmission, respectively (Lee *et al.*, 2001). The molecular mass of the capsid protein of BSBMV was estimated to be 22.5 kDa. Based on sequence analysis and serology, BSBMV is found to be a distinct member of the genus *Benyvirus* (Koenig & Lesemann, 2000b).

Epidemiology

BSBMV is transmitted by *P. betae* and is also transmitted by mechanical inoculation. BNYVV and BSBMV are often found in the same sugar beet field and even in the same plant. The Rz gene, conferring resistance to BNYVV, did not confer resistance to BSBMV. In the absence of BNYVV, BSBMV always attained high titres in plants either susceptible or resistant to BNYVV. In the absence of BSBMV, BNYVV attained high titres in BNYVV susceptible plants, but low titres in resistant plants. BNYVV may suppress BSBMV in mixed infection, even in rhizomania-resistant cultivars (Wisler *et al.*, 2003).

Control

Little is known of the impact and economic importance of BSBMV under field conditions and no control work has been attempted. BNYVV and BSBMV are closely related and often found in the same sugar beet field. The Rz 2 gene does not confer resistance to BSBMV; attention should be paid to the possibility of recombination between these two viruses. Recombination may result in a new strain, capable of overcoming the BNYVV resistant gene, and may cause severe disease.

Beet virus Q

Beet virus Q (BVQ) was first isolated from a sugar beet taproot obtained from a rhizomania field near Braunschweig, Germany (Koenig *et al.*, 1998). BVQ has also been reported in Belgium, Bulgaria, France, Hungary, Italy, and the Netherlands (Meunier *et al.*, 2003).

Symptoms

BVQ symptoms on sugar beet have so far not been observed. It causes local lesions on *C. quinoa*. The lesions have a more irregular shape with a tendency to spread along the veins. Systemic infections of *C. quinoa* were not observed. BVQ could not be transmitted to *Nicotiana benthamiana* or *N. clevelandii*, nor could it be retransmitted by mechanical means to sugar beet leaves or roots (Koenig *et al*., 1998).

Causal agent

BVQ belongs to a member of the genus *Pomovirus* (Koenig & Lesemann, 2000a). BVQ contains tubular particles with a tripartite genome. RNA 1 encodes a protein with a methyltransferase-like region. RNA 1 also encodes for a readthrough protein which contains an RNA-dependent RNA polymerase region. RNA 2 carries the coat protein gene, a coat protein readthrough protein gene and two additional ORFs. RNA 3 carries a triple gene block resembling that of several other rod-shaped viruses (Koenig *et al*., 1998).

Epidemiology

BVQ is transmitted by *P. betae*. Meunier *et al.* (2003) collected soil samples from rhizomania infected fields in Europe and reported that the most frequently detected virus was BSBV, followed by BVQ and then BNYVV. Association of BNYVV with one or two different pomoviruses was observed. However, in no case was BVQ found alone.

Control

Little is known about BVQ and no control work has been reported.

Beet oak-leaf

Beet oak-leaf virus (BOLV) is a soil-borne virus with rod-shaped particles. The virus appears to be widespread in the USA. It has been found in California, Colorado, Michigan, Minnesota, Nebraska and Wyoming (Liu *et al*., 2003). This disease has not yet been reported outside the USA.

Symptoms

The infected sugar beet leaves showed oak-leaf pattern symptoms (Plate 21) and in some varieties were symptomless. BOLV produces chlorotic local lesions with a necrotic ring after it is mechanically inoculated to *Chenopodium quinoa*.

Causal agent

Particles of BOLV in leaf dips are rigid rod shaped, 20 nm wide and range from 80 to 640 nm long with three modal lengths: 180–200 nm, 260–280 nm, and 300–320 nm. The particles are similar to *Beet necrotic yellow vein virus* (BNYVV) in appearance. Serologically, BOLV was distinct from BNYVV and all other *Polymyxa* transmitted viruses. The molecular mass of the capsid protein was estimated to be 46.0 kDa. The host range of BOLV is similar to BNYVV; it mainly infects *Chenopodiaceous* plants.

Epidemiology

BOLV is transmitted by the *Polymyxa betae* Keskin and is also mechanically transmitted. BOLV has been found associated with BNYVV. When the environmental conditions are in favour to the BNYVV, the conditions are also favourable to BOLV.

Control

Little is known of the overall incidence and economic importance of BOLV and no control work has been attempted.

Beet distortion mosaic

Beet distortion mosaic virus (BDMV) is a soil-borne virus with long flexuous particles. The virus is unique in its properties and has thus far been found only in Texas, USA (Liu *et al*., 1987).

Symptoms

The symptoms of BDMV are characterized by extreme distortion of leaf blades. The midrib may be twisted and blade tissue may separate into twisted lobes. Green islands of tissue are surrounded by light green mottled areas. The light green areas become thinner and minor veins protrude giving the under-leaf surface a sunken, roughened appearance. The symptoms approach the puckered appearance of cucumber mosaic, but the light-coloured areas are light green and roughened. The virus causes leaf distortion (Plate 22).

Causal agent

Particles of BDMV in leaf dips are long, flexuous rods about 12 nm in width and with two modal lengths, 225 nm and 650 nm. The particles are similar to closteroviruses in appearance. Also, vesicles similar to those described in closterovirus infections are present (Fail & Hoefert, 1991). The particles are also similar in length to some potyviruses or bymoviruses; however, pinwheel inclusion bodies have not been found.

Epidemiology

BDMV has been found associated with BNYVV. The virus is soil-borne, and early studies indicated transmission by the fungus *Polymyxa betae*. However, later transmission attempts with virus isolates collected several years ago have failed.

Control

Little is known of the overall incidence, distribution and importance of BDMV and no control work has been attempted.

VIRUS YELLOWS

The yellowing of fields of sugar beet was first described by Quanjer (1934), who had observed it since 1910. The implication of a virus as the causal agent was made by Roland (1936) and Van Schreven (1936), who showed that the yellowing disease agent was transmitted by aphids. Petherbridge and Stirrup (1935) suggested the name 'virus yellows' to distinguish the disease from other types of yellowing and suggested that the disease might occur in the UK.

At this time, all virus-induced yellowing was termed 'virus yellows' (Plate 23). Watson (1940) positively identified the disease in the UK and called it (sugar) beet yellows. Clinch and Loughnane (1948) found that two yellowing diseases of sugar beet were common in Ireland, Irish mild yellows and seed-transmitted 41-yellows; they thought that the viruses were probably strains of the *Beet yellows virus* (BYV). Watson (1952) first pointed out the possibility that virus yellows may be induced by a complex of yellowing viruses. The mild yellowing isolates from Ireland did not precipitate specifically with BYV antiserum and confirmation was obtained that the isolates did not protect against typical BYV.

Based upon lack of a serological response to BYV antiserum, Russell (1958) detailed the widespread distribution in the UK and economic significance of (sugar) *Beet mild yellowing virus* (BMYV). During this same period in the USA, Duffus (1960; 1961) characterized a 'second' economically significant beet yellowing virus, distinguished from BYV on the basis of vector relationships and host range: (radish yellows) *Beet western yellows virus* (BWYV).

Poleroviruses

Currently, the sugar beet 'mild' yellowing viruses are classified within the family *Luteoviridae* of which there are three genera: *Luteovirus*, *Polerovirus* and *Enamovirus*. Within the *Polerovirus* genus there are three key beet-infecting species, *Beet mild yellowing virus* (BMYV), *Beet western yellows virus-USA* (BWYV) and *Beet chlorosis virus* (BChV) (Stevens *et al.*, 2005a). A fourth polerovirus, *Turnip yellows virus* (TuYV; syn. European non-beet infecting strains of BWYV) shares many characteristics with these viruses but does not infect *Beta* species. The distribution and nomenclature of the beet poleroviruses along with the role these viruses play in the epidemiology of crops such as sugar beet and oilseed rape, has remained a contentious issue since their initial identification in the mid-1950s. However, molecular characterization of these viruses has shed new light on their interrelationships and the roles that they play in disease complexes.

In the USA, *Beet western yellows virus* (BWYV) is the most widely distributed and abundant virus disease of sugar beet and is responsible for yield losses wherever the crop is grown. It occurs as a number of strains differing in severity and host range. These strains may induce similar reactions in some plant species and distinct reactions in others with regard to susceptibility, stunting, and yellowing.

In Europe, early work showed that *Beet mild yellowing virus* (BMYV) was distinct from BWYV in host range and epidemiology (Duffus & Russell, 1970). The isolates of BMYV that were tested had host ranges with affinities in the *Chenopodiaceae* and were less extensively distributed in the *Cruciferae* and *Compositae* than typical BWYV strains studied at that time. All European isolates characterized as BMYV infect sugar beet. European BWYV isolates generally infect a broad range of commercially important crops such as *Brassica* spp. (e.g. oilseed rape), field bean (*Fabaceae*) and lettuce, but do not infect sugar beet. In addition, the majority of European BWYV isolates infect a broader range of cruciferae species than do BMYV isolates.

Discrimination between BMYV and the non-beet-infecting strains of BWYV is of particular importance in the study of the role these viruses play in the epidemiology of virus yellows. Polyclonal antiserum raised to either BMYV or BWYV does not distinguish the two poleroviruses in a double-sandwich ELISA technique (Duffus & Russell, 1975; Govier, 1985). The close serological relationship between BMYV and BWYV, and the similarities in host range has caused many to believe that they are strains of the same virus. However, a monoclonal antibody raised against *Barley yellow dwarf virus* (BYDV-PAV-IL-1) can distinguish BMYV and BWYV (D'Arcy *et al*., 1989), and comparisons of the complete viral genome sequences of BMYV and BWYV isolates has led to the conclusion that BMYV and BWYV are two distinct viruses (Mayo, 2002). More recently, sequence data of a number of geographically distinct beet polerovirus isolates has shown that the coat protein amino acid sequences are highly conserved (more than 90% homology), whereas the P0 sequences (open reading frame, ORF 0) at the 5′ end of the genome are highly variable; isolates within P0 clusters exhibit similar biological and serological properties (Schubert *et al*., 1998; Hauser *et al*., 2000b; Stevens *et al*., 2005b). Also, the sequence diversity at the 5′ end of the genomes has been exploited to provide methods to discriminate the different beet polerovirus species (Lemaire *et al*., 1995; Hauser *et al*., 2000a). Interestingly, the complete genomic sequence of a BWYV sugar beet infecting isolate from the USA has also recently been obtained which has shown that it is distinct from the other sugar beet poleroviruses (M. Beuve, INRA-Colmar, France, 2004, personal communication). It is proposed that the name BWYV should be retained to describe those sugar beet isolates from the USA, although work is ongoing to determine the biological, serological and molecular relationships between these isolates and BMYV from Europe.

Symptoms and damage

Initial symptoms of beet polerovirus-infected sugar beet are diffuse chlorotic areas on fully expanded leaves, and these areas eventually expand and merge (Plate 24). The leaves develop a golden yellow coloration and become thickened and brittle. Yellow leaves are susceptible to attack by secondary fungi such as *Alternaria alternata* (Fr.) Keisser, which may destroy the leaf.

Infection of sugar beet plants with beet poleroviruses causes chlorosis of leaves, which disrupts photosynthetic, respiratory and other metabolic processes. These changes increase the levels of amino nitrogen, sodium and potassium in roots and this adversely affects extractability of sugar during processing.

BMYV causes greatest yield loss when the plants are infected at an early growth stage with infection reducing light interception by up to 40% (De Koeijer & Van der Werf, 1995) and yields being decreased by up to 30% (Smith & Hallsworth, 1990; Stevens *et al*., 2004). Later infection, when the plants have more than 20 leaves, is currently thought to have little effect on yield. In the UK, losses to virus yellows (predominantly BMYV but also includes the impact of beet yellows closterovirus) after taking into account the efficacy of treatments was estimated to cost the sugar industry 24 700 t/year of sugar. This is the equivalent to 1.8% of national yield and a financial loss of £5.5 million; in the absence of control measures the losses were approximately double (Jaggard *et al.*, 1998).

Causal agent and vectors

The isometric virus particles of BMYV are approximately 26 nm in diameter (Plate 25) and the genome consists of a single strand of positive-sense RNA with a molecular weight of 2×10^6. The protein shell consists of 180 subunits each having a molecular weight of 24 000–35 400; the weight of the whole particle is 6.5×10^6 (Chevallier *et al.*, 1983; Govier, 1985). The complete sequence of the genomic RNA (5722 nucleotides) of BMYV (the French isolate 2ITB) was determined by Guilley *et al.* (1995). It contains six open reading frames (ORFs) of which the three 3′-proximal ORFs encode for the coat protein, putative movement protein and the readthrough domain. At the 5′ end of the genome three extensively overlapping ORFs are found.

Most members of the *Chenopodiaceae* are susceptible, including commercial crops of sugar beet, fodder beet, mangolds, red beet and spinach. Many arable weed species are also hosts, including *Stellaria media*, *Spergula arvensis*, *Senecio vulgaris* and *Capsella bursa-pastoris*, and Russell (1965) concluded that weeds are important reservoirs of BMYV, particularly if they survive the winter. Jadot (1974), studying naturally infected weeds in Belgium, found that 23 species from 12 families were susceptible; the most frequently infected species were *S. media*, *Plantago lanceolata*, *Plantago major*, *Veronica persica*, *S. vulgaris* and *C. bursa-pastoris*. Stevens *et al.* (1994a) examined 20 common arable weed species using *M. persicae* to transmit BMYV. The virus was detected by ELISA and by transmissions to indicator plants. Nine weed species from seven of the 14 families became infected; two species remained symptomless (*Chrysanthemum segetum* and *Viola arvensis*) but were shown by ELISA to be infected. Confirmatory tests showed that aphids could acquire BMYV from all except *Papaver rhoeas* and transmit to sugar beet and *C. bursa-pastoris*. Graichen and Rabenstein (1996) showed that 21 out of 101 species belonging to 10 families were susceptible to BMYV. A conspectus of plant species as hosts for sugar beet yellowing diseases (BMYV and/or BYV) has been made by Peters (1988) summarizing the work of 22 authors.

Beet poleroviruses are transmitted by aphids and have a persistent (circulative, non-propagative) relationship with the vector. *Myzus persicae* (Sulzer) the green peach aphid or, in Europe, the peach-potato aphid is regarded as the principal vector of BMYV. Vectors retain the ability to transmit the virus after moulting but do not transmit it to their progeny. The minimum acquisition feeding period is 5 minutes, and the minimum inoculation feeding period is 10 minutes; the latent period is 12–24 hours. *M. euphorbiae* has been regarded as a poor vector of BMYV (Heathcote & Cockbain, 1966; Jadot, 1975). However, Stevens *et al.* (1995) found that approximately 1% of *M. euphorbiae* caught in water-pans in sugar beet crops contained BMYV and this aphid species was found in the crop earlier than *M. persicae*. Hence, *M. euphorbiae* could establish foci of infection when the crop was small and highly susceptible to infection (two to four leaf stage) from which secondary spread by *M. persicae* could occur. Schliephake *et al.* (2000) found that *M. persicae* was almost 16 times more efficient at transmitting BMYV than *M. euphorbiae*. They also found that *Aphis fabae* could transmit BMYV, although very inefficiently; contrary to earlier studies. Transmission rates with *Aphis fabae* are usually less than 1%, with some clones unable to transmit at all. Other vectors of BMYV include *Myzus ascolonicus*, *Aulacorthum solani*, *Rhopalosiphoninus staphyleae tulipaellus* (Heathcote, 1988) and *Phorodon humuli* and *Brachycaudus helichrysi* (Thornhill & Hinckes, 1986). None of the beet poleroviruses are transmitted via seed or pollen.

Beet chlorosis virus

Beet chlorosis virus (BChV; Plate 24) was first identified in 1989 in the UK (Stevens *et al.*, 1994b) and the USA (Duffus & Liu, 1991) and more recently in a number of countries across north-west Europe

(Stevens *et al.*, 2005b). In the UK, it was originally described as a second strain of BMYV because this species produced paler symptoms in beet, it failed to react with Mab BYDV-PAV-IL-1 (hence, similar to BWYV), and the virus did not infect the traditional indicator species *Montia perfoliata* and *Capsella bursa-pastoris*.

The new yellowing disease of sugar beet in the USA was found to be serologically related to BWYV, but the host range of American BChV is much narrower than for American BWYV. The viruses can be distinguished from one another based on infectivity of differential hosts. Like the European BChV, the American isolate also fails to infect *C. bursa-pastoris*. American BWYV infects *C. bursa-pastoris*, but cannot infect *Chenopodium capitatum*. The name BChV was proposed as a result of the symptoms of interveinal chlorosis observed on infected sugar beet leaves. Comparisons of the coat protein and ORF 0 sequences of BChV, BWYV and BMYV showed that all virus species were closely related in the CP (less than 10% diversity in the amino acid sequences), but there was little sequence homology when comparing P0. More recently the complete genomic sequence of an American and European isolate of BChV has been deduced (Hauser *et al.*, 2002). The genomic organization of BChV identifies this species as a typical *Polerovirus* member; however, it appears that BChV originated from recombination events between a *Polerovirus*-like ancestor which provided the P0 and replicase complex and a virus similar to BMYV or BWYV which donated the 3′ end of the genome downstream of the intergenic region.

BChV decreases the yield of beet following early season infection (mid-May), although the effects on sugar yield were found to be more variable and less damaging than BMYV (Stevens *et al.*, 2004). However, inoculations with BChV in July caused greater root and sugar losses than inoculations with BMYV at that time.

Control

Winged *M. persicae* cannot be prevented from entering sugar beet crops and feeding on individual plants, therefore crops are potentially at risk from virus infection every year. To minimize the development of initial foci of infection and subsequent virus spread, growers are encouraged to adopt an integrated control programme that includes removing sources of infection, the use of cultural practices to reduce the risk of infection, the application of insecticides to seed, soil or foliage and, if available, the use of virus-tolerant varieties.

Growers are advised to sow early to achieve maximum yields; older plants are less physiologically attractive to aphids (Williams, 1995), therefore by sowing early there is a greater chance that plants will have matured before peak aphid migrations. Late sown crops are more susceptible to infection as winged *M. persicae* are attracted to the yellowish-green leaves of younger sugar beet plants.

In Europe, a selection of different chemical products is available to prevent the build-up of virus-carrying aphids. Carbamate insecticidal sprays, for example pirimicarb, have a fumigant effect but they are not systemic and do not prevent the initial colonization of plants. However, unlike organophosphates, pirimicarb does not kill beneficial predators, such as coccinellids, and is more effective against resistant aphids. Synthetic pyrethroids rapidly intoxicate aphids and can also act as repellents, preventing probing and virus transmission. However, direct contact is necessary for the chemical to be effective and therefore aphids protected by the canopy remain unaffected. This problem can be overcome by mixing two aphicides with different properties, for example a pyrethroid with either a carbamate or organophosphate compound. Since the introduction of the seed treatment imidacloprid in the early 1990s, this option has become increasingly popular throughout Europe for the control of the aphid vectors and other economically damaging soil pests. In 2004, in the UK, over 70% of the national crop was treated with imidacloprid. A more comprehensive review of aphid control can be found in Chapter 13 (Pests).

Forecasting incidence

A close relationship was found between temperatures in winter and early spring and virus incidence in sugar beet crops at the end of August (Hurst, 1965; Watson, 1966). Watson *et al.* (1975) examined weather data and aphid numbers in the field and used this information to predict the incidence of virus yellows for the following sugar beet crop. This annual forecast was revised and improved by Harrington *et al.* (1989) to include aphid flight data from the Broom's Barn 12.2 m-suction trap. The advantage of this system is that a preliminary forecast can be issued before crops are sown, enabling growers to revise their control strategy if the risk of infection appears high. Werker *et al.* (1998) re-developed the forecast to include the relationship between the spread of virus yellows and the population dynamics of *M. persicae*. It also examines the processes of primary and secondary infection and the age of the crop at the time of infection. More recently, Qi *et al.* (2004) have further refined the forecast equations to take into account the current widespread use of the seed treatment imidacloprid.

Tolerant and resistant cultivars

In Europe, considerable effort has been put into breeding for resistance and virus tolerance (Plate 26). Resistant varieties would provide an alternative, environmentally acceptable control strategy, but no commercial varieties are available at present. Also, no major sources of BMYV resistance have been found, although partial resistance has been identified in *Beta* germplasm (Asher *et al.*, 2001).

In the USA, cultivars with moderate resistance to BWYV have been developed in a breeding programme by the Agricultural Research Service of the US Department of Agriculture (Lewellen, 2002; 2004). These cultivars should be planted in areas such as California, where the risk of infection by BWYV is high.

Beet yellows

Beet yellows virus (BYV) was the first component in the complex of diseases known as virus yellows to be characterized (Watson, 1940) and is widely distributed throughout the beet-growing areas of the world. A number of closely-related strains of the virus produce symptoms in sugar beet which range from mild yellowing to severe vein etching and leaf necrosis (Plate 27).

Symptoms and damage

Virulent isolates of BYV first induce vein clearing or vein yellowing in the younger leaves of infected plants. The vein clearing may be very bright yellow or have a necrotic appearance. Secondary and intermediate veins often appear sunken and develop an etch symptom. Tissue associated with veins in diseased leaves fails to form protruding vein ribs, and the mesophyll is considerably thickened (Esau, 1960).

After vein clearing, the characteristic symptom is a general pale yellowing of entire leaf blades or sectors of the older leaves. The leaves become thick, leathery, and brittle. The increase in thickness of the mesophyll results from a hypertrophy of cells, the leathery texture from greater rigidity of walls and close packing of cells (Esau, 1960).

In some instances, small, translucent, pinpoint spots appear on leaves approaching maturity (Bennett, 1960). Small necrotic spots, sometimes reddish or brown, develop on many of the older yellowed leaves. The combination of necrotic spots and yellowing often gives leaves a distinct bronze cast. The necrotic spots and enlarged necrotic areas distinguish BYV infections from the other known beet yellowing viruses.

As with BWYV, sugar yield losses depend on the time of infection; late infection (i.e. after mid-July in northern Europe) has little effect, whereas early infection can decrease yield by up to 47% as well as increasing the level of impurities (Heijbroek, 1988; Smith & Hallsworth, 1990; Clover *et al.*, 1999). Plants infected with BYV show a reduced formation of leaf area compared to healthy or BMYV-infected plants. Also, leaves developing after infection are smaller than healthy or BMYV-infected sugar beet (De Koeijer & Van der Werf, 1999).

Causal agent and vectors

Beet yellows virus is the type member of the genus *Closterovirus*, family *Closteroviridae*. Virus particles are flexuous filaments about 1300 nm long and 12 nm in diameter (Leyon, 1951; Brandes & Zimmer, 1955; Plate 28), made up of a 15.5 kb positive sense RNA genome and five proteins. Since the early molecular characterization of this virus it has been used as a model by many researchers to study mechanisms such as virus movement and replication (Dolja, 2003).

BYV occurs in a number of closely-related strains that produce symptoms in sugar beet, from mild yellowing to severe vein etching and leaf necrosis. All isolates that produce vein clearing are apparently serologically related, and complete cross-protection appears to exist between them.

The host range of BYV is moderate in extent. Although species in at least 15 *Dicotyledonous* families have been infected, most of the hosts occur in only four families: *Amaranthaceae*, *Aizoaceae*, *Caryophyllaceae* and, principally, *Chenopodiaceae* (Bennett & Costa, 1954; Canova, 1955; Roland, 1955; Björling, 1958; Bennett, 1960). Diagnostic species are *Chenopodium capitatum* (L.) Aschers and *Montia perfoliata*.

M. persicae and *Aphis fabae* Scopoli are the most important vectors of BYV, although the virus is transmitted by at least 22 species of aphids. Transmission is in a semi-persistent manner; vectors retain the virus for 1–4 days (Sylvester, 1956). The minimum feeding periods for acquisition and inoculation are 5–10 minutes and the maximum transmission efficiency occurs 6–12 hours after feeding. No indication of a latent period has been observed. Vectors do not transmit BYV to their progeny and do not retain it after moulting, one of the characteristics of the non-circulative transmission manner, conversely to *Luteoviridae*. The virus is mechanically transmitted with difficulty e.g. to *Nicotiana benthamiana*. These transmission characteristics cause virus spread to be marginal, i.e. disease incidence is high in areas adjacent to the virus source but quickly becomes progressively less as the distance from the virus source increases (Duffus, 1963). Distances of 2–3 km are effective barriers to the distribution of BYV.

Studies in Europe (Hull & Watson, 1945; Broadbent *et al.*, 1949) and the USA (Bennett, 1960; Duffus, 1963) have shown that beet plants themselves are the principal sources of BYV. In Europe, the sources include beet seed crops (Ribbands, 1964), escaped beet plants (Hull & Watson, 1945), and clamps containing infected mangolds (Dunning, 1975). In the USA, sources are escaped beet plants growing in waste places and over-wintering sugar beet fields. Spinach grown as a winter crop is often infected in the autumn and may carry the virus through the winter to serve as a source of infection for beet crops in late winter and early spring.

There is very little direct evidence that weeds serve as a major source of infection of BYV (Björling, 1958; Bennett, 1960; Russell, 1965) although it has been recovered from a limited number of over-wintered weed species which may serve to perpetuate the disease in an area without playing an important role in its epidemiology (Björling, 1958; Bennett, 1960; Heathcote *et al.*, 1965; Russell, 1965).

Control

The fact that the beet itself is the most important reservoir of BYV and that weeds have only a minor role as sources of infection, is of considerable significance in devising control strategies. The elimination of over-wintered beet plants (in root crop fields, clamps, seed crop fields, or escapes) has effectively reduced the incidence of this virus (Hull, 1954; Duffus, 1963; 1978).

In Europe, the application of insecticides to control the aphid vectors effectively reduces the within-field spread of BYV (Hull & Heathcote, 1967; Dewar, 1988). See also the section on polerovirus control and Chapter 13.

In some areas of California, populations of *M. persicae* drop to very low levels during the hot summer months. Planting at later dates to avoid aphid flights has resulted in fewer yellows and higher yields, but these yield increases must be balanced against the possibility of increasing the damage caused by rhizomania, curly top, or beet cyst nematode.

OTHER DISEASES

Beet cryptic

Beet cryptic virus (BCV) is widespread in different sugar beet varieties and cultivars of *Beta vulgaris*. BCV can also be found in spinach beet, red beet, fodder beet, chard, mangolds, and in *Beta maritima* (Kassanis *et al.*, 1977; White & Woods, 1978; Kuhne *et al.*, 1987; Hammer *et al.*, 1990; Xie *et al.*, 1993).

Symptoms

In most instances, plants with BCV are symptomless or do not show recognizable symptoms. However, some work indicated that certain varieties or breeding lines may show mild yellowing or interveinal chlorosis and impaired root development (Kassanis *et al.*, 1978).

Causal agent

BCV belongs to the genus *Alphacryptovirus* in the family *Partitiviridae*. The virions are isometric and 30 nm in diameter. The coat protein molecular weight was estimated at 52.5–54.5 kDa and the virions contain two dsRNA segments (Accotto & Boccardo, 1986). The virus occurs as two or three serologically distinct entities (Boccardo *et al.*, 1983).

Epidemiology

BCV is seed-transmitted through both ovules and pollen (Kassanis *et al.*, 1978); it is not transmitted mechanically or by insects or other known vectors tested to date. Kassanis *et al.* (1977) reported BCV can be transmitted from beet to beet by grafting. It is assumed that the high seed transmission rate is sufficient to maintain the virus in beet cultivars.

Control

The lack of knowledge on the economic significance of BCV in beet plants has discouraged research on control measures. Attempts to free sugar beet from BCV by meristem tip culture with or without heat therapy were successful (Volkmann *et al.*, 1990).

Beet curly top

Beet curly top virus (BCTV) occurs in the arid and semi-arid regions of western North America from Mexico to Canada. The virus is endemic in the Mediterranean basin and may be present in other semi-arid areas of Europe, Africa and Asia (Bennett & Tanrisever, 1958; Bennett, 1971; Thomas & Mink, 1979). Other similar diseases, transmitted by various leafhopper species, have been reported in South America and Australia (Bennett & Costa, 1949; Thomas & Bowyer, 1980).

In the western USA, it is found in the eastern slopes of the Rocky Mountains, and occasionally east of the Mississippi River. The occurrence of curly top in eastern USA, Wisconsin, Illinois and Maryland is apparently from the long distance migration of its leafhopper vector, *Circulifer tenellus* (Baker) (Duffus & Ruppel, 1993).

Symptoms

On susceptible beet varieties, the young leaves show vein clearing and become twisted, rolled, or crinkled. All leaves produced later are characterized by dwarfing, crinkling, and rolling upward and inward (Plate 29). Veins are roughened on the lower side of leaves and often produce swellings and spine-like outgrowths. Roots are dwarfed, and rootlets tend to become twisted and distorted and are often killed. Phloem tissue often becomes necrotic and phloem exudates appear on stems and leaves. Resistant varieties may have a high percentage of infection but show only mild symptoms (Bennett & Leach, 1971).

Causal agent

BCTV is the type member of the genus *Curtovirus* (formerly subgroup II) in the family *Geminiviridae*. BCTV is a beet leafhopper-transmitted, monopartite geminivirus. Virions contain one molecule of closed circular single stranded DNA. Total genome length is 2994 nucleotides (Stanley *et al.*, 1986). The doublet particles, or dimers, are 20 × 28 nm in size. Both components of the geminate particles are required for infection (Larsen & Duffus, 1984).

The virus comprises a complex of strains that vary in virulence, host range and other properties (Thomas, 1970; Stenger *et al.*, 1990; Stenger & McMahon, 1997). Strains exhibit little evidence of interference or cross-protection, either in the host or in the vector. BCTV has an extensive host range, including more than 300 species in 44 plant families.

Epidemiology

BCTV is transmitted by the beet leafhopper, *C. tenellus* in North America (Plate 30), but can also be transmitted by *C. opacipennis* in the Mediterranean basin. The epidemiology of BCTV has been extensively studied since the early 1920s (Bennett, 1971). The insect is a very efficient vector of BCTV and has a persistent relationship with the vector; it may acquire the virus in a matter of minutes and retain the particles for a month or more. *C. tenellus* has an extensive host range and a high reproductive capacity, and can move hundreds of kilometres from its breeding grounds to cultivated areas. The natural vegetation of the western USA does not favour the production of large populations of beet leafhoppers (Piemeisel, 1932) but they can breed readily on mustard, Russian thistle and other weeds, producing several generations during the summer (Carter, 1930). Beet leafhoppers migrate into the foothills in late autumn, over-winter on perennial weed, and lay eggs on annual weeds. The nymphs are thought to acquire virus from the winter annual or perennial weeds in the foothills and as these plants senesce, the leafhoppers migrate into the valley to feed on and infect crops. The severity of an attack of curly top depends on climatic factors affecting the weed hosts of the virus, the prevalence and severity of the virus, and the reproductive capacity and migration of the leafhopper.

Control

The wide host range of the virus and abundance of the insect vector have made managing the virus difficult. In recent years it has not been as serious as expected in California because a complex control programme has been developed involving cultivars that are resistant or tolerant to the virus, cultural practices that delay infection, vector control in and outside production areas, reduction of the leafhopper's breeding areas, and reduction of virus sources (Duffus, 1983).

Beet leaf curl

Beet leaf curl virus (BLCV) is currently found in Germany, Poland, the Czech and Slovak Republics, and countries of the former USSR. The first symptoms of this disease in sugar beet may be confused with beet mosaic, but the subsequent intense leaf curling and its transmission by *Piesma quadratum* Fieb. distinguish this disease from all other beet infecting diseases. The virus was at one time a serious problem, but now has little economic significance (Proesler, 1983).

Symptoms

The first symptom is vein clearing of the youngest leaves. Soon afterwards the affected leaves begin to curl inward towards the apex. Leaves are crinkled and dwarfed. Sugar beet tops and roots are markedly stunted and the growth of the root ceases prematurely.

Causal agent

Virions of BLCV are enveloped, bullet-shaped particles measuring about 80 nm in diameter and 225–350 nm long. They have an electron-dense core with a central channel and an enveloping membrane with small protrusions (Eisbein, 1973). The virus only affects members of the *Chenopodiaceae* and *Aizoaceae*; sugar beet and fodder beet are the most important hosts (Schmutterer & Ehrhardt, 1966).

Epidemiology

BLCV is transmitted by *P. quadratum* in a persistent manner; the virus multiplies in the vector, which remains infective for life. There is no evidence of transmission to its progeny. The insect can acquire the virus within 30 minutes and inoculates plants in feeding periods of about 40 minutes after an initial latent period of 7–35 days. Both the adult and nymph stages can acquire and transmit the virus (Proesler, 1966). *P. quadratum* over-winters at the edges of groves, along the banks of ditches, and in other protected areas. In the spring, it moves into beet fields and transmits the virus to young plants. It moves by crawling and by short flights, so that fields far from its over-wintering areas tend to escape infection.

Control

Insecticide treatments of crops near over-wintering areas, as well as planting away from infected areas, are effective control measures.

Beet mosaic

Beet mosaic virus (BtMV) is a non-persistently aphid-transmitted potyvirus infecting mainly sugar beet and its close relatives. BtMV is one of the most widely distributed sugar beet viruses and is probably present in all major beet-producing regions of the world. High percentages of infection occur only in those areas where the sources of infection are present in abundance throughout the year. If plants are infected early, yield losses of up to 10% can occur (Bennett, 1964).

Symptoms

BtMV causes mottling symptoms on beets, similar to other mosaic viruses seen on plant species. The initial symptoms are the appearance of chlorotic spots or chlorotic rings on young leaves with green centres and vein clearing. Subsequent growth will show only mottling (Plate 31). Much variation exists in the type of mottling, but the mosaic pattern usually consists of irregular patches of various shades of green. Symptoms tend to be less evident as plants increase in size. Later in the season the symptoms may be difficult to detect on mature leaves.

Causal agent

The virus particles of BtMV are flexuous, filamentous rods about 695–770 nm long and 13 nm in diameter. The virus is a member of the potyvirus group and induces the formation of intracellular cytoplasmic inclusions (pinwheels) readily detectable by light microscopy (Hoefert, 1969).

The host range of BtMV is moderately wide. Most host species are in the *Chenopodiaceae*, *Solanaceae* and *Leguminosae*, although species in about ten dicotyledonous families are susceptible (Bennett, 1949).

Epidemiology

BtMV is transmitted by many species of aphids in a non-persistent manner but *Myzus persicae* and *Aphis fabae* are the principal vectors in the field (Russell, 1971; Dusi & Peters, 1999). Acquisition and inoculation thresholds are reached within seconds during feeding, with no latent period. Viruliferous aphids retain the virus for only a few hours at most. The virus is also readily transmitted by mechanical inoculation (Cockbain *et al.*, 1963). The principal sources of infection are other beet plants, and since the persistence of BtMV in vectors is very brief the virus moves fairly short distances in a season.

Control

The best choice to control BtMV is reduction or elimination of sources of infection. The elimination of overlapping crops, or the separation of such crops by distances of at least 2 km, is the most important control measure for BtMV (Duffus, 1963). In addition, the destruction of wild and escaped beets (for example in set-aside) in the vicinity of recently planted beet fields keeps infection levels to a minimum.

Beet savoy

Sugar *Beet savoy virus*, transmitted by the lace bug, *Piesma cinerea* Say, has been known in the USA since 1890. Although the insect vector occurs throughout the western hemisphere, the savoy disease has been limited to North America, including Canada. In the USA, the disease had been reported in the east of the Rocky Mountains. In commercial sugar beet fields, plants affected by savoy have ranged from a trace to 1–2%, occasional fields showing an incidence as high as 10–14%. The sugar content of infected beets is significantly lowered and the total yield seriously affected (Coons *et al.*, 1950).

Symptoms

The first symptoms of savoy disease are vein clearing and vein enlargement, resulting in a netlike leaf surface. Afterwards, the edges of leaves, especially of younger ones, bend downwards. Roots of affected plants show phloem necrosis and discoloration similar to symptoms of curly top. Both tops and roots are markedly stunted.

Causal agent

The causal agent of *Beet savoy virus* is transmitted by the lace bug *P. cinerea*. The agent has not been transmitted by aphids or the beet leafhopper or by mechanical inoculation. There is no evidence that the causal agent of beet savoy is a virus similar to the *Beet leaf curl virus* or a rickettsia-like organism (similar to the causal agent of latent rosette disease), both of which are transmitted by the beet lace bug, *P. quadratum* (Duffus & Ruppel, 1993).

Epidemiology

P. cinerea over-winters in grassy, shrubby, or woody areas. It breeds on weed hosts, such as *Amaranthus retroflesus* L., *A. blitoides* Wats., and other species of *Amaranthus*. The insect will feed on sugar beets in the absence of its weed hosts. Flights of the vector are short, and infection occurs mostly at the edges of fields closest to breeding areas (Coons *et al*., 1958).

Control

The disease could probably be controlled by elimination of the vector or its hosts near beet fields. Sugar beet varieties were found to react differentially to the virus.

Beet yellow net

The *Beet yellow net* (BYN) disease is characterized by the production of conspicuous chlorosis or yellowing of the veins and veinlets of leaves of affected plants. This disease has not yet been shown to be induced by a virus. However, the transmission characteristics of the agent are very similar to those of the poleroviruses. The disease has been reported only in California and the UK (Sylvester, 1948; Watson, 1962).

Symptoms

Usually the first symptoms are expressed on the youngest leaf of the plant. The main lateral veins arising from the midrib are affected by the chlorosis. As the leaf expands and matures, the chlorosis involves more and more of the veinlet network. The extent of yellowing varies; occasionally only the larger veins are affected, but in other instances virtually every veinlet is affected (Plate 32). In the spring, infected plants are conspicuous because of their marked bright yellow colour, and sometimes clusters of them form bright yellow areas recognizable from considerable distances. In some cases, as the plants grow older, the symptoms tend to become milder or even disappear (Sylvester, 1948).

Causal agents

The causal agents of BYN are transmitted by *Myzus persicae*; the viruses persist in the vector for life and are not mechanically transmitted (Sylvester, 1958). This virus is related to the beet poleroviruses and when transmitted alone causes a mild yellowing symptom akin to BMYV. Plants that are infected with BYN virus contain not only the polerovirus but also two low molecular weight double-stranded RNA species (Sugars *et al*., 1998). Watson (1962) has suggested that the second component cannot be transmitted without the polerovirus component. The reported host range of the BYN agents is very narrow, including several *Beta* species, tobacco, *C. bursa-pastoris* and *P. floridana*.

Epidemiology

Sources for spring infection of sugar beet fields are not clearly defined, but patterns of field occurrence sometimes indicate that weed hosts may be involved as virus sources.

Control

BYN infected plants have shown little reduction in yield; under present conditions, no control measures are required.

Beet yellow stunt

Beet yellow stunt closterovirus (BYSV) is a potentially destructive virus disease of sugar beet (Duffus, 1972). In California, it is widespread particularly in sowthistle (*Sonchus oleraceus* L.). It has also been reported in the UK (Wright *et al.*, 1989). The virus is similar to *Beet yellows virus* (BYV), but these viruses are not serologically related. They differ markedly in host range, especially within the *Compositae*; BYSV infects sowthistle and lettuce, which are immune to BYV.

Symptoms

Initial symptoms are severe twisting, cupping and epinasty of one or two leaves of intermediate age. Petioles are shortened, and the leaves become mottled and yellow. Young leaves are dwarfed, malformed, twisted, and slightly mottled. In the later stage, the mottle becomes more intense, and sometimes the leaves become completely chlorotic. The plants are severely stunted and may collapse and die (Plate 33).

Causal agent

BYSV is a closterovirus with long, flexuous, filamentous particles about 1400 nm long and 12.5 nm in diameter (Duffus, 1979). The virions of BYSV are composed of a single species of single-stranded RNA of about 18 Kb, encapsidated with a coat protein of 23.7 kDa (Reed & Falk, 1989; Karasev *et al.*, 1994; 1996; 1998).

The host range of the virus includes species in the families *Chenopodiaceae*, *Compositae*, *Geraniaceae*, *Portulacaceae* and *Solanaceae*. BYSV produces diagnostic symptoms on lettuce, *Lactuca sativa* L. and *M. perfoliata*.

Epidemiology

BYSV is transmitted by aphids in a semipersistent manner. The sowthistle aphid, *Hyperomyzus lactucae* (L.), is the most efficient vector; it is commonly found on sowthistle, *Sonchus oleraceus*, but feeds only transiently on lettuce and rarely on sugar beet. The virus is transmitted less efficiently by *Myzus persicae* and the potato aphid, *Macrosiphum euphorbiae* (Thomas). Most aphids cease to transmit the virus 1 or 2 days after acquisition, but a few are able to transmit the virus for up to 4 days. BYSV is not transmitted by insects after moulting.

Sowthistle is the principal source of the virus and the only rearing host of *H. lactucae*. A wild lettuce, *L. serriola* L., is also commonly infected. No evidence has been found that the virus is seedborne in beet or lettuce.

H. lactucae apparently does not reproduce on beet or lettuce and it transmits the virus readily to lettuce but very inefficiently to beet. *M. persicae* is a relatively poor vector of the virus. For these reasons, the disease is unlikely to reach serious proportions on sugar beet.

Control

The distribution of BYSV in wild *Sonchus* spp. in California is so extensive that elimination of the virus would be virtually impossible. New plantings of susceptible crops, however, should be isolated from large areas of weeds.

Beet yellow vein

A disease of sugar beet characterized by yellowing of veins and dwarfing of plants, has been found in New Mexico, California, Arizona, Utah, Colorado, Kansas, Nebraska, Oklahoma and Texas (Maxon, 1948; Bennett, 1956). Individual plants are severely affected, and root weights may be reduced by as much as 50%. In 1963 and 1964, some fields in south-west Kansas showed infection of up to 31% (Gaskill & Schneider, 1966). This level of infection could cause appreciable reduction in root yield.

Symptoms

First symptoms of yellow vein appear on young leaves of infected plants as dwarfing and vein yellowing (Plate 34). As the disease develops, the main vein turns yellow, and the discoloration often extends into the adjacent tissues producing conspicuous vein banding. Smaller infected veins may develop yellow spots isolated from other yellow areas. Dwarfing usually occurs on only one side of the plant, causing a stunted, asymmetric growth pattern (Duffus & Ruppel, 1993).

Causal agent

The causal agent of *Beet yellow vein virus* has not been identified. There is no real evidence that beet yellow vein is caused by a virus but the causal agent can be transmitted mechanically. The disease agent has a very narrow host range; the only known hosts are *Beta macrocarpa* Guss., *B. maritima* L., *B.vulgaris* L., *Chenopodium capitatum*, *Senecio vulgaris* and *Spinacia oleracea* L.

Epidemiology

The causal agent of *Beet yellow vein virus* is transmitted by grafting and mechanical inoculation (Ruppel & Duffus, 1971). Transmission by the leafhopper *Aceratagallia calcaris* Oman has been reported (Staples *et al.*, 1970).

The common insects that feed on sugar beet appear to be unable to transmit the disease agent. The wide geographical distribution of the disease indicates an extensive distribution of the agent and vector, but the low incidence of infectivity suggests that the vector is either very scarce or very inefficient (Duffus & Ruppel, 1993).

Control

No control measures can be suggested until more is known about the causal agent and its mode of transmission.

Cucumber mosaic

Cucumber mosaic virus (CMV) has been a limiting factor in the production of cucurbits. It also attacks many other types of plants including dicotyledonous and monocotyledonous crop plants and weeds (Bhargava, 1951). The virus is distributed throughout the temperate regions of the world and has been reported on sugar beet wherever the crop is grown.

Symptoms

Young leaves show mottling, characterized by chlorotic spots of various shapes and sizes. As the disease progresses, mottling continues to be produced and leaves may be dwarfed and distorted, developing green blisters. Many isolates of CMV produce chlorotic spots on leaves inoculated mechanically or by aphids. These lesions continue to increase in size, and the virus may become systemic. In sugar beet grown for seed production, plants infected at the early stages of bolting show mottled and distorted leaves on the seed stalks and reduction in their size (Bennett & Leach, 1971).

Causal agent

CMV is the type member of the genus *Cucumovirus* of the family *Bromoviridae*. CMV has three functional pieces of single-stranded RNA, in three classes of icosahedral particles about 30 nm in diameter. The particles all sediment at the same rate (Scott, 1963). CMV may harbour satellite RNAs of about 330–400 nucleotides. CMV has a very wide host range with over 470 species representing 67 families reported as being natural hosts of the virus.

Epidemiology

CMV is readily transmitted mechanically, in a non-persistent manner, by more than 60 species of aphids. Little evidence exists of spread from beet to beet in affected fields, and most infection apparently comes from host plants outside the fields. Severe infections within sugar beet fields have resulted from the development of large populations of aphids on extensive areas of weeds and the movement of many winged aphids into the beet fields as the weed vegetation senesced (Bennett *et al.*, 1958).

CMV is also transmissible by seeds of certain plants, including some weed species. Dissemination and persistence in weed seeds may be important in the epidemiology of the virus (Tomlinson & Carter, 1970), but there is no evidence that it is transmitted through the seed of sugar beet.

Control

Since there is very little spread of virus from beet to beet after the virus enters the field, control of weeds in areas surrounding sugar beet crops is the most effective control measure for CMV.

Lettuce infectious yellows

Lettuce infectious yellows virus (LIYV) occurs only in the south-west desert region of the USA (Duffus & Flock, 1982; Duffus *et al*., 1986). This disease is transmitted by the sweet potato whitefly, *Bemisia tabaci* (Gennadius) (Plate 35). The virus can have serious effects on sugar beet yields, with losses of 20–30% experienced in southern California (Duffus, 1982). As a result of changes in the whitefly biotype population dynamics in the desert region (Cohen *et al*., 1992; Liu *et al*., 1992), this disease is now of little economic importance.

Symptoms

Interveinal yellowing or reddening and stunting of affected plants are characteristic of LIYV on a wide range of crop and weed hosts. Symptoms on most hosts are almost identical to those caused by aphid-transmitted yellowing viruses and can readily be confused with them. The early symptom on sugar beet plants infected by LIYV is a very mild mottle, which develops into interveinal yellowing (Plate 36).

Causal agent

LIYV has a bipartite genome and is the type member of the genus *Crinivirus* of the family *Closteroviridae* (Martelli *et al*., 2000; 2002). Particles are flexuous, filamentous rods, measuring between 700 and 750 nm long (Liu *et al*., 2000). The virions are composed of a single major capsid protein with a molecular weight of 28 kDa and a bipartite genome (RNA 1 is 8118 nucleotides and RNA 2 is 7193 nucleotides) (Klaassen *et al*., 1994; 1995). The virus induces intracellular inclusions including vesicles which are very similar to those induced by closteroviruses (Hoefert *et al*., 1988). However, it is not serologically related to aphid transmitted BYV, BYSV, or any other whitefly transmitted viruses.

The virus has a broad host range which extends over 15 families and includes important crop plants in the *Chenopodiaceae*, *Compositae* and *Cucurbitaceae.*

Epidemiology

Whitefly populations have been extremely high since the early 1980s, and large numbers of susceptible weeds serve as abundant sources of infection for susceptible crops. The crops affected by the disease, including sugar beet, lettuce, cucurbits and carrot, are virtually 100% infected during the late summer and early autumn period. Among wild plants, *Helianthus annuus* L., *Lactuca serriola* and *Physalis wrightii* Gray play a major role in the carryover of the virus from season to season. Cotton serves as an important build-up host of the whitefly. The autumn cucurbits are an additional breeding host of the whitefly and serve as the most important source of LIYV for newly emerging crops.

In the early 1990s, *Bemisia* population changed from biotype A to biotype B in the south-west desert region of the USA (Liu *et al*., 1992). The introduction of the new biotype of whitefly into the south-west desert, coupled with its inefficiency to transmit LIYV, significantly altered the epidemiological characteristics of LIYV in the region. In spite of the record high population of whitefly in 1991, LIYV levels in desert sugar beet and lettuce were less than 1% in 1991 in comparison to over 70% in 1990. Although LIYV is still present in this area, it currently is not considered as a problem.

Control

The elimination of autumn cucurbits would greatly reduce whitefly populations and the major source of LIYV. Sugar beet germplasm and breeding lines with resistance to LIYV have been released (Lewellen & Skoyen, 1987) and incorporated into commercial lines.

REFERENCES

Abe, H. (1974) Factors affecting the rhizomania of sugar beet. *Bulletin of the Hokkaido Prefectural Agricultural Experiment Station* **30**, 95–102.

Abe, H. (1987) Studies of the ecology and control of *Polymyxa betae* Keskin as a fungal vector of the causal virus (*beet necrotic yellow vein virus*) of rhizomania disease of sugar beet. *Bulletin of the Hokkaido Prefectural Agricultural Experiment Station* **60**.

Abe, H. & Tamada, T. (1986) Association of *beet necrotic yellow vein virus* with isolates of *Polymyxa betae* Keskin strains in rhizomania infested soils of sugar beet in Japan. *Annals of the Phytopathological Society of Japan* **52**, 235–247.

Accotto, G.P. & Boccardo, G. (1986) The coat proteins and nucleic acid of two beet cryptic viruses. *Journal of General Virology* **67**, 363–366.

Adams, M. & Welham, S. (1995) Use of the most probable number technique to quantify soil-borne plant pathogens. *Annals of Applied Biology* **126**, 181–196.

Asher, M.J.C. (1988) Approaches to the control of fungal vectors of viruses with special reference to rhizomania. *Proceedings of the British Crop Protection Council – Pests and Diseases*. pp. 615–627.

Asher, M.J.C., Luterbacher, M. & Frese, L. (2001) Wild *Beta* species as a source of resistance to sugar beet pests and diseases. *International Sugar Journal* **103**, 447–451.

Asher, M.J.C., Chwarszczynska, D.M. & Leaman, M. (2002) The evaluation of rhizomania resistant sugar beet for the UK. *Annals of Applied Biology* **141**, 101–109.

Bartsch, D. & Brand, U. (1998) Saline soil condition decreases rhizomania infection of *Beta vulgaris*. *Journal of Plant Pathology* **80**, 219–223.

Bennett, C.W. (1949) Some unreported host plants of sugar beet mosaic virus. *Phytopathology* **39**, 669–672.

Bennett, C.W. (1956) Sugar beet yellow vein disease. *Plant Disease Reporter* **40**, 611–614.

Bennett, C.W. (1960) Sugar beet yellows disease in the United States. *USDA Technical Bulletin* 1218.

Bennett, C.W. (1964) Isolates of Beet mosaic virus with different degrees of virulence. *Journal of the American Society of Sugar Beet Technologists* **13**, 27–32.

Bennett, C.W. (1971) The curly top disease of sugarbeet and other plants. *Phytopathological Monograph no. 7.* American Phytopathological Society, St. Paul, MN.

Bennett, C.W. & Costa, A.S. (1949) The Brazilian curly top of tomato and tobacco resembling North American and Argentine curly top of sugar beet. *Journal of Agriculture Research* **78**, 675–693.

Bennett, C.W. & Costa, A.S. (1954) Observation and studies of virus yellows of sugar beet in California. *Proceedings of the American Society of Sugar Beet Technologists* 8 (Part 2). pp. 230–235.

Bennett, C.W. & Leach, L.D. (1971) Disease and their control. In: Johnson, R.T., Alexander, J.T., Rush, G.E. & Hawkes, G.R. (eds) *Advances in Sugarbeet Production: Principles and Practices.* Iowa State University, IA, pp. 223–285.

Bennett, C.W. & Tanrisever, A. (1958) Curly top disease in Turkey and its relationship to curly top in North America. *Journal of the American Society of Sugar Beet Technologists* **10**, 189–211.

Bennett, C.W., Jewell, H.K. & Hills, O.A. (1958) Cucumber mosaic in seed fields of sugar beet in the Salt River Valley of Arizona. *Journal of the American Society of Sugar Beet Technologists* **10**, 220–231.

Bhargava, K.W. (1951) Some properties of four strains of Cucumber mosaic virus. *Annals of Applied Biology* **38**, 377–388.

Biancardi, E., Lewellen, R.T., Biaggi, M.D., Erichsen, A.W. & Stevanato, P. (2002) The origin of rhizomania resistance in sugarbeet. *Euphytica* **127**, 383–397.

Björling, K. (1958) Incidence of beet yellows virus in weeds in Sweden and some notes on differential hosts for strains of the virus. *Annales Academiae Regiae Scientiarum Upsaliensis* **2**, 17–32.

Blunt, S.J. (1989) The ecology of *Polymyxa betae*, a fungal root parasite of *Beta vulgaris*. PhD thesis, University of Cambridge.

Blunt, S.J., Asher, M.J.C. & Gilligan, C.A. (1991) Infection of sugar beet by *Polymyxa betae* in relation to soil temperature. *Plant Pathology* **40**, 257–267.

Blunt, S.J., Asher, M.J.C. & Gilligan, C.A. (1992) The effect of sowing date on infection of sugar beet by *Polymyxa betae*. *Plant Pathology* **41**, 148–153.

Boccardo, G., Lisa, V. & Milne. R.G. (1983) Cryptic viruses in plants. In: Compans, R.W. & Bishop, D.H.L. (eds) *Double-stranded RNA Viruses*. Elsevier, Amsterdam, pp. 425–430.

Brandes, J. & Zimmer, K. (1955) Elektronenmikroskopische Untersuchungen über die virüse Vergilbungskrankheit der Rübe (beet yellows). *Phytopathologisches Zeitschrift* **24**, 211–215.

Broadbent, L., Cornford, C.E., Hull, R. & Tinsley, J.W. (1949) Overwintering of aphids, especially *Myzus persicae* (Sulzer), in root clamps. *Annals of Applied Biology* **36**, 513–524.

Canova, A. (1955) Una nuova forma di giallume della barbabietola. *Phytopathologische Zeitschrift* **23**, 161–176.

Canova, A. (1959) On the pathology of sugarbeet. *Informatore Fitopatologico* **9**, 390–396.

Canova, A. (1966) Si studia la rizomanie della bietola. *Informatore Fitopatologico* **16**, 235–239.

Carter, W. (1930) Ecological studies of the beet leaf hopper. *US Department of Agricultural Technical Bulletin* no. 206.

Chevallier, D., Engel, A., Wurtz, M. & Putz, C. (1983) The structure and characterization of a closterovirus, beet yellows virus, and a luteovirus, beet mild yellowing virus, by scanning transmission electron microscopy, optical diffraction of electron images and acrylamide gel electrophoresis. *Journal of General Virology* **64**, 2289–2293.

Clinch, P.E.M. & Loughnane, J.B. (1948) Seed transmission of virus yellows of sugar beet (*Beta vulgaris* L.) and the existence of strains of this virus in Eire. *Royal Dublin Society Proceedings* **24**, 307–318.

Clover, G.R.G., Azam-Ali, S.N., Jaggard, K.W. & Smith, H.G. (1999) The effects of beet yellows virus on the growth and physiology of sugar beet (*Beta vulgaris*). *Plant Pathology* **48**, 129–138.

Cockbain, A.J., Gibbs, A.J. & Heathcote, G.D. (1963) Some factors affecting the transmission of sugar beet mosaic and pea mosaic by *Aphis fabae* and *Myzus persicae*. *Annals of Applied Biology* **52**, 135–143.

Cohen, S., Duffus, J.E. & Liu, H.Y. (1992) A new *Bemisia tabaci* biotype in the southwestern United States and its role in silverleaf of squash and transmission of *Lettuce infectious yellows virus*. *Phytopathology* **82**, 86–90.

Coons, G.H., Kotila. J.E. & Stewart. D. (1950) Savoy, a virus disease of beet transmitted by *Piesma cinerea*. *Proceedings of the American Society of Sugar Beet Technologist* **6**, 500–501.

Coons, G.H., Stewart. D., Bockstahler, H.W. & Schneider, C.L. (1958) Incidence of savoy in relation to the variety of sugar beets and to the proximity of wintering habitat of the vector, *Piesma cinerea*. *Plant Disease Reporter* **41**, 502–511.

Danielsen, S., Mugrabi, M., Albrechtsen, M. & Thomsen, A. (1992) Rhizomania in sugar beet. Survey for *Beet necrotic yellow vein virus* (BNYVV), *Beet soil-borne virus* (BSBV) and *Polymyxa betae* in Denmark. *Tidsskrift for Planteavl* **96**, 87–96.

D'Arcy, C.J., Torrance, L. & Martin, R.R. (1989) Discrimination among luteoviruses and their strains by monoclonal antibodies and identification of common epitopes. *Phytopathology* **79**, 869–873.

De Koeijer, K.J. de & Van der Werf, W. (1995) Effect of beet yellowing viruses on light interception and light use efficiency of the sugar beet crop. *Crop Protection* **14**, 291–297.

De Koeijer, K.J. & Van der Werf, W. (1999) Effects of beet yellows virus and beet mild yellowing virus on leaf area dynamics of sugar beet (*Beta vulgaris* L.). *Field Crops Research* **61**, 163–177.

Dewar, A.M. (1988) Chemical control. In: *Virus Yellows Monograph*. IIRB Pests and Diseases Study Group, pp. 59–67.

Dikova, B. (1997) Weeds in sugar beets – infection containers for the virus of the 'Rhizomania' *Beet necrotic yellow vein virus* – BNYVV. *Rasteniev dni Nauki* **34**, 93–96.

Dolja, V.V. (2003) Beet yellows virus: the importance of being different. *Molecular Plant Pathology* **4**, 91–98.

Duffus, J.E. (1960) Radish yellows, a disease of radish, sugar beet, and other crops. *Phytopathology* **50**, 389–394.

Duffus, J.E. (1961) Economic significance of beet western yellows (radish yellows) on sugar beet. *Phytopathology* **51**, 605–607.

Duffus, J.E. (1963) Incidence of beet virus diseases in relation to overwintering beet fields. *Plant Disease Reporter* **47**, 428–431.

Duffus, J.E. (1972) Beet yellow stunt, a potentially destructive virus disease of sugar beet and lettuce. *Phytopathology* **62**, 161–165.

Duffus, J.E. (1978) The impact of yellows control on California sugarbeets. *Journal of the American Society of Sugar Beet Technologists* **20**, 1–5.

Duffus, J.E. (1979) *Beet Yellow Stunt Virus*. CMI/AAB Description of Plant Viruses no. 207.

Duffus, J.E. (1982) A new yellowing virus threat to desert sugarbeets, transmitted by the whitefly, *Bemisia tabaci*. *California Sugar Beet*, 31–32.

Duffus, J.E. (1983) Epidemiology and control of curly top diseases of sugar beet and other crops. In: Plumb, R.T. & Thresh, J.M. (eds) *Plant Virus Epidemiology*. Blackwell Scientific, Oxford, pp. 297–304.

Duffus, J.E. & Flock, R.A. (1982) Whitefly-transmitted disease complex of the desert southwest. *California Agriculture* **36**, 4–6.

Duffus, J.E. & Liu, H.Y. (1991) Unique beet western yellows virus isolates from California and Texas. *Journal of Sugar Beet Research* **28**, 68.

Duffus, J.E. & Ruppel, E.G. (1993) Diseases. In: Cooke, D.A. & Scott, R.K. (eds) *The Sugar Beet Crop*. Chapman and Hall, London, pp. 347–427.

Duffus, J.E. & Russell, G.E. (1970) Serological and host range evidence for the occurence of beet western yellows virus in Europe. *Phytopathology* **60**, 1199–1202.

Duffus, J.E. & Russell, G.E. (1975) Serological relationship between beet western yellows and beet mild yellowing viruses. *Phytopathology* **65**, 811–815.

Duffus, J.E., Larsen, R.C. & Liu, H.Y. (1986) *Lettuce infectious yellows virus* – a new type of whitefly-transmitted virus. *Phytopathology* **76**, 97–100.

Dunning, R.A. (1975) Aphids and yellows control. *British Sugar Beet Review* **43** (1), 56–78.

Dusi, A.N. & Peters, D. (1999) Beet mosaic virus: its vector and host relationship. *Journal of Phytopathology* **147**, 293–298.

Eisbein, K. (1973) Weitere elektronenmikroskopische untersuchungen des Rubenkrauselvirus (Beta virus 3) in Ultradunnschnien und rach Reinigung aus der Futterrube. *Archiv fur Phytopathologie und Pflanzenschutz* **9**, 91–94.

Esau, K. (1960) The development of inclusions in sugar beets infected with the beet-yellows virus. *Virology* **11**, 317–328.

Fail, G.L. & Hoefert, L.L. (1991) Electron microscopy of sugar beet leaves infected with *Beet distortion mosaic virus*. *Journal of Sugar Beet Research* **28**, 69.

Farzadfar, S., Pourrahim, R., Golnaraghi, A. & Shahraeen, N. (2002) First report of Beet soil-borne virus on sugar beet in Iran. *Plant Disease* **86**, 187.

Francis, S.A., Redfearn, M., Chwarszczynska, D.M., Asher, M.J.C. & Lewellen, R.T. (1998) Use of molecular markers in breeding for disease resistance in sugar beet (*Beta vulgaris* L.). *Aspects of Applied Biology* **52**, 279–285.

Gaskill, J.O. & Schneider, C.L. (1966) Savoy and yellow vein diseases of sugar beet in the Great Plains in 1963–64–65. *Plant Disease Reporter* **50**, 457–459.

Gerik, J.S. & Duffus, J.E. (1988) Differences in vectoring ability and aggressiveness of isolates of *Polymyxa betae*. *Phytopathology* **78**, 1340–1343.

Gerik, J.S., Hubbard, J.C. & Fus, J.E. (1990) Soil matric potential effects on infection by *Polymyxa betae* and BNYVV. In: *Proceedings of the First Symposium of the International Working Group on Plant Viruses with Fungal Vectors*. Braunschweig, Eugen Ulmer, Stuttgart, pp. 75–78.

Govier, D.A. (1985) Purification and partial characterisation of beet mild yellowing virus and its serological detection in plants and aphids. *Annals of Applied Biology* **107**, 439–447.

Graichen, K. & Rabenstein F. (1996) European isolates of beet western yellows virus (BWYV) from oilseed rape (*Brassica napus* L. spp. napus) are non-pathogenic on sugar beet (*Beta vulgaris* L. var. altissima) but represent isolates of turnip yellows virus (TuYV). *Zeitschrift für Pflanzenkrankheiten und Pflanzenschutz* **103**, 233–245.

Grondona, I., Hermosa, M.R., Vizcaino, J.A., Garcia Benavides, P., Redondo, J., Rico, C., Monte, E. & Garcia Acha, I. (2001) Integrated control of rhizomania disease by *Tri-*

choderma and cultural management. *Bulletin OILB/SROP* **24**, 213–216.

Guilley, H., Richards, K.E. & Jonard, G. (1995) Nucleotide sequence of beet mild yellowing virus RNA. *Archives of Virology* **140**, 1109–1118.

Hammer, K., Stanarius, A. & Kuhne, T. (1990) Differential occurrence of beet cryptic viruses – a new tool for germplasm characterization and evolutionary studies in beets? *Euphytica* **45**, 23–28.

Harju, V.A., Mumford, R.A., Bockley, A., Boonham, N., Clover, G.R.G., Weekes, R. & Henry, C.M. (2002) Occurrence in the United Kingdom of *Beet necrotic yellow vein virus* isolates which contain RNA 5. *Plant Pathology* **811**.

Harrington, R., Dewar, A.M. & George, B. (1989) Forecasting the incidence of virus yellows in sugar beet in England. *Annals of Applied Biology* **114**, 459–469.

Hauser, S., Weber, C., Vetter, G., Stevens, M., Beuve, M. & Lemaire, O. (2000a) Improved detection and differentiation of poleroviruses infecting beet or rape by multiplex RT-PCR. *Journal of Virological Methods* **89**, 11–21.

Hauser, S., Stevens, M., Mougel, C., Smith, H.G., Fritsch, C., Herrbach, E. & Lemaire, O. (2000b) Biological, serological and molecular variability suggest three distinct polerovirus species infecting beet or rape. *Phytopathology* **90**, 460–466.

Hauser, S., Stevens, M., Beuve, M. & Lemaire, O. (2002) Biological properties and molecular characterization of beet chlorosis virus (BChV). *Archives of Virology* **147**, 745–762.

Heathcote, G.D. (1988) Vectors and virus transmission. In: *Virus Yellows Monograph.* Institut International de Researches Betteravieres, Brussels, pp. 43–48.

Heathcote, G.D. & Cockbain, A.J. (1966) Aphids from mangold clamps and their importance as vectors of beet viruses. *Annals of Applied Biology* **57**, 321–336.

Heathcote, G.D., Dunning, R.A. & Wolfe, M.D. (1965) Aphids on sugar beet and some weeds in England, and notes on weeds as a source of beet viruses. *Plant Pathology* **14**, 1–10.

Heidel, G.B., Rush, C.M., Kendall, T.L., Lommel, S.A. & French, R.C. (1997) Characteristics of *Beet soil-borne mosaic virus*, a furo-like virus infecting sugar beet. *Plant Disease* **81**, 1070–1076.

Heijbroek, W. (1988) Factors affecting sugar-beet losses caused by beet mild yellowing virus and beet yellows virus. *Mededelingen Faculteit Landbouewwetenschappen, Rijksuniversiteit Gent* **53** (1a), 507–514.

Heijbroek, W. (1989) The development of rhizomania in two areas of the Netherlands and its effect on sugar-beet growth and quality. *Netherlands Journal of Plant Pathology* **95**, 27–35.

Heijbroek, W., Musters, P.M.S. & Schoone, A.H.L. (1999) Variation in pathenogenicity and multiplication of *Beet necrotic yellow vein virus* (BNYVV) in relation to the resistance of sugarbeet cultivars. *European Journal of Plant Pathology* **105**, 397–405.

Hoefert, L.L. (1969) Proteinaceous and virus-like inclusions in cells infected with *Beet mosaic virus. Virology* **37**, 498–501.

Hoefert, L.L., Pinto, R.L. & Fail, G.L. (1988) Ultrastructural effects of *Lettuce infectious yellows virus* in *Lactuca saliva* L. *Journal of Ultrastructural and Molecular Structural Research* **98**, 243–253.

Hull, R. (1954) Control of yellows in sugar-beet seed crops in Great Britain. *Journal of the Ministry of Agriculture* **6**, 205–210.

Hull, R. & Heathcote, G.D. (1967) Experiments on the time of application of insecticide to decrease the spread of yellows viruses of sugar beet, 1954–66. *Annals of Applied Biology* **60**, 469–478.

Hull, R. & Watson, M.A. (1945) Virus yellows of sugarbeet. *Journal of the Ministry of Agriculture* **52**, 66–70.

Hurst, G.W. (1965) Forecasting the severity of sugar beet yellows. *Plant Pathology* **14**, 47–53.

Hutchinson, P.J., Henry, C.M. & Coutts, R.H.A. (1992) A comparison, using dsRNA analysis, between *Beet soil-borne virus* and some other tubular viruses isolated from sugar beet. *Journal of General Virology* **73**, 1317–1320.

Ivanovic, M. & Macfarlane, I. (1982) A tubular virus associated with infection of sugar beet by *Polymyxa betae. Annual Report of the Rothamsted Experimental Station for 1981*, pp. 190–191.

Jadot, R. (1974) Étude de l'épidémiologie des virus de la jaunisse de la betterave V. Les plantes rudérales sources de jaunisse grave ou de jaunisse modérée. *Parasitica* **30**, 37–44.

Jadot, R. (1975) Transmission des virus de la jaunisse de la betterave par quelques espèces d'aphides. *Parasitica* **31**, 62–66.

Jaggard, K.W., Dewar, A.M. & Pidgeon, J.D. (1998) The relative effects of drought stress and virus yellows on the yield of sugarbeet in the UK, 1980–95. *Journal of Agricultural Science* **130**, 337–343.

Jupin, I., Guilley, H., Richards, K.E. & Jonard, G. (1992) Two proteins encoded by *Beet necrotic yellow vein virus* {RNA} 3 influence symptom phenotype on leaves. *The EMBO Journal* **11**, 479–488.

Karasev, A.V., Nikolaeva, O.V., Koonin, E.V., Gumpf, D.J. & Garnsey, S.M. (1994) Screening of the closterovirus genome by degenerate primer-mediated polymerase chain reaction. *Journal of General Virology* **75**, 1415–1422.

Karasev, A.V., Nikolaeva, O.V., Mushegian, A.R., Lee, R.F. & Dawson, W.O. (1996) Organization of the 3' terminal half of *Beet yellow stunt virus* genome and implications for the evolution of closteroviruses. *Virology* **221**, 199–207.

Karasev, A.V., Nikolaeva, O.V., Lee, R.F., Wisler, G.C., Duffus, J.E. & Dawson, W.O. (1998) Characterization of the *Beet yellow stunt virus* coat protein gene. *Phytopathology* **88**, 1040–1045.

Kassanis, B., White, R.F. & Woods, R.D. (1977) *Beet cryptic virus. Phytopathologische Zeitschrift* **90**, 350–360.

Kassanis, B., Russell, G.E. & White, R.F. (1978) Seed and pollen transmission of *Beet cryptic virus* in sugar beet plants. *Phytopathologische Zeitschrift* **91**, 76–79.

Kaufmann, A., Li, Y., Koenig, R., Breyel, E., Maiss, E., Luddecke, P. & Commandeur, U. (1992) Single- and double-stranded RNAs associated with an isolate of *Beet soil-borne virus. Intervirology* **33**, 97–102.

Kaufmann, A., Koenig, R. & Rohloff, H. (1993) Influence of *Beet soil-borne virus* on mechanically inoculated sugar beet. *Plant Pathology* **42**, 413–417.

Keskin, B. (1964) *Polymyxa betae* n. sp., a parasite in the roots of *Beta vulgaris* tournefort, particularly during the early growth of the sugar beet. *Arch Mikrobiol* **19**, 348–374.

Klaassen, V.A., Boeshore, M., Dolja, V.V. & Falk, B.W. (1994) Partial characterization of the *Lettuce infectious yellows virus* genomec RNAs identification of the coat protein gene and comparison of its amino acid sequence with those of other filamentous RNA plant viruses. *Journal of General Virology* **75**, 1525–1533.

Klaassen, V.A., Boeshore, M., Koonin, E.V., Tian, T. & Falk, B.W. (1995) Genome structure and phylogenetic analysis of *Lettuce infectious yellows virus,* a whitefly-transmitted, bipartite closterovirus. *Virology* **208**, 99–110.

Koenig, R. & Lennefors, B.L. (2000) Molecular analyses of European A, B and P type sources of *Beet necrotic yellow vein virus* and detection of the rare P type in Kazakhstan. *Archives of Virology*, 1561–1570.

Koenig, R. & Lesemann, D.-E. (2000a) Genus *Pomovirus.* In: Van Regenmortel, M.H.V., Fauquet, C.M. & Bishop, D.H.L. (eds) *Virus Taxonomy. 7th Report of the International Committee on Taxonomy of Viruses.* Academic Press, San Diego, CA, pp. 908–913.

Koenig, R. & Lesemann, D.-E. (2000b) Genus *Benyvirus.* In: Van Regenmortel, M.H.V., Fauquet, C.M. & Bishop, D.H.L. (eds) *Virus Taxonomy. 7th Report of the International Committee on Taxonomy of Viruses.* Academic Press, San Diego, CA, pp. 917–922.

Koenig, R., Jarausch, W., Li, Y., Commandeur, U., Burgermeister, W., Gehrke, M. & Luddecke, P. (1991) Effect of recombinant *Beet necrotic yellow vein virus* with different {RNA} compositions on mechanically inoculated sugarbeets. *Journal of General Virology* **72**, 2243–2246.

Koenig, R., Luddecke, P. & Haeberle, A.M. (1995). Detection of beet necrotic yellow vein virus strains, variants and mixed infections by examining single-strand conformation polymorphisms of immunocapture RT-PCR products. *Journal of General Virology* **76**, 2051–2055.

Koenig, R., Haeberle, A.M. & Commandeur, U. (1997) Detection and characterization of a distinct type of *Beet necrotic yellow vein virus* RNA 5 in a sugarbeet growing area in Europe. *Archives of Virology*, 1499–1504.

Koenig, R., Pleij, C.W., Beier, C. & Commandeur, U. (1998) Genome properties of *Beet virus Q*, a new furo-like virus from sugarbeet, determined from unpurified virus. *Journal of General Virology* **79**, 2027–2036.

Kruse, M., Koenig, R., Hoffman, A., Kaufmann, A., Commandeur, U., Solovyev, A.G., Savenkov, I. & Burgermeister, W. (1994). Restriction fragment length polymorphism analysis of reverse transcription PCR products reveals the existence of two major strain groups of *Beet necrotic yellow vein virus. Journal of General Virology* **75**, 1835–1842.

Kuhne, T., Stanarius, A. & Kleinhempel, H. (1987) *Beet cryptic virus* – Reinigung und serologischer Nachweis in vier Varietaten von *Beta vulgaris* L. *Archiv fur Phytopathologie und Pflanzenschutz* **23**, 95–104.

Kutluk, N.D., Erkan, S. & Bicken, S. (2000) Weeds as hosts for Rhizomania's agent. *Zeitschrift fur Pflanzenkrankheiten und Pflanzenschutz* **17**.

Larsen, R.C. & Duffus, J.E. (1984) A simplified procedure for the purification of curly top virus and the isolation of its monomer and dimmer particles. *Phytopathology* **74**, 114–118.

Lauber, E., Janssens, L., Weyens, G., Jonard, G., Richards, K.E., Lefebvre, M. & Guilley, H. (2001) Rapid screening for dominant negative mutations in the *Beet necrotic yellow vein virus* triple gene block proteins P13 and P15 using a viral replicon. *Transgenic Research* **10**, 293–302.

Lee, L., Telford, E.B., Batten J.S., Scholthof, K.-B.G. & Rush, C.M. (2001) Complete nucleotide sequence and genome organization of *Beet soil-borne mosaic virus*, a proposed member of the genus *Benyvirus. Archives of Virology* **146**, 2443–2453.

Legreve, A., Delfosse, P. & Maraite, H. (2002) Phylogenetic analysis of *Polymyxa* species based on nuclear 5.8S and internal transcribed spacers ribosomal DNA sequences. *Mycological Research* **106**, 138–147.

Lemaire, O., Merdinoglu, D., Valentin, P., Putz, C., Ziegler-Graff, V., Guilley, H., Jonard, G. & Richards, K. (1988) Effect of *Beet necrotic yellow vein virus* RNA composition on transmission by Polymyxa betae. *Virology*, **162**, 232–235.

Lemaire, O., Herrbach, E., Stevens, M., Bouchery, Y. & Smith, H.G. (1995) Detection of sugar-beet-infecting beet mild yellowing virus isolates with a specific RNA probe. *Phytopathology* **85**, 1513–1518.

Lesemann, D.E., Koenig, R., Lindsten, K. & Henry, C. (1989) Serotypes of *Beet soil-borne furovirus* from FRG and Sweden. *Bulletin of EPPO/OEPP* **19**, 539–540.

Lewellen, R.T. (2002) Registration of monogerm rhizomania resistant sugarbeet parental lines C833–5 and C833–5CMS. *Crop Science* **42**, 321–322.

Lewellen, R.T. (2004) Registration of sugar beet germplasm lines C927–4, C929–62, C930–19, and C930–35 with resistance to rhizomania, virus yellows, and bolting. *Crop Science* **44**, 359–361.

Lewellen, R.T. & Skoyen. I.O. (1987) Registration of 17 monogerm, self-fertile germplasm lines of sugar beet derived from three random-mating populations. *Crop Science* **27**, 371–372.

Leyon, H. (1951) Sugar beet yellows virus. Some electron microscopical observations. *Arkiv För Kemi* **3**, 105–109.

Lindsten, K. & Rush, C.M. (1994) First report of *Beet soil-borne virus* in the United States. *Plant Disease* **78**, 316.

Liu, H.Y. & Duffus, J.E. (1988) The occurrence of a complex of viruses associated with rhizomania of sugarbeet. *Phytopathology* **78**, 1583.

Liu, H.Y., Duffus, J.E. & Gerik, J.S. (1987) Beet distortion mosaic – a new soilborne virus of sugar beet. *Phytopathology* **77**, 1732.

Liu, H.Y., Cohen, S. & Duffus, J.E. (1992) The use of isozyme patterns to distinguish sweetpotato whitefly (*Bemisia tabaci*) biotypes. *Phytoparasitica* **20**, 187–194.

Liu, H.Y., Wisler, G.C. & Duffus, J.E. (2000) Particle lengths of whitefly-transmitted criniviruses. *Plant Disease* **84**, 803–805.

Liu, H.-Y., Sears, J.L. & Lewellen, R.T. (2003) A new beny-like sugarbeet virus emerging in the United States. In: *Proceedings of the 1st Joint meeting of the IIRB–ASSBT Congress.* San Antonio, TX, pp. 843–847.

Mannerlof, M., Lennerfors, B.L. & Tenning, P. (1996) Reduced titer of BNYVV in transgenic sugar beets expressing the BNYVV coat protein. *Euphytica* **90**, 293–299.

Martelli, G.P., Agranovsky, A.A., Bar-Joseph, M., Boscia, D., Candresse, T., Coutts, R.H.A., Dolja, V.V., Duffus, J.E., Falk, B.W., Gonsalves, D., Jelkmann, W., Karasev, A.V., Minafra, A., Murant, A.F., Namba, A.F., Niblett, C.L., Vetten, H.J. & Yoshikawa, N. (2000) Family *Closteroviridae*. In: Regenmortel, M.H.V., Fauquet, C.M., Bishop, D.H.L., Carstens, E.B., Estes, M.K., Lemon, S.M., Maniloff, J., Mayo, M.A., McGeoch, D.J., Pringle, C.R. & Wickner, R.B. (eds) *Virus Taxonomy. 7th Report of the International Committee on Taxonomy of Viruses.* Academic Press, San Diego, CA, pp. 943–952.

Martelli, G.P., Agranovsky, A.A., Bar-Joseph, M., Boscia, D., Candresse, T., Coutts, R.H.A., Dolja, V.V., Falk, B.W., Gonsalves, D., Jelkmann, W., Karasev, A.V., Minafra, A., Namba, S., Vetten, H.J., Wisler, G.C. & Yoshikawa, N. (2002) The family Closterovirudae revised. *Archives of Virology* **147**, 2039–2044.

Martin, F.N. & Whitney, E.D. (1990) In-bed fumigation for control of rhizomania of sugar beet. *Plant Disease* **74**, 31–35.

Maxon, A.C. (1948) *Insects and Diseases of the Sugar Beet*. Beet Sugar Development Foundation, Fort Collins, CO, 425pp.

Mayo, M.A. (2002) ICTV at the Paris ICV: Results of the Plenary Session and the Binomial Ballot. *Archives of Virology* **147**, 2254–2260.

Mesbah, M., Scholten, O.E., Bock, T.S.M.D. & Lange, W. (1997) Chromosome localisation of genes for resistance to *Heterodera schachtii, Cercospora beticola* and *Polymyxa betae* using sets of *Beta procumbens* and *B. patellaris* derived monosomic additions in *B. vulgaris. Euphytica* **97**, 117–127.

Meunier, A., Schmit, J.-F., Stas, A., Kutluk, N. & Bragard, C. (2003) Multiplex reverse transcription-PCR for simultaneous detection of *Beet necrotic yellow vein virus*, *Beet soilborne virus*, and *Beet virus Q* and their vector *Polymyxa betae* Deskin on sugar beet. *Applied and Environmental Microbiology* **69**, 2356–2360.

Miyanishi, M., Kusume, T., Saito, M. & Tamada, T. (1999) Evidence for three groups of sequence variants of *Beet necrotic yellow vein virus* RNA5. *Archives of Virology* **144**, 879–892.

Mouhanna, A.M., Nasrallah, A., Langen, G. & Schlösser, E. (2002) Surveys for *Beet necrotic yellow vein virus* (the cause of Rhizomania), other viruses, and soil-borne fungi infecting sugar beet in Syria. *Journal of Phytopathology* **150**, 657–662.

Nielsen, S.L., Nicolaisen, M., Scheel, C. & Dinesen, I.G. (2001) First record of *Beet necrotic yellow vein virus* in Denmark. *Plant Disease* **85**, 559.

Pelsy, F. & Merdinoglu, D. (1996) Identification and mapping of random amplified polymorphic DNA markers linked to a rhizomania resistance gene in sugar beet (*Beta vulgaris* L.) by bulked segregant analysis. *Plant Breeding* **115**, 371–377.

Peters, D. (1988) A conspectus of plant species as hosts for viruses causing beet yellows diseases. In: *Virus Yellows Monograph*. Institut International de Researches Betteravieres, Brussels, pp. 87–117.

Petherbridge, F.R. & Stirrup, H.H. (1935) *Pests and Diseases of the Sugar-beet, Ministry of Agriculture* Bulletin no. 95. Her Majesty's Stationery Office, London.

Piemeisel, R.L. (1932) Weedy abandoned lands and the weed hosts of the beet leafhopper. *US Department of Agriculture circular* no. 229.

Prillwitz, H. & Schlosser, E. (1993a) Interactions between *Beet soil-borne virus* (BSBV2) and *Beet necrotic yellow vein virus* (BNYVV). *Proceedings of the Symposium of the International Working Group on Plant Viruses with Fungal Vectors, 4th Denver, American Society of Sugar Beet Technologists*. pp. 71–74.

Prillwitz, H. & Schlosser, E. (1993b) *Beet soil-borne virus* occurrence symptoms and effect on plant development. *International Symposium on Crop Protection*. Gent, Belgium, May 5, 1992, pp. 295–302.

Proesler, G. (1966) Beziehungen zwischen der Ruben Krauselvirus. II: Injection- versuche. *Phytopathologische Zeitschrift* **56**, 213–237.

Proesler, G. (1983) *Beet leaf curl virus*. CMI/AAB Description of Plant Viruses no. 268.

Putz, C. (1977) Composition and structure of *Beet necrotic yellow vein virus*. *Journal of General Virology* **35**, 397–401.

Putz, C., Wurtz, M., Merdinoglu, D., Lemaire, O. & Valentin, P. (1988) Physical and biological properties of *Beet necrotic yellow vein virus* isolates. In: Cooper, J.I. & Asher, M.J.C. (eds) *Viruses with Fungal Vectors. Developments in Applied Biology 2*. Association of Applied Biologists, Wellesbourne, pp. 83–97.

Qi, A., Dewar, A.M. & Harrington, R. (2004) Decision making in controlling virus yellows of sugar beet in the UK. *Pest Management Science* **60**, 727–732.

Quanjer, H.M. (1934) Enkele kenmarken der 'vergelings' – Ziekte van suiker-en voederbieten ter onderscheiding van de 'zwarte houtvaten'- ziekte. *Tijdschrift over Plantenziekten* **40**, 201–214.

Reed, R.R. & Falk, B.W. (1989) Purification and partial characterization of *Beet yellow stunt virus*. *Plant Disease* **73**, 358–362.

Resca, R., Basaglia, M., Poggiolini, S., Vian, P., Bardin, S., Walsh, U.F., Barreiros, C.M.E., O'Gara, F., Nuti, M.P., Casella, S. & Peruch, U. (2001) An integrated approach for the evaluation of biological control of the complex *Polymyxa betae/Beet Necrotic Yellow Vein Virus*, by means of seed inoculants. *Plant and Soil* **232**, 215–226.

Reza, A., Mohammad, M., Mahmoud, M., Sadeghian, S.Y., Ghannadha, M.R. & Ramatollah, I. (2003) The inheritance of resistance to *Beet necrotic yellow vein virus* (BNYVV) in *B. vulgaris* subsp. *maritima*, accession WB42: statistical comparisons with Holly-1–4. *Euphytica* **132**, 363–373.

Ribbands, C.R. (1964) The control of the sources of virus yellows of sugar beets. *Bulletin of Entomological Research* **54**, 661–674.

Richard-Molard, M. (1984) Beet rhizomania disease: the problem in Europe. *Proceedings of the British Crop Protection Council – Pests and Diseases. Vol.2*. pp. 837–845.

Richard-Molard, M. & Cariolle, M. (2001) Biotic and abiotic stress and genetic improvement in France. In: *Proceedings of the 64th IIRB Congress*. Bruges, pp. 153–158.

Roland, G. (1936) Recherches sur la jaunisse de la betterave et quelques observations sur la mosaique de cette plant. *Sucrerie Belge* **55**, 213–293.

Roland, G. (1955) Sur une nouvelle plante-hôte du virus de la jaunisse de betterave (*Beta* virus 4 Roland et Quanjer). *Parasitica* **11**, 124–125.

Ruppel, E.G. & Duffus, J.E. (1971) Mechanical transmission, host range, and physical properties of *Beet yellow vein virus. Phytopathology* **61**, 1418–1422.

Rush, C.M. (2003) Ecology and epidemiology of benyviruses and plasmodiophorid vectors. *Annual Review of Phytopathology* **41**, 567–592.

Russell, G.E. (1958) Sugar beet yellows: a preliminary study of the distribution and interrelationships of viruses and virus strains found in East Anglia, 1955–57. *Annals of Applied Biology* **46**, 393–398.

Russell, G.E. (1965) The host range of some English isolates of beet yellowing viruses. *Annals of Applied Biology* **55**, 245–252.

Russell, G.E. (1971) *Beet mosaic virus.* CMI/AAB Description of Plant Viruses no. 53.

Saito, M., Kiguchi, T., Kusume, T. & Tamada, T. (1996) Complete nucleotide sequence of the Japanese isolates of *Beet necrotic yellow vein virus* RNA and comparison with European isolates. *Archives of Virology* **141**, 2163–2175.

Schaufele, W.R. & Buttner, G. (2002) Studies on beet soil – Part 3: recycling of beet soil from sugar factories on fields with sugarbeet in the crop rotation. *Zuckerindustrie* **127**, 163–170.

Schliephake, E., Graichen, K. & Rabenstein, F. (2000) Investigations on the vector transmission of the *Beet mild yellowing virus* (BMYV) and the *Turnip yellows virus* (TuYV). *Zeitschrift fur Pflanzenkrankheiten Pflanzenschutz* **107**, 81–87.

Schlosser, E. (1988) Epidemiology and management of *Polymyxa betae* and *Beet necrotic yellow vein virus.* In: Cooper, J.I. & Asher, M.J.C. (eds) *Viruses with Fungal Vectors. Developments in Applied Biology 2.* Association of Applied Biologists, Wellesbourne, pp. 281–292.

Schmit, J.F., Meunier, A., Stas, A., Legreve, A., Bragard, C. & Wauters, A. (2002) A real explosion of rhizomania in 2002. *Betteravier (Bruxelles)* **36**, 8–10.

Schmutterer, H. & Ehrhardt, P. (1966) Zur Kenntnis des WirtspflanzenKreises beim RubenKrausel-virus (Beta virus 3). *Zeitschrift fur Pflanzenkrankheiten und Pflanzenschutz* **73**, 271–283.

Scholten, O. & Lange, W. (2000) Breeding for resistance to rhizomania in sugar beet: a review. *Euphytica* **112**, 219–231.

Scholten, O.E., Jansen, R.C., Keizer, L.C.P., Bock, T.S.M.D. & Lange, W. (1996) Major genes for resistance to *Beet necrotic yellow vein virus* (BNYVV) in *Beta vulgaris. Euphytica* **91**, 331–339.

Scholten, O.E., Bock, T.S.M.D., Klein-Lankhorst, R.M. & Lange, W. (1999) Inheritance of resistance to *Beet necrotic yellow vein virus* in *Beta vulgaris* conferred by a second gene for resistance. *Theoretical and Applied Genetics* **99**, 740–746.

Schubert, J., Rabenstein, F., Graichen, K. & Richter, K. (1998) Comparison of the 5'-end nucleotide sequences of luteoviruses from oilseed rape and sugar beet. *Archives of Phytopathology and Plant Protection* **31**, 519–530.

Scott, H.A. (1963) Purification of *Cucumber mosaic virus. Virology* **20**, 103–106.

Sherwood, J.L. & Rush, C.M. (1999) *Proceedings of the Symposium of the International Working Group on Plant Viruses with Fungal Vectors, 4th Denver.* American Society of Sugar Beet Technologists.

Smith, H.G. & Hallsworth, P.B. (1990) The effects of yellowing viruses on yield of sugarbeet in field trials, 1985 and 1987. *Annals of Applied Biology* **116**, 503–511.

Stanley, J., Markham, P.G., Callis, R.J. & Pinner, M.S. (1986) The nucleotide sequence of an infectious clone of the geminivirus *Beet curly top virus. The EMBO Journal* **5**, 1761–1767.

Staples, R., Jansen, W.P. & Anderson, L.W. (1970) Biology and relationship of the leafhopper *Aceratagallia calcaris* to yellow vein disease of sugar beets. *Journal of Economic Entomology* **63**, 460–463.

Stas, A., Meunier, A., Schmit, J.F. & Bragard, C. (2001a) First report of Beet virus Q in Belgium. *Plant Disease* **85**, 1288.

Stas, A., Meunier, A., Schmit, J.F., Marlier, A., Steyer, S. & Bragard, C. (2001b) The Beet soilborne pomovirus in Belgium and relationship with rhizomania. *Mededelingen – Faculteit Landbouwkundige en Toegepaste Biologische Wetenschappen, Universiteit Gent. Faculteit Landbouwkundige en Toegepaste Biologische Wetenschappen, Ghent, Belgium* **66**, 39–45.

Stenger, D.C. & McMahon, C.L. (1997) Genotypic diversity of *Beet curly top virus* populations in the western United States. *Phytopathology* **87**, 737–744.

Stenger, D.C., Carbonaro, D. & Duffus, J.E. (1990) Genomic characterization of phenotypic variants of *Beet curly top virus. Journal of General Virology* **71**, 2211–2215.

Stevanato, P., Biaggi, M.D., Skaracis, G.N., Colombo, M., Mandolino, G. & Biancardi, E. (2001) The sea beet (*Beta vulgaris* L. ssp. *maritima*) of the Adriatic coast as source of resistance for sugar beet. *Sugar Tech World Media, New Delhi, India* **3**, 77–82.

Stevens, M., Smith, H.G. & Hallsworth, P.B. (1994a) The host range of beet yellowing viruses among common arable weed species. *Plant Pathology* **43**, 579–588.

Stevens, M., Smith, H.G. & Hallsworth, P.B. (1994b) Identification of a second distinct strain of BMYV using monoclonal antibodies and transmission studies. *Annals of Applied Biology* **125**, 515–520.

Stevens, M., Smith, H.G. & Hallsworth, P.B. (1995) Detection of luteoviruses, beet mild yellowing virus and beet western yellows virus, in aphids caught in sugar beet and oilseed rape crops 1990–1993. *Annals of Applied Biology* **127**, 309–320.

Stevens, M., Hallsworth, P.B. & Smith, H.G. (2004) The effects of *Beet mild yellowing virus* and *Beet chlorosis virus* on the yield of field-grown sugar beet, 1997, 1999 and 2000. *Annals of Applied Biology* **144**, 113–119.

Stevens, M., Freeman, B., Liu, H.-Y., Herrbach, E. & Lemaire, O. (2005a) Beet poleroviruses: close friends or distant relatives? *Molecular Plant Pathology* **6**, 1–9.

Stevens, M., Patron, N.J., Dolby, C.A., Weekes, R., Hallsworth, P.B., Lemaire, O. & Smith, H.G. (2005b) Distribution and properties of geographically distinct isolates of sugar beet yellowing viruses. *Plant Pathology* **54**, 100–107.

Suarez, M.B., Grondona, I., Garcia-Benavides, P., Monte, E. & Garcia-Acha, I. (1999) Characterization of beet necrotic yellow vein furovirus from Spanish sugar beets. *Interna-*

tional Microbiology **3**, 87–92.

Sugars, J.M., Lennon, E.A., Plumb, R.T. & White, R.F. (1998). Sugar beet yellow net complex contains a luteovirus component. *Plant Pathology* **47**, 89–94.

Sylvester, E.S. (1948) The yellow-net disease of sugar beets. *Phytopathology* **38**, 429–439.

Sylvester, E.S. (1956) Beet yellows virus transmission by the green peach aphid. *Journal of Economic Entomology* **49**, 789–800.

Sylvester, E.S. (1958) Latent period phenomena in transmission of sugar beet yellow net virus by green peach aphids. *Journal of Economic Entomology* **51**, 812–818.

Tamada, T. (1999) Benyviruses. In: Granoff, A. & Webster, R.G. (eds) *Encyclopedia of Virology 2nd edition*. Academic Press, San Diego, pp. 154–160.

Tamada, T. & Baba, T. (1973) *Beet necrotic yellow vein virus* from rhizomania-affected sugar beet in Japan. *Annals of the Phytopathological Society of Japan*, 325–332.

Tamada, T., Baba, T. & Abe, H. (1971) A virus isolated from sugar beet showing 'Rizomania' like symptoms and its transmission in soil. *Proceedings of the Sugar Beet Research Association of Japan*. 13, pp. 179–186.

Tamada, T., Shirako, Y., Abe, H., Saito, R., Kiguchi, T. & Harada, T. (1989) Production and pathogenicity of isolates of *Beet necrotic yellow vein virus* with different numbers of RNA components. *Journal of General Virology* **70**, 3399–3409.

Thomas, P.E. (1970) Isolation and differentiation of five strains of curly top virus. *Phytopathology* **60**, 844–848.

Thomas, P.E. & Mink, G.I. (1979) *Beet curly top virus. CMI/AAB Descriptions of Plant Viruses* No. 210.

Thomas, P.E. & Bowyer, J.W. (1980) Properties of tobacco yellow dwarf and bean summer death viruses. *Phytopathology* **70**, 214–217.

Thornhill, W.A. & Hinckes, J.A. (1986) Infectivity of alate aphids with beet yellowing viruses. In: *Report of Rothamsted Experimental Station for 1985*, Part 1, 46.

Tomlinson, J.A. & Carter, A.L. (1970) Studies on the seed transmission of *Cucumber mosaic virus* in chickweed (*Stellaria media*) in relation to the ecology of the virus. *Annals of Applied Biology* **66**, 381–386.

Torrance, L. & Mayo, M.A. (1997) Proposed re-classification of furoviruses. *Archives of Virology* **142**, 435–439.

Tuitert, G. (1990) Assessment of the inoculum potential of *Polymyxa betae* and *Beet necrotic yellow vein virus* (BNYVV) in soil using the most probable number method. *Netherlands Journal of Plant Pathology* **96**, 331–341.

Tuitert, G. & Hofmeester, Y. (1994) Epidemiology of *Beet necrotic yellow vein virus* in sugar beet at different initial inoculum levels in the presence of absence of irrigation: disease incidence, yield and quality. *European Journal of Plant Pathology* **100**, 19–53.

Van Geyt, J.P.C., Lange, W., Oleo, M. & De Bock, T.S.M. (1990) Natural variation within the genus *Beta* and its possible use for breeding sugar beet: a review. *Euphytica* **49**, 57–76.

Van Schreven, D.A. (1936) De vergelingsziekte bij de biet en haar oorzaak. *Meddelandefran Institutet foer Suikerbiet* **6**, 1–36.

Volkmann, D., Stanarius, A. & Kuhne, T. (1990) Studies on the elimination of *Beet cryptic virus* from sugar beet plants (*Beta vulgaris* L. var. *altissima*) by heat treatment and meristem culture. *Archiv fur Phytopathologie und Pflanzenschutz* **25**, 413–420.

Wang, Q., Wang, H., Yu, J. & Liu, Y. (2003) Screening of actinomyces against *Polymyxa betae* and detection of effectiveness on rhizomania disease. *Journal of China Agricultural University* **8**, 56–60.

Watson, M.A. (1940) Studies on the transmission of sugar beet yellows virus by the aphid, *Myzus periscae* (Sulz.). *Proceedings of the Royal Society, London, Series B* 128, pp. 535–552.

Watson, M.A. (1952) Beet yellows virus and other yellowing virus diseases of sugar beet. *Rothamsted Experimental Station Report for 1951*, pp. 157–167.

Watson, M.A. (1962) Yellow-net virus of sugar beet. 1: Transmission and some properties. *Annals of Applied Biology* **50**, 451–460.

Watson, M.A. (1966) The relation of annual incidence of beet yellowing viruses in sugar beet to variations in weather. *Plant Pathology* **15**, 157–167.

Watson, M.A., Heathcote, G.D., Lauckner, F.B. & Sowray, P.A. (1975) The use of weather data and counts of aphids in the field to predict the incidence of yellowing viruses of sugar-beet crops in England in relation to the use of insecticides. *Annals of Applied Biology* **81**, 181–198.

Webb, C.R., Gilligan, C.A. & Asher, M.J.C. (2000) Modelling the effect of temperature on the development of *Polymyxa betae*. *Plant Pathology* **49**, 600–607.

Weber, W.E., Borchardt, D.C. & Koch, G. (2000) Marker analysis for quantitative traits in sugar beet. *Plant Breeding* **119**, 97–106.

Werker, A.R., Dewar, A.M. & Harrington, R. (1998). Analysis of virus yellows incidence in sugar beet in relation to migrations of the vector, *Myzus persicae*. *Journal of Applied Ecology* **35**, 811–818.

White, R.F. & Woods, R.D. (1978) *Beet cryptic virus* in some varieties of *Beta vulgaris*. *Phytopathologische Zeitschrift* **91**, 91–93.

Williams, C.T. (1995) Effects of plant age, leaf age and virus yellows infection on the population dynamics of *Myzus persicae* (Homoptera: Aphididae) on sugar beet in field plots. *Bulletin of Entomological Research* **85**, 557–567.

Wintermantel, W.M., Crook, T. & Fogg, R. (2003) First report of rhizomania disease of sugar beet caused by *Beet necrotic yellow vein virus* in the Great Lakes production region. *Plant Disease* **87**, 201.

Wisler, G.C. & Duffus, J.E. (2000) A century of plant virus management in the Salinas valley of California, 'East of Eden'. *Virus Research* **71**, 161–169.

Wisler, G.C., Liu, H.-Y., Li, R.H. & Duffus, J.E. (1996) Comparative molecular analysis of several BNYVV- and BSBMV-related furoviruses infecting sugarbeet. In: *Proceedings of the 3rd Symposium of International Working Group of Plant Viruses with Fungal Vectors*. Dundee, Scotland, pp. 53–60.

Wisler, G.C., Widner, J.N., Duffus, J.E., Liu, H.-Y. & Sears, J.L. (1997) A new report of rhizomania and other furoviruses infecting sugar beet in Minnesota. *Plant Disease* **81**, 229.

Wisler, G.C., Lewellen, R.T., Sears, J.L., Wasson, J.W., Liu, H.-Y. & Wintermantel, W.M. (2003) Interactions between *Beet necrotic yellow vein virus* and *Beet soil-borne mosaic virus* in sugar beet. *Plant Disease* **87**, 1170–1175.

Wright, D.M., Fletcher, J.T. & McPherson, G.M. (1989) Detection of *Beet yellow stunt virus* in England. *Plant Pathology* **38**, 297–299.

Xie, W.S., Antoniw, J.F., White, R.F. & Wood, R.D. (1993) A third cryptic virus in beet (*Beta vulgaris*). *Plant Pathology* **42**, 465–470.

Chapter 12

Fungal and Bacterial Diseases

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INTRODUCTION

Fungal and virus diseases have played a major role in the development of the sugar beet crop and, even today, constitute a major constraint on production in some areas. Many problems have largely been solved through the development of resistant cultivars or the use of fungicides, but new diseases inevitably arise as cropping practices or climatic conditions change. Intensification of production leading to tighter crop rotations, along with the increased movement of soil by larger machinery, has contributed to an increase in the incidence and severity of a number of soil-borne diseases (e.g. rhizomania and rhizoctonia root rot), especially in Europe. Changes in cultivar use such as the widespread deployment of rhizomania-resistant cultivars worldwide in recent years, with their generally greater susceptibility to powdery mildew and rust, have also brought new problems.

Soil-borne seedling diseases, such as those caused by *Aphanomyces cochlioides* and *Pythium* spp. have been controlled very effectively by the widespread introduction of fungicides applied to the seed. Also, since the 1990s, new chemistry, in the form of triazole and strobilurin fungicides, has been increasingly applied to the sugar beet crop, giving a broader spectrum of activity against foliar diseases. Continuing environmental and economic pressures to reduce pesticide use will inevitably place greater emphasis on genetic resistance as the primary means of disease control. In particular, considerable progress is likely to be made over the next few years in improving resistance to cercospora leaf spot and rhizoctonia root rot, both diseases of global significance. This will add to the significant achievement of plant breeders over the past decade in developing high-yielding cultivars with resistance to rhizomania.

This chapter reviews the significant fungal and bacterial diseases of sugar beet worldwide with emphasis on their biology, symptomatology, distribution and current methods of control.

SEEDLING DISEASES

Aphanomyces seedling disease

Symptoms

Generally, seedling emergence is not affected, but 1–3 weeks after emergence a dark grey, water-soaked lesion develops on the hypocotyl. The lesion expands rapidly, and soon the entire hypocotyl appears dark grey or brown to black and shrinks to become threadlike, hence the term 'blackleg' or 'black root'. Occasional spread of the lesion up to the base of the cotyledon leaves is generally diagnostic for this disease (Plate 37). Infected seedlings are stunted and have reduced vigour; they may fall over and die or be broken off by the action of wind, but often they survive and show some recovery. Plants surviving disease at the seedling stage may develop the chronic root rot phase (see Aphanomyces root rot).

Causal agent

Aphanomyces cochlioides Drechs. is a chromist (previously classified as a fungus) in the class Oomycetes. Hyphae are hyaline, 3–9 μm in diameter, and coenocytic. Slender, irregular, filamentous sporangia (up to 3–4 mm in length) are produced at right angles to the parent hypha. Primary zoospores differentiate within sporangia, are extruded and encyst in clusters at the ends of long evacuation tubes from sporangial elements. This can be observed by incubating infected tissue in sterile water (Byford & Stamps, 1975). Biflagellate, reniform, secondary zoospores emerge from primary zoospore cysts and, after a period of motility, these encyst and finally germinate by germ tube. The teleomorph stage develops in older rotted tissue as subspherical, terminal, smooth-walled oogonia, 20–29 μm in diameter, each having one to five (usually three to four) terminal antheridia borne on branches wrapped around the oogonium. After fertilization, a smooth, hyaline to yellowish oospore develops, which is 16–24 μm in diameter.

Distribution

Aphanomyces seedling disease is prevalent in the USA, Canada, Chile, France, Germany, Hungary, Japan, the Netherlands, Spain, the countries of the former USSR and the UK. *Amaranthus retroflexus*, *Chenopodium album* and spinach have been reported as natural hosts of the pathogen, which has also has been isolated from *Mollugo verticillata*, *Saponaria ocymoides* and *Tetragonia tetragonioides*. Schneider (1965) reported 28 species in eight families as new experimental hosts and 19 species in six families as natural hosts of the chromist. The disease is also a problem in red beet (Martin, 2003).

Epidemiology

Oospores survive for long periods in soil or infected plant debris. Under conditions of high soil moisture, oospores germinate by germ tube, which can directly infect the host, or produce an apical sporangium giving rise to zoospores (Drechsler, 1929). These can swim to the host and eventually form germ tubes. Host penetration probably is direct and may be aided by endopolygalacturonase produced by the chromist (Herr, 1977). All stages of sugar beet can be attacked, but seedlings are more susceptible than older plants (Buchholtz & Meredith, 1944). The pathogen can be spread in infested soil and locally by movement of asexual zoospores. Zoospore-attractant chemicals (Tahara *et al.*, 1999) that have been found in sugar beet roots (Islam *et al.*, 2003) may play a role in infection.

High soil moisture and free water are needed for sporangium formation and zoospore dispersal, but little disease progress occurs if soil temperature is too low. Warren (1948) reported that disease development increased as soil temperatures increased from 18 to 32°C, with an optimum around 25°C. Thus, sugar beet crops planted in cool soil often survive infection by *Aphanomyces*, or, if soils cool down after initial infection, the plants tend to recover, although they remain stunted and may show symptoms of latent infection.

Other environmental factors may affect disease intensity and progress. Payne *et al.* (1994) found that the disease was more frequent in acid soils. They found no association between soil type and disease severity, although Fink and Buchholtz (1954) found that more disease occurred in heavy than lighter soils. The disease is more prevalent in infertile soils, particularly those that are phosphate-deficient (Coons *et al.*, 1946).

Control

Early sowing into cool moist soils enables seedlings to emerge and develop resistance before soils warm and pathogen activity is enhanced. High soil fertility, especially high levels of phosphorus, promotes rapid seedling growth and reduces the severity of black root (Coons *et al.*, 1946; Warren, 1948).

Rotation with non-susceptible crops such as maize, soybean, potatoes, or small grains reduces black root severity in subsequent sugar beet crops (Afanasiev *et al.*, 1942; Coons *et al.*, 1946). Crops such as alfalfa (lucerne), beans, sweetclover and clover increase disease incidence and intensity, and should not precede sugar beet (Coons & Kotila, 1935).

Seedling disease caused by *A. cochlioides* is more difficult to control by seed treatment than that caused by *Pythium* spp. Metalaxyl, which has specific activity against *Pythium* spp., has shown some activity against *Aphanomyces* (Windels & Jones, 1989). Hymexazol is particularly effective (Payne & Williams, 1990) and is now used as a standard treatment in most countries (Cooke *et al.*, 1989).

Attempts to develop bacterial (Williams & Asher, 1996) or fungal (Grondona *et al.*, 1997; McQuilken *et al.*, 1998) biocontrol agents have yet to achieve commercial application.

Early improvements in resistance to *A. cochlioides* in sugar beet cultivars were summarized by Doxtator and Finkner (1954). Later, methods for producing inoculum, inoculation, and selecting at the seedling stage in the glasshouse led to the development of lines having relatively high levels of resistance (Schneider, 1954; Coe & Schneider, 1966). Most commercial hybrids incorporating these resistant germplasms have been developed for north central USA.

Pythium damping-off

Symptoms

Soil-borne *Pythium* spp. are aggressive colonizers of seed, particularly under wet conditions that slow germination, and most damage occurs pre-emergence resulting in poor plant populations. However, water-soaked, grey-black lesions can also develop on the hypocotyls of germinated seedlings, causing post-emergence damping-off (Plate 38).

Causal agents

Several species of *Pythium* have been isolated from diseased sugar beet seedlings (Vestberg *et al.*, 1982; O'Sullivan & Kavanagh, 1992) but the predominant pathogenic species under temperate conditions appear to be *P. ultimum* Trow, *P. sylvaticum* Campbell and Hendrix and *P. intermedium* de Bary. Isolates previously identified as *P. debaryanum*, which is not recognized as a separate species by Van der Plaats-Niterink (1981), were probably one of these. Under warm soil conditions, *P. aphanidermatum*, a high temperature species, is often the most serious pathogen (Leach, 1986). All produce abundant non-septate mycelia and, in some cases (e.g. *P. aphanidermatum*, *P. ultimum* var. *sporangiiferum*), sporangia and zoospores when diseased tissue is incubated in sterile water at room temperature. Characteristic thick-walled oospores, enabling long-term survival, are produced in infected tissue. A full description of these species is given by Van der Plaats-Niterink (1981).

Distribution

Pythium spp. are ubiquitous in agricultural soils and can cause plant losses wherever high soil moisture and other factors impede seed germination and emergence. In the past, particular problems have been recorded in Sweden, Finland and France but because effective fungicidal seed treatments are now so widely used the prevalence of these fungi is largely overlooked.

Control

In general, *Pythium* spp. have a wide host range and can survive for several years in the soil as oospores. Despite reports of disease levels being influenced by the nature of the previous crop, results have often been inconsistent and 'suppressive' crops have not been widely adopted as a control measure. Maintenance of good drainage and a well aerated seedbed will favour more rapid germination and disease 'escape'. Protection of the seed with fungicides, particularly metalaxyl, thiram or hymexazol, is very effective at controlling *Pythium*; pelleting the seed gives additional benefits by providing a physical barrier to infection (Asher & Dewar, 1994). Potential alternatives to chemical control include seed priming treatments to accelerate germination and emergence, and biological control agents (Bardin *et al.*, 2003), which could be applied as part of the priming process (Walker *et al.*, 2004).

Rhizoctonia damping-off

Symptoms

The fungus can induce some pre-emergence damping-off but usually affects seedlings after emergence. A dark brown lesion begins just below the soil surface and extends up the hypocotyl, with a sharp line between diseased and healthy tissue. When the hypocotyl is girdled, the seedling collapses and dies.

R. solani can also colonize the roots of young plants that survive initial attack, causing 'fangy' roots and a proliferation of lateral rootlets (Plate 39). This leads to characteristic kite-shaped patches in crops, where plants in the centre have been killed and those immediately surrounding are stunted in growth (Payne, 1986). The fungus also causes foliar blight (see Rhizoctonia foliar blight) and a serious root rot later in the season (see Rhizoctonia root rot).

Causal agent

Rhizoctonia solani Kühn (teleomorph, *Thanatephorus cucumeris* (Frank) Donk) is a basidiomycete in the family Ceratobasidiaceae. The imperfect stage of the fungus has been characterized by Parmeter and Whitney (1970). Hyphae are pale to dark brown, branching near the distal septum of hyphal cells, often nearly at right angles; branch hyphae are commonly constricted at the point of origin. Aggregates of thick-walled, dark brown monilioid cells ('barrel-shaped cells', 'bulbils') are also produced. Individual cells are multinucleate and have a prominent dolipore septal apparatus (Bracker & Butler, 1963). No asexual spores are produced by *R. solani*.

Genetic relationships of *R. solani* are determined by their relative ability to anastomose in dual cultures (see Rhizoctonia root rot section). Isolates in anastomosis groups AG-4 and AG-2-2 can cause seedling damping off.

Epidemiology

The fungus survives as hyphae, monilioid cells and sclerotia in organic debris in soil (Boosalis & Scharen, 1959; Roberts & Herr, 1979), becoming active when soil temperatures reach 25–33°C (LeClerg, 1939). Sclerotia have been reported to survive in soil for several years (Sherwood, 1970). Damping-off of seedlings may occur if sugar beet crops are sown in warm soil, and infection may occur in petioles, crowns, or roots of older plants when soil temperatures increase.

Isolates (AG-2-2) of the fungus from sugar beet have induced damping-off in barley, bean, maize, milo, muskmelon, *Amaranthus retroflexus*, red beet, soybean, sugar beet and wheat (Ruppel, 1972). While Ruppel (1972) reported no damping-off in alfalfa (lucerne), LeClerg (1934) reported damping-off of alfalfa, as well as cabbage, fodder beet, pea, rutabaga, sugar beet, sweet clover, Swiss chard, table beet, tomato, and turnip, with three root-rot isolates. Potato also serves as a host to some isolates (Schuster & Harris, 1960).

Control

Sugar beet seeds planted into warm soils require a protectant fungicide for control of damping-off, and thiram is used in the USA. The potential for replacing chemicals with biological control agents is also being explored (Abada, 1994; Thrane *et al*., 2001).

Phoma seedling disease

Symptoms

Under cool, moist conditions, *Phoma betae* can induce pre-emergence damping-off, but seedlings are usually attacked after they emerge, resulting in dark brown to black hypocotyls (blackleg) and retarded growth (Leach, 1986). Some seedlings are killed, but many survive and recover to varying degrees. A shallow, dark brown rot often develops in the crown tissue of those seedlings that recover from the blackleg phase (Schneider & Whitney, 1986). Such roots may develop a serious postharvest rot when they are stored before processing (see Phoma root rot).

Causal agent

The teleomorph *Pleospora bjoerlingii* (Byford) is an ascomycete in the order Pleosporales and family Pleosporaceae. *Phoma betae* (Frank) is in the Fungi Imperfecti (Deuteromycetes) and is the most common form in nature. Fruiting bodies (pycnidia and pseudothecia) and spores are rarely found on infected seedlings and are described elsewhere (see Phoma leaf spot). Identification of *P. betae* can be achieved by isolating the fungus on water agar and examining cultures for the characteristic 'holdfasts' (Mangan, 1971).

Epidemiology

The fungus is seed-borne and can survive in crop debris in soil for up to 26 months (Bugbee & Soine, 1974). Severe disease usually occurs at temperatures of 5–12°C (Nölle, 1960). The pathogen can attack sugar beet, table beet and fodder beet, as well as *Chenopodium album* and oats (Bugbee & Soine, 1974). Physiological specialization in the pathogen has been reported (Bugbee, 1979).

Control

To avoid colonization of ripening seed by *P. betae*, seed crops should be grown in areas which are warm and dry during the period of seed maturation and cultivation and harvesting methods that delay seed ripening should be avoided (Byford, 1978). Harvested seed should be processed to remove the outer cortical layers which are most likely to harbour the fungus (Leach & MacDonald, 1976). Fungicides, especially thiram, have been successfully used to control seed-borne infection. For deep-seated infection, steeping seed in a liquid suspension for 8–16 h at 25°C is recommended (Durrant *et al.*, 1988). Biological control with *Pythium oligandrum* applied to seed has been demonstrated in glasshouse tests (Walther & Gindrat, 1987) but has not been developed for field use.

FOLIAR DISEASES

Cercospora leaf spot

Symptoms

Cercospora leaf spot is typified by delimited, circular spots (2–5 mm) that develop first on older leaves (Ruppel, 1986). Heart leaves are usually lesion-free. Lesions are tan to light brown with dark brown or reddish-purple margins. Elongated lesions occur on petioles, and lesions may occur on exposed sugar beet crowns (Giannopolitis, 1978b). Minute black dots (pseudostromata) are often visible in the centre of mature lesions. Under humid conditions, the spots become grey and velvety with conidiophores and conidia. Individual spots coalesce as the disease progresses, and large areas or entire leaves become necrotic (Plate 40). Blighted leaves eventually collapse and fall to the ground but remain attached to the crown. All above-ground parts of seed plants, including seed clusters, are affected.

Causal agent

Cercospora beticola Sacc. is an ascomycete in the Mycosphaerellaceae (Stewart *et al.*, 1999). Hyphae are hyaline to pale olivaceous brown, septate, 2–4 µm in diameter. In the host, the hyphae grow intercellularly and form pseudostromata in substomatal cavities from which conidiophores are borne in clusters.

Conidiophores are 10–100 µm (mostly 46–60 µm) × 3–5.5 µm, unbranched, straight or flexous, mildly geniculate, sparingly septate, pale brown near the base and almost hyaline near the apex, with small conspicuous conidial scars at the geniculations and the apex. Conidia, 20–200 × 2.5–4 µm (mostly 36–107 × 2–3 µm), are smooth-walled, straight to slightly curved, hyaline, acicular, gradually attenuated from the truncate base, with 3–14 (sometimes up to 24) septa. While no sexual stage is known for *C. beticola*, DNA sequence analysis indicates a probable *Mycosphaerella* teleomorph (Stewart *et al.*, 1999; Goodwin *et al.*, 2001).

Distribution

Cercospora leaf spot is one of the most widespread and destructive foliar diseases of sugar beet. Severe epiphytotics occur in Austria, Bosnia and Herzegovinia, Bulgaria, southern France and Germany, Greece, Hungary, India, Italy, Japan, Kazakhstan, Macedonia, Morocco, parts of the Russian Federation, Romania, Slovenia, Spain, Turkey, the USA, and Yugoslavia (Holtschulte, 2000). The disease has been reported in other parts of Europe, Chile, China, and Syria (Holtschulte, 2000).

The fungus attacks most cultivated and wild species of *Beta*, spinach (*Spinacia oleracea*), and species of *Amaranthus, Atriplex, Chenopodium,* and *Plantago* (Fransden, 1955). Vestal (1933) obtained infection in 24 species with artificial inoculation.

Epidemiology

Conidia of *C. beticola* persist in infected leaf debris for only 1–4 months (Pool & McKay, 1916), but pseudostromata may survive for 1–2 years and serve as sources of primary inoculum (Pool & McKay, 1916; McKay & Pool, 1918; Canova, 1959b). Other sources of inoculum include infested seed (McKay & Pool, 1918; Canova, 1959b) and weed hosts (Vestal, 1933). Researchers also have reported infection following root inoculation (Vereijssen & Schneider, 2003) indicating that soil-borne inoculum could be a factor.

Conidial production and infection of sugar beet is favoured by day temperatures of 27–32°C, night temperatures above 16°C, and relative humidity above 60% for at least 15–18 hours each day (Pool & McKay, 1916). During periods of high relative humidity (98–100%), sporulation can occur between 10–35°C, with an optimum of 30°C (Bleiholder & Weltzien, 1972). Severe epidemics can be expected when the relative humidity stays above 96% for 10–12 hours each day for 3–5 days and the temperature remains above 10°C (Mischke, 1960). Conidial release is effected by rain and dew (Meredith, 1967) and conidia are disseminated by rain-splash (Pool & McKay, 1916; Carlson, 1967), wind (McKay & Pool, 1918; Lawrence & Meredith, 1970), irrigation water, insects and mites (McKay & Pool, 1918; Canova, 1959a; Meredith, 1967).

Control

An integrated approach is recommended for controlling cercospora leaf spot, including cultural measures, resistant cultivars, and fungicides (Ruppel, 1986; Meriggi *et al.*, 2000; Franc *et al.*, 2001). A 3-year rotation with non-host crops should be practised, with removal of infected tops to reduce inoculum potential for subsequent sugar beet (Pool & McKay, 1916; Pundhir & Mukhopadhyay, 1987). Deep ploughing hastens the breakdown of infected tops, leading to death of the fungus (Canova, 1959b). Sugar beet cultivars with quantitative resistance to the pathogen are available and should be grown wherever the disease is endemic and important. Resistance to several biotypes of *C. beticola* has been stable in tests conducted in Europe and the USA (Smith, 1985). The use of biological control agents for cercospora leaf spot control has been investigated (Collins & Jacobsen, 2003) and shows some promise for the future.

Resistance to cercospora leaf spot that is used commercially is rate-reducing resistance rather than immunity (Rossi, 2000). Because there is no immunity to the disease, supplemental fungicide sprays often are necessary when conditions are favourable for leaf spot development. A number of different compounds has proved effective, provided they are used very early in the disease cycle, preferably with the first spray applied immediately before the onset of disease (Franc *et al.*, 2001). Prediction models based on the number of hours of high relative humidity and mean temperature have been used with some success in various areas to optimize fungicide spray schedules (Shane & Teng, 1984; Windels *et al.*, 1998). Strategies based on action thresholds have also been developed (Wolf & Verreet, 2002).

Of the protectant fungicides, organotins have given good disease suppression in the past (Wysong *et al.*, 1968; Kaw *et al.*, 1979). However, tolerance to the organotins has been found in several areas (Giannopolitis, 1978a; Cerato & Grassi, 1983; Maric *et al.*, 1984; Bugbee, 1995), limiting the effectiveness of these compounds.

Several systemic fungicides have been used for disease control, including benzimidazoles, demythylation inhibitors (DMIs), morpholines, and dithiocarbamates. However, resistance or tolerance to benzimidazoles (Georgopoulos & Dovas, 1973; Ruppel & Scott, 1974; D'Ambra *et al.*, 1975; Campbell *et al.*, 1998, Briere *et al.*, 2001) and DMIs (Karaoglanidis *et al.*, 2000a) have been reported. While benzimidazoles are still used in disease control, their exclusive use is not recommended. For the DMIs, disease control in the field still has been acceptable even in areas where resistance has been found (Karaoglanidis *et al.*, 2000a). Over time, control materials may need to change as fungicide sensitivity varies (Briere *et al.*, 2001). Alternating applications or using tank mixes of fungicides with differing modes of action (Ruppel, 1986; Meriggi *et al.*, 2000; Franc *et al.*, 2001) may delay the development of fungicide-resistant pathogen strains and thus is recommended.

Powdery mildew

Symptoms

Small, dispersed, radiating, whitish colonies of hyphae and conidia first appear on the lower, older leaves of sugar beet plants 2–6 months after sowing (Ruppel *et al.*, 1975b). The fungus spreads rapidly over the upper, and sometimes lower, leaf surfaces until all leaves may appear dusty-white from epiphytic mycelium and conidia (Plate 41). Underlying tissue may become chlorotic, eventually taking on a purplish-brown hue. The teleomorph stage, which has not been found in some areas, consists of minute, spherical, orange to brown or black ascocarps (cleistothecia) embedded in the fungal mycelium.

Causal agent

Erysiphe betae (Vanha) Weltz. (syn. *E. polygoni* DC) is an ascomycete in the order Erysiphales and family Erysiphaceae. Weltzien (1963) renamed the fungus *E. betae*, based on the specificity of the fungus to *Beta* species and differences in ascocarp size from that previously reported for *E .polygoni.* This nomenclature has been reaffirmed more recently (Braun, 1995; Francis, 2002).

The morphology of the fungus was summarized by Drandarevski (1969a). Hyaline, elliptic, one-celled conidia (30–56 × 13–20 μm) are formed basipetally in small chains on 60–100 μm long conidiophores arising from epiphytic hyphae on the surface of leaves. When mature, cleistothecia are black and spherical with a diameter of 75–135 μm. They have sparse, simple or branched hyaline appendages and usually contain four to eight asci. Asci are 45–85 × 30–50 μm, each with two to four hyaline, elliptic, smooth-walled ascopsores that measure 18–28 × 12–21 μm.

Distribution

Powdery mildew occurs almost wherever sugar beet is grown but is a serious disease in arid climates of the Middle East, Central Asia, southern Europe and the south-western USA. It can also predominate in temperate maritime regions with relatively mild winters, such as the UK.

The host range of *E. betae* from sugar beet is limited to *Beta* species, including all types of cultivated beets, sea beet (*B. vulgaris* ssp. *maritima*) and other wild *Beta* species (Ruppel & Tomasovic, 1977; Drandarevski, 1978; Luterbacher *et al.*, 2004). There are no known physiologic races of *E. betae.*

Epidemiology

Conidia are short-lived and the fungus probably survives in temperate climates as hyphae or haustoria in groundkeeper crowns, wild *Beta* spp., or over-wintering beet seed crops, producing new conidiophores and conidia when conditions are favourable. Asher and Williams (1991) have described a forecasting model for temperate maritime climates based on the severity of the preceding winter and its effect on surviving inoculum. Ascospores are apparently not important sources of primary inoculum (Mamluk, 1970).

Disease development was followed by Drandarevski (1969b), and the formation of the teleomorph stage studied by Mamluk and Weltzien (1973). Conidial production occurs most abundantly at 30–40% relative humidity. Conidia germinate by germ tube over a range of 0–100% relative humidity, with germination increasing as humidity increases, and at temperatures between 15 and 30°C (optimum 25°C). As hyphae of the pathogen grow epiphytically on the leaf surface, appressoria are formed from which infection hyphae (one per appressorium) directly penetrate the host epidermis or, occasionally, enter stomata. Nutrient-absorbing haustoria with six to fourteen lobes are formed within host cells. Secondary hyphae from conidia grow on the host surface, initiating secondary infections and the production of conidiophores and conidia. Cleistothecia develop at temperatures ranging from 12–22°C and a relative humidity of at least 30%, their abundance increasing with disease severity. Disease severity generally increases with the age of the plant at infection (Ruppel & Tomasovic, 1977), and, although disease development is faster when leaves are turgid, greater damage occurs in water-stressed plants because of the rapid death of wilting, infected leaves.

Control

Disease control is achieved through a combination of partial resistance and the use of fungicides. Partial resistance is now available, to a greater or lesser extent, in a wide range of cultivars. It operates by slowing infection and appears to be under polygenic control (Janssen *et al.*, 2003). Other more resistant sources are available in cultivated beets (e.g. leaf beets) and the sea beet, *B. vulgaris* ssp. *maritima* (Luterbacher *et al.*, 2004) and some of these have already been incorporated into breeding programmes and shown to be under simple genetic control (Lewellen & Schrandt, 2001; Janssen *et al.*, 2003). Up until relatively recently, sulphur was the most widely used fungicide for controlling powdery mildew but this has now been replaced in many countries with more broad spectrum systemic products such as the triazoles and strobilurins, some of which have both curative and protectant properties. Early application of fungicides, at the first sign of disease, is critical for effective control and integrated management systems based on this approach have been developed (Wolf & Verreet, 2002).

Downy mildew

Symptoms

Although seedlings may be killed by the fungus, the pathogen most often attacks young heart leaves of established plants, inducing a rosette of small, pale green, distorted, thickened, puckered leaves with down-curled margins (Leach, 1931) (Plate 42). Diseased plants often show a proliferation of small, young leaves, and under cool, moist conditions, a white to dull violet-grey fungal growth develops on the lower and sometimes upper leaf surfaces. Such leaves may wither and die. If dry, warm conditions prevail, a secondary heartrot may develop and older leaves become yellow, simulating virus yellows infection. Some plants may recover, whereas others are killed. On seed beet, inflorescences become compact, production of flower parts is suppressed, and leaf proliferation is stimulated, giving a 'witch's-broom' effect. Fungal hyphae and oospores form within seed clusters.

Causal agent

The pathogen, *Peronospora farinosa* (Fr.) Fr. f. sp. *betae* Byford (syn. *P. betae, P. schachtii*), is an obligate parasite in the class Oomycetes, order Peronosporales, family Peronosporaceae (Hawksworth *et al.*, 1983). Leach (1931) summarized the morphology of the pathogen. The fungus grows intercellularly, obtaining nutrients through digitate haustoria that penetrate host cells. Dichotomously-branched conidiophores, varying in length from 177 to 653 μm emerge singly or in groups of two or three from stomata. Conidia (sporangiosphores) are borne on sterigmata of the branches. They are oval, single-celled, hyaline to pale violet, smooth, and measure 20–28 × 17–24 μm; they normally germinate by germ tube. Oogonia and antheridia are formed in the teleomorph stage, and, after fertilization, they form yellowish oospores intercellularly in infected tissue and in the integuments of seeds. Oospores measure 26–38 μm in diameter; they germinate by germ tube or by the formation of motile zoospores. The fungus attacks only *Beta* species, including fodder beet, sugar beet, table beet, and Swiss chard (Leach, 1931; Byford, 1967b).

Distribution

In the past, downy mildew has been a serious problem in northern Europe and countries of the former USSR, along with Argentina, Egypt, Japan, Palestine, and California, USA (Duffus & Ruppel, 1993). However, in more recent years the importance of the disease has declined because of the widespread use of resistant cultivars, the separation of seed crops from root crops and improved crop hygiene measures.

Epidemiology

The disease cycle of sugar beet downy mildew has been summarized by Leach (1931) and Byford (1967a). The fungus persists in roots and crowns of groundkeepers, in carry-over seed crops, in wild and volunteer *Beta* species, and, to some extent, in seed as hyphae or oospores. Under cool, moist conditions, oospores germinate by germ tube on which conidiophores are borne; conidiophores may also develop on over-wintered mycelia. Conidia, formed on the conidiophores, are disseminated by wind to foliage. Abundant conidial production occurs on infected plants, and these conidia serve as both primary and secondary inoculum. Conidia germinate by germ tube, penetrating the host only through stomata.

The disease spreads rapidly from plant to plant in the field (Leach, 1931). When sugar beet plants are infected early, they often recover completely and rapidly. Plants infected later in the season usually do not recover completely (Byford, 1967a).

The development of the fungus is strongly influenced by environmental conditions (Leach, 1931; Carsner *et al*., 1942). Conidia are produced at temperatures of 5–20°C and a relative humidity of 80–90%, with an optimum between 8 and 10°C at 90% relative humidity. Conidia germinate and infect the host at temperatures between 0.5 and 30°C, with an optimal range of 4–7°C.

Control

To reduce disease spread, seed or steckling crops should be separated from sugar beet root crops by at least 400–1500 m (Byford & Hull, 1967) and preferably grown in separate regions. Full, uniform plant stands, an optimal amount of nitrogen fertilizer, and early sowing also reduce disease incidence (Byford, 1967c). Destruction of groundkeepers and crop rotation help reduce primary inoculum for subsequent sugar beet crops (Byford, 1981).

Resistant cultivars are available for the USA and Europe (McFarlane, 1968; Brown, 1977) and are now the main means of control. Russell (1969) reported monogenic, dominant resistance in one line, and Howard *et al.* (1970) reported apparent polygenic resistance to infection or to sporulation in several sugar beet lines. Control with fungicides has not been widely used, but some chemicals, including metalaxyl, have reduced disease incidence (Byford & Hull, 1963; Byford, 1975; Byford, 1981).

Rust

Symptoms

On seedstalks, petioles and both leaf surfaces, beet rust develops as raised, circular 1–2 mm diameter pustules, which may be randomly dispersed or grouped in rings and often surrounded by a yellow halo (Hull, 1960) (Plate 43). The host epidermis ruptures with the formation of reddish-brown urediospores within the pustules. At the end of the season, the pustules may become dark brown as a result of the formation of teliospores (teleutospores) (Plate 44). The appearance of yellowish-brown sunken spots on the adaxial surface of leaves of young plants in spring is evidence of the spermagonial stage. An aecial stage is indicated by small, clustered, cup-like, orangish-yellow aecia on abaxial surfaces of leaves. Severely rusted older leaves may senesce prematurely.

Seedling rust usually occurs on the lower surface of cotyledons and occasionally on the first true leaves of sugar beet seedlings as bright yellowish-orange pustules (aecia) aggregated in rings (Pool & McKay, 1914). Spermagonia (pycnia) may be present on the adaxial leaf or cotyledon surfaces. Uredial and telial stages of this rust do not occur on sugar beet.

Causal agents

The rust pathogens are basidiomycetes in the subclass Heterobasidiomycetes and order Uredinales. Beet rust (*Uromyces beticola* (Bell.) Boerema *et al.* 1987 (syn. *Uromyces betae*)) is an autoecious rust, completing its entire life cycle on sugar beet. Seedling rust (*Puccinia subnitens* Diet.) is a dioecious rust, with sugar beet as the alternate host and saltgrass (*Distichlis stricta* (Torr.) Rydb.) as the primary host.

Urediospores of *U. betae* are golden to reddish-brown, ellipsoidal to obovoid, and measure 26–33 × 19–23 μm (Walker, 1952). They are borne subepidermally in erumpent uredial pustules. Teliospores are pedicellate, ellipsoidal or obovate, and dark golden brown, with an apical pore covered by a papilla. Aeciospores are globoid, measuring 23–26 × 19–24 μm. Aeciospores of *P. subnitens* are globoid, measuring 14–23 × 13–20 μm, and have finely verrucose walls.

Distribution

Beet rust occurs in most northern and eastern European countries (Byford, 1996), countries of the former USSR and in Asia and the western USA. Seedling rust has been reported from the USA but is of no economic importance.

Epidemiology

The disease cycle of beet rust has been described by Newton and Peturson (1943), Hull (1960) and Pozhar and Assaul (1971). In spring, teliospores surviving on dead leaf tissue, on volunteer beet, in clamped fodder beet, in seed-crop stecklings, on wild beet or, possibly, on seed (Agarkov & Assaul, 1963) germinate to produce sporidia (basidiospores), which infect the foliage of young plants, producing aecia on the adaxial surface of leaves. Aeciospores reinfect the plant to produce the uredial pustules and urediospores which serve as secondary inocula. Germination of urediospores is optimal at 10–22°C, and disease development occurs between 15° and 22°C during cool, moist weather. Urediospores are disseminated mainly by wind but can also be spread by rain and splashing water. Disease development is most intense when moisture from dew prevails for long periods, and the disease subsides with the onset of warm, dry weather. Where winters are very mild, the aecial stage rarely occurs, and the disease cycle is perpetuated by urediospores.

Control

In the USA and Europe, cultivars with partial resistance to rust are used to control the disease. Where resistance alone is inadequate triazole fungicides can give good control (O'Sullivan, 1996).

Ramularia leaf spot

Symptoms

Ramularia attacks older leaves of sugar and fodder beet when relative humidity is high and temperatures fall between 17 and 20°C. Leaf spots are light brown, and larger (4–7 mm in diameter) and more angular than those caused by *Cercospora*. Lesions may or may not have a dark brown to reddish-brown margin, and their centres become silvery grey to white upon sporulation of the fungus (Plate 45). Under persistent wet conditions, the lesions expand and eventually coalesce, leading finally to leaf death and defoliation.

Causal agent

Conidiophores of *Ramularia beticola* Fautr. and Lambotte, a Deuteromycete fungus, which grow out through leaf stomata, are clustered, short, subhyaline to hyaline, and have prominent conidial scars. Conidia (8.2 × 1.5 μm) are hyaline, cylindric, and often are formed in short chains; they are typically two-celled, but many are one-celled and a few may have three cells.

Distribution

Ramularia leaf spot occurs in the cool, moist climates of northern Europe (especially in parts of Denmark, Ireland, the UK, Belgium, France and Germany) as well as in the northern USA, western Canada and former countries of the USSR. However, it generally appears late in the growing season and is not often economically damaging (Byford, 1996).

Epidemiology

Dissemination is mainly by wind-blown conidia, but the fungus can also be locally splash-dispersed and may be seed-borne. Conidia and hyphae probably over-winter in infected crop debris. Under conditions of high relative humidity and low temperature (17–20°C), conidia germinate and penetrate leaves through stomata. At 17°C the incubation period for symptom development is 16–18 days.

Control

Ramularia is rarely of economic importance in root crops, and control measures usually are not warranted. However, in situations where disease control is required, some triazoles have been shown to be effective (Byford, 1996; Hermann & Meeus, 1996).

Phoma leaf spot

Symptoms

In addition to seedling damping-off and a root rot caused by *Phoma betae* (see Phoma seedling disease and Phoma root rot) leaves of the root crop and stalks of seed plants can also be infected. On seed stalks, elongated lesions develop in which black pycnidia of the fungus are embedded in the greyish lesion centres (Mukhopadhyay, 1987). When leaves are infected, individual, light brown, 1–2 cm diameter, round to oval lesions develop (Pool & McKay, 1915) (Plate 46). Within the lesions, concentric dark brown rings occur near the perimeter in which minute, spherical, black pycnidia develop.

Causal agent

Fruiting bodies (pycnidia) produced by *P. betae* are black when mature, ostiolate, lenticular to globose, 95–275 μm in diameter, and immersed in host tissue. Conidia produced in pycnidia are hyaline, elliptic, single-celled, and 1.6–4.9 × 3.8–9.3 μm in size. The *Pleospora* stage develops in autumn or winter under lesion surfaces, producing black, hemispherical pseudothecia (230–340 × 160–205 μm) embedded in outer tissues of stems of over-wintering seed plants (Bugbee, 1979). Asci (20–30 × 100–130 μm) form in pseudothecia; each ascus produces eight pale, yellow-green, muriform ascospores, measuring 10–13 × 20–30 μm.

Epidemiology

The fungus is seed-borne and can survive in crop debris in soil for up to 26 months (Bugbee & Soine, 1974). When heavy rainfall splashes soil and fungus onto the lower, older leaves, leaf spots can develop (Pool & McKay, 1915), and lesions can also develop on seed stalks and leaves. Under moist conditions (either rain or high humidity), conidia are exuded from pycnidia in gelatinous masses (cirri), which are disseminated by splashing rain or overhead irrigation (Leach & MacDonald, 1976). Rainy periods during the 60 days preceding seed harvest or after seed stalks have been cut can result in a high percentage of infected seed.

Control

A minimum 4-year crop rotation and control of *Chenopodium album* is recommended, particularly for seed crops (Bugbee & Soine, 1974). Seed should be free of *P. betae* infection (see Phoma seedling disease). The disease rarely develops significantly in root crops and fungicides targeted at controlling *Phoma* leaf spot, or cultivars with resistance, have not been developed.

Alternaria leaf spot

Symptoms

Leaf lesions caused by the two *Alternaria* species causing leaf spot under cool, moist conditions are circular to irregular, dark brown to black, frequently zonate, and measure 2–10 mm in diameter. Blackish fungal growth and conidia often cover the lesions. *A. alternata* is a secondary organism that invades only chlorotic interveinal areas of leaves, especially those of sugar beet plants infected with BMYV or BWYV (Russell, 1965) (Plate 47) or suffering from a nutritional (especially magnesium) deficiency. Leaf spot induced by the primary pathogen *A. brassicae* was reported by McFarlane *et al.* (1954).

Causal agents

Alternaria alternata (Fr.) Keissl. (syn. *A. tenius* Nees) and *A. brassicae* (Berk.) Sacc. can be distinguished by conidial morphology. Conidia of *A. alternata* are 9–42 × 6–16 μm, muriform, borne in long chains, obclavate to elliptic or ovoid, and dark, with little or no apical beak. Those of *A. brassicae* are 20–100 × 8–18 μm, muriform, borne singly (sometimes in chains of two or three *in vitro*), obclavate, dark, and have long, tapering apical beaks.

Control

Usually, no control measures are needed. Russell (1965), however, obtained increased sugar yields with fungicide sprays on virus-infected plants that also were infected by *Alternaria*. *A. alternata* is commonly found on seed (Wright *et al.*, 2003) but normally eradicated with standard processing and fungicide treatments.

Beet tumour (*Urophlyctis*)

Symptoms

This disease is caused by *Urophlyctis leproides*, a primitive chytrid. The fungus induces greenish-brown, rough galls on leaf blades; the galls are less than 1 cm in diameter, but may coalesce to form larger complexes (Plate 48). Red to greenish-brown galls 8–10 cm in diameter and attached by a narrow base also occur on sugar beet crowns. Bisected galls reveal small cavities filled with brown spores of the pathogen.

Causal agent

Urophlyctis leproides (Trabut) Magn. (syn. *Phytoderma leproides* (Trabut) Karling) has intracellular fungal hyphae usually terminating in turbinate cells (7.5–15 μm in diameter) that have rhizoid projections. Resting sporangia (20–30 × 35–45 μm) are light brown, hemispherical or concave, and often are crowned with haustoria-like projections (Whitney, 1971). An empty, turbinate vesical may be attached to a resting sporangium.

Distribution

Beet tumour is generally more of a curiosity than an economic problem and has been recorded in Europe, Argentina, North Africa, Palestine and the USA (Ruppel, 1986). More recently, damaging outbreaks have been reported from Iran (Mahmoody *et al*., 1997) and Spain (J. Ayala, AIMCRA, Spain, 2000, personal communication). The disease is also found on wild annual beet and is exacerbated by irrigation.

Control

Control measures have not been developed for beet tumour.

Rhizoctonia foliar blight

Symptoms

Heart leaves are reduced to blackened stubs of petioles and distorted portions of leaf blades (Kotila, 1947) (Plate 49). Large, brown to black, irregular blighted areas occur on older leaves in wet weather.

Causal agent

Rhizoctonia solani Kühn is described in full under Rhizoctonia damping-off. Isolates from anastomosis groups AG-1, AG-2, and AG-4 have been reported to cause foliar blight.

Distribution

The disease can be a problem in Japan and occurs sporadically in the USA (see review by Herr, 1996). The disease is favoured by hot, humid weather (Kotila, 1947).

ROOT DISEASES

Aphanomyces root rot

Symptoms

Aphanomyces root rot is evidenced by dull green foliage, foliar chlorosis, wilting, and unthrifty top growth. Abundant lateral roots are formed, which quickly become black and shrivelled. Root lesions start out yellow-brown and appear water-soaked, later becoming dark brown to black. The fungus may invade the lower portion of the taproot, inducing a tip rot (Plate 50). The basal portion of the root can become fibrous or tasselled in appearance as vascular tissue remains after rotting of the cortical tissue. Plants with so-called latent infections have stunted, distorted roots and superficial, scabby lesions on the root surface.

Causal agent

Aphanomyces cochlioides Drechs. is a chromist (formerly classified as a fungus) in the class Oomycetes, which produces oospores in diseased tissue, enabling long-term survival. Its life-cycle is described in full under Aphanomyces seedling disease.

Distribution

Aphanomyces cochlioides-induced disease has been reported as a serious problem in sugar beet in Canada, Chile, Europe, Japan, and the USA. The chronic root rot of older beets varies in its importance in different areas. The 'latent infection' and root rot are reported to reduce yield and sucrose/sugar content and roots have higher levels of impurities (Papavizas & Ayers, 1974; Windels & Nabben-Schindler, 1996). The host range of the pathogen is referred to in the section on Aphanomyces seedling disease.

Epidemiology

The life cycle is described in detail under Aphanomyces seedling disease. High soil moisture and free water are needed for sporangium formation and zoospore dispersal, but little disease progress occurs if soil temperature is too low. Warren (1948) reported that disease development increased as soil temperatures increased from 18 to 32°C, with an optimum around 25°C. Under dry soil conditions, infection can occur on older plants whose taproots have grown into zones of higher moisture, leading to the tip rot phase. See also Aphanomyces seedling disease.

Control

Rotation with non-susceptible maize, soybean, potatoes, or small grains reduces black root severity in subsequent sugar beet crops (Afanasiev *et al.*, 1942; Coons *et al.*, 1946). Crops such as alfalfa, bean, sweetclover, and clover increase disease incidence and intensity, and should not precede sugar beet (Coons & Kotila, 1935).

Early improvements in resistance to *A. cochlioides* root rot in sugar beet cultivars were summarized by Doxtator and Finkner (1954). Later, improved selection methods led to the development of lines having relatively high levels of resistance (Schneider, 1954; Coe & Schneider, 1966). Most commercial hybrids incorporating these resistant germplasms have been developed for the north central USA.

Rhizoctonia root and crown rot

Symptoms

The first above ground sign of root and crown rot is a sudden wilting and chlorosis of foliage, with dark brown to black lesions at the base of the petioles. Such leaves collapse and die but remain attached to the crowns, forming a rosette of brown leaves (Plate 51). Roots show varied degrees of a dark brown to blackish rot, often beginning at the crown and extending down the taproot (Plate 52). Deep cankers or fissures are common in the crown area and on the side of affected roots, and brownish fungal hyphae may be visible within such cavities. Internally, there is generally a sharp margin between diseased and healthy tissue. Dry rot canker is a form of root rot reported by Richards (1921) in the USA. Numerous circular, zonate, dark brown lesions occur on the surface of the taproot, and deep cankers filled with fungal hyphae form beneath the lesions. Little is known about this phase of root rot.

Causal agent

Rhizoctonia solani Kühn is described in full under Rhizoctonia damping-off. Genetic relationships of *R. solani* are determined by their relative ability to anastomose in dual cultures (reviewed in Ogoshi, 1987). Thirteen anastomosis groups (AG) are recognized (Carling *et al.*, 1999; Carling *et al.*, 2002). Anastomosis groups have been further subdivided (Ogoshi, 1987). Based on this designation, most isolates from root and crown rot of sugar beet are in AG-2-2 (Ruppel, 1972; Herr & Roberts, 1980; Guillemaut *et al.*, 2003), although isolates in AGs 1, 4, and 5 have been reported from sugar beet (Herr & Roberts, 1980; Windels & Jones, 1989; Rush *et al.*, 1994; Guillemaut *et al.*, 2003).

The teleomorph stage of various AGs of *R. solani* occasionally develops, during periods of high relative humidity, on the abaxial side of infected petioles as a powdery, greyish-white, pellicle-like hymenium composed of barrel-shaped to subcylindrical basidia (6–12 × 1.5–3.5 μm) (Kotila, 1947; Herr, 1981). Up to four sterigmata form on each basidium, each bearing a smooth, thin-walled, apiculate, ovate, hyaline basidiospore (4.8–8.0 × 8.0–12.9 μm).

Distribution

Root and crown rot is the most serious root disease in sugar beet in the USA, and has been increasing in importance in Europe (Büttner *et al.*, 2003). It occurs wherever sugar beet crops are grown in warm climates. The fungus also causes seedling damping-off and certain strains can cause a leaf blight (see Rhizoctonia damping-off and Rhizoctonia foliar blight).

Epidemiology

The fungus survives as hyphae, monilioid cells and sclerotia, or in organic debris in soil (Boosalis & Scharen, 1959; Roberts & Herr, 1979), becoming active when soil temperatures reach 25–33°C (LeClerg, 1939). Sclerotia of *R. solani* survive in soil for several years (Sherwood, 1970). Infection may occur in petioles, crowns, or roots of older plants when soil temperatures increase.

Keijer (1996) and Weinhold and Sinclair (1996) reviewed pathogenesis in *Rhizoctonia* diseases. As the fungus grows over the surface of the host, hyphae attach to the plant surface. From repetitive formation of 'T-shaped branches' compact masses of hyphae (infection cushions) are formed, from which infection pegs directly penetrate the host by hydrostatic pressure with the aid of cell wall-degrading enzymes, or penetrate through wounds (reviewed by Herr, 1996). The fungus grows inter- and intra-cellularly within sugar beet root tissue (Ruppel, 1973), and younger plants are more severely affected than older plants (Pierson & Gaskill, 1961). The pathogen can move in infested soil by methods such as wind, irrigation water, or the transport of tare soil.

Control

In the USA, the fungicide azoxystrobin is approved for controlling root and crown rot. However, the timing of application is critical for effective disease control (Kiewnick *et al.*, 2001; Stump *et al.*, 2002). In addition, measures to promote good plant growth through proper tillage and fertilization should be practised, and hilling of soil around plants during cultivation should be avoided (Schneider *et al.*, 1982). A 3–5 year rotation with small grains preceding sugar beet reduces disease incidence, mainly in soils low in organic matter (Baba & Abe, 1966), although rotation with wheat has been reported to increase disease severity (Rush *et al.*, 1994). Severe root rot occurs in monoculture of sugar beet, or if sugar beet follows bean, alfalfa, or potato (Baba & Abe, 1966), although a long rotation with these crops may show lower disease (Schuster & Harris, 1960). Baba and Abe (1966) reported that a 3–5 year rotation with maize preceding sugar beet reduced disease incidence, but others have found that maize can serve as a host for AG-2-2 (Ruppel, 1985; Sumner & Minton, 1989). If rotation is used for disease management, weed control is important for disease reductions since several weeds are susceptible to AG-2-2 (Schuster & Harris, 1960; Ruppel, 1985; Harveson, 2003). Biological control has been investigated and may show promise for the future (Herr, 1988; Abada, 1994; Kiewnick *et al.*, 2001).

Polygenic, partially-dominant resistance to *R. solani* has been selected in germplasms in the USA (Hecker & Ruppel, 1977; 1988; Ruppel & Hecker, 1994). Several commercial cultivars with moderate levels of resistance have been developed by breeding companies through the use of these germplasms.

Violet root rot

Symptoms

The disease is first evident in discrete patches or on individual plants in fields, rarely affecting an entire crop. Plants are unthrifty and may show some wilting. Roots of affected plants exhibit purplish areas and a felt-like, reddish-purple mycelial growth that advances over the root surface from the tip to the crown (Plate 53), causing much soil adherence to diseased roots (Hull, 1960; Schneider & Whitney, 1986). At first, rotting under the mycelial mat is superficial, but it later becomes deeper as a result of the action of secondary organisms (Hull, 1960).

Causal agent

The disease is induced by *Rhizoctonia crocorum* (Pers: Fr.) DC. (teleomorph *Helicobasidium brebissonii* (Desm.) Donk (syn. *H. purpureum*)). Synonyms include *R. violaceae* and *R. aspargi.* The asexual stage resembles *R. solani*, except that the hyphae are violet-coloured. Sclerotia, occurring on the host or in soil, are flattened or rounded, covered with a thick, velvety felt, and range from 1–20 mm in diameter. Diagnostic, small, dark violet to almost black, stromatoid aggregates of hyphae form on the host surface and function as infection cushions from which infection pegs penetrate the host surface.

In England, the basidial stage has occurred on roots during a limited period in spring as a purple to violet, felt-like hymenium near the soil line (Buddin & Wakefield, 1927). The basidium is hyaline, the elongating apex gradually bending over while septa are formed. Two to four sterigmata arise from each cell. These vary in length from 10 to 36 μm and bear hyaline, ovate, elliptic, oblong or reniform basidiospores measuring 10–12 × 6–7 μm.

Distribution

Violet root rot is an increasing problem in Europe but occurs only sporadically in the USA. The fungus can attack many crop species, including carrots, potatoes, swedes, clover and alfalfa (Hull, 1960). Several perennial seed species are also susceptible, including *Lychnis alba*, *Sonchus oleraceus*, *Achillea millefolium*, *Capsella bursa-pastoris* and *Senecio vulgaris* (Schneider & Whitney, 1986).

Epidemiology

The pathogen persists as sclerotia and hyphae in infected organic debris in soil or on roots of several perennial weeds. The fungus becomes active and attacks susceptible roots as soil temperatures rise above 13°C (optimum 22–25°C), usually in mid to late season. The disease can develop in sugar beet crops on most soil types but is favoured by light sandy, gravelly or peaty loams, especially alkaline soils, and by poor drainage (Hull, 1960). The fungus can be disseminated by any means that moves soil, but within-field spread is largely through cultivations and, thus, the disease is usually restricted to patches in a field. Little is known about the importance of basidiospores in the disease cycle.

Control

An extended break from susceptible crops and weed eradication are the principal recommended control measures. Deep ploughing and summer fallow with frequent cultivations reduce the pathogen population in soil, but infected roots should not be ploughed back into the land (Hull, 1960). Infected roots should not be stored for a prolonged period following harvest. No resistant cultivars are yet available.

Charcoal rot

Symptoms

The first symptom is wilting of the foliage, which soon turns brown and dies. Brownish-black, irregular lesions appear externally on the crown with mustard-yellow coloured lesions in internal tissue. In older lesions, masses of charcoal-coloured sclerotia are formed in cavities. Affected roots may shrivel and become mummified (Tomkins, 1938; Karadimos *et al*., 2002).

Causal agent

The disease is caused by *Macrophomina phaseolina* (Tassi) Goid. (syn. *M. phaseoli* (Maubl.) Ashby; anamorph *Sclerotium bataticola* Taub). Hyphae are dark and sclerotia are smooth, jet black, spherical to irregular, and vary in size from 50 to 150 μm in diameter. The pycnidial stage has not been found on sugar beet.

Distribution

Charcoal rot has been reported from California in the USA, Egypt, Greece, Hungary, India and in countries of the former USSR (Hull, 1960; Schneider & Whitney, 1986; Abada, 1994; Karadimos *et al*., 2002; Potyondi & Kimmel, 2003). The fungus also attacks beans, maize, potato, and many other crops.

Epidemiology

The fungus attacks sugar beet plants that are under stress, weakened, or injured. High temperatures (optimum 31°C) favour disease development (Tomkins, 1938).

Control

Although the disease can reduce root yield and sugar content, no control measures have been developed as disease incidence is generally low.

Phymatotrichum root rot

Symptoms

Initial symptoms include a slight yellowing or bronzing of leaves, followed by a sudden wilting of plants. The fungus spreads over the root surface as a thin, felt-like layer of yellowish mycelium. Eventually, affected roots develop a rather superficial, yellow to tan rot (Plate 54).

Causal agent

The fungal pathogen *Phymatotrichum omnivorum* Dug. (syn. *Phymatotrichopsis omnivore* (Dug.) Henn.) grows vegetatively in the soil as brown, fuzzy hyphal strands that can attack the host when soil temperature exceeds 28°C. Globose to ovoid conidia (4–6 × 5–8 μm) are produced on the soil surface in crust-like mycelial mats during summer rains. Eventually, thick-walled, black sclerotia (2–4 mm in diameter) are produced, which are the survival structures of the pathogen (Streets & Bloss, 1973).

Epidemiology

Little is known about the epidemiology of this disease in sugar beet. Disease intensity increases when temperatures exceed 28°C. The disease causes serious losses in other crops, and has been reported on sugar beet crops grown in hot, dry areas of the south-western USA (Schneider & Whitney, 1986).

Control

No control measures have been devised, but planting sugar beet crops in infested fields is not recommended.

Phytophthora root rot

Symptoms

Temporary wilting during the heat of the day is the first symptom; later, plants wilt permanently and may die. Blackish spots appear toward the base of roots and a wet rot eventually spreads upward on the taproot. Rotted tissue is brown, with a blackish margin between healthy and diseased areas.

Causal agent

The two reported oomycete pathogens are *Phytophthora drechsleri* Tucker and *P. cryptogea* Pethybr. and Lafferty. *Phytophthora drechsleri* produces hyaline to yellow or light brown, thin-walled spheroidal oogonia (27–40 μm in diameter) and amphyginous antheridia (10–14 μm in diameter). Thick-walled, spherical, smooth oospores (24–36 μm) form singly in oogonia. Internally proliferous sporangia (22–40 × 24–56 μm) germinate directly by germ tubes or indirectly by the formation of motile zoospores (10–12 μm in diameter). Chlamydospores (7–15 μm in diameter) are also produced. *Phytophthora cryptogea* produces fine hyphae with oval to obpyriform (39–80 × 24–40 μm) sporangia. A third species, *P. capsici* Leonian has been reported to affect seedlings of red beet following artificial inoculation (Tian & Babadoost, 2004), but its interaction with sugar beet is not known.

Distribution

Phytophthora root rot, or 'wet rot', has been reported in sugar beet crops in Greece, Iran, and the USA (Tomkins *et al.*, 1936; Stirrup, 1939; Karaoglanidis *et al.*, 2000b).

Epidemiology

The disease occurs in wet, poorly-drained soils or in irrigated fields during very hot weather. High temperatures (28–31°C) favour disease development (Tomkins *et al*., 1936). Oospores and chlamydospores can survive in soil for several years.

Control

Good tillage, adequate drainage and diligent water management as well as growing on raised beds are the only control measures suggested.

Pythium root rot

Symptoms

Affected plants wilt, turn yellow, and the lower leaves die. Petioles may become water-soaked and discoloured. Taproots develop a deep, brown to blackish wet rot, which progresses upward from the lower portion of the root. Lesions may be covered with white mycelium.

Causal agent

Pythium aphanidermatum (Edson) Fitzp. has white, slender (2–8 µm diameter), profusely branching coenocytic hyphae. Hyphae give rise to terminal or intercalary filamentous, lobate sporangia. Oogonia (22–27 µm in diameter) are terminal, spherical and smooth, with smooth, spherical aplerotic oospores (17–19 µm in diameter) and stalked antheridia (9–11 × 10–14 µm), usually one (rarely two) per oogonium.

Distribution

The disease has been reported in Arizona, California, and Colorado in the USA, and in Iran.

Epidemiology

Pythium root rot occurs under conditions of high soil temperature and excessive soil moisture (Hine & Ruppel, 1969). The pathogen survives in soil as oospores.

Control

Control measures recommended for Phytophthora root rot apply also to Pythium root rot.

Rhizopus root rot

Symptoms

Symptoms begin with a wilt of the tops, which are soon transformed to a dry, brittle rosette of leaves around the crown, similar to *Rhizoctonia* root and crown rot. Grey to brown lesions appear on taproots, turning roots dark and spongy. Eventually, roots turn black and whitish hyphae grow over the surface. A frothy, white exudate has been reported coming from crowns of plants infected by *R. arrhizus* (Stanghellini & Kronland, 1977). Rotting roots emit a characteristic acidic smell. In cases where surface soils are not excessively wet but subsurface water is trapped by a hard pan, the tips of sugar beet taproots growing into the lower saturated soil can become infected, in which case the rot progresses upward to the crown (Plate 55).

Causal agents

The two reported zygomycete pathogens are *Rhizopus stolonifer* (Ehr.) Vuill. and *R. arrhizus* Fisch. (syn. *R. oryzae* Went. and Prins. Geerl.). The fungi produce primarily asexual spores, forming small round sporangia with greyish spores on coarse aerial mycelium with numerous rhizoids.

Rhizopus root rot can cause considerable damage in sugar beet under conditions of excessive soil moisture (Edson, 1915; Hildebrand & Koch, 1943; Stanghellini & Kronland, 1977). Insect damage or mechanical wounding facilitates pathogen entry into the roots. *Rhizopus arrhizus* is more likely to cause disease when soil temperatures reach 30–40°C and *R. stolonifer* at cooler soil temperatures of 14–16°C.

Control

Judicious water management, practices that allow good soil drainage, and the avoidance of excessive injury and insect damage are the only recommended control measures.

Southern sclerotium root rot

Symptoms

The fungus induces unthrifty top growth and wilting, which becomes permanent. A very watery, blackish rot develops in the taproots, which become covered with thick, ropey strands of cottony hyphae and vast numbers of sclerotia (Mukhopadhyay, 1987) (Plate 56). These hyphal strands and sclerotia can also be found in the soil, radiating outwards from diseased roots.

Causal agent

Sclerotium rolfsii Sacc. (teleomorph, *Athelia rolfsii* (Curzi) Tu and Kimbr.) lacks asexual spores. Sclerotia (1–3 mm in diameter) are spherical and white to dark brown. The teleomorph stage produces funnel-shaped apothecia, from which clouds of hyaline, ovate ascospores are discharged. The importance of ascospores in the disease cycle has not been determined.

Distribution

Southern sclerotium root rot can be a limiting factor in the cultivation of sugar beet in the southern USA, and in the warmer, humid areas of Europe, the Middle East, India and Asia. More than 200 species of plant are susceptible to the fungus.

Epidemiology

Sclerotia, which persist for long periods in soil, serve as the source of primary inoculum. They are spread via cultivation and irrigation practices. The disease is favoured by moist soil and temperatures between 25–35°C (Schneider & Whitney, 1986), with optimal fungal growth between 27–30°C.

Control

Breeding for resistance and fungicide soil drenches have had limited success in India. Nitrogenous fertilizers have reduced losses in California (Leach & Davey, 1942) and India (Mukhopadhyay, 1987). Because the pathogen has a wide host range and can persist in soil indefinitely, rotation schemes are unsuccessful. In other crops, soil solarization has had some success in pathogen control (Mihail & Alcorn, 1984; Punja, 1985; Greenberger *et al.*, 1987; Ristaino *et al.*, 1991) and biological control has reduced disease severity (Elad *et al.*, 1980; Punja, 1985; Ristaino *et al.*, 1991; Tsahouridou & Thanassoulopoulos, 2002).

Phoma root rot

Symptoms

Dark brown, depressed lesions on the root surface near the crown are the first signs of this rot caused by *Phoma betae*. A soft watery rot develops beneath these lesions and spreads into neighbouring areas of the root. The rotting tissue is dark brown to black, subsequently darkening further and becoming dry and shrunken (Schneider & Whitney, 1986). Black dots, the pycnidia of *P. betae*, can be found embedded in the surface of the lesions, and slimy masses of pink spores are exuded from them under moist conditions (Hull, 1960).

Causal agent

This rot is caused by *Phoma betae* Frank (teleomorph *Pleospora bjoerlingii* Byford), which has been described in detail under Phoma seedling disease and Phoma leaf spot.

Distribution

The disease has been recorded wherever sugar beet is grown, particularly in Europe, Asia and North America (Mukhopadhyay, 1987) but generally occurs at low levels and is not considered of economic importance.

Epidemiology

The fungus can survive on crop debris in soil and is also transmitted in seed. It attacks seedlings causing a damping-off disease (see Phoma seedling disease) but surviving seedlings can develop the crown or heart rot in mature plants, particularly those under physiological stress in alkaline soils (pH < 7.8; Bugbee, 1986). However, the disease can also be found in good crops with vigorous foliage, particularly under wet conditions (Hull, 1960). Though its effects on the growing crop are generally negligible, infected roots deteriorate rapidly if stored after harvesting.

Control

Measures aimed at reducing seed infection (see Phoma seedling disease) and a 4-year rotation to limit soil-borne inoculum (Bugbee & Soine, 1974) should also reduce the incidence of root rot.

Apart from this, the restricted economic significance of this disease has not merited the development of specific control measures. No cultivars with resistance to *P. betae* have been developed.

Fusarium root rot

Symptoms

Fusarium culmorum is a secondary invader of roots damaged by other causes and the disease occurs in patches or on individual plants but rarely over an entire field. The fungus generally invades via the crown, but can also enter the side of the root through cracks or wounds, causing an internal rot which is light to dark brown with a dark brown to black margin. When the decay has enveloped the whole of the upper part of the root, the leaves and growing points die (Plate 57). Superficial white mycelium develops on the surface of infected roots and this may later turn pink when sporulation occurs.

Causal agent

Fusarium culmorum (W. G. Smith) Sacc is an imperfect fungus in the Section Discolor with no known perfect stage. It grows rapidly in pure culture producing abundant floccose aerial hyphae and a deep red pigmentation on alkaline media. Microconidia are absent but macroconidia develop after a few days attached to phialides borne on loosely branched conidiophores. Macroconidia with three to five septa are slightly curved, 4–7 × 26–50 μm, with a pointed apex and well-developed foot cell (Booth, 1971). Chlamydospores are oval to globose, generally intercalary but occasionally terminal, smooth to rough walled, 10–14 × 9–12 μm. They form singly, in chains or clumps.

Distribution

F. culmorum is a common saprophytic inhabitant of soils as well as being a serious pathogen of cereals such as maize, wheat, barley, oats and rye, particularly under dry conditions. It has a wide host range including many other major crop species. Hence it is found in almost all arable soils.

Epidemiology

Sugar beet roots subjected to mechanical damage, physiological stress or invasion by a primary pathogen are often colonized by *F. culmorum* surviving as chlamydospores in the soil or mycelium in fragments of plant tissue. In particular, the fungus can gain entry through leaf scars following severe drought stress and consequent leaf death (Hull, 1960). It can also follow infection by *Phoma betae* (see Phoma root rot) or boron deficiency, which causes a hollow cavity within the root crown (Hull, 1960). Cracks in the root caused by mechanical damage, or periods of rapid growth following rain or irrigation, can also be points of entry.

Control

Because of the long survival and ubiquitous distribution of this pathogen, particularly on other crops in the rotation, extending the break between sugar beet crops has little effect on the disease. Avoiding severe drought stress by judicious use of irrigation and limiting other contributory factors (e.g. mechanical damage and boron deficiency) will be beneficial. Where the disease has become established, early harvesting and immediate processing are recommended, as infected roots deteriorate rapidly if stored.

Fusarium yellows

Symptoms

Initial signs of disease include interveinal yellowing of older leaves (Plate 58). As the disease progresses, younger leaves may also show yellowing, and the chlorotic areas of older leaves may turn necrotic. Entire leaves eventually die but remain attached to the plant. Some wilting of the foliage occurs during the day, but plants usually regain turgor overnight. Roots may be stunted but usually show no external symptoms. However, biotypes of the pathogen cause a black rot of the root tip, which may be accompanied by adventitious root proliferation along the taproot (Martyn *et al.*, 1989). In both cases, internal root symptoms consist of greyish-brown vascular discoloration. The fungus also causes a stalk blight of seed beet (Goss & Leach, 1973).

Causal agents

F. oxysporum Schlect. f. sp. *betae* (Steward) Snyd. and Hans. produces generally single-celled oval to kidney-shaped microconidia, in false heads, and straight to slightly curved macroconidia (3.5–5.5 × 21–35 μm) *in vitro.* One or two-celled chlamydospores are globose to ovoid, 7–11 μm in diameter, and terminal or intercalary. On potato dextrose agar (PDA), the undersurface of cultures may be colourless to dark blue or purple (Nelson *et al.*, 1983). Isolates that cause tip rot have been proposed as a different *forma specialis*, *F. oxysporum* f. sp. *radicis-betae* (Harveson & Rush, 1998).

F. acuminatum Ell. and Ev. (teleomorph *Gibberella acuminata* Wollenw.) produce thin, strongly curved macroconidia *in vitro.* Chlamydospores are formed singly, in chains, or in clumps. On PDA, cultures usually have a red under-surface with white aerial mycelium (Nelson *et al.*, 1983). *F. acuminatum* caused typical ‘yellows’ symptoms after artificial inoculation of 3-month-old plants in the glasshouse (Ruppel, 1991), and pathogenic isolates have been isolated as a sole pathogen, but much less frequently than *F. oxysporum*, from sugar beet plants showing symptoms in the field (Ruppel, 1991; Hanson *et al.*, 2003).

Other *Fusarium* species have been associated with sugar beet. *F. avenaceum* and *F. verticillioides* (synonymous with *F. moniliforme*) cause seedling damping-off (Mukhopadhyay, 1987; Ruppel, 1991) and *F. solani* can cause a root rot (Abada, 1994), but these species are not of widespread importance. Some isolates of these species also may cause yellows symptoms (Hanson & Hill, 2004).

Distribution

In Belgium, eastern Germany, India, the Netherlands, and areas of the western USA, *Fusarium* yellows can be a serious problem. The disease also has been reported in the Red River valley of the USA (Khan *et al.*, 2003).

Epidemiology

The fungi survive in the soil, mainly as chlamydospores, but also as conidia and hyphae in infected root debris. The disease is favoured by high temperatures. *F. oxysporum* f. sp. *betae* has been reported to infect spinach and *Amaranthus retroflexus* (MacDonald & Leach, 1976). Dry bean can serve as a symptomless host of *F. oxysporum* f. sp. *betae* (Wickliffe *et al.*, 2000). *Fusarium acuminatum* is commonly a pathogen on small grains.

Control

Because the fungi survive for long periods, rotation with other crops is of limited value as a control measure. Management of sugar beet cyst nematode and maintaining optimal soil moisture can reduce disease severity. Some resistant germplasms have been developed for *F. oxysporum* (Bockstahler, 1940; McFarlane, 1981).

Verticillium wilt

Symptoms

Foliage of affected plants initially turns straw coloured, then older leaves wilt and die. Often only one half of the leaf lamina is affected initially (Plate 59). Heart leaves become twisted and malformed and may be yellowed. Vascular elements of affected roots appear as fine brown strands, but there is little, if any, root rot.

Causal agent

The disease can be induced by *Verticillium albo-atrum* Reinke and Berth. or *Verticillium dahliae* Kleb. Both species produce verticilliate conidiophores upon which are borne hyaline conidia. *Verticillium albo-atrum* produces dark, thick walled melanized hyphae while *V. dahliae* produces small, generally nearly round dark microsclerotia. In culture, the growth optimum for *V. dahliae* (25–28°C) is slightly higher than the growth optimum for *V. albo-atrum* (20–25°C).

This disease occurs locally in the USA and some European countries (Karadimos *et al.*, 2000). Sucrose percentage and brei purity are reduced, but the disease causes little loss in root yield.

Epidemiology and control

Little is known about the epidemiology of this disease in sugar beet, although the fungus can attack nearly 200 plant species. Weed control and crop rotation are the only control measures recommended.

BACTERIAL DISEASES

Beet vascular necrosis and rot

Symptoms

Foliar symptoms, when produced, include black streaks along the petioles, a white froth in the centre of crowns, and wilt following severe root rot. Root symptoms vary from soft to dry rot, and vascular bundles become necrotic (Plate 60). When the root is cut to expose the necrotic vascular bundles, surrounding areas turn pink or reddish within 20–30 seconds.

Causal agent

The disease is caused by the bacterium *Erwinia carotovora* (Jones) Bergey *et al.* spp. *betavasculorum* Thomson *et al.* The bacterium is a single-celled, gram-negative, straight rod with peritrichous flagella. Colonies are white with a yellow to orange centre and wavy to coralloid margins. Colonies are strongly pectolytic on pectate medium.

Host plants include carrot, tomato, potato, chrysanthemum, *Beta vulgaris*, *B. maritima*, *B. macrocarpa*, and *B. corolliflora* Zoss (Thomson *et al.*, 1977; Whitney, 1982).

This disease has been reported only from localized beet-growing areas in the western USA (Ruppel *et al.*, 1975a; Thomson *et al.*, 1977; Whitney, 1987) where it can cause yield losses of up to 70%.

Epidemiology

The bacterium over-winters in groundkeeper beet plants for up to 2 months after harvest, and has been isolated from weeds (Whitney, 1986). Transmission is probably by soil deposited in plant crowns through farming operations, by insects, or splashing water. Apparently, injury to the plant is needed for infection to occur, and disease progress is favoured by warm temperatures (25–30°C); the pathogen is not seed-borne (Thomson *et al.*, 1977).

Thomson *et al.* (1981) studied cultural practices that affected rot epiphytotics. Disease incidence increased with increased nitrogen fertilizer, and rapid growth induced by wide plant spacing predisposed sugar beet to infection. Young plants are more susceptible than older plants.

Control

Cultivation practices that cause injury to the plants should be avoided. Judicious nitrogen fertilization and early planting at within-row spacing of 15–20 cm also help reduce disease incidence. Resistant cultivars have been developed and should be used wherever the disease is endemic (Whitney, 1986). Resistance is apparently of two types: resistance to *Erwinia* is monogenic and dominant, whereas resistance governing the rate of development of soft rot within the root may be quantitative (Lewellen *et al.*, 1978).

Bacterial leaf spot

Symptoms

Dark brown to almost black streaks and spots occur on leaves (Plate 62), particularly along the veins, and occasionally on seedstalks and petioles; a seedling blight also can occur (Brown & Jamieson, 1913). The spots may coalesce, giving a blighted appearance to the leaves. Often, bacterial ingress occurs at a hydathode, resulting in a spreading necrotic lesion with a yellowish margin.

Causal agent

The pathogen, *Pseudomonas syringae* van Hall pv. *aptata* (syn. *P. aptata* N.A. Brown and Jamieson), is a fluorescent, motile bacterium, 0.7–1.2 × 1.5–3.0 μm, with polar multitrichous flagella. On nutrient agar, colonies are white, circular and smooth, with entire margins. Hosts include sugar beet, bean, aubergine (egg plant), lettuce and pepper.

Distribution

Bacterial leaf spot or blight is rarely of economic importance in sugar beet, although it is common in many production areas. The disease occurs in the western and Midwestern USA, Japan, and western Europe.

Epidemiology and control

The bacterium survives on living plants or organic matter in soil, and is also seed-borne (Ark & Leach, 1946). It usually infects through a wound caused by insects or farming operations, but may enter through hydathodes. Warm temperatures (25–30°C) and moist conditions favour the disease. No control measures have been developed.

Crown gall

Symptoms

A tumorous outgrowth develops on the side of the root sometimes growing even larger than the root itself (Plate 61). The gall or galls tend to be covered by a corky or warty surface and are attached to the root by a relatively small neck of tissue. Small galls occasionally develop on leaves (Hull, 1960).

Causal agent

The galls are caused by *Agrobacterium tumefaciens* (E. F. Sm. and Town.) Conn., a commonly occurring soil-borne bacterium with a wide host range, including fruit trees.

Distribution, epidemiology and control

The crown gall bacterium is found almost wherever sugar beet is grown but generally affects only isolated plants and is of no economic importance. It enters through wounds and causes an abnormal proliferation of root cells. No control measures have been devised.

A similar disease, termed bacterial pocket is caused by *Xanthomonas beticola* (E. F. Sm. *et al.*) Burkh. Galls formed by this bacterium, mainly on the sugar beet crown, are more deeply fissured and rougher than those caused by *A. tumefaciens* and are joined to the root by a wide bridge of tissue. This disease occurs mainly in the USA and is of no economic importance.

Scab

Symptoms

Brown, round or oval, corky or scaly wart-like growths are found scattered over the root surface (Plate 63). Often they may be concentrated in bands around the root and, although usually superficial, they can penetrate deeply. They are dry and do not cause a root rot, although the root often responds to infection by forming masses of corky cells.

Causal agent

Common scab is caused by *Streptomyces scabies* (Thaxt.) Wksman and Henrici (syn. *Actinomyces scabies* (Thaxt.) Güssow), a common soil inhabiting bacterial species.

Distribution, epidemiology and control

The disease is most common in calcareous soils but affected plants are usually scattered, symptoms are superficial and losses are negligible. No control measures have been developed.

Yellow wilt

Symptoms

The disease may have two distinct symptom expressions (Bennett *et al.*, 1967). Early in the season, or where cool, moist temperatures prevail, plants may develop an overall chlorosis. New leaves may be dwarfed, with their tips turned downward.

Older leaves may show only sectors that are yellow, and some leaves may have chlorotic veins. Plants that are infected for a long period often show considerable leaf necrosis, or leaves may be narrow or strap-like (Plate 64). Droplets of phloem exudate may appear along the veins of some leaves with early yellowing symptoms. Tips of lateral roots die; new lateral roots are produced, but their tips also die, resulting in the formation of tufts of rootlets along the taproot.

At high temperatures, infected plants may wilt and die within a few days without producing other specific shoot symptoms. Wilting is preceded by a shrinking and softening of the main root which usually progresses to complete rot.

Causal agent and epidemiology

The rickettsia-like organism (Urbina-Vidal & Hirumi, 1974; Hoefert, 1981) is transmitted by a leafhopper, *Paratanus exitiosus* Beamer. It has also been transmitted by dodder (*Cuscuta californica* and *C. campestris*) and by grafting, but not by juice transmission (Bennett & Munck, 1946). Leafhoppers can transmit it to all types of *Beta vulgaris* and to plants in the families Chenopodiaceae, Amaranthaceae, and Solanaceae, resulting most commonly in the yellowing symptom. The pathogen has an incubation period of 24–30 days in the plant. Leafhoppers are rather inefficient vectors, 20–50 per plant being required for a high level of transmission. Transmission can occur after feeding times of 1–48 hours; some leafhoppers can remain infectious for over 11 days (Bennett *et al.*, 1967).

Distribution

This destructive disease is found only in Argentina and Chile, where serious losses have occurred in sugar beet (Bennett *et al.*, 1967).

Control

The main control strategy has been to move the sugar beet industry out of areas favourable for reproduction of the vector. This has not been entirely satisfactory, however, and the disease still causes major losses. Research suggests that genes for resistance occur in sugar beet; the level of resistance is apparently not high, but indications are that further progress can be achieved.

Latent rosette

Symptoms

Initially, leaves are twisted and chlorotic, and their tips turn downward (Bennett & Duffus, 1957). As the rosette stage develops, terminal and axillary shoots with strap-like leaves proliferate to give a 'witch's broom' effect. Eventually, older symptomless leaves die, leaving only the rosette of leaves.

Causal agent

Nienhaus and Schmutterer (1976) identified the agent as a rickettsia-like organism (150 × 700–1400 nm).

Distribution

This disease, also known as beet rosette, has been reported in western Germany and the USA. It is sporadic in occurrence, and usually only a few plants are affected.

Epidemiology and control

Little is known about the host range of the pathogen, except that it infects sugar beet and spinach. Adults and nymphs of the beet lace bug, *Piesma quadratum*, can act as vectors. An incubation period of 10–30 days is required before transmission. The pathogen can be acquired by the vector in 15 minutes and persists in the vector for life (Proeseler, 1980). No control measures have been developed.

Low sugar syndrome (Basses richesses)

Symptoms

The symptoms of this disease appear in late summer as a premature yellowing and necrosis of older leaves accompanied by the production of new shoots with small, narrow chlorotic leaves. Within the taproot a 'honey-brown' discoloration of vascular tissues is observed (Plate 65). Affected plants may be scattered throughout the crop or occur at high density and their sugar content is reduced by 2–4% (Gatineau *et al*., 2002).

Causal agent

Two organisms have been implicated, both transmitted by the cixiid planthopper, *Pentastiridius beievi* and restricted to the phloem tissue of affected plants. A stolbur phytoplasma has been detected in some plants showing symptoms of the disease whereas, in others, a gram negative bacterium-like organism (BLO; identified as a new plant pathogenic γ-3 *Proteobacteria*) (Boudon-Padieu *et al*., 2003) was observed. Both were associated with cell necrosis and cell-wall lignifaction in phloem cells but the BLO also caused the deposition of phenolic compounds in the lumen of these cells (Gatineau *et al*., 2002).

Distribution

This disorder was first reported from eastern France in 1991 and has occurred in this region in subsequent years, causing severe yield losses locally. There have been no records from elsewhere.

Control

No control methods have yet been developed for this disease.

REFERENCES

Abada, K.A. (1994) Fungi causing damping-off and root rot on sugar-beet and their biological control with *Trichoderma harzianum*. *Agriculture, Ecosystems and Environment* **51**, 333–337.

Afanasiev, M.M., Morris, H.E. & Carlson, W.E. (1942) The effect of preceding crops on the amount of seedling diseases of sugar beets. *Proceedings of the American Society of Sugar Beet Technologists* **3**, 435–436.

Agarkov, V.A. & Assaul, B.D. (1963) Issledovanija ravini sahrnoi svekli. Puti poluenija visokih uroajev saharn, svekli, zerovih I zernobob, kuljtur. *Kiev Gosseljhozizdat*, USSR, pp. 164–173.

Ark, P.A. & Leach, L.D. (1946) Seed transmission of bacterial blight of sugar beet. *Phytopathology* **36**, 549–553.

Asher, M.J.C. & Dewar, A.M. (1994) Control of pests and diseases in sugar beet by seed treatments. In: *Seed Treatments: Progress and Prospects*. British Crop Protection Council Monograph No 57, pp. 151–158.

Asher, M.J.C. & Williams, G.E. (1991) Forecasting the annual incidence of sugar-beet powdery mildew from weather data in Britain. *Plant Pathology* **40**, 100–107.

Baba, T. & Abe, H. (1966) Influence of preceding crops upon incidence of the sugar beet crown root. *Bulletin of Sugar Beet Research, Japan* Supplement No. 7, pp. 69–71.

Bardin, S.D., Huang, H.C., Liu, L. & Yanke, L.J. (2003) Control by microbial seed treatment of damping-off caused by *Pythium* sp. on canola, safflower, dry pea and sugar beet. *Canadian Journal of Plant Pathology* **25**, 268–275.

Bennett, C.W. & Duffus, J.E. (1957) Rosette disease of sugar beet. *Plant Disease Reporter* **41**, 1001–1004.

Bennett, C.W. & Munck, C. (1946) Yellow wilt of sugar beet in Argentina. *Journal of Agricultural Research* **73**, 45–64.

Bennett, C.W., Hills, F.J., Ehrenfeld, K.R., Valenzuela, B.J. & Klein, K.C. (1967) Yellow wilt of sugar beet. *Journal of the American Society of Sugar Beet Technologists* **4**, 480–510.

Bleiholder, H. & Weltzien, H.C. (1972) Beiträge zur Epidemiologie von *Cercospora beticola* Sacc. And Zuckerrübe. II: Die Konidienbildung in Abhängigkeit von den Umweltbedingungen Temperatur, relative Luftfeuchtigkeit und Licht. *Phytopathologische Zeitschrift* **73**, 46–68.

Bockstahler, H.W. (1940) Resistance to *Fusarium* yellows in sugar beets. *Proceedings of the American Society of Sugar Beet Technologists* **2**, 191–198.

Boerema, G.H., Loerakker, W.M. & Hamers, M.E.C. (1987) Check-list for scientific names of common parasitic fungi. *Netherlands Journal of Plant Pathology* **93**, (1).

Booth, C. (1971) *The Genus Fusarium*. Commonwealth Mycological Institute, Kew.

Boosalis, M.J. & Scharen, A.L. (1959) Methods of microscopic detection of *Aphanomyces euteiches* and *Rhizoctonia solani* and for isolation of *Rhizoctonia solani* associated with plant debris. *Phytopathology* **49**, 192–198.

Boudon-Padieu, E., Gatineau, F., Larrue, J. & Richard-Molard, M. (2003) Role de bactéries du phloème dans le syndrome des basses richesses (SBR). Biologie de leur transmission par un cixiide (*Hemiptera fulgoromorpha*). Perspectives de la lutte contre la maladie. *Proceedings of the 1st Joint IIRB-ASSBT Congress*. 27 Feb-1 March 2003, San Antonio, TX, pp. 275–288.

Bracker, C.E. & Butler, E.E. (1963) The ultrastructure and development of septa in hyphae of *Rhizoctonia solani*. *Mycologia* **55**, 35–58.

Braun, U. (1995) *The Powdery Mildews (Erysiphales) of Europe*. Fischer Verlag, Jena.

Briere, S.C., Franc, G.D. & Kerr, E.D. (2001) Fungicide sensitivity characteristics of *Cercospora beticola* isolates recovered from the high plains of Colorado, Montana, Nebraska, and Wyoming. 1. Benzimidazole and triphenyltin hydroxide. *Journal of Sugar Beet Research* **38**, 111–120.

Brown, N.A. & Jamieson, C.O. (1913) A bacterium causing a disease of sugar beet and nasturtium leaves. *Journal of Agricultural Research* **1**, 189–210.

Brown, S.J. (1977) Selecting for resistance to downy mildew of sugar beet. *Annals of Applied Biology* **86**, 261–266.

Buchholtz, W.F. & Meredith, C.H. (1944) Pathogenesis of *Aphanomyces cochlioides* on taproots of the sugar beet. *Phytopathology* **34**, 485–489.

Buddin, W. & Wakefield, E.M. (1927) Studies on *Rhizoctonia crocorum* (Pers.) DC. and *Helicobasdium purpureum* (Tul.) Pat. *Transactions of the British Mycological Society* **12**, 116–140.

Bugbee, W.M. (1979) *Pleospora bjoerlingii* in the USA. *Phytopathology* **69**, 277–278.

Bugbee, W.M. (1986) Storage rot of sugar beet. In: Whitney, E.D. & Duffus, J.E. (eds) *Compendium of Beet Diseases and Insects.* APS Press, St Paul, MN, pp. 37–39.

Bugbee, W.M. (1995) *Cercospora beticola* tolerant to triphenyltin hydroxide. *Journal of Sugar Beet Research* **32**, 167–174.

Bugbee, W.M. & Soine, O.C. (1974) Survival of *Phoma betae* in soil. *Phytopathology* **64**, 1258–1260.

Büttner, G., Pfähler, B. & Petersen, J. (2003) Rhizoctonia root rot in Europe – incidence, economic importance and concept for integrated control. *Proceedings of the 1st Joint IIRB-ASSBT Congress.* 27 February – 1 March, San Antonio, Texas. pp. 897–901.

Byford, W.J. (1967a) Field experiments on sugar-beet downy mildew (*Peronospora farinose*). *Annals of Applied Biology* **60**, 97–107.

Byford, W.J. (1967b) Host specialization of *Peronospora farinosa* on *Beta spinacia* and *Chenopodium. Transactions of the British Mycological Society* **50**, 603–607.

Byford, W.J. (1967c) The effect of some cultivation factors on the incidence of downy mildew in sugar-beet root crops. *Plant Pathology* **16**, 160–161.

Byford, W.J. (1975) Fungal diseases of sugar beet in England and the prospects for the use of fungicides. *Proceedings of the 8th British Insecticide and Fungicide Conference.* 1975, pp. 465–741.

Byford, W.J. (1978) Factors influencing the prevalence of *Pleospora bjoerlingii* on sugar beet seed. *Annals of Applied Biology* **89**, 15–19.

Byford, W.J. (1981) Downy mildews of beet and spinach. In: Spencer, D.M. (ed.) *The Downy Mildews.* Academic Press, London, pp. 531–543.

Byford, W.J. (1996) A survey of foliar diseases of sugar beet and their control in Europe. In: *Proceedings of the 59th IIRB Congress.* Brussels, February 1996, pp. 1–10.

Byford, W.J. & Hull, R. (1963) Control of sugar-beet downy mildew (*Peronospora farinosa*) by sprays. *Annals of Applied Biology* **52**, 415–422.

Byford, W.J. & Hull, R. (1967) Some observations on the economic importance of sugar-beet downy mildew in England. *Annals of Applied Biology* **60**, 281–296.

Byford, W.J. & Stamps, D.J. (1975) *Aphanomyces cochlioides* in England. *Transactions of the British Mycological Society* **65**, 157–158.

Campbell, L.G., Smith, G.A., Lamey, H.A. & Cattanach, A.W. (1998) *Cercospora beticola* tolerant to triphenyltin hydroxide and resistant to thiophanate methyl in North Dakota and Minnesota. *Journal of Sugar Beet Research* **35**, 29–41.

Canova, A. (1959a) Richerche su la biologia e l'epidemiologia della *Cercospora beticola* Sacc., Parte III. *Annali Della Sperimentazione Agraria*, N.S. 13, 477–497.

Canova, A. (1959b) Richerche su la biologia e l'epidemiologia della *Cercospora beticola* Sacc., Parte IV. *Annali Della Sperimentazione Agraria*, N.S. **13**, 685–776.

Carling, D.E., Pope, E.J., Brainard, K.A. & Carter, D.A. (1999) Characterization of mycorrhizal isolates of *Rhizoctonia solani* from an orchid, including AG-12, a new anastomosis group. *Phytopathology* **89**, 942–946.

Carling, D.E., Baird, R.E., Gitaitis, R.D., Brainard, K.A. & Kuninaga, S. (2002) Characterization of AG-13, a newly reported anastomosis group of *Rhizoctonia solani. Phytopathology* **92**, 893–899.

Carlson, L.W. (1967) Relation of weather factors to dispersal of conidia of *Cercospora beticola* Sacc. *Journal of the American Society of Sugar Beet Technologists* **14**, 319–323.

Carsner, E., Price, C. & Gillespie, G.E. (1942) Effect of temperature on the epidemiology of sugar-beet downy mildew. *Phytopathology* **32**, 827.

Cerato, C. & Grassi, G. (1983) Triphenyltin-tolerant strains of *Cercospora beticola. Informatore fitopatologico* **33**, 67–69 (summary in English).

Coe, G.E. & Schneider, C.L. (1966) Selecting sugar beet seedlings for resistance to *Aphanomyces cochlioides. Journal of the American Society of Sugar Beet Technologists* **14**, 164–167.

Collins, D.P. & Jacobsen, B.J. (2003) Optimizing a *Bacillus subtilis* isolate for biological control of sugar beet Cercospora leaf spot. *Biological Control* **26**, 153–161.

Cooke, D.A., Dewar, A.M. & Asher, M.J.C. (1989) Pests and diseases of sugar beet. In: Scopes, N. & Stables, L. (eds) *Pest and Disease Control Handbook.* British Crop Protection Council, Thornton Heath, pp. 241–259.

Coons, G.H. & Kotila, J.E. (1935) Influence of preceding crops on damping-off of sugar beet. *Phytopathology* **25**, 13.

Coons, G.H., Kotila, J.E. & Bockstahler, H.W. (1946) Black root of sugar beets and possibilities for its control. *Proceedings of the American Society of Sugar Beet Technologists* **4**, 364–380.

D'Ambra, V., Mutto, S. & Caruba, G. (1975) Research on a population of *Cercospora beticola* Sacc. tolerant to benomyl. *Industria Saccarifera Italiana* **68**, 91–93 (summary in English).

Doxtator, C.W. & Finkner, R.E. (1954) A summary of results in the breeding for resistance to *Aphanomyces cochlioides* (Drecks) [sic] by the American Crystal Sugar Company since 1942. *Proceedings of the American Society of Sugar Beet Technologists* 8, (part 2), pp. 94–98.

Drandarevski, C.A. (1969a) Untersuchungen über den echten Rübenmehltau *Erysiphe betae* (Vanha) Weltzien I: Morphologie and Taxonomie des Pilzes. *Phytopathologische Zeitschrift* **65**, 54–68.

Drandarevski, C.A. (1969b) Untersuchungen über den echten Rübenmehltau *Erysiphe betae* (Vanha) Weltzien II: Biologie und Klimmabhängigkeit des Pilzes. *Phytopathologische Zeitschrift* **65**, 124–154.

Drandarevski, C.A. (1978) Powdery mildews of beet crops. In: Spencer, D.M. (ed.) *The Powdery Mildew.* Academic Press, London, pp. 323–346.

Drechsler, C. (1929) The beet water mold and several related root parasites. *Journal of Agricultural Research* **38**, 309–361.

Duffus, J.E. & Ruppel, E.G. (1993) Diseases. In: Cooke, D.A. & Scott, R.K. (eds) *The Sugar Beet Crop.* Chapman and Hall, London, pp. 346–427.

Durrant, M.J., Payne, P.A., Prince, J.W.F. & Fletcher, R. (1988) Thiram steep seed treatment to control *Phoma betae* and improve the establishment of the sugar-beet plant stand. *Crop Protection* **7**, 319–326.

Edson, H.A. (1915) Seedling diseases of sugar beets and their relation to root-rot and crown-rot. *Journal of Agricultural Research* **4**, 135–168.

Elad, Y., Chet, I. & Katan, J. (1980) *Trichoderma harzianum*: a biocontrol agent effective against *Sclerotium rolfsii* and *Rhizoctonia solani. Phytopathology* **70**, 119–121.

Fink, H.C. & Buchholtz, W.F. (1954) Correlation between sugar beet crop losses and greenhouse determinations of soil infestations by *Aphanomyces cochlioides. Proceedings of the American Society of Sugar Beet Technologists* 8 (Part 1), 252–259.

Franc, G.D., Harveson, R.M., Kerr, E.D. & Jacobsen, B.J. (2001) Disease Management. In: *Sugarbeet Production Guide.* University of Nebraska Cooperative Extension EC01–156, University of Nebraska, pp. 131–160.

Francis, S.A. (2002) Sugar-beet powdery mildew (*Erysiphe betae*). *Molecular Plant Pathology* **3**, 119–124.

Fransden, N.O. (1955) Über den Wirtskreis und die systematische verwandtschaft von *Cercospora beticola. Archiv für Mikrobiologie* **22**, 145–174.

Gatineau, F., Jacob, N., Vautrin, S., Larrue, J., Lherminier, J., Richard-Molard, M. & Boudon-Padieu, E. (2002) Association with the syndrome 'Basses Richesses' of sugar beet of a phytoplasma and bacterium-like organism transmitted by a *Pentastiridius* sp. *Phytopathology* **92** (4), 384–392.

Georgopoulos, S.G. & Dovas, C. (1973) A serious outbreak of strains of *Cercospora beticola* resistant to benzimidazole fungicides in northern Greece. *Plant Disease Reporter* **57**, 321–324.

Giannopolitis, C.N. (1978a) Occurrence of strains of *Cercospora beticola* resistant to triphenyltin fungicides in Greece. *Plant Disease Reporter* **62**, 205–208.

Giannopolitis, C.N. (1978b) Lesions on sugarbeet roots caused by *Cercospora beticola. Plant Disease Reporter* **62**, 424–427.

Goodwin, S.B., Dunkle, L.D. & Zismann, V.L. (2001) Phylogenetic analysis of *Cercospora* and *Mycosphaerella* based on the internal transcribed spacer region of ribosomal DNA. *Phytopathology* **91**, 648–658.

Goss, D.C. & Leach, L.D. (1973) Stalk blight of sugar beet crops caused by *Fusarium oxysporum* f. sp. *betae. Phytopathology* **63**, 1216.

Greenberger, A., Yogev, A. & Katan, J. (1987) Induced suppressiveness in solarized soils. *Phytopathology* **77**, 1663–1667.

Grondona, I., Hermosa, R., Tejada, M., Gomis, M., Mateos, P.F., Bridge, P.D., Monte, E. & Garcia-Acha, I. (1997) Physiological and biochemical characterization of *Trichoderma harzianum*, a biological control agent against soilborne fungal plant pathogens. *Applied and Environmental Microbiology* **63**, 3189–3198.

Guillemaut, C., Edel-Hermann, V., Camporota, P., Alabouvette, C., Richard-Molard, M. & Steinberg, C. (2003) Typing of anastomosis groups of *Rhizoctonia solani* by restriction analysis of ribosomal DNA. *Canadian Journal of Microbiology* **49**, 556–558.

Hanson, L.E. & Hill, A.L. (2004) *Fusarium* species causing Fusarium yellows of sugarbeet. *Journal of Sugar Beet Research* **41**, 163–178.

Hanson, L.E., Hill, A.L. & Panella, L. (2003) Variable virulence and genetic diversity in *Fusarium oxysporum* from sugar beet. *Proceedings of the 1st Joint IIRB-ASSBT Congress.* 27 February – 1 March, San Antonio, TX, pp. 887.

Harveson, R.M. (2003) Common weeds serving as alternate hosts for pathogens of dry-edible beans and sugar beets in the Nebraska panhandle. *Phytopathology* **93**, (Supplement), S34 (abstract).

Harveson, R.M. & Rush, C.M. (1998) Characterization of Fusarium root rot isolates from sugar beet by growth and virulence at different temperatures and irrigation regimes. *Plant Disease* **82**, 1039–1042.

Hawksworth, D.L., Sutton, B.C. & Ainsworth, C.C. (1983) *Ainsworth and Bisby's Dictionary of the Fungi,* 7th edn. Commonwealth Mycological Institute, Kew.

Hecker, R.J. & Ruppel, E.G. (1977) *Rhizoctonia* root rot resistance in sugarbeet: breeding and related research. *Journal of the American Society of Sugar Beet Technologists* **19**, 246–256.

Hecker, R.J. & Ruppel, E.G. (1988) Registration of *Rhizoctonia* root rot resistant sugarbeet germplasm FC 709. *Crop Science* **28**, 1039–1040.

Hermann, O. & Meeus, P. (1996) Incidence relative de *Ramularia beticola* chez la betterave sucrière. In: *Proceedings of the 59th IIRB Congress.* Brussels, February 1996, pp. 95–103.

Herr, L.J. (1977) Pectolytic activity of *Aphanomyces cochlioides* in culture and in diseased sugarbeets. *Journal of the American Society of Sugar Beet Technologists* **19**, 219–232.

Herr, L.J. (1981) Basidial stage of *Rhizoctonia solani*, anastomosis groups 2 and 4, on sugarbeets in Ohio (abstract). *Phytopathology* **71**, 224.

Herr, L.J. (1988) Biocontrol of Rhizoctonia crown and root rot of sugar beet by binucleate *Rhizoctonia* spp. and *Laetisaria arvalis. Annals of Applied Biology* **113**, 107–118.

Herr, L.J. (1996) Sugar beet diseases incited by *Rhizoctonia* spp. In: Sneh, B., Jabaji-Hare, S., Neate, S. & Dijst, G. (eds) *Rhizoctonia Species: Taxonomy, Molecular Biology, Ecology, Pathology and Disease Control.* Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 341–349.

Herr, L.J. & Roberts, D.L. (1980) Characterization of *Rhizoctonia* populations obtained from sugarbeet fields with differing soil textures. *Phytopathology* **70**, 476–480.

Hildebrand, A.A. & Koch, L.W. (1943) *Rhizopus* root rot of sugar beet. *Canadian Journal of Research Sect. C*, **21**, 235–248.

Hine, R.R. & Ruppel, E.G. (1969) Relationship of soil temperature and moisture to sugarbeet root rot caused by *Pythium aphanidermatum* in Arizona. *Plant Disease Reporter* **53**, 989–991.

Hoefert, L.L. (1981) Rickettsias as etiologic agents of sugarbeet yellow wilt. *Proceedings of the 13th International Botanical Congress.* Sydney, Australia, 21–28 August, p. 298.

Holtschulte, B. (2000) *Cercospora beticola* – worldwide distribution and incidence. In: *Cercospora beticola* Sacc.: Biology, agronomic influence and control measures in sugar beet. *Advances in Sugar Beet Research 2*. International Institute for Beet Research, Brussels, Belgium, pp. 5–16.

Howard, H.W., Johnson, R., Russell, G.E. & Wolfe, M.S. (1970) Problems in breeding for resistance to diseases and pests. *Report of the Plant Breeding Institute*, *Cambridge for 1969*, pp. 6–36.

Hull, R. (1960) *Sugar Beet Diseases.* Ministry of Agriculture, Fisheries and Food Bulletin no. 142, HMSO, London.

Islam, M.T., Toshiaki, I. & Tahara, S. (2003) Host-specific plant signal and G-protein activator, mastoparan, trigger differentiation of zoospores of the phytopathogenic oomycete *Aphanomyces cochlioides. Plant and Soil* **255**, 131–142.

Janssen, G.J.W., Nihlgard, M. & Kraft, T. (2003) Mapping of resistance genes to powdery mildew (*Erysiphe betae*) in sugar beet. *International Sugar Journal* **105**, 448–451.

Karadimos, D.A., Karaoglanidis, G.S. & Klonari, K. (2000) First report of Verticillium wilt of sugar beet, caused by *Verticillium dahliae* in Greece. *Plant Disease* **84**, 593.

Karadimos, D.A., Karaoglanidis, G.S. & Klonari, K. (2002) First report of charcoal rot of sugar beet caused by *Macrophomina phaseolina* in Greece. *Plant Disease* **86**, 1051.

Karaoglanidis, G.S., Ioannidis, P.M. & Thanassoulopoulos, C.C. (2000a) Reduced sensitivity of *Cercospora beticola* isolates to sterol-demethylation-inhibiting fungicides. *Plant Pathology* **49**, 567–572.

Karaoglanidis, G.S., Karadimos, D.A. & Klonari, K. (2000b) First report of Phytophthora root rot of sugar beet, caused by *Phytophthora cryptogea*, in Greece. *Plant Disease* **84**, 593.

Kaw, R.N., Mukhopadhyay, A.N. & Dulloo, A.K. (1979) Fungicidal control of *Cercospora* leaf spot of sugar beet in seed producing area. *Indian Phytopathology* **32**, 405–408.

Keijer, J. (1996) The initial steps of the infection process by *Rhizoctonia solani.* In: Sneh, B., Jabaji-Hare, S., Neate, S. & Dijst, G. (eds) *Rhizoctonia Species: Taxonomy, Molecular Biology, Ecology, Pathology and Disease Control.* Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 149–162.

Khan, M.F.R., Bradley, C.A. & Windels, C.E. (2003) Fusarium yellows of sugarbeet. *North Dakota State University Extension Bulletin* PP-1247.

Kiewnick, S., Jacobsen, B.J., Braun-Kiewnick, A., Eckhoff, J.L.A. & Bergman, J.W. (2001) Integrated control of Rhizoctonia crown and root rot of sugar beet with fungicides and antagonistic bacteria. *Plant Disease* **85**, 718–722.

Kotila, J.E. (1947) *Rhizoctonia* foliage blight of sugar beets. *Journal of Agricultural Research* **74**, 289–314.

Lawrence, J.S. & Meredith, D.S. (1970) Wind dispersal of conidia of *Cercospora beticola*. *Phytopathology* **60**, 1076–1078.

Leach, L.D. (1931) Downy mildew of the beet, caused by *Peronospora schachtii* Fuckel. *Hilgardia* **6**, 203–251.

Leach, L.D. (1986) Seedling diseases. In: Whitney, E.D. & Duffus, J.E. (eds) *Compendium of Beet Diseases and Insects.* APS Press, St Paul, MN, pp. 4–8.

Leach, L.D. & Davey, A.E. (1942) Reducing southern *Sclerotium* rot of sugar beets with nitrogenous fertilizers. *Journal of Agricultural Research* **64**, 1–18.

Leach, L.D. & MacDonald, J.D. (1976) Seed-borne *Phoma betae* as influenced by area of sugarbeet production, seed processing and fungicidal seed treatments. *Journal of American Society of Sugar Beet Technologists* **19**, 4–15.

LeClerg, E.L. (1934) Parasitism of *Rhizoctonia solani* on sugar beet. *Journal of Agricultural Research* **49**, 407–431.

LeClerg, E.L. (1939) Studies on dry-rot canker of sugar beets. *Phytopathology* **29**, 793–800.

Lewellen, R.T. & Schrandt, J.K. (2001) Inheritance of powdery mildew resistance in sugar beet derived from *Beta vulgaris* ssp. *maritima*. *Plant Disease* **85**, 627–631.

Lewellen, R.T., Whitney, E.D. & Goulas, C.K. (1978) Inheritance of resistance to *Erwinia* root rot in sugarbeet. *Phytopathology* **68**, 947–950.

Luterbacher, M.C., Asher, M.J.C., DeAmbrogio, E., Biancardi, E., Stevenato, P. & Frese, L. (2004) Sources of resistance to diseases of sugar beet in related *Beta* germplasm: I. Foliar diseases. *Euphytica* **39**, 105–121.

MacDonald, J.D. & Leach, L.D. (1976) Evidence for an expanded host range of *Fusarium oxysporum* f. sp. *betae*. *Phytopathology* **66**, 822–827.

Mahmoody, B., Minassian, V. & Kashani, A. (1997) Occurrence of leaf and crown wart disease, caused by *Urophlyctis leproides*, its importance and effects on sugar yield and quality in Khuzestan. *Iranian Journal of Plant Pathology* **33**, 64–70.

Mamluk, O.F. (1970) Beobachtungen über die vereinzelte Keimung der Ascosporen von *Erysiphe betae* (Vanha) Weltzien. *Phytopathologische Zeitschrift* **67**, 87–88.

Mamluk, O.F. & Weltzien, H.C. (1973) Untersuchungen über die Hauptfruchtform des echten Rübenmehltaus, *Erysiphe betae* (Vanha) Weltzien. II: Die Fruchtkörperbildung im Verlauf der Pilzkulture. *Phytopathologische Zeitschrift* **76**, 285–302.

Mangan, A. (1971) A new method for the detection of *Pleospora bjoerlingii* infection of sugar beet seed. *Transactions of the British Mycological Society* **57**, 169–172.

Maric, A., Masirevic, S. & Jerkovic, Z. (1984) Increase in the resistance of *Cercospora beticola* to benomyl and first occurrence of strains tolerant to fentin acetate in Yugoslavia. *Zastita Bilja* **35**, 207–215 (summary in English).

Martin, H.L. (2003) Management of soil-borne diseases of beetroot in Australia. *Australian Journal of Experimental Agriculture* **43**, 1281–1292.

Martyn, R.D., Rush, C.M., Biles, C.L. & Baker, E.H. (1989) Etiology of a root rot disease of sugar beet in Texas. *Plant Disease* **73**, 879–884.

McFarlane, J.S. (1968) Elimination of downy mildew as a major sugarbeet disease in the coastal valleys of California. *Plant Disease Reporter* **52**, 297–299.

McFarlane, J.S. (1981) Fusarium stalk blight resistance in sugarbeet. *Journal of the American Society of Sugar Beet Technologists* **21**, 175–183.

McFarlane, J.S., Bardin, R. & Snyder, W.C. (1954) An *Alternaria* leaf spot of the sugar beet. *Proceedings of the American Society of Sugar Beet Technologists*. Part 1, 8, 241–246.

McKay, M.B. & Pool, V.W. (1918) Field studies of *Cercospora beticola*. *Phytopathology* **8**, 119–136.

McQuilken, M.P., Powell, H.G. & Budge, S.P. (1998) Effect of storage on the survival and biocontrol activity of *Pythium* *oligandrum* in pelleted sugar beet seed. *Biocontrol Science and Technology* **8**, 231–241.

Meredith, D.S. (1967) Conidium release and dispersal in *Cercospora beticola*. *Phytopathology* **57**, 889–893.

Meriggi, P., Rosso, F., Ioannidis, P.M. & Ayala Garcia, J. (2000) Fungicide treatments against Cercospora leaf spot in sugar beet (*Beta vulgaris* L.). In: *Cercospora beticola* Sacc.: Biology, agronomic influence and control measures in sugar beet. *Advances in Sugar Beet Research 2.* International Institute for Beet Research, Brussels, Belgium, pp. 77–102.

Mihail, J.D. & Alcorn, S.M. (1984) Effects of soil solarization on *Macrophomina phaseolina* and *Sclerotium rolfsii*. *Plant Disease* **68**, 156–159.

Mischke, W. (1960) Untersuchungen über den Einfluss des Bestandsklimas auf die Entwicklung der Ruben-Blattfleckenkrankheit (*Cercospora beticola* Sacc.) im Hinblick auf die Einrichtung eines Warndienstes. *Bayer Landwirtschaft Jahrbuch* **37**, 197–227.

Mukhopadhyay, A.N. (1987) *Handbook on Diseases of Sugar Beet*, Vol. I. CRC Press, Boca Raton, FL.

Nelson, P.E., Toussoun, T.A. & Marasas, W.F.O. (1983) *Fusarium Species: An Illustrated Manual for Identification.* The Pennsylvania State University Press, University Park, PA.

Newton, M. & Peturson, B. (1943) *Uromyces betae* in Canada. *Phytopathology* **33**, 10.

Nienhaus, F. & Schmutterer, H. (1976) Rickettsialike organisms in latent rosette (witches' broom) diseased sugar beet (*Beta vulgaris*) and spinach (*Spinacia oleracea*) plants and in the vector *Piesma quadratum* Fieb. *Zeitschrift fürPflanzenkrankheiten und Pflanzenschutz* **83**, 641–646.

Nölle, H.H. (1960) Über den Wurzelbrand der Zuckerrübe und seine Bekämpfung. *Phytopathologische Zeitschrift* **38**, 161–200.

Ogoshi, A. (1987) Ecology and pathogenicity of anastomosis and intraspecific groups of *Rhizoctonia solani* Kühn. *Annual Review of Phytopathology* **25**, 125–143

O'Sullivan, E. (1996) Effect of fungicides on the incidence of rust disease, root yield and sugar content in sugar beet. *Irish Journal of Agriculture and Food Research* **35**, 159–164.

O'Sullivan, E. & Kavanagh, J.H. (1992) Characteristics and pathogenicity of *Pythium* spp. associated with damping-off of sugar beet in Ireland. *Plant Pathology* **41**, 582–590.

Papavizas, G.C. & Ayers, W.A. (1974) Aphanomyces species and their root diseases in pea and sugarbeet. *USDA, Agric. Res. Serv. Tech. Bull. 1485*, Washington, DC.

Parmeter, J.R. Jr. & Whitney, H.S. (1970) Taxonomy and nomenclature of the imperfect state. In: Parmeter, J.R. Jr. (ed.) *Rhizoctonia solani*: *Biology and Pathology.* University of California Press, Berkeley, pp. 7–19.

Payne, D.A. & Williams, G.E. (1990) Hymexazol treatment of sugar-beet seed to control seedling disease caused by *Pythium* spp. and *Aphanomyces cochlioides*. *Crop Protection* **9**, 371–377.

Payne, P.A. (1986) *Rhizoctonia solani* and Barney patch disorder. *Aspects of Applied Biology* **13**, 127–129.

Payne, P.A., Asher, M.J.C. & Kershaw, C.D. (1994) The incidence of *Pythium* spp. and *Aphanomyces cochlioides* associated with the sugar-beet growing soils of Britain. *Plant Pathology* **43**, 300–308.

Pierson, V.G. & Gaskill, J.O. (1961) Artificial exposure of sugar beets to *Rhizoctonia solani*. *Journal of the American Society of Sugar Beet Technologists* **11**, 574–590.

Pool, V.W. & McKay, M.B. (1914) *Puccinia subnitens* on the sugar beet. *Phytopathology* **4**, 204–206.

Pool, V.W. & McKay, M.B. (1915) *Phoma betae* on the leaves of sugar beet. *Journal of Agricultural Research* **4**, 169–177.

Pool, V.W. & McKay, M.B. (1916) Climatic conditions as related to *Cercospora beticola*. *Journal of Agricultural Research* **6**, 21–60.

Potyondi, L. & Kimmel, J. (2003) Present situation in Hungarian sugarbeet production. *Proceedings of the 1st Joint IIRB-ASSBT Congress.* 27 February – 1 March, San Antonio, TX, pp. 849–855.

Pozhar, Z.A. & Assaul, B.D. (1971) Biologija vozvuditelja rzavcini saharnoi svekli *Uromyces betae* (Pers.) Lev. *Mikologija I Fitopatologija* **6**, 161–166.

Proeseler, G. (1980) Piesmids. In: Harris, K.F. & Maramorosch, K. (eds) *Vectors of Plant Pathogens.* Academic Press, London, pp. 97–113.

Pundhir, V.S. & Mukhopadhyay, A.N. (1987) Recurrence of *Cercospora* leaf-spot of sugarbeet. *Indian Journal of Agricultural Sciences* **57**, 186–189.

Punja, Z.K. (1985) The biology, ecology, and control of *Sclerotium rolfsii*. *Annual Review of Phytopathology* **23**, 97–127.

Richards, B.L. (1921) A dryrot canker of sugar beets. *Journal of Agricultural Research* **22**, 47–52.

Ristaino, J.B., Perry, K.B. & Lumsden, R.D. (1991) Effect of solarization and *Gliocladium virens* on sclerotia of *Sclerotium rolfsii*, soil microbiota, and the incidence of southern blight of tomato. *Phytopathology* **81**, 1117–1124.

Roberts, D.L. & Herr, L.J. (1979) Soil populations of *Rhizoctonia solani* from areas of healthy and diseased beets within four sugarbeet fields differing in soil texture. *Canadian Journal of Microbiology* **25**, 902–910.

Rossi, V. (2000) Cercospora leaf spot infection and resistance in sugar beet. In: *Cercospora beticola* Sacc.: Biology, agronomic influence and control measures in sugar beet. *Advances in Sugar Beet Research 2.* International Institute for Sugar Beet Research, Brussels, Belgium, pp. 17–48.

Ruppel, E.G. (1972) Correlation of cultural characters and source of isolates with pathogenicity of *Rhizoctonia solani* from sugar beet. *Phytopathology* **62**, 202–205.

Ruppel, E.G. (1973) Histopathology of resistant and susceptible sugar beet roots inoculated with *Rhizoctonia solani*. *Phytopathology* **63**, 871–873.

Ruppel, E.G. (1985) Susceptibility of rotation crops to a root rot isolate of *Rhizoctonia solani* from sugar beet and survival of the pathogen in crop residues. *Plant Disease* **69**, 871–873.

Ruppel, E.G. (1986) Foliar diseases caused by fungi. In: Whitney, E.D. & Duffus, J.E. (eds) *Compendium of Beet Diseases and Insects.* APS Press, St Paul, MN, pp. 8–9.

Ruppel, E.G. (1991) Pathogenicity of *Fusarium* spp. From diseased sugar beets and variation among sugar beet isolates of *F. oxysporum*. *Plant Disease* **75**, 486–489.

Ruppel, E.G. & Scott, P.R. (1974) Strains of *Cercospora beticola* resistant to benomyl in the USA. *Plant Disease Reporter* **58**, 434–436.

Ruppel, E.G. & Tomasovic, B.J. (1977) Epidemiological factors of sugar beet powdery mildew. *Phytopathology* **67**, 619–621.

Ruppel, E.G. & Hecker, R.J. (1994) Rhizoctonia root rot on sugarbeet cultivars having varied degrees of resistance. *Journal of Sugar Beet Research* **31**, 135–142.

Ruppel, E.G., Harrison, M.D. & Nielson, A.K. (1975a) Occurrence and cause of bacterial vascular necrosis and soft rot of sugarbeet in Washington. *Plant Disease Reporter* **59**, 837–840.

Ruppel, E.G., Hills, F.J. & Mumford, D.L. (1975b) Epidemiological observations on the sugarbeet powdery mildew epiphytotic in western USA in 1974. *Plant Disease Reporter* **59**, 283–286.

Rush, C.M., Carling, D.E., Harveson, R.M. & Mathieson, J.T. (1994) Prevalence and pathogenicity of anastomosis groups of *Rhizoctonia solani* from wheat and sugar beet in Texas. *Plant Disease* **78**, 349–352.

Russell, G.E. (1965) The control of *Alternaria* species on leaves of sugar beet infected with yellowing viruses. I. Some effects of four fungicides on two beet varieties. *Annals of Applied Biology* **56**, 111–118.

Russell, G.E. (1969) Resistance to fungal diseases of sugar beet leaves. *British Sugar Beet Review* **38** (1), 27–30, 35.

Schneider, C.L. (1954) Methods of inoculating sugar beets with *Aphanomyces cochlioides* Drechs. *Proceedings of the American Society of Sugar Beet Technologists* **8**, 247–251.

Schneider, C.L. (1965) Additional hosts of the beet water mold, *Aphanomyces cochlioides* Drechs. *Journal of the American Society of Sugar Beet Technologists* **13**, 469–477.

Schneider, C.L. & Whitney, E.D. (1986) Root diseases caused by fungi. In: Whitney, E.D. & Duffus, J.E. (eds) *Compendium of Beet Diseases and Insects.* APS Press, St Paul, MN, pp. 17–23.

Schneider, C.L., Ruppel, E.G., Hecker, R. & Hogaboam, G.J. (1982) Effect of soil deposition in crowns on development of *Rhizoctonia* root rot in sugar beet. *Plant Disease* **66**, 408–410.

Schuster, M.L. & Harris, L. (1960) Incidence of Rhizoctonia crown rot of sugar beet in irrigated crop rotation. *Journal of the American Society of Sugar Beet Technologists* **11**, 128–136.

Shane, W.W. & Teng, P.S. (1984) *Cercospora beticola* infection prediction model presented. *Sugar Producer* **10** (3), 14–15, 19.

Sherwood, R.T. (1970) Physiology of *Rhizoctonia solani.* In: Parmeter, J.R. Jr. (ed.) *Rhizoctonia solani, Biology and Pathology.* University of California Press, pp. 69–92.

Smith, G.A. (1985) Response of sugarbeet in Europe and the US to *Cercospora beticola* infection. *Agronomy Journal* **77**, 126–129.

Stanghellini, M.E. & Kronland, W.C. (1977) Root rot of mature sugar beets by *Rhizopus arrhizus. Plant Disease Reporter* **61**, 255–256.

Stewart, E.L., Liu, Z., Crous, P.W. & Szabo, L.J. (1999) Phylogenetic relationships among some cercosporoid anamorphs of *Mycosphaerella* based on rDNA sequence analysis. *Mycological Research* **103**, 1491–1499.

Stirrup, H.H. (1939) Sugar beet diseases. *Annals of Applied Biology* **26**, 402–404.

Streets, R.B. & Bloss, H.E. (1973) *Phymatotrichum Root Rot.* Monograph 8. American Phytopathological Society, St Paul, MN.

Stump, W.L., Franc, G.D., Miller, S.D. & Wilson, R.G. (2002) Azoxystrobin and post emergence herbicide combinations for Rhizoctonia and weed management in sugarbeet. *Journal of Sugar Beet Research* **39**, 37–58.

Sumner, D.R. & Minton, N.A. (1989) Crop losses in corn induced by *Rhizoctonia solani* AG-2-2 and nematodes. *Phytopathology* **79**, 934–941.

Tahara, S., Mizutani, M., Takayama, T. & Ohkawa, K. (1999) Plant secondary metabolites regulating behaviour of the phytopathogenic fungus *Aphanomyces cochlioides. Pesticide Science* **55**, 209–211.

Thomson, S.W., Schroth, M.N., Hills, F.J., Whitney, E.D. & Hildebrand, D.C. (1977) Bacterial vascular necrosis and rot of sugarbeet: general description and etiology. *Phytopathology* **67**, 1183–1189.

Thomson, S.W., Hills, F.J., Whitney, E.D. & Schroth, M.N. (1981) Sugar and root yield of sugar beets as affected by bacterial vascular necrosis and rot, nitrogen fertilisation, and plant spacing. *Phytopathology* **71**, 605–608.

Thrane, C., Nielsen, M.N., Sorensen, J. & Olsson, S. (2001) *Pseudomonas fluorescens* DR54 reduces sclerotia formation, biomass development and disease incidence of *Rhizoctonia solani* causing damping-off in sugar beet. *Microbial Ecology* **42**, 438–445.

Tian, D. & Babadoost, M. (2004) Host range of *Phytophthora capsici* from pumpkin and pathogenicity of isolates. *Plant Disease* **88**, 485–489.

Tomkins, C.M. (1938) Charcoal root rot of sugarbeet. *Hilgardia* **12**, 75–81.

Tomkins, C.M., Richards, B.L., Tucker, C.M. & Gardner, M.W. (1936) *Phytophthora* rot of sugar beet. *Journal of Agricultural Research* **52**, 205–216.

Tsahouridou, P.C. & Thanassoulopoulos, C.C. (2002) Proliferation of *Trichoderma koningii* in the tomato rhizosphere and the suppression of damping-off by *Sclerotium rolfsii. Soil Biology and Biochemistry* **34**, 767–776.

Urbina-Vidal, C. & Hirumi, H. (1974) Search for causative agents of the sugarbeet yellow wilt in Chile. *Journal of the American Society of Sugar Beet Technologists* **18**, 142–162.

Van der Plaats-Niterink, A.J. (1981) *Monograph of the Genus Pythium. Studies in Mycology No. 21.* Centralbureau voor Schimmelcultures, Baarn, the Netherlands.

Vereijssen, J. & Schneider, J.H.M. (2003) Potential primary site of infection of *Cercospora beticola* in sugar beet. *Proceedings of the 1st Joint IIRB-ASSBT Congress.* 27 February – 1 March, San Antonio, TX, pp. 863–864.

Vestal, E.F. (1933) Pathogenicity, host response and control of *Cercospora* leaf-spot of sugar beets. *Iowa Agricultural Research Station Bulletin* **168**, 43–72.

Vestberg, M., Tahvonen, R., Raininko, K. & Nourmala, N. (1982) Damping-off of sugar beet in Finland. 1: Causal agents and some factors affecting disease. *Journal of the Scientific Agricultural Society of Finland* **54**, 225–244.

Walker, J.C. (1952) *Diseases of Vegetable Crops.* McGraw-Hill, New York.

Walker, R., Rossall, S. & Asher, M.J.C. (2004) Comparison of application methods to prolong the survival of potential biocontrol bacteria on stored sugar-beet seed. *Journal of*

Applied Microbiology **97**, 293–305.

Walther, D. & Gindrat, D. (1987) Biological control of *Phoma* and *Pythium* damping-off of sugar beet with *Pythium oligandrum*. *Journal of Phytopathology* **119**, 167–174.

Warren, J.R. (1948) A study of the sugar beet seedling disease in Ohio. *Phytopathology* **38**, 883–892.

Weinhold, A.R. & Sinclair, J.B. (1996) *Rhizoctonia solani*: Penetration, colonization, and host response. In: Sneh, B., Jabaji-Hare, S., Neate, S. & Dijst, G. (eds) *Rhizoctonia Species: Taxonomy, Molecular Biology, Ecology, Pathology and Disease Control*. Kluwer Academic Publishers, Dordrecht, the Netherlands, pp. 163–174.

Weltzien, H.C. (1963) *Erysiphe betae* (Vanha) comb. Nov., the powdery mildew of beets. *Phytopathologische Zeitschrift* **47**, 123–128.

Whitney, E.D. (1971) The first confirmable occurrence of *Urophlyctis leproides* on sugar beet in North America. *Plant Disease Reporter* **55**, 30–32.

Whitney, E.D. (1982) The susceptibility of fodder beet and wild species of Beta to an *Erwinia* sp. from sugar beet. *Plant Disease* **66**, 664–665.

Whitney, E.D. (1986) Diseases caused by bacteria and bacterialike organisms. In: Whitney, E.D. & Duffus, J.E. (eds) *Compendium of Beet Diseases and Insects*. APS Press, St Paul, MN, pp. 23–26.

Whitney, E.D. (1987) Identification and aggressiveness of *Erwinia caratovora* supsp. *betavasculorum* on sugar beet from Texas. *Plant Disease* **71**, 602–603.

Wickliffe, E., Otto, K., Schwartz, H.F., Brick, M.A., Ogg, B., Byrne, P., Fall, A., Panella, L. & Hill, A. (2000) Fusarium wilt variability in dry bean and sugarbeet. *Annual Report of the Bean Improvement Cooperative* **43**, 92–93.

Williams, G.E. & Asher, M.J.C. (1996) Selection of rhizobacteria for the control of *Pythium ultimum* and *Aphanomyces cochlioides* on sugar beet seedlings. *Crop Protection* **15**, 479–486.

Windels, C.E. & Jones, R.K. (1989) Seedling and root rot diseases of sugar-beets. *Minnesota Extension Service Bulletin AG-FO-3702*.

Windels, C.E. & Nabben-Schindler, D.J. (1996) Limitations of a greenhouse assay for determining potential of Aphanomyces root rot in sugarbeet fields. *Journal of Sugar Beet Research* **33**, 1–13.

Windels, C.E., Lamey, H.A., Hilde, D., Widner, J. & Knudsen, T. (1998) A Cercospora leaf spot model for sugar beet, in practice by an industry. *Plant Disease* **82**, 716–726.

Wolf, P.F.J. & Verreet, J.A. (2002) An integrated pest management system in Germany for the control of fungal leaf diseases in sugar beet. *Plant Disease* **86**, 336–344.

Wright, B., Prowse, H. & Whipps, J.M. (2003) Microbial population dynamics on seeds during drum and steeping priming. *Plant and Soil* **255**, 631–640.

Wysong, D.S., Schuster, M.K., Finkner, R.E. & Kerr, E.D. (1968) Chemical control of *Cercospora* leaf spot on sugarbeets in Nebraska, 1965. *Journal of the American Society of Sugar Beet Technologists* **15**, 221–227.

Chapter 13
Pests

Alan M. Dewar and David A. Cooke

INTRODUCTION

The list of pests that can attack sugar beet is a long one and includes representatives of several, widely differing, animal groups (Table 13.1). Every commercial beet crop is host to some of these pests during its growth, although the relative importance of each species varies from field to field, country to country and year to year. It would take too long to deal with each pest in detail in this chapter, but extensive well-illustrated descriptions of most of them, and their effects on the sugar beet crop, are given by Lejealle and d'Aguilar (1982) and Benada *et al.* (1987). These publications give no information on control measures, and decisions on preventing pest damage (for example by applying pesticides) must take account of national regulations and local conditions; such information is best obtained from trained crop advisers or advisory publications, e.g. Jaggard (1989), Cooke and Dewar (1992) or Lane *et al.* (2000) in the UK, Whitney and Duffus (1986) in the USA and Jorritsma (1985) in the Netherlands. More general accounts of pest management techniques and the principles underlying them are given by Jones and Jones (1984), Brown and Kerry (1987) and Hill (1987).

Research and development programmes have provided farmers with several ways of minimizing the extent of yield loss resulting from pest attack, particularly by increasing the number of available pesticides. In recent years, however, there has been a great deal of public concern over the hazards that these materials present to manufacturers and users, their effects on wildlife and the possibility of toxic residues remaining in harvested crops or leaching into ground water. Recently this has been manifest in the withdrawal of aldicarb for use in sugar beet in many European countries by 2007, and many of the organophosphorous products that were the mainstay of crop protection in the 1970s. While many of

Table 13.1 Pests of sugar beet.

Phylum (Class)	Order	Family	Sugar beet pests
Nematoda (Secernentea)	Tylenchida	Tylenchidae	Stem nematode (*Ditylenchus dipsaci*)
		Pratylenchidae	False root knot nematode (*Nacobbus aberrans*)
		Heteroderidae	Cyst nematodes (*Heterodera schachtii, H. trifolii*)
		Meloidogynidae	Root-knot nematodes (*Meloidogyne incognita, M. javanica, M. hapla, M. naasi*)
Nematoda (Adenophorea)	Dorylaimida	Trichodoridae	Stubby root nematodes (*Trichodorus* spp.*, *Paratrichodorus* spp.*)
		Longidoridae	Needle nematodes (*Longidorus* spp.*)
Mollusca (Gastropoda)		Arionidae	Slugs (e.g. *Arion hortensis, A. fasciatus*)
		Limacidae	Slugs (e.g. *Deroceras reticulatum*)
Arthropoda (Diplopoda)	Polydesmoidea	Polydesmidae	Flat millipedes (e.g. *Brachydesmus superus*)
	Iuliformia	Blaniulidae	Snake millipedes (e.g. *Blaniulus guttulatus*)
Arthropoda (Symphyla)		Scutigerellidae	Symphylids (e.g. *Scutigerella immaculata*)

Phylum (Class)	Order	Family	Sugar beet pests
Arthropoda (Insecta)	Collembola	Onychiuridae	Springtails (e.g. _Onychiurus armatus_)
		Sminthuridae	Springtails (e.g. _Sminthurus viridis_)
	Orthoptera	Gryllotalpidae	Crickets (e.g. _Gryllotalpa gryllotalpa_)
		Acrididae	Locusts (e.g. _Dociostaurus maroccanus_), grasshoppers (e.g. _Melanoplus_ spp.)
	Dermaptera	Forficulidae	Earwig (_Forficula auricularia_)
	Thysanoptera	Thripidae	Thrips (_Thrips angusticeps, T. tabaci, Caliothrips fasciatus_)
	Hemiptera	Miridae	Capsid bugs (_Calocoris norvegicus, Lygus rugulipennis, Lygocoris pabulinus_)
		Piesmidae	Lace bugs (_Piesma cinerea_*, _P. quadratum_*)
		Aphididae	Aphids (_Myzus persicae_*, _Aphis fabae_*, _Macrosiphum euphorbiae_*, _Pemphigus betae, P. fuscicornis, P. populivenae, Aulacorthum solani_*)
		Cicadellidae	Leafhoppers (_Eutettix tenellus_*, _Paratanus exitiosus_*, _Macrosteles laevis_)
	Lepidoptera	Arctiidae	Tiger moth caterpillars (e.g. _Ocnogyna baetica, O. loewi, Hyphantria cunea, Estigemenae acrea_)
		Gelechiidae	Beet moth caterpillars (_Scrobipalpa ocellatella_), sugar beet crown borer (_Hulstia undullatella_)
		Pyralidae	Beet webworm caterpillars (_Margaritia sticticalis, M. similis, M. commixtalis_)
		Caradrinidae	Potato stem borer (_Hydraecia micacea_)
		Noctuidae	Cutworms (_Agrotis_ spp., _Euxoa_ spp.), armyworms (e.g. _Spodoptera_ spp.), silver Y moth caterpillars (_Autographa gamma_)
	Coleoptera	Elateridae	Wireworms (e.g. _Agriotes_ spp., _Limonius_ spp., _Athous_ spp., _Corymbites_ spp.)
		Chrysomelidae	Tortoise beetles (_Cassida_ spp.), beet flea beetle (_Chaetocnema concinna_), other flea beetles (e.g. _Systena_ spp.)
		Curculionidae	Weevils (_Tanymecus palliatus, Lixus junci, Philopedon plagiatus, Otiorhynchus_ spp., _Bothrynoderos punctiventris, Conorhynchus mendicus_)
		Silphidae	Beet carrion beetle (_Aclypea opaca_)
		Scarabaeidae	Chafer grubs (_Melolontha melolontha, Amphimallon solstitialis, Phyllopertha horticola_)
		Carabidae	_Clivina fossor_
		Cryptophagidae	Pygmy beetle (_Atomaria linearis_)
	Diptera	Tipulidae	Leatherjackets (_Tipula paludosa, T. oleracea_)
		Anthomyidae	Beet leaf miner (mangel fly, beet fly) (_Pegomya hyoscyami_), other leaf miners (_Liriomyza_ spp., _Psilopa leucostoma_)
		Bibionidae	Bibio larvae (_Bibio hortulanus, B. marci_)
		Otitidae	Sugar beet root maggot (_Tetanops myopaeformis_)
Arachnida	Acari	Tetranychidae	Two-spotted spider mite (_Tetranychus urticae_)
Chordata (Aves)		Phasianidae	Pheasant (_Phasianus colchicus_), partridge (_Perdix perdix_)
		Columbidae	Pigeon (_Columba palumbus_)
		Alaudidae	Skylark (_Alauda arvensis_)
		Ploceidae	Sparrow (_Passer domesticus_)
		Corvidae	Rook (_Corvus frugilegus_)
Chordata (Mammalia)	Insectivora	Talpidae	Mole (_Talpa europaea_)
	Artiodactyla	Cervidae	Deer (_Dama dama_, _Cervus_ spp.)
		Suidae	Wild boar (_Sus scrofa_)
	Rodentia	Capromyidae	Coypu (_Myocaster coypus_)
		Cricetidae	Vole (_Microtus_ spp., _Arvicola terrestris_), hamster (_Cricetus cricetus_)
		Muridae	Field mouse (_Apodemus sylvaticus_), rat (_Rattus norvegicus_)
	Lagomorpha	Leporidae	Rabbit (_Oryctolagus cuniculus_), hare (_Lepus capensis_)

* Vectors of virus diseases.

these older chemicals have been surpassed by more active, relatively safer (to the environment) new insecticides (see p. 346), the total number available to growers is constantly shrinking because the rate of development of new chemicals has slowed to a trickle in recent years as a result of the ever more stringent registration requirements by regulatory authorities.

A further consequence of these changing attitudes towards pesticide usage has been the dramatic shift in emphasis of publicly-funded research programmes towards developing alternative methods of pest population management. For many years, sugar beet research workers have advocated the use of integrated systems of pest management, recommending established cultural techniques (e.g. appropriate crop rotations, beet-free periods to prevent carry-over of diseases or their vectors, early planting to avoid severe damage in the seedling stage) to supplement or replace pesticides. Research projects have also investigated alternative methods of crop protection (e.g. pest-resistant sugar beet lines, biological control techniques) or ways of improving the existing methods (e.g. better forecasting of pest attack in order to limit the use of insurance pesticide treatments, improved pesticide formulations or application techniques). Some of these techniques have been both more effective and more environmentally acceptable, and have readily been incorporated into pest management systems (Dewar, 1994).

This chapter discusses the effects on yield of pest attack at different stages of crop growth and on different parts of the plant, the major groups of sugar beet pests, and pest management strategies.

EFFECTS OF PESTS ON ESTABLISHMENT, GROWTH AND YIELD

Crop establishment

Several groups of pests can cause the loss of plants at the seedling stage. A single field mouse (*Apodemus sylvaticus* L.) can excavate and destroy hundreds of seeds in one night, and although field mouse populations are relatively small (two or three per hectare) in the spring, their feeding can sometimes necessitate the re-drilling of whole fields. Birds can reduce plant populations in various ways. Some (e.g. skylarks *Alauda arvensis* L.) may set back or kill very young seedlings as a result of grazing on cotyledons or destroying the growing point whilst feeding; some (e.g. rooks *Corvus frugilegus* L.) can pull up seedlings whilst searching for soil insects such as leatherjackets (*Tipula* spp.); and some (e.g. pheasants *Phasianus colchicus* L.) can sever the foliage from older plants by pecking at the roots at soil level. Slugs (e.g. *Deroceras reticulatum* Müller) can reduce seedling numbers, especially in moist, heavy soils or those with high humus content, as a result of feeding on leaves, cotyledons or hypocotyls. Grazing, particularly by rabbits (*Oryctolagus cuniculus* L.) or hares (*Lepus capensis* L.), can cause serious plant losses in the worst-affected fields. Most of the pest-induced plant loss, however, results from damage caused by the feeding of a range of soil arthropods, the most important being millipedes (e.g. *Brachydesmus superus* Latzel, *Blaniulus guttulatus* Bosc.), springtails (e.g. *Onychiurus armatus* Tullberg), symphylids (e.g. *Scutigerella immaculata* Newport), wireworms (e.g. *Agriotes* spp.), leatherjackets (e.g. *Tipula paludosa* Meigen) and pygmy beetles (*Atomaria linearis* Stephens).

Better pesticides and improvements in our understanding of the factors influencing the occurrence and severity of damage have helped to restrict such losses. Nevertheless, large numbers of plants are killed or injured by soil pests every year, and, if sugar yield were the only criterion for success, the best crops would probably still be those in which seeds were sown thickly and the surviving seedlings subsequently thinned by hand-hoeing to leave an evenly-spaced plant population of about 75 000/ha comprising the most vigorous plants. However, increased labour costs, together with the development of monogerm varieties and improved seed quality (i.e. with better laboratory germination), have ensured that almost all crops in the USA and western Europe are now sown at wide seed spacings (> 12 cm) with no subsequent hand-hoeing. This means that, although a certain amount of plant loss can be tolerated because of compensatory growth of adjacent plants, the majority of sown seeds must germinate to give seedlings that survive to produce harvestable roots if yield potentials are to be fully realized.

The effect of a sub-optimal population of established plants on crop yield depends on the distribution of the remaining plants and the timing of seed or plant loss. This is because the magnitude of yield loss is a function of the loss of leaf canopy, since the yield of the crop is closely related to the amount of solar radiation that is intercepted by the foliage (Fig. 7.7).

Plant loss can occur randomly (e.g. from seed-borne diseases), in a 'clumped' distribution (e.g. from damage by most pests and diseases) or along lengths of row (e.g. field mouse damage). Because of the ability of adjacent plants to compensate for uniformly distributed plant loss, the greatest yield losses occur where the plant losses are least uniform. Table 13.2 shows the effects on yield of irregularly spaced plants (alternate spaces differing in the ratio of 4:1) and regularly spaced plants at four population densities (Scott & Jaggard, 1985).

In most fields, plants can extend their leaf canopy and root systems to about 50 cm diameter; when crops are grown in rows 50 cm apart, sugar yield is lost when within-row gaps exceed about 45 cm (Fig. 13.1 and see Chapter 7). In the UK, more than 95% of crops are now sown at seed spacings of more than 16 cm (1.25 units/ha) (British Sugar Crop Survey information); at these spacings gaps exceeding 45 cm will occur often enough to decrease yield where plant establishment is less than 70%, and this figure is now accepted as the target which UK growers must aim to achieve. At different seed spacings the frequency of occurrence of yield-limiting gaps varies. Figure 7.17 (produced by a combination of measurement and modelling) shows the effect of seed spacing and seedling establishment on sugar yield assuming a random distribution of plant loss (Scott & Jaggard, 1985).

Table 13.2 The influence of plant distribution on the relationship between sugar yield and plant density (from Scott & Jaggard, 1985).

	Plant density (thousands/ha)			
	25	50	75	100
Distribution	Sugar yield t/ha			
Regular	5.7	7.2	7.5	7.3
Irregular	4.9	6.8	7.3	7.4

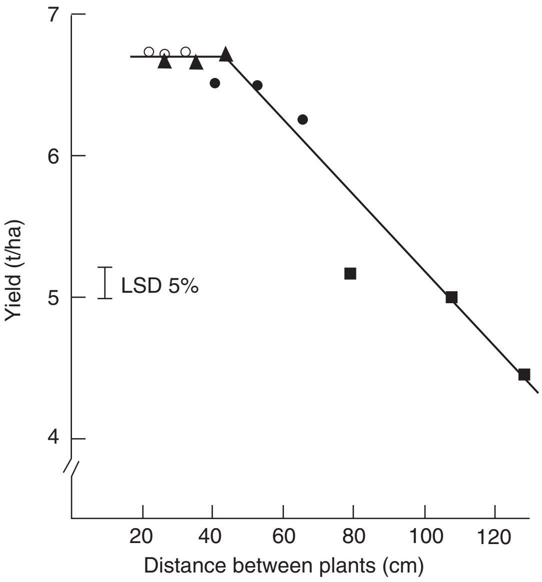

Fig. 13.1 The relationship between sugar yield and gappiness of the stand. Data from three experiments comparing the effects of plant densities of 25 000/ha (squares), 50 000/ha (solid circles), 75 000/ha (triangles) and 100 000 (open circles) in regular, irregular (alternate plant spaces in ratio 1:2) and very irregular (alternate plant spaces in ratio 1:4) distributions.

Irregularly distributed plant losses, which commonly result from pest attack (Brown, 1981), produce even greater yield reductions. In ten trials conducted in the UK where soil pests were causing damage, no yield loss occurred until plant populations were fewer than 70 000/ha. Below that level significant yield losses were not recorded until at least 10% more plants were lost; thereafter yield loss was linearly correlated with plant population (Dewar, 1996).

Defoliation

Some of the pests discussed in the previous section, which can kill seedlings and older plants (e.g. rabbits, hares, skylarks, slugs, pygmy beetles and leatherjackets), can also cause non-lethal defoliation. In addition, there are several pests which can partially or completely defoliate plants but rarely kill them (e.g. adults of several weevil species, leaf miners, tortoise beetles, flea beetles, the caterpillars of several moths and two-spotted spider mites). The effects of this damage are more difficult to quantify than the effects of poor establishment. Accurate estimates of yield losses are seldom possible in field trials using pesticides to control damage, because pest attack is rarely sufficiently uniform or severe to permit the collection of reliable data; the pesticides may also give incomplete control, especially if applied too late, and often have secondary effects. Because of this, attempts have been made to simulate pest damage in artificial defoliation trials.

In one such trial series sugar beet was defoliated at different dates from May to October (Dunning & Winder, 1972). Half defoliation (i.e. removing one cotyledon) in May had no effect on yield. In one typical year, when the trial was harvested in mid-November, the sugar yield losses from complete defoliation increased from about 4% following defoliation in May to 36% following defoliation in August, but then decreased to 9% following defoliation in October (Fig. 13.2). In these trials new leaves grew rapidly, so early defoliation had little effect on the total amount of radiation intercepted by the crop; however, later in the year, as both the amount of incoming radiation and the leaf area index of untreated crops increased, the effect of complete defoliation became greater. Using Dunning and Winder's data, Scott and Jaggard (1985) calculated that complete defoliation in mid-September would render the crop unproductive for the rest of the season, because the new leaf surface would not be active for long enough to replace the sugar used during leaf production.

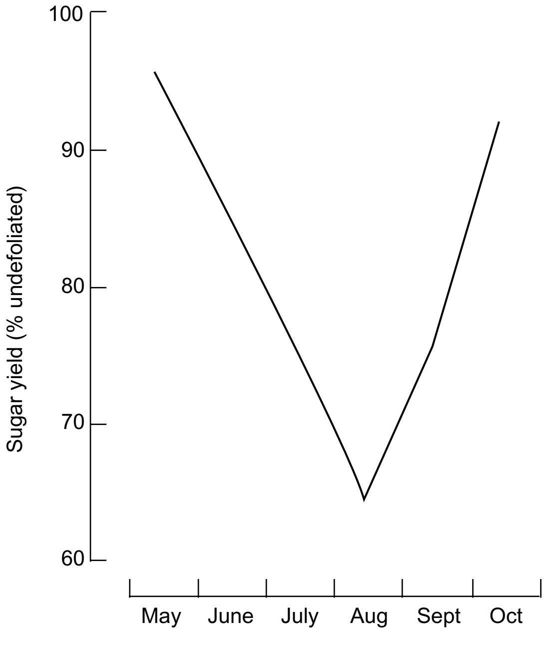

Fig. 13.2 Sugar yield of plots defoliated at different times in the season as a percentage of the yield of undefoliated plots.

Different defoliation experiments have produced apparently contradictory results. Jones *et al.* (1955) and Dunning and Winder (1972) found small yield losses from early defoliation in the spring but larger losses following defoliation in the summer; in general the effects on sugar yield of anything less than complete defoliation were negligible. However, Roebuck (1932) found that removal of half the leaf surface at the end of May decreased final root yield by 25% and that losses became progressively smaller following later defoliation treatments. Similarly, in bird grazing experiments involving prolonged defoliation, Green (1978) found sugar yield losses of around 25% resulting from the loss of about 60% of the cotyledon area, and Dunning *et al.* (1977) found that a single early defoliation treatment reduced sugar yield by 6% in late-sown plots and 30% in early-sown plots, while repeated defoliation decreased yields in both early and late sowings by 40%.

Clearly, defoliation can produce different effects on crop growth and yield depending on the timing and method of foliage removal and other environmental factors. The weather conditions subsequent to foliage loss are certain to affect the crop's response: there is likely to be relatively less effect on yield in years of severe drought or low radiation receipts. Disease incidence may be affected differentially; for example, Dunning and Winder (1972) found that early defoliation decreased the proportion of plants showing symptoms of virus yellows, whereas later defoliation increased incidence. However, in a subsequent experiment, Dunning *et al.* (1977) found that defoliation had little effect on virus yellows, but greatly increased the incidence of *Beet mosaic virus*, although this latter effect may have been enhanced by mechanical transmission by the cutting implements.

Estimates of the losses in sugar yield which result from defoliation are important to growers, who need to make decisions on control measures to prevent such damage. It seems important to prevent defoliation in the cotyledon stage, partly because this can, in some situations, result in large yield losses and partly because many of the pests that are responsible can also decrease plant establishment, which has an even greater effect on yield. Mid-season defoliation can decrease sugar yield but only when large proportions of the foliage are removed. It also depends on the timing of defoliation. Complete defoliation of beet plants by silver Y moth larvae (*Autographa gamma* L.) in July 1996 had little effect on final yield because of compensatory growth by the beet plants during the rest of the summer (Dewar & Haylock, 1996), but later defoliation in September by two-spotted spider mites (*Tetranychus urticae* Koch) in 1995 caused serious losses due to the stimulation of substantial regrowth of leaves by the plant, which reduced the sugar concentration in the roots (Dewar & Haylock, 1995). Theoretical calculations of such losses on the basis of intercepted radiation should be treated with some caution because it is not known whether partially severed or damaged leaves are as efficient at creating plant material as intact leaves, or whether removal of whole leaves alters the efficiency of those that remain. Late season defoliation in October, when radiation receipts are small, will have correspondingly small effects on yield.

Foliar efficiency

Several sugar beet diseases, particularly those which cause yellowing of the foliage, decrease the crop's photosynthetic efficiency, reducing both root weight and sugar content (Smith & Hallsworth, 1990; Stevens *et al.*, 2004; Chapter 11). Although foliage pests such as aphids and leafhoppers are of major importance as vectors of these diseases (see the relevant sections and Chapter 11), the direct damage they cause is usually of little significance. The damage caused by some other pests, for example the mining of larvae of mangel fly (*Pegomya hyoscyami* Panzer syn. *P. betae*) and the yellowing of the distal portions of leaves fed on by some capsid bugs (e.g. *Calocoris norvegicus* (Gmelin)), may impair foliar efficiency directly, but is rarely sufficiently extensive to cause significant losses. However, the damage to the under-surface of leaves by spider mites can reduce the functioning of the leaf sufficiently to reduce yield, especially when the new leaves produced to compensate for loss of function are also colonized by these pests (Legrand *et al.*, 2000).

Some soil-borne pests, in particular beet cyst nematode (*Heterodera schachtii* Schmidt), can damage roots and impair their ability to absorb water and transport it to the leaf. This can cause crops to wilt prematurely, i.e. at soil water potentials in which the foliage of undamaged crops would be able to maintain turgidity. At leaf water potentials of about 15 bar the leaf wilts, its growth rate falls to zero and its photosynthetic ability is severely curtailed because the stomata close and carbon dioxide is no longer assimilated from the atmosphere (Milford & Lawlor, 1976). These secondary effects of root damage add to the sugar yield losses which result directly from decreased root growth.

Root growth

Many of the soil-inhabiting arthropods which can feed on seedling roots and kill the young plant are also capable of sub-lethal grazing. Although plants appear to tolerate damage by the time they have developed four true leaves (Jones & Dunning, 1972) the effects of their feeding during the earlier period of plant growth can stunt young seedlings and lead to a loss in final sugar yield. Using previously unpublished data from four pesticide experiments, Brown (1985) compared sugar yields on damaged plots with the predicted yields based on seedling establishment. He found actual yield losses of about 15% on plots where losses of only 5% were predicted and concluded that the additional loss of yield was most likely to have resulted from the sub-lethal effects of pest feeding on the established plants (Fig. 13.3).

Free-living nematodes occur commonly and feed ectoparasitically on the roots of several crops including sugar beet. Stubby root nematodes (*Trichodorus* spp. and *Paratrichodorus* spp.) feed on epidermal cells or root hairs, causing them to collapse; taproots can be damaged at an early stage and develop a forked (fangy) appearance. Needle nematodes (*Longidorus* spp.) use their long feeding stylets to penetrate the vascular tissue of roots

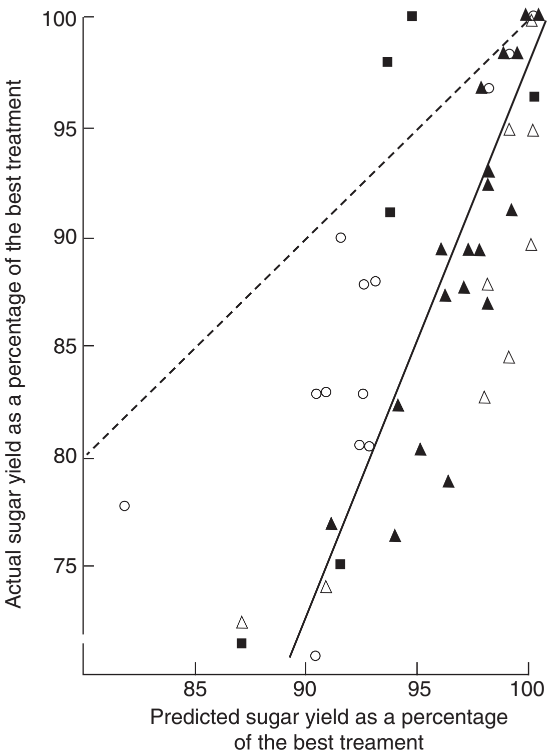

Fig. 13.3 The relationship between actual sugar yield from plants damaged by soil-inhabiting pests and yields predicted by Jaggard's (1979) model. The dashed line is the equality line (actual = predicted) and the solid line the best fit to the unpublished data gathered from four sites (indicated by the different symbols).

causing galling and a reduction of root growth. When soil conditions allow early and prolonged feeding by these nematodes, large root yield losses can occur, and, although there are no clear relationships between nematode numbers and yield, nematicide treatments on infested fields have resulted in root yield increases of up to 15 t/ha (Cooke & Draycott, 1971; Cooke *et al.*, 1974; Cooke, 1976; 1989; Dewar *et al.*, 2004b).

Beet cyst nematode (*Heterodera schachtii*) is a major pest of sugar beet throughout the world (Müller, 1999). Root invasion, the subsequent migration through cortical tissues, and the establishment and exploitation of feeding sites cause a variety of symptoms including a proliferation of lateral root growth, stunting of the taproot, reduced and abnormal leaf growth and premature wilting of the foliage. The relationship between initial population of *H. schachtii* (*Pi*) and root yield (*Y*) has been described by the equation:

$$Y = Y_{\text{min.}} + (Y_{\text{max.}} - Y_{\text{min.}})Z^{Pi-T} \qquad (13.1)$$

where $Y_{\text{min.}}$ is the minimum yield, $Y_{\text{max.}}$ is the yield in the absence of the nematode, Z is a constant slightly less than 1 and T is the tolerance limit (i.e. the population below which yield is not affected) (Cooke, 1991). An economic threshold of 500 eggs/100 ml soil has been postulated (Steudel *et al.*, 1981) at which level at least 5% yield loss must be expected. In individual field experiments, carried out in very different environmental conditions, initial populations of 10 eggs + juveniles/g of soil resulted in root yield losses of between 1% and 64% (Cooke & Thomason, 1979; Greco *et al.*, 1982; Cooke, 1984; 1991).

More direct damage to the roots of established sugar beet crops is caused by the soil-inhabiting stages of various insects. Larvae of cockchafers (e.g. *Melolontha melolontha* L.) can eat right through the roots of young plants, which then die; feeding on older plants can result in the formation of cavities around which secondary diseases can develop. Fortunately, damage is usually confined to isolated plants in the field and is rarely of economic significance. Similar damage can be caused by the caterpillars (often called cutworms) of various species of noctuid moths, (e.g. *Euxoa* spp., *Agrotis* spp.) whose feeding can cause pitting with large irregular holes on the surface. Potentially more damaging are caterpillars of the potato stem borer (*Hydraecia micacea* (Esper)) which tunnel inside the crown and upper root and can kill the plant; the pest also usually attacks only isolated plants so crop loss is minor, but severe damage has been reported from Scandinavia and Finland. Wireworms, the larvae of click beetles (e.g. *Agriotes* spp., *Limonius* spp.), also tunnel through large roots, although the damage that they can inflict on seedlings is more serious (see the Wireworm section). Larvae of some weevils (e.g. *Bothrynoderes punctiventris* Germ., *Conorhynchus mendicus* Gyll.) can also tunnel out extensive galleries within beet roots, and in some fields large proportions of the crop can be attacked. Root aphids (*Pemphigus* spp.) feed ectoparasitically on lateral and taproots, affecting the uptake of nutrients and water, so that affected crops turn yellow and wilt. The extent of damage varies, but is worst in crops suffering from drought where, in extreme cases, plants can be killed.

Disease vectors

Pests and diseases rarely occur in isolation, and the feeding activity of all pest species, particularly those that damage the epidermal cells of crown or root tissues, can provide points of entry for secondary pathogens. Virus diseases, transmitted by a range of insect, nematode and fungal vectors, constitute a particularly serious threat to crop yields because, once the plant is infected, it remains infected throughout its life and cannot compensate for damage caused. These diseases are dealt with in Chapter 11, but a brief mention of pests that constitute the most important vectors can be made here.

Many aphid species feed on sugar beet plants and can cause direct damage to roots or foliage. However, they have a more significant role in the pathology of the crop as vectors of virus diseases, including *Beet yellows virus* (BYV) (Clover *et al.*, 1999), *Beet mild yellowing virus* (BMYV) (Stevens *et al.*, 1995), *Beet chlorosis virus* (BChV) (Hauser *et al.*, 2002; Stevens *et al.*, 2004) and *Beet western yellows virus* (BWYV) (USA only; Wisler & Duffus, 2000). The peach-potato aphid, *Myzus persicae* (Sulzer), called the green peach aphid in the USA, is the commonest vector of these yellowing viruses although the latter three can be transmitted by several other aphid species (Heathcote & Cockbain, 1966). *Beet mosaic virus* (BMV), *Beet yellow net virus* (BYNV) and *Cucumber mosaic virus* (CMV) also have *M. persicae* as the most important among several aphid vectors, and *Beet yellow stunt virus* (BYSV) is transmitted most efficiently by *Hyperomyzus lactucae* (L.), the sowthistle aphid.

The beet leafhopper (*Eutettix tenellus* Baker, syn. *Circulifer tenellus*) transmits beet curly top virus (BCTV), a potentially catastrophic disease of beet crops in the USA. It was responsible for enormous crop losses in the 1920s and 1930s, but is controlled today by a complex programme involving resistant cultivars, cultural practices and vector control methods. Another potentially devastating disease, beet yellow wilt, is caused by a Rickettsia-like-organism (RLO) transmitted by leafhoppers, but only occurs in South America (Stevens & Dewar, 1996; Hepp & Sandoval, 1997; see Chapter 12).

Lace bugs (*Piesma* spp.) transmit two virus diseases of only local importance. *P. quadratum* (Fieber) is the vector of *Beet leaf curl virus*, which is found only in eastern Europe, and *P. cinerea* Say is the vector of *Beet savoy virus*, which occurs in the USA.

Stubby root nematodes (*Trichodorus* spp. and *Paratrichodorus* spp.) can transmit *Tobacco rattle virus* (TRV), and needle nematodes (*Longidorus* spp.) transmit *Tomato black ring virus* (TBRV). Both viruses can affect yield and/or quality in other crops, but in neither case is the effect on sugar yield from the virus likely to be as great as that resulting from direct damage caused by the vector, and, usually, only isolated plants show symptoms.

DISTRIBUTION, BIOLOGY AND PATHOGENICITY OF MAJOR PESTS

In this section descriptions are given of the major sugar beet pests, together with brief accounts of their biology and damage which they can cause to the crop. More detailed accounts of some of these pests are given by Cooke and Dewar (1992) and more profusely illustrated ones by Lejealle and d'Aguilar (1982) and Benada *et al.* (1987).

Nematodes

Many of the nematode pests that damage sugar beet also attack several other crops. A useful review of these in vegetable crops is given by Johnson (1998), and reviews of those that attack sugar beet are given by Caubel (1990) and Cooke (1993).

Stem nematodes

Stem nematode, *Ditylenchus dipsaci* (Kühn), is a migratory endoparasite that feeds on parenchymatous tissue in stems and bulbs. The species is a complex mixture of races with different host ranges (Whitehead *et al.*, 1987); some of these (e.g. the oat race and the onion race) can attack sugar beet and are regarded as serious pests of the crop in some countries (e.g. Switzerland).

Description and biology

Adults are vermiform, usually 1.0–1.3 mm long, with no clear distinction between the sexes. The mouth spear (which is used to penetrate and feed on host plant cells) is small, with distinct basal knobs; the body is slender and the tail pointed. There are four juvenile stages, similar in shape to the adults (only smaller) with the moult to the second stage occurring in the egg.

Feeding and multiplication take place continuously within host plant tissues, so that eggs, juveniles and adults occur together. Mating is necessary for reproduction, and a single fertilized female can lay hundreds or even thousands of eggs. The life cycle, egg to mature adult, takes about 3–4 weeks under favourable conditions. Sugar beet seedlings can be invaded, usually by fourth stage juveniles, soon after emergence and particularly in cool, moist conditions. Nematodes occur in the hypocotyl, petioles, cotyledons and leaves of seedlings but later in the season they can invade the crown of the maturing plant, or re-enter the soil to invade neighbouring plants. The resistant stage of the nematode is the fourth stage juvenile, which can survive in a desiccated state, often in plant residues, for several years.

Distribution and damage

D. dipsaci is most widely distributed in temperate areas and is recognized as a fairly common pest in most European countries, although it usually affects only a small number of plants in any field. In Switzerland however, it can damage crops on a much wider scale necessitating chemical control in many areas, usually by applications of a granular formulation of aldicarb at sowing, followed by parathion granules in July/August to prevent re-infestation.

Early infestations cause twisting, swelling and distortion of cotyledons, leaf petioles and laminae. The growing point of seedlings can be killed; axillary growing points develop, producing a plant with multiple crowns and small distorted leaves. Later in the season infestation of the crown can occur, causing much more serious damage to plants. It appears first in the autumn as raised pustules among the leaf scars, then rot forms, which spreads and may encircle the crown and which soon harbours secondary pathogens. Seriously affected crops should be harvested as early as possible, and delivered to the factory without prior clamping.

False root knot nematodes

The false root knot nematode, *Nacobbus aberrans* (Thorne and Schuster), is a sedentary endoparasite that causes root galling similar to that caused by *Meloidogyne* spp. (see Root-knot nematodes). It is a serious pest of sugar beet in some areas of the western USA.

Description and biology

Mature females are 0.7–1.9 mm long with oval, white-cream bodies. Males and juveniles are vermiform, the juveniles having the robust stylets typical of the family Pratylenchidae to which they belong.

The second stage juveniles hatch from the eggs and move through the soil to invade roots of host plants, which, in addition to sugar beet, include weeds such as *Chenopodium album* L. (Gray *et al*., 1997). Successive juvenile stages migrate through root tissues and can leave and reinvade roots. The females become sedentary, and, after maturing, discharge fertilized eggs into a gelatinous matrix. The life cycle is completed in about 48 days at 25°C (Inserra *et al*., 1983).

Distribution and damage

N. aberrans is a native of South and Central America and the western USA. It damages beet crops in Nebraska, Montana, Wyoming, South Dakota, Colorado and Kansas.

The juvenile stages can cause necrosis and hypertrophy of epidermal and cortical cells resulting in small swellings on infested young roots. The establishment of the nematode's permanent feeding site initiates the formation of large, rather flat, galls with numerous lateral roots. Nutrient and water uptake are reduced so that affected plants are often stunted and yellow. Yield losses of over 20% have been reported. Control can be achieved by rotation with non-host crops (e.g. cereals, lucerne, potatoes, brassicas) or soil fumigation. Aldicarb and iprodione drench treatment gave significant reduction in gall formation in Wyoming, but no increase in yield (Beaupre *et al.*, 1990).

Cyst nematodes

Beet cyst nematode (*Heterodera schachtii*) is the most important nematode pest of beet, and has been the subject of extensive investigation for well over 100 years; this work has been reviewed by Cooke (1987) and more recently by Müller (1998). In addition to *H. schachtii*, a host race of clover cyst nematode (*H. trifolii*), called yellow beet cyst nematode, has been found damaging beet crops in the Netherlands, Sweden, Switzerland and Germany (Maas & Heijbroek, 1982; Andersson, 1984; Valloton, 1985; Schlang, 1990).

Description and biology

The most distinctive stage of *H. schachtii* is the lemon-shaped cyst that is formed from the cuticle of the dead female, and contains up to 600 eggs. Second stage juveniles hatch from the eggs, escape from the cyst through the oral or vulval aperture and move through the soil to invade host plant roots. Hatch can occur quite readily in soil in which host plants are not growing, but, where host plants are grown, exudates from their roots stimulate additional hatch and attract juveniles to invasion sites. After invading the roots, juveniles move through the cortex to permanent feeding sites adjacent to the vascular cylinder, where salivary secretions stimulate the formation of transfer cells. After developing through third and fourth stage juveniles to adults, the vermiform males escape into the soil and are attracted to the white females which remain attached to the roots but swell to split the cortex, exposing the posterior vulva. After mating, the males soon die, while the females turn brown and drop off the roots into the soil. The rate of development is dependent on soil temperature, requiring about 300°C days above a base temperature of 10°C for completion of the life cycle; this means that two to three generations can be completed in northern Europe, three in southern Europe and five in the long growing season and warm soils of southern California.

Distribution and damage

H. schachtii is found in almost all beet-growing areas of the world but is particularly prevalent where beet or other host crops have been grown (often in close rotations) for many years (e.g. in parts of Germany and the Netherlands (Müller, 1998), or the organic soils of the Fens in the UK (Cotten *et al.*, 1992)), or where conditions particularly favour population increase and dispersal (e.g. irrigated fields of the Imperial Valley of southern California). In Europe, yield losses have been conservatively estimated at 89m Euros ($95m) per annum (Müller, 1998).

Damage to crops is usually first noticed when patches of stunted plants appear which wilt before the surrounding, less heavily infested area. Affected plants have small taproots with many laterals, on which the nematodes may be seen as small, white cysts.

Control is usually based on widening the rotation of host crops although other techniques (e.g. the use of soil fumigants, granular nematicides or nematode-resistant catch crops (see p. 346)) may be used in some countries. However, fumigants such as dichloropropene have been, or are now being, withdrawn in many of these countries because of their toxic effects on non-target organisms; they have been banned in Germany since 1990. Granular nematicides have some small effect in controlling cyst nematodes, but at the rates approved for use in sugar beet are only partially effective. Nematode resistant catch crops such as white mustard (*Sinapis alba* L.) or oil radish (*Raphanus sativus* L.) have been more popular in recent years, particularly in Germany. The catch crops stimulate egg hatch in infested soils prior to growing sugar beet, but are resistant to colonization by the young larvae, which become sedentary in the plant roots. This reduces the inoculum in the soil by up to 70% (Schlang, 1989), with consequent benefits for sugar beet yields the following year. Nematode-resistant varieties are now available, often developed in conjunction with rhizomania resistance. However, they still yield less than the highest yielding susceptible varieties in the absence of the pest. In addition, experiments suggest that the resistance is not completely transmitted, and can break down under high population pressure as a result of resistance-breaking pathotypes. Future resistant varieties may need to be developed with transgenic technology to allow transference solely of the resistance gene(s) without the undesirable genes often transferred using traditional breeding techniques.

Biological control measures (e.g. fungi such as *Cylindrocarpon destructans* (Zinssmeister), and *Verticillium chlamydosporium* Goddard), which attack different generations of nematodes, have been investigated (Crump, 1991; Crump & Irving, 1992; Sosnowska, 2001), but so far without commercial success. It is likely that parasitic fungi are responsible for the slower population development of *H. schachtii* in so-called suppressive soils (Gao & Becker, 2002).

Some reductions in cyst populations were achieved with cacao shell powder, with consequent benefits on yield (Schlang, 1991), but again there has been no commercial development to date.

Root-knot nematodes

Root-knot nematodes (*Meloidogyne* spp.) are the most important group of plant nematode pests worldwide, attacking several agricultural and horticultural crops, particularly in the tropics. Franklin (1978) gave a general account of the genus, the taxonomy of which was reviewed by Jepson (1987). Only a few of the 50 or more described species can parasitize sugar beet; these include *M. incognita* (Kofoid and White), *M. arenaria* (Neal), *M. javanica* (Treub), *M. chitwoodi* Golden *et al.*, *M. hapla* Chitwood, *M. naasi* Franklin and *M. thamesi* Chitwood (Cooke, 1993).

Description and biology

Female root-knot nematodes have white, swollen bodies 0.4–1.0 mm long and a short anterior 'neck'. The features of the posterior end, including the vulva, anus and cuticular striations, form a perineal pattern which is used in identification.

The life cycle is similar to cyst nematodes. Females deposit numerous (50–100) eggs externally in a gelatinous matrix. Second stage juveniles hatch from the eggs and move through the soil to invade host plant roots in which development through third and fourth stage juvenile to adult male or female takes place. Males are usually functionless and reproduction is nearly always parthenogenetic. In ideal conditions the life cycle takes 20–25 days, so four to five generations may be completed per year in warmer countries but fewer in the cooler climates of northern Europe (Gooris & d'Herde, 1972).

Distribution and damage

The warm-climate species, *M. incognita*, *M. javanica* and *M. arenaria*, can seriously damage sugar beet crops, particularly in coarse sandy soils, in the more southerly beet growing areas of Europe (e.g. Greece and Italy) and the USA (e.g. California, Arizona and southern Colorado). The temperate-climate species *M. hapla* and *M. naasi* are both distributed very widely and can damage sugar beet crops in northern Europe, Japan and the USA, but damage is relatively minor compared to the tropical species (Cooke, 1993).

Infested plants are stunted and tend to wilt in warm weather. The nematodes cause the formation of characteristic galls on lateral roots; where early and severe infestations occur, galls can form on the taproots and plants may even be killed. Some control may be achieved by the use of appropriate crop rotations and sensible husbandry (e.g. removal of infested crop residues, control of weed hosts, early planting of crops when soil temperatures are below the optimum for nematode invasion). In heavily infested fields nematicides may have to be used. Carbamate and organophosphorous nematicides have improved yields but are often less effective than fumigants (Villeroy & Pourcharesse, 1975; Di Vito & Lamberti, 1977; Smith *et al.*, 1978; Casagrandi *et al.*, 1996). Other methods of controlling *Meloidogyne* spp. on sugar beet include use of trap cropping (Heijbroek *et al.*, 1998), biological control using parasitic fungi such as *Verticillium chlamydosporium* (De Leij & Kerry, 1991; Kerry, 1998), and the search for resistant varieties using non-cultivated sea beet, *Beta maritima* (L.) (Yu, 1995; Yu *et al.*, 1999; Yu & Lewellen, 2004).

Free-living nematodes

Several species of free-living nematodes can feed on sugar beet. Of particular importance are the stubby root nematodes (*Trichodorus* spp. and *Paratrichodorus* spp.) and needle nematodes (*Longidorus* spp.). These migratory ectoparasites are particularly prevalent and damaging on light sandy soils.

Description and biology

Stubby root nematodes (*Trichodorus* spp. and *Paratrichodorus* spp.) are rather plump with a characteristically curved mouth stylet and rounded tail. All stages are vermiform with adults varying in length from about 0.5–1.5 mm. Needle nematodes (*Longidorus* spp.) are much longer (adults usually 5–10 mm) and, although very slender, can sometimes be seen by the naked eye resembling short lengths of fine, white thread. They have a long stylet with which they puncture plant roots and feed on cell contents.

Eggs of all these nematodes are laid in the soil; juvenile stages and adults occur together and feeding and reproduction take place throughout the growing season of the host plant. All species have wide host ranges and, unlike cyst nematodes, there is no resistant stage in the life cycle. Males of some species (e.g. *P. teres* (Hooper), *L. attenuatus* Hooper, *L. elongatus* (de Man)) are rare and reproduction is parthenogenetic, whereas in other species (*P. pachydermus* (Seinhorst), *T. primitivus* (de Man)) males are common and sexual reproduction occurs. In temperate climates the life cycle of stubby root nematodes is completed in 6–7 weeks whereas that of needle nematodes takes 1–2 years.

Stubby root nematodes can transmit *Tobacco rattle virus* and needle nematodes can transmit *Tomato black ring virus* to sugar beet crops. Neither virus disease seriously affects yields, but symptoms are frequently seen on the foliage (usually on isolated plants within a field) indicating the presence of the nematode vector.

Distribution and damage

All three genera have worldwide distributions although certain species have more limited geographical ranges. Most species of stubby root nematode are largely restricted to lighter soils (although *T. primitivus* can occur in a wide range of soils). Needle nematodes occur in a variety of soils but tend to prefer undisturbed conditions (e.g. grass leys, hedgerows and perennial rather than annual crops).

Stubby root nematodes aggregate round the tips of young roots, causing a browning and collapse of epidermal cells. Root growth stops, resulting in characteristic stubby root symptoms (Plate 66); severe, early damage can kill the growing point of the taproot resulting in poorly yielding fangy roots at harvest. Needle nematodes feed on root tips, often causing a swelling and necrosis around the point of stylet insertion; severely-affected roots remain stunted and yield poorly. Damage to beet crops is restricted to light, sandy soils and is most severe following wet weather during the few weeks after germination. It is known as Docking disorder in the UK and t-disease in the Netherlands and can be reliably controlled only by the prophylactic use of nematicides (Cooke, 1989). Yield losses can be high (up to 30%) (Dewar *et al*., 2004b) when wet conditions prevail during the early season, which allow the nematodes to aggregate around young roots more easily.

Slugs

Slugs (particularly *Deroceras reticulatum* but also *Arion hortensis* Férussac and *A. fasciatus* (Nilsson)) are widespread in Europe and can damage sugar beet crops particularly on heavier or poorly-drained soils, where organic manure has been used, where conservation tillage is practised (Pringas *et al*., 2003), in organic crops (Cormack *et al*., 2004), and after a wet autumn or during a wet spring. They can feed below soil level (on the hypocotyls) or above soil level (on stems and young leaves) causing irregular wounds or holes. Damaging populations are best controlled by baits containing metaldehyde or methiocarb, but these must be used carefully as they can have adverse effects on other wildlife, such as mice. The use of parasitic rhabditid nematodes, *Phasmarhabditis hermaphro-*

dita Schneider, is being investigated (Ester *et al.*, 2004), but is not yet in commercial practice in sugar beet crops.

Arthropods

These can be roughly classed as soil or foliar pests; some can cause damage to both roots and leaves.

Millipedes

Two groups of millipedes occur commonly in sugar beet fields: snake millipedes (e.g. the spotted snake millipede, *Blaniulus guttulatus*) and flat millipedes (e.g. *Brachydesmus superus*).

Description and biology

Blaniulus guttulatus has a slender off-white body about 1 mm in diameter and up to 20 mm long, comprising up to 60 segments, each with two pairs of legs and a bright orange-red spot on both sides. *Brachydesmus superus* is light brown or grey, about 1 mm in diameter and 10 mm long with up to 19 segments, each with a pair of lateral projections and two pairs of legs.

Millipedes breed in the spring and summer, and females lay their eggs in clusters in 'nests' made of soil particles. The young millipedes have only three pairs of legs; as they grow the number of body segments increases and it may take 2 or 3 years before the full number is reached.

Distribution and damage

Millipedes thrive in moist conditions and prefer soils that have appreciable clay content, an open texture and contain ploughed-in stubble or other organic matter. They are particularly prevalent in northern Europe, where they are an important component of the soil pest complex. They can be extremely numerous (populations of 16 million spotted snake millipedes per hectare have been recorded).

Millipedes often tend to aggregate around roots that have been injured by other soil pests, but are usually the primary cause of plant damage. Seedling growth is slowed and severe injury can kill the young plants; little damage is caused after the four-leaf stage has been reached. Controlling damage is difficult, but reducing the amount of fresh organic matter in the soil and ensuring that seedbeds are firm will discourage the build-up of large populations. Most reliable control of damage is given by insecticides applied as seed treatments (e.g. tefluthrin, imidacloprid, clothianidin + beta cyfluthrin and thiamethoxam + tefluthrin) (Dewar, 1989a; 1992; Vincinaux *et al.*, 1992; Asher & Dewar, 1994; Dewar & Asher, 1994; Heijbroek & Huijbregts, 1995; Wauters & Dewar, 1996; Elfstrom, 1997; Dewar *et al.*, 2000a; Hermann *et al.*, 2001). Carbamate granules such as carbosulfan, oxamyl and benfuracarb applied at sowing may also give good control (Larsson *et al.*, 1991; Winder *et al.*, 1993). Soil surface applications of insecticides such as gamma HCH are no longer approved because of their toxic effects on non-target organisms. The targeted application of seed treatments is more environmentally friendly than either overall sprays that are subsequently incorporated, or granules placed down the furrow (Dewar *et al.*, 1990; Baker *et al.*, 2002).

Symphylids

Symphylids are small, extremely active arthropods with several pairs of legs. *Scutigerella immaculata*, called the glasshouse symphylid in the UK or the garden symphylid in the USA, is recognized as a pest of sugar beet, often occurring together with other soil arthropods making up the soil pest complex.

Description and biology

Glasshouse symphylids occur commonly both in the glasshouse and the field. Adults are slender, white animals, 5–7 mm long, with 12 pairs of legs and a pair of long, mobile antennae.

Batches of up to 20 eggs are laid throughout the year in the soil. They are tended by the adult until they hatch after 1–3 weeks and the young symphylids, which have only three pairs of legs, emerge. The first moult occurs within 3 days and further moults take place at intervals of 2–6 weeks. An additional pair of legs is added at each moult until 12 pairs are present. After a further two or three moults the symphylids are sexually mature and the females start to lay eggs, but they continue to moult at approximately monthly intervals for the rest of their lives. The complete life cycle takes at least 3 months (usually much longer) and in favourable conditions adults can survive for a number of years.

Movement is usually restricted to existing cracks and fissures in the soil, but symphylids are capable of extensive vertical migration in suitable conditions, penetrating as far as 1.8 m below the surface. They migrate to the upper layers of soil in warm, moist conditions, especially when a suitable crop is present, and are usually most numerous in the surface soil in the spring and early summer.

Distribution and damage

S. immaculata is widely distributed throughout most sugar beet growing countries (including the USA) but, in sugar beet, appears to be most damaging in temperate areas. It can attack a wide variety of other crops including potatoes, tomatoes and lettuce in the UK. It is particularly prevalent on silt or chalky soils where numbers as high as 600/m^2 have been recorded.

Symphylids can attack seedlings soon after emergence, feeding on roots, root hairs and hypocotyls. This can kill some seedlings and cause a reduction in the rate of growth of those that remain. The damage often appears as small black marks on the root where hemispherical pieces of tissue have been scooped out. These lesions may aid invasion by pathogenic fungi or other organisms causing root rots. Control is best achieved either by pesticide seed treatments or by pesticide granules applied at drilling, as with millipedes.

Springtails

Springtails are primitive, wingless insects most of which are characterized by a forked springing organ (furcula) on the fourth abdominal segment enabling them to jump relatively large distances. Some species (e.g. *Sminthurus viridis* L., *Bourletiella hortensis* Fitch.) feed on stems or leaves but are of little economic importance. The root feeding species (e.g. *Folsomia fimetaria* L. and, especially, *Onychiurus armatus*) are much more damaging to beet crops.

Description and biology

Onychiurus armatus are white, blind springtails that live in the soil and, unusually, do not possess a springing organ. They are 0.8–2.0 mm long with an elongated body and may be extremely numerous (arable soils frequently containing 5×10^7–8×10^8/ha). In UK sugar beet fields they have two breeding peaks in the year, the first in late spring and the second in autumn/winter (Brown, 1982).

Distribution and damage

All of the above-mentioned species are widely distributed. *O. armatus* is the only one considered to be a serious pest problem of sugar beet, mainly in northern Europe where its activity at low temperatures enables it to attack newly germinated seedlings before emergence. Feeding produces small, rounded pits on the root or hypocotyl which may provide entry points for secondary pathogenic fungi. It is an important component of the soil pest complex which can be responsible for widespread seedling losses. Control measures are the same as for millipedes. Seed treatments gave especially good control of *O. armatus* in Spain (Ayala, 1996). In Germany, use of organic manure can reduce damage caused by springtails by providing alternative food (Sievers & Ulber, 1990).

Pygmy beetles

Pygmy beetle (*Atomaria linearis*) is a potentially devastating pest of sugar beet. Its importance declined in the UK following the general use of wider rotations of beet crops but it is still a major pest in Belgium, France, Germany and parts of the Netherlands.

Description and biology

Adults are small (< 2 mm long), slim, dark brown or black beetles (Plate 67a) which over-winter in the soil and move to the surface as the weather warms up in the spring; host plants are largely restricted to sugar beet and closely related crops, so the adult beetles must fly to new feeding grounds, unless such crops have been grown successively. Eggs are laid in the soil around the beet seedlings in late spring and throughout the summer; the hatched larvae feed on the roots without causing significant damage.

Distribution and damage

A. linearis is found throughout Europe and is a pest in all northern European countries. The most severe damage occurs when sugar beet follows another *Beta* crop and large numbers of beetles start to feed on the emerging seedling, causing characteristic pits in the hypocotyls and roots, and small circular holes in cotyledons and heart leaves (Plate 67b), which can result in complete crop loss. Even in fields where beet is grown in rotation, seedling loss can result from damage by beetles arriving early from nearby fields which grew beet in the previous year. Later damage, i.e. after the plant has reached the six-leaf stage, is relatively unimportant. Sensible crop rotations remain the best control measure but insecticidal granules (Hurej *et al*., 1994), sprays and, especially, seed treatments such as tefluthrin, imidacloprid, thiamethoxam and clothianidin can provide additional protection (Dewar, 1988a; Wauters, 1993; Senn *et al*., 1998; Proft *et al*., 1999).

Leatherjackets

Leatherjackets are the larvae of craneflies, or daddy longlegs. Several pest species are recognized, but the most important on sugar beet are *Tipula paludosa* and *T. oleracea* (L.).

Description and biology

Adult craneflies with their long legs and thin bodies are instantly recognizable. They emerge from the soil in late summer/early autumn to mate and lay their eggs in the soil, particularly in grassland. These hatch after 10–14 days to produce grey, legless, leathery-skinned larvae that are very susceptible to desiccation, requiring cool, moist conditions for survival. They feed on plant roots throughout the autumn, winter and spring, moulting four times before pupating in the summer to complete their life cycle in a single year.

Distribution and damage

Craneflies are widely distributed throughout Europe, northern Asia and North America but damage to sugar beet crops by *T. paludosa* occurs mainly in northern Europe. The leatherjackets feed above ground level on leaves, petioles or stems of seedlings, often destroying the growing point, or just below ground level, where plants may be completely severed. Leatherjackets tend to feed at night, presumably to avoid predation by birds. They sever young seedlings at ground level, or cut off leaves of older plants, and drag them into their burrows to devour later. Damage is most frequent where sugar beet follows a grass ley, and in damp or low-lying fields. Because the life cycle is completed in one year serious damage usually occurs only in the year after ploughing up grassland.

Numbers can be decreased by early ploughing of the previous crop (causing desiccation and increasing the amount of predation by birds) or rolling the soil, but insecticide sprays such as chlorpyrifos, or baits may be required if populations remain large.

Wireworms

Wireworms are the larvae of click beetles (particularly *Agriotes* spp. in Europe and *Limonius* spp. in the USA). Several species can damage sugar beet crops.

Description and biology

Adult click beetles are elongated and 6–20 mm long; pest species are usually brown or black. Their name derives from their ability to flick themselves into the air with an audible click if they have been trapped on their backs. Eggs are laid just below the soil surface in early summer and hatch after about a month. Young wireworms are white and only about 1.3 mm long, but as they grow (to a maximum of about 25 mm) and moult they darken to a characteristic golden brown; they have a brown head with biting mouthparts and three pairs of short legs (Plate 68). They develop slowly, typically spending 4 years in the soil in the UK (though only 2–3 years in warmer countries), feeding mostly on plant roots. They then burrow deeper and pupate in small cells in the soil, emerging as adults 3–4 weeks later. The relatively long developmental period and susceptibility to dry conditions makes undisturbed pasture an ideal environment; arable crops are therefore particularly at risk from damage during the 2 years after ploughing up grassland. However, wireworm problems occasionally occur in all-arable rotations, particularly on chalky soils.

Distribution and damage

Wireworms are widely distributed throughout Europe, Asia and North America. *Agriotes obscurus* (L.), *A. lineatus* (L.) and *A. sputator* (L.) are the most common pest species on sugar beet in Europe and *Limonius* spp. the most common in North America.

There are usually two periods of active feeding during the year – spring and autumn. During the spring, wireworms feed on the taproot or the below-ground part of the hypocotyls (Plate 68), causing wounds which are relatively small but which result in wilting or death of seedlings. During the autumn, damage to roots is visible as superficial, blackened pits which have little effect on crop yield. The extent of damage in the spring can be decreased by late sowing to ensure rapid plant growth during the period at risk. Insecticide seed treatments (e.g. tefluthrin, imidacloprid, fipronil, thiamethoxam) can also reduce damage to some extent (Richard-Molard, 1988; Wauters & Dewar, 1996; Furlan & Toffanin, 1998; Proft *et al.*, 1999; Barcic *et al.*, 2000; Dewar *et al.*, 2000a; Hermann *et al.*, 2001; Fedorenko, 2002), but further treatment (e.g. with a granular pesticide) may be required to protect crops if wireworm populations are very large. A forecasting method based on a plate trap (Jossi & Bigler, 1997) gave 85–90% success in predicting the need for control measures in trials in sugar beet and maize fields in Switzerland.

Thrips

Thrips, or thunder flies, are small insects with rasping and sucking mouthparts; some species (particularly *Thrips angusticeps* Uzel, *T. tabaci* Lind. and *Caliothrips fasciatus* Perg.) can feed on sugar beet leaves. Sometimes they can also act as predators of spider mites if they are present on the leaves later in the season.

Description and biology

T. angusticeps, the most important species on sugar beet, over-winters at all stages in the soil. Adults of the over-wintering generation are short-winged (brachypterous) and unable to fly, so that in the spring they can move only a short distance to host plants. There are five instars; the adults (fifth instars) which are produced in the summer have long, narrow wings fringed with setae and can fly away from the crop.

Distribution and damage

T. angusticeps and *T. tabaci* are widespread throughout Europe, but severe damage only occurs in the north. *C. fasciatus* occurs in the USA. Thrips feed mainly on younger leaves by piercing the cell surface and sucking the contents causing a superficial silvering, browning or reddening. Damage to still-curled, heart leaves can be quite severe because it prevents normal growth and expansion, and sprays of pyrethroids can give some control. Damage to hypocotyls at or just under the soil surface is more difficult to prevent; it can result in seedling death, and, in severe cases, necessitate redrilling. Imidacloprid seed treatment can give good control, carbamate granules less so.

Cutworms and other caterpillars

Cutworms, or surface caterpillars, are the larvae of various noctuid moths (e.g. *Agrotis* spp., *Euxoa* spp. in Europe and the USA; *Peridroma saucia* (Hübner), *Crymodes devastator* (Brace), *Amathes c-nigrum* (L.) and *Feltia ducens* Walker in the USA); several species are known to damage sugar beet, usually feeding on stem bases or crowns. Larvae of many other moths (e.g. *Hydraecia micacea*, *Margaritia sticticalis* (L.), *Scrobipalpa ocellatella* Boyd, *Spodoptera* spp., *Pseudaletia unipuncta* (Haworth) and *Loxostege* spp.) can also cause damage to foliage or crowns of beet plants. Very brief accounts are given of some of the most important species.

Turnip moth: Eggs of the turnip moth (*Agrotis segetum* (Denis and Schiff)) are laid on plants or surface litter in midsummer and hatch in 1–4 weeks. Young caterpillars feed on leaves but later instars enter the soil and feed on crowns and upper roots. Damage is most common, though rarely serious, in central Europe and Russia; it occurs less commonly in north-western Europe.

Garden dart moth: Eggs of the garden dart moth (*Euxoa nigricans* L.) are laid in late summer and over-winter to hatch in the following spring. Larvae feed at night and can kill beet seedlings by gnawing through stem bases. This species occurs throughout Europe.

Beet armyworm: Beet armyworms are caterpillars of *Spodoptera exigua* (Hübner), a widespread, polyphagous moth which can produce up to eight generations per year in warm climates. They are small and green (later becoming variable green or brown) and usually have a lateral stripe; young armyworms skeletonize the underside of leaves but older ones eat the entire lamina.

Beet webworm: Beet webworms are caterpillars of the moth *Loxostege sticticalis* (L.); they are about 40 mm long, olive green with a darker band running up the back and lighter bands on each side. They move rapidly and spin webs over the remains of leaves, usually near the base. This species and others in the same genus were once important pests of sugar beet, particularly in the western USA, being able to defoliate crops completely in a very short time. However, their importance has diminished since the development of modern insecticides.

Potato stem borer: Potato stem borers are caterpillars of the rosy rustic moth (*Hydraecia micacea*). They are up to 35 mm long, pinkish with a red dorsal stripe and large lateral brown spots. After hatching in the spring (from eggs laid in the previous autumn) they tunnel inside the crown and upper root of young beet plants which may be killed by early attacks. They are widely distributed, but are most serious as sugar beet pests in Finland and Scandinavia.

Control of all species can be given by organophosphate and pyrethroid insecticide sprays when the caterpillars are on the leaves (Khan *et al.*, 1993), but these are less effective when the caterpillars are underground. Heavy rain often reduces the risk of damage, as the caterpillars suffer severe mortality in such circumstances. Monitoring of adult moth activity using synthetic pheromone traps has been used to guide pesticide timings in Italy (Bongiovanni *et al.*, 1990)

Chafers

Chafer grubs are the larvae of chafer beetles; in the USA they (together with the larvae of scavenger beetles) are known as white grubs. Several species can attack sugar beet roots, but the most common, particularly in northern Europe, is the cockchafer or May bug (*Melolontha melolontha*).

Description and biology

Adult cockchafers are large beetles (about 25 mm long) with a reddish-brown body and black head. After emerging from the soil in May they fly to woodland where they feed on leaves, fruit or flowers of various trees, to which they continue to swarm, mainly at dusk. They lay their eggs in the soil, usually in grassland or cereals, during the summer and the larvae then take 3 years to become fully grown. During the third year the larvae are very large (up to 60 mm long) and have a characteristic U shape with a swollen posterior end. They pupate and adults develop from the pupae to over-winter in the soil.

Distribution and damage

M. melolontha occurs throughout Europe. Damage to taproots of sugar beet is caused by the feeding of larvae in the second or third year and can occur throughout the summer. Large cavities are eaten out, which blacken as they are invaded by secondary pathogens; often the roots may be severed completely, and the plants wilt and die. Attacks are sporadic and localized, usually affecting a relatively small number of plants in the field, so specific control measures are unlikely to be economic.

Clivina

Carabid beetles (ground beetles) are usually beneficial to agricultural crops, preying on aphids, slugs and other pests. However, *Clivina fossor* L. is a carabid beetle that has recently been recognized as a pest of sugar beet in some European countries (particularly Sweden), feeding near the soil surface, and able to eat through roots up to 1–2 cm in diameter. Some control was achieved with carbosulfan sprays in Sweden (Elfstrom, 1997).

Sugar beet root maggot

The sugar beet root maggot (*Tetanops myopaeformis* (Röder)) is the major insect pest of the central and western sugar beet growing areas in the USA and Canada.

Description and biology

Adult flies, which are shiny black in colour and about the size of a housefly, emerge from pupae in April to June, and fly to nearby sugar beet fields where they lay their eggs around the roots of young plants. Up to 200 eggs can be laid by each female, usually in batches of 6–20. They hatch in 1–3 days and the emerging maggots feed on the roots until about August when they are fully-grown. They remain dormant over winter, pupating during the following spring.

Distribution and damage

T. myopaeformis occurs in Canada (particularly Alberta) and the USA (in Colorado, Nebraska, Wyoming, Idaho, Montana, Minnesota and North Dakota). Young roots can be severed as a result of larvae feeding; older plants can also be damaged, both directly and as a result of invasion by secondary pathogens. Action thresholds based on numbers of flies caught by coloured sticky traps have been determined in Idaho; these varied from 38–61 flies per trap depending on the cost of treatment and the price of roots (Bechinski *et al.*, 1989). Control is given by insecticide granules (e.g. terbufos, chlorpyrifos or aldicarb) applied at sowing (Armstrong *et al.*, 2000). Damage can be reduced by using oats as a cover crop (Dregseth *et al.*, 2003), and some success has been achieved with entomophagous fungi, such as *Metarhizium anisopliae* (Mtech.) (Campbell *et al.*, 2000b; Campbell, 2001) and *Syngliocladium tetanopsis* (Smith, 2000), and resistant varieties (Campbell *et al.*, 2000a).

Aphids

While aphids can occasionally cause serious damage to sugar beet by direct feeding, it is their ability to transmit virus diseases that makes them the most important group of sugar beet pests. Several species may be found on the foliage of sugar beet crops and, although *Myzus persicae* is easily the most important vector of virus yellows and other virus diseases (Heathcote & Cockbain, 1966; see Chapter 11), other species, e.g. *Macrosiphum euphorbiae* (Thomas), *Aulacorthum solani* (Kaltenbach), *Myzus ascalonicus* Doncaster and *Aphis fabae* (Scopoli), are occasional, though less efficient, vectors. Feeding damage to the foliage of root and seed crops is more likely to be caused by *A. fabae* (Hurej & Van der Werf, 1993), and to roots by *Pemphigus betae* Doane (Hutchison & Campbell, 1994; Winter, 1999).

Peach-potato aphid, *Myzus persicae*: Although classed as green aphids, the wingless (apterous) forms can range from pale to dark green, but can also be red, pink or dark purple (Plate 69a). The adult wingless forms are pear shaped, approximately 1.4–2.5 mm long with two pale, slightly swollen appendages (siphunculi) projecting from the abdomen. The winged (alate) form is 1.4–2.0 mm long and has a black head and thorax and a black patch covering most of its abdomen; because of this patch it is often misidentified as a black aphid. Its identity as a peach-potato aphid can be confirmed by turning it over to expose the dark green abdomen.

M. persicae is a sexually reproducing host-alternating aphid in some countries, living on peach trees in the spring and autumn, but migrating to herbaceous plants, including crops such as potatoes and sugar beet, in the summer. In temperate beet-growing areas where peach trees are scarce, *M. persicae* has evolved an asexual life style, and it is this type that has made this species so important in the sugar beet crop. Instead of migrating back to peach trees to produce egg-laying females (oviparae), which mate with later migrating winged males before laying eggs in twig crevices, it spends the winter months as active stages on hardy overwintering plants, including a number of weeds, crops such as oilseed rape and vegetable brassicas, and garden crops such as seakale beet and spinach. It can also live in fodder beet clamps and cleaner-loader heaps. In spring or early summer, when populations become overcrowded and they have exhausted the nutritional value from these hosts, they produce winged forms, which migrate to summer hosts including young sugar beet seedlings, potatoes, brassicas, shepherd's purse, chickweed and other weeds.

This species causes little direct feeding damage to the beet because it rarely builds up to large numbers. However, it is a very efficient vector of the three viruses that cause virus yellows. The viruses concerned can only be passed from one aphid to another via the host plant on which they feed. They cannot be passed via the egg stage, and the primary hosts are not susceptible to the viruses. So where host-alternation is the main method of over-wintering (e.g. in central and southern Europe), virus yellows is much less common; conversely where asexual over-wintering is common (e.g. in the UK, northern France, Imperial Valley in California), virus yellows can be a serious problem.

Once winged *M. persicae* colonize sugar beet, they give birth almost exclusively to wingless offspring, and it is these that tend to spread viruses within the crop. It is very difficult to prevent primary infection by the winged forms, so the wingless forms are the target of any insecticides that are applied. However, the beet plants themselves have an effect on this species. As the plants mature they become less palatable to the aphids, eventually causing their death by starvation as their guts become blocked by a black substance (Kift *et al.*, 1997; 1998a,b). Virus yellows infection can halt this process by changing the physiology of the plant so that it becomes more suitable for the aphid (Williams, 1995; Williams *et al.*, 1997).

M. persicae has a worldwide distribution, and many physiological races, with distinct host preferences, have been recorded. It is known to transmit over 100 virus diseases to over 30 families of plants. Insecticide sprays are often relatively ineffective as a result of the development of one or more of at least three resistance mechanisms in this species (Dewar *et al.*, 1998; Foster *et al.*, 2002), so control strategies need to encompass a range of integrated pest management techniques, taking account of the prevalence of these mechanisms. To this end the resistance status of *M. persicae* in the UK is constantly monitored by testing alates caught in Rothamsted Insect Survey suction traps at four sites within the beet growing area, using various testing methods including ELISA (Harrington *et al.*, 2003; Waters *et al.*, 2004). These aphids are also tested for virus infectivity (Stevens *et al.*, 1994). Advice on control strategies is given in the light of this information.

Potato aphid, *Macrosiphum euphorbiae*: Both apterous and alate potato aphids are predominantly green, but, as with *M. persicae* they can be many shades of green, and also yellowish, pink or purple. The adult wingless aphid is far larger than a peach-potato aphid, 1.7–3.4 mm long; its body is more of an elongated pear-shape, and it has long legs, long antennae with darkish joints and a long cauda. The juvenile wingless forms have a darker stripe along their body and can have a light dusting of whitish-grey wax. The winged form is 1.7–3.4 mm long, with a pale, apple-green body. All forms have two long siphunculi, the distal end of which is slightly tapered and then flared, and has reticulation (a faint net pattern).

Sexually reproducing clones of *M. euphorbiae* are host-alternating between rose and various secondary hosts, but most clones in England are asexual on herbaceous plants such as potatoes, beet, and many species of weeds. Thus, it too is a vector of yellowing viruses in beet, but is less efficient than *M. persicae*. However, it is very difficult to distinguish between the two species when the offspring are very young, and hence the advice for control in beet is based on numbers of green aphids, not the individual species. Like *M. persicae*, *M. euphorbiae* does not cause much direct feeding damage as it does not reach high numbers on beet, because it also suffers from the blocked gut syndrome on mature plants. Control of this species is easier because it has not yet developed resistance to the main pesticides applied to control it.

Black bean aphid, *Aphis fabae*: The wingless adults are sooty black, sometimes with white waxy stripes across the abdomen, between 1.3 and 2.6 mm long, and with short black siphunculi (Plate 69b). Winged adults are also sooty black, but with shiny wings.

A. fabae is a classically host-alternating species. In spring, eggs laid on the primary host, spindle (*Euonymus europaeus* L.), or the sterile guelder rose (*Viburnum opulum* var *roseum* L.) hatch as the buds burst, giving rise to two to three apterous generations before winged migrants are formed. These then fly to secondary hosts including beans, beet and many other plants such as goosefoot, poppy, dock and thistles. Beans are the favoured hosts in early summer, although some can be found on beet then. However, they do not usually colonize beet successfully until midsummer, from mid-June onwards, when the plants are much bigger, and the aphids can find more shelter from predators and adverse weather. Their populations usually eventually crash in early August as a result of predation and infestations of the fungal disease, *Entomophthora*, but enough survive to produce the sexual forms (gynoparae and males) that migrate back to spindle in the autumn. The gynoparae give birth to egg-laying oviparae, which mate with the later-arriving males and lay their shiny black eggs in twig crevices.

Black aphids are not major vectors of the yellowing viruses. Indeed they can transmit only one of them efficiently – *Beet yellows virus* (see Chapter 11) – and usually only once that virus has been introduced to the crop by another species. However, they can cause serious direct feeding damage to some plants when populations reach thousands per plant (Hurej & Van der Werf, 1993), although the plants often recover and compensate for this, particularly if water is not limiting. In drought conditions, significant yield loss can occur. Control by insecticides then may be economic.

Feeding can cause curling of the foliage, necrosis, virus infection and impairment of efficiency due to the growth of moulds on the honeydew excreted by the aphids. Prevention of damage may require treatment with insecticides, but these must be chosen so as not to destroy resident aphid predators. Factors affecting the relative abundance of *M. persicae* and *A. fabae* on beet have been discussed by Williams *et al.* (1999).

Glasshouse potato aphid, *Aulacorthum solani*: The wingless adult aphids can be either light green or yellow in colour, 1.8–3.0 mm long, with long siphunculi that have flared, black tips. The winged aphids are the same length as the wingless adults, but tend to be greener and have vertical stripes on the abdomen; they also have dark tips to their siphunculi, and dark knee joints on the legs.

A. solani is a non-host-alternating species favouring herbaceous plants such as foxglove to lay its eggs on over winter, even though those plants are killed by frosts. It also over-winters asexually on potatoes in store or on waste heaps. Winged forms migrate into beet in spring and early summer from both sources but are rarely found on older plants. They can transmit viruses, but are more likely to cause distortion of the leaves of young seedlings by injecting a plant growth hormone that alters the physiology of the plant to the aphid's advantage. The effect is transitory, and disappears as the plant grows. Affected plants occur mostly on headlands and are rarely seen in the centre of fields. It is not economic to attempt to control this damage; by the time symptoms appear affected plants can not be protected and further spread will not occur.

Root aphids, *Pemphigus spp.*: Beet root aphids are small, round and pale yellow, with a waxy covering giving colonies the appearance of being mouldy. They have rudimentary siphunculi, small antennae, cauda and legs; large appendages would hinder their movement underground. They can occur in large numbers on the fibrous roots of sugar beet, causing plants to remain stunted and wilt.

They are host-alternating aphids; alates fly from poplar trees (*Populus angustifolia* James) into beet crops between June and early August. Alates fly back to poplar trees in the autumn to lay eggs. Root aphids are not an important problem in northern Europe, but damage is caused by *P. fuscicornis* Koch in central and eastern Europe, *P. populivenae* Fitch in the USA and *P. betae* in Canada. Control is difficult because few insecticides are downwardly translocated to the roots, and seed treatments are not persistent enough to control aphids arriving in late June.

Control

Aphids are best controlled by systemic insecticides that are transported in the vascular tissues of the plants, as they often feed in places where contact insecticide sprays cannot reach (e.g. in the heart leaves or the under-surface of large leaves). The best products available currently are neonicotinoid insecticides such as imidacloprid, clothianidin and thiamethoxam (see p. 347) applied as a film coating to pelleted seed. In many countries, these have given excellent control of *M. persicae* and *M. euphorbiae* up to 10 weeks after sowing, with consequent reduction in virus yellows incidence and concomitant increases in yield (Dewar & Read, 1990; Schmeer *et al.*, 1990; Merkens & Groeneweg, 1991; Muchembled, 1991; Courbon, 1992; Dewar *et al.*, 1992; Heatherington & Meredith, 1992; Tossens *et al.*, 1992; Wauters, 1993; Bosch & Schäufele, 1994; Kuthe, 1995; Ayala *et al.*, 1996; Dewar *et al.*, 1996; Wauters & Dewar, 1996; Heltbech *et al.*, 1999; Proft *et al.*, 1999; Dewar *et al.*, 2001; Dewar *et al.*, 2002; Dewar *et al.*, 2004a). In trials comparing strategies for control, imidacloprid seed treatment reduced virus infection to just 7% compared to 12% with two spray applications of pirimicarb or triazamate, and 25% with aldicarb granules; infection in untreated plots was 70% (Dewar *et al.*, 1996). The persistence of the seed treatment was the main factor resulting in such good control. In other trials with spray treatments only, triazamate gave good control of aphids compared to pirimicarb and mixtures of the latter with deltamethrin (Dewar *et al.*, 1996; Dewar & Haylock, 1997). The persistence of triazamate was much greater than pirimicarb against both *M. persicae* and *A. fabae*, lasting at least 6 days (Dewar & Haylock, 1997; Westwood *et al.*, 1997). However, when *M. persicae* with the MACE resistance mechanism were present, only imidacloprid applied as a seed treatment gave effective control (Dewar *et al.*, 1998).

Capsid bugs

Capsids are oval, flattened and often attractively-coloured bugs; a few species (particularly *Lygus rugulipennis* Poppius, *Lygocoris pabulinus* (L.) and *Calocoris norvegicus*) are known to damage beet crops.

Description and biology

Capsids have a characteristic arrangement of veins in the forewing and conspicuous four-jointed antennae. Adults of *L. rugulipennis* (the tarnished plant bug) are about 6 mm long and predominantly brown in colour; they over-winter in sheltered places such as hedgerows and in the spring they fly into beet or other crops to feed on seedlings. Eggs, which are laid in the growing point and petioles, hatch to produce nymphs which go through five moults before pupating to give adults in midsummer. Two generations usually occur in the UK.

L. pabulinus and *C. norvegicus* over-winter in woody hosts (e.g. in hedgerows or orchards) as eggs; wingless nymphs migrate by walking into crops during the summer.

Distribution and damage

The three species mentioned above are found throughout most of Europe. In the USA, other species of *Lygus* (e.g. *L. hesperus* Knight, *L. elisus* van Duzee) are more common and can be pests of seed crops.

Like aphids, capsid bugs feed by piercing plant cells with their elongated mouthparts, injecting saliva and ingesting the cell contents. The saliva is toxic, causing death or distortion of cells around the point of injection. This damage, when caused by early migrations of winged *L. rugulipennis*, can kill the growing point of young seedlings, resulting in multiple-crowned, poorly yielding plants. Damage to older plants by *L. pabulinus* and *C. norvegicus* occurs in the summer months and is usually confined to field margins which are within range of walking bugs. They feed on the leaf veins, in which darkened stab marks can be seen (Plate 70); beyond such wounds the distal portion of the leaves pucker and turn yellow. Many granular, seed-furrow-applied pesticides and imidacloprid seed treatment will control the early damage to seedlings but later damage rarely warrants specific control measures.

Lace bugs

Lace bugs (or leaf bugs) feed in a similar manner to capsid bugs. However, direct damage to crops is rare, and these insects are more important as vectors of the virus diseases *Beet leaf curl rhabdovirus* in eastern Europe (transmitted by the beet lace bug *Piesma quadratum*) (Korcz *et al*., 1997) and *Beet savoy* in the USA (transmitted by the lace bug *P. cinerea*). In Poland, some control of the former has been given by imidacloprid seed treatment, comparable to the standard insecticide, carbofuran (Korcz *et al*., 1998).

Leafhoppers and planthoppers

The leafhoppers are a large group of plant bugs, second only in abundance to the aphids. They can damage beet crops directly, but are far more important as vectors of the potentially devastating diseases, curly top in the USA (transmitted by *Circulifer tenellus* Baker) and yellow wilt in South America (transmitted by *Paratanus exitiosus* Beamer).

Description and biology

Leafhoppers are small slender insects that are abundant in field crops. They rest on plants in a position ready for jumping and when disturbed they leap into the air and fly off. Several species are found on beet crops in Europe, and most are greenish-yellow to brown in colour and 3–4 mm long. Adults are usually polyphagous and in summer they lay their eggs in rows on the stems or leaves of various plants. There are six instars and some species pass through two or even three generations in a season. They over-winter either as adults or in the egg stage.

In the USA, the beet leafhopper (*C. tenellus*) over-winters as an adult in uncultivated fields in arid and semi-arid regions, feeding on various weed hosts (e.g. mustards and desert plantains). When these plants begin their spring growth the female leafhopper deposits her eggs, and the spring generation develops. When it reaches the adult stage the over-wintering hosts become dry and scarce and the leafhopper moves to summer hosts such as sugar beet. About three generations are completed each year in the more northern areas of the USA, and five or more in California and Arizona.

A planthopper, *Pentastiridius beieri* Wagner, has been implicated in the transmission of a new disease called Syndrome des Basses Richesse, which has appeared in France in recent years (Gatineau *et al*., 2001). The disease is caused by a Phytoplasma and gives symptoms similar to yellow wilt, namely brown necrosis in the vascular tissue of the roots and yellowing of the leaves in late season (see Chapter 12). Planthoppers, which feed on beet roots, carry the virus into beet fields in summer from nearby cereal crops.

Distribution and damage

In Europe most of the species that occur on sugar beet plants do not significantly affect crop performance. However, *Macrosteles laevis* Rib. can, if sufficiently numerous, cause direct damage to young seedlings when feeding on the leaves or cotyledons; small flecks form at the feeding site where cells are emptied of their contents. In northern Europe, *M. laevis* appears on the crop too late to affect crop growth.

The beet leafhopper, *C. tenellus*, is widely distributed in the warmer beet-growing areas of the USA, Europe, Asia and northern Africa. Earlier this century it was extremely important, especially in the USA, as the vector of curly top but improved control measures have decreased the threat posed to the crop by this disease. Other species of leafhopper transmit related forms of curly top in South America.

In Chile, *P. exitiosus* comprised 64% of ten species of leafhoppers sampled in beet fields in 1994–1995, and, along with *Xerophloea viridis* Fabricius, were the only leafhoppers able to reproduce on sugar beet under laboratory conditions (Casals *et al*., 1999).

Flea beetles

These beetles are usually small, but have long hind legs that enable them to jump when disturbed. Crucifers are favoured hosts, being attacked by several species, but sugar beet may be damaged by the beet flea beetle (*Chaectocnema concinna* (Marsh.); syn. *C. tibialis*) in northern Europe and by a range of species in North America.

Description and biology

Adults of *C. concinna* are 2 mm long, metallic bronze in colour with rows of deep punctations on the elytra. They over-winter in sheltered spots (e.g. hedges) and emerge in the spring to feed mainly on leaves of sugar beet or mangel crops and polygonaceous weeds. Eggs are laid in the late spring and the larvae feed on the roots of host plants before pupating in the soil. After 2–3 weeks, adults emerge to start feeding on host plant foliage. Damage by *C. concinna* is caused by the over-wintered adults feeding on the upper or lower surfaces of cotyledons, leaves or petioles, causing the formation of small, round pits that develop into holes in the expanding leaves, giving them a ragged or lace-like appearance. This can severely affect establishment and growth, especially in crops which have not received prophylactic pesticide treatments, and may justify the use of pyrethroid insecticide sprays (Szymczak-Nowak & Wasacz, 1998). Systemic insecticide seed treatments (e.g. imidacloprid, thiamethoxam) have given good control in Belgium (Tossens *et al*., 1992), Croatia (Barcic *et al*., 2000), France (Vincinaux *et al*., 1992), Finland (Eronen *et al*., 2001), Italy (Maines *et al*., 1994), Japan (Sato *et al*., 1995), Spain (Ayala & Bermejo, 2001), USA (Kaffka & Babb, 2001) and the UK (Heatherington & Bolton, 1992).

In the USA the most serious damage is caused by the larvae of the pale-striped flea beetle (*Systena blanda* Melsheimer) which feeds on the underground portions of young seedlings and may necessitate replanting.

Tortoise beetles

Adults and larvae of tortoise beetles (*Cassida* spp.) feed on the leaves, causing damage similar to that caused by flea beetles. Damage never occurs in western Europe but can be severe in warmer Mediterranean regions (Ayala & Dominguez, 1996), North Africa (Salama & Elnagar, 1992; Aabdou & Boulif, 2004) and Russia (Bichuk *et al*., 1986).

Control is achieved with various insecticide sprays applied at the egg stage (Bichuk *et al*., 1986; Saleh, 1994; Ayala & Dominguez, 1996), but these can also kill natural enemies (El-Khouly & Omar, 2002). Some control has been achieved with insect growth regulators (e.g. teflubenzuron, azadirachtin) in Egypt without affecting predators (El-Khouly, 2002). Imidacloprid seed treatment gave as good control as carbofuran against *Cassida nobilis* L. in Russia (Kornienko *et al*., 1994). Cultural control has been achieved in the Ukraine by earthing up plants in combination with inter-row cultivations (Nuzhdin, 1997). Damage in Egypt was avoided by planting in August after the larvae had matured to adults (Salama & Elnagar, 1992).

Carrion beetles

Carrion beetle adults and larvae can feed on the foliage of sugar beet, which they may destroy completely. Such damage rarely occurs on a large scale, but in Finland, Denmark and Belarus the beet carrion beetle (*Aclypea opaca* L.) is considered to be important, and in the northern USA and Canada the spinach carrion beetle (*Silpha bituberosa* Lec.) is an occasional pest.

Weevils

Weevils are beetles with heads elongated into a characteristic snout that carries the antennae. Adults and larvae of several species can damage sugar beet crops, mainly in central, eastern and southern Europe, northern Africa and the Near East. The sand weevil (*Philopedon plagiatus* (Schall.)) is restricted to sandy soils in which adults over-winter, emerging in April to feed on leaves and cotyledons. In May and June they lay eggs in the soil where the root-feeding larvae live for about 18 months, before pupating. The worst damage occurs in weed-free fields where no alternative hosts are present. In southern Europe, *Aubeonymus mariaefranciscae* Roudier has become a new problem in spinach beet and sugar beet (Marco *et al*., 1998) and *Temnorrhinus mendicus* Gyll. occurs in Italy (Boselli *et al*., 1991). In Gansu province in China *Bothrynoderes punctiventris* and *Phacephorus umbratus* (Fald.) have caused problems; the former species is also common in Russia.

Beet leaf miners

Beet leaf miners are the larvae of *Pegomya hyoscyami* (the beet fly or mangel fly) in most countries, but *Liriomyza huidobrensis* (Blanchard) is more common in Chile (Stevens & Dewar, 1996).

Description and biology

Adult *P. hyoscyami* flies are about 6 mm long (about the same size of a housefly), grey and bristly (Plate 71a). They emerge from the over-wintering pupae in the spring. After mating, the females are attracted to undamaged, uninfested young beet seedlings by volatiles (Rottger & Klingauf, 1978; Rottger, 1979a), and lay on average 56 elongated, white eggs in groups of two to twelve, arranged in parallel on the underside of beet or mangel leaves (Plate 71b) (Rottger, 1979b). These hatch in 3–5 days and the emerging larvae bore into the leaf tissues feeding on the mesophyll, causing characteristic galleries which join together to form a large blister (Plate 71c). After 10–15 days, the larvae drop into the soil where they pupate. In northern Europe there are 2–3 overlapping generations (Hurej, 1986). The third generation is most susceptible to parasitism by parasitic Diptera such as *Opius nitidulator* (Nees) (Rottger, 1979b).

Distribution and damage

P. hyoscyami occurs throughout Europe, and in much of northern Asia, North Africa and North America (Harper & Whitfield, 1983). The most severe damage is caused by the first generation of larvae, especially in late-sown crops that have little leaf area when the eggs hatch. Damage caused by later generations has little effect on yield, but does make crops look untidy (Plate 71d). Systemic seed treatments and granular pesticides applied at sowing control early damage (Rimsa, 1979; Winder & Dunning, 1986; Heatherington & Bolton, 1992; Kuthe, 1995; Meredith & Morris, 2003), and in untreated crops insecticide sprays can be applied if numbers of eggs plus larvae warrant it. Thresholds for treatment vary between countries; in the UK, sprays are warranted if the number of eggs plus larvae exceed the square of the number of true leaves (Dunning, 1961), but in Finland it is more than 10 eggs per plant at the five-leaf stage (Varis & Rautapaa, 1978). Sprays containing a pyrethroid give good control (Dewar & Read, 1993).

Silver Y moth caterpillars

Adult silver Y moths (*Autographa gamma*) (Plate 72a) occur regularly each year in central and northern Europe, migrating from North Africa. After mating they lay their eggs in many broad-leaved crops, including peas, potatoes and sugar beet. Occasionally they cause epidemics in some countries when weather conditions encourage early migration, and rapid reproduction at the destination (Dewar & Woiwod, 1994; Dewar & Haylock, 1996; Legrand & Wauters, 1997; Beltrami *et al*., 2004). Thresholds for control are set around three to four caterpillars per plant, timed to control the larger instars (Plate 72b) that are the most voracious. Control by pyrethroids is very effective (Wauters & Legrand, 1996), but these can exacerbate other pest problems such as spider mites, by killing field-resident predators. Control with *Bacillus thuringiensis*, applied at first appearance of the damage to leaves, is recommended as an environmentally safer option (Cioni, 2003). Once caterpillars pupate, further damage does not occur, as adults emerging from the pupae usually leave the crop to search for undamaged crops elsewhere.

Locusts, grasshoppers and crickets

These large insects are only occasional pests of sugar beet although some species of locust (e.g. *Dociostaurus maroccanus* Thumb.) attack crops in the Mediterranean basin, nymphs of some grasshoppers (e.g. *Melanoplus* spp.) feed on beet seedlings in North America and crickets (especially *Gryllus campestris* L.) have also been reported as possible pests.

Earwigs

Common earwigs (*Forficula auricularia* L.) can feed on the heart leaves of sugar beet but damage is very sporadic (Kuthe, 1996), and is probably outweighed by their beneficial effects as predators on other insects, especially caterpillars.

Spider mites

Two-spotted spider mites, *Tetranychus urticae* Koch are small, round, yellowish-green in colour with two dark, almost black spots on their abdomens, and have four pairs of legs (Plate 73a). Their life cycle consists of five stages: eggs, first instar larvae, protonymphs (second instar), deutonymphs (third instar) and adults. Adults only over-winter as diapausing females, usually beneath fallen leaves and other vegetable debris in field margins. They have a convoluted sex life, and the production of males and females depends on whether or not the females have mated. Mated females produce individuals of both sexes, but virgin females produce only males; this results in the balance of sexes being maintained.

In the spring and early summer, the females lay between 60 and 115 eggs on the underside of host plant leaves in indentations where the microclimate has higher humidity. The eggs are often covered with very fine silk threads, which help to protect them from predators; they are round, have a diameter of about 0.14 mm, and are transparent when laid. The older eggs become opaque and by the time the larvae emerge have turned a straw colour.

At the time of emergence the larvae have three pairs of legs, are colourless or pinkish and have two dark red eyes. Their body colour changes to light green, brownish-yellow or dark green after they have eaten and it is at this stage that two dark spots appear in the middle of the abdomen. When they have eaten enough to progress to the next stage they settle on a leaf and retract their legs until they have developed into protonymphs. This period of quiescence is the equivalent of a chrysalis stage in insects. Protonymphs are slightly larger than larvae and have four pairs of legs. Their colour varies from light to dark green and the spots become more pronounced.

These develop in to deutonymphs, again after a period of quiescence. At this point the females are slightly larger than the males. Eventually the duetonymphs enter the final stage of adulthood, and the life cycle begins again. The generation time can be as short as 6–8 days when temperatures are above 30°C.

Distribution and damage

Spider mites are mostly pests of sugar beet in hot climates such as those that occur in southern Europe, North Africa, the USA and Chile. In recent years there have been several outbreaks in northern France (Szilvasi *et al.*, 1998; Muchembled, 1999), Belgium (Legrand *et al.*, 2000), the Czech Republic (Bittner, 2002) and the UK (Dewar & Haylock, 1995; Asher & Dewar, 1997).

Spider mites invade sugar beet from their overwintering hosts by migrating on silken threads carried in the wind, rather like parachutes. Thus plants in headlands are the first to be colonized, and are also the first to show damage symptoms. These are first seen as small yellow spots on the upper surface of the leaves, with brown colouration underneath, often associated with webs. Damaged leaves turn brown and die (Plate 73b), eventually falling off the plant. Severe defoliation can occur in August/September, which can result in serious yield losses. The subsequent regrowth of leaves from the storage root causes a reduction of the sugar content in the root, and therefore affects the final yield.

Some control, leading to yield increases, can be given by various acaricides (Legrand *et al.*, 1999; Dewar *et al.*, 2000b), but few are currently approved for use in sugar beet. Control by the pyrethroid bifenthrin is recommended in Belgium and France. Varietal resistance is more likely to give long term control of this pest (Legrand *et al.*, 1997; Haylock & Dewar, 2003).

Vertebrate pests

Birds

Several bird species feed on sugar beet crops and, especially when recently emerged seedlings are the target, this feeding can be a serious problem to the grower. However, methods of decreasing damage must be sympathetic to the often conflicting requirements of ornithologists, conservationists and sportsmen (some of the pest species being game birds, which may themselves provide the grower with additional income or recreation). Descriptions of the main pest species would be superfluous, but brief accounts of their effects on the crop are given below.

Skylark: Skylarks (*Alauda arvensis*) can feed on the cotyledons and first leaves of sugar beet seedlings, removing large proportions of the foliage. Seedlings usually recover (although some plant loss may occur if damage occurs very early) but field trials in which birds have been excluded from control plots suggest that yield losses from complete defoliation by birds can vary from 19–39% (Green, 1978).

House sparrow: Grazing by house sparrows (*Passer domesticus* L.) can cause similar damage to skylarks, but is usually confined to areas of crops near farm buildings or straw stacks.

Partridge: The red-legged partridge (*Perdix perdix* L.) feeds on the foliage of seedling sugar beet plants causing similar damage to that caused by skylarks (Green, 1978). They are often more numerous in weedy beet fields, where the presence of alternative food sources offsets the greater number of birds with respect to the effect on the crops.

Woodpigeon: Woodpigeons (*Columba palumbus* L.) also graze on sugar beet seedlings. In the summer they feed on the laminae (but not the veins) of older plants, which may be stunted, but are rarely killed.

Pheasant: Pheasants (*Phasianus colchicus*) are common in sugar beet fields, especially near woodland. They can cause large, localized, losses by pecking the roots at soil level, severing the foliage and greatly reducing populations in the worst-affected areas.

Rook: Rooks (*Corvus frugilegus*) can kill plants by uprooting them whilst searching for wireworms and other soil invertebrates. The importance of this species as a pest has declined in recent years.

Mammals

Several mammals, from voles to wild boar, can feed on foliage or roots of sugar beet. However, the most important pest species are probably the field mouse, the rabbit and the hare.

Field mouse: Using its sense of smell, the field mouse (*Apodemus sylvaticus*), often called the long-tailed field mouse, is able to detect the exact location of ungerminated sugar beet seeds at a depth of at least 3 cm, shortly after they have been sown. It can dig the seeds up and split open the pellet and husk to eat the endosperm. Large numbers of seeds can be removed in a single night, usually along lengths of row so that losses cannot be completely compensated for by improved growth of neighbouring plants. Damage is worst in early-sown crops (where mice are more numerous and germination may be delayed), in dry or cloddy seedbeds (when seeds are often not well covered and germination may also be delayed) and in fields where occasional seeds are left exposed on the soil surface (e.g. at the ends of rows, when lifting the drill) allowing the mice to discover that they are a source of food and to recognize their smell (Green, 1978).

Control of field mice is by poison baits or break-neck traps set across the most vulnerable areas (at around five per hectare); care must be taken with poison baits not to put other wildlife at risk by placing the baits in small containers that cannot be accessed by birds or larger mammals.

Rabbit: Rabbits (*Oryctolagus cuniculus*) can graze on cotyledons, leaves, petioles and crowns of sugar beet plants. A large proportion of plants can be killed in affected areas (which are often at the edges of fields, especially near woodland) so that compensation does not occur.

Hare: Damage by hares (*Lepus capensis*) is similar to that caused by rabbits, but damaged plants are usually distributed more uniformly over fields so that compensatory growth can take place and yields are less affected.

MINIMIZING YIELD LOSSES CAUSED BY PESTS

Forecasting

Accurate prediction of pest attacks can greatly increase the efficiency of pest management programmes. In particular it can help to rationalize the use of pesticides by improving the timing of sprays and by persuading growers to abandon unnecessary prophylactic treatments.

Prediction of damage by beet cyst nematode can be based on population levels in soil samples taken before sowing; populations should be calculated as the number of eggs + juveniles per unit weight of soil, not as cysts or viable cysts which are less well correlated with crop yield (Griffin, 1981). In an experiment on an infested field in California the tolerance level (T in Equation 13.1) was 100 eggs/g, $Y_{\text{max.}}$ was 62 t/ha and Z was 0.99886. Assuming the cost of a fully effective nematicide treatment (A) to be \$30/t the economic threshold (T_{E}), above which treatment is economically justified, was calculated, using Equation 13.2, as 143 eggs/g (Cooke & Thomason, 1979).

$$T_{\text{E}} = \left\{\log \frac{Y_{\text{max.}} - (A/B)}{Y_{\text{max.}}} \times \frac{1}{\log Z}\right\} + T \qquad (13.2)$$

Similar calculations could be made in other geographical areas but estimates of economic thresholds have to be treated with caution because the relationship between initial nematode population and root yield varies greatly within the same area, largely because of sowing date differences but also because of other factors such as soil moisture content at hatching and invasion, the level of parasitism of the nematode population and intrinsic differences between the aggressiveness of different nematode populations (Cooke, 1991). In the Netherlands, advice on rotations and nematicides is based on population levels in soil samples (Heijbroek, 1973). There are seven population categories, which vary according to soil type (for example 15–30 eggs/g soil on a light soil is classified as a severe infestation with considerable risk of damage and beet growing should be delayed for 4–5 years unless a nematicide is used, in which case a 2-year delay is desirable).

It has not been possible to determine damage thresholds for free-living nematode pests on the basis of samples taken at or before drilling, because the extent of damage is much more closely related to soil moisture levels after germination than to nematode populations before sowing (Cooke, 1973). The most effective nematicides are applied at drilling, so annual prophylactic treatment is essential in areas at risk from damage.

Large field-to-field differences in the abundance of arthropods of the soil pest complex indicate the need for a field-based rather than a regional forecasting technique. Attempts have been made to predict damage using a system of baited traps (perforated drinking straws filled with a bran/dried meat mix) to which springtails and millipedes are attracted. Early results on a limited number of fields were encouraging and suggested a threshold level of three millipedes and/or springtails per straw (Brown, 1984). However, the technique was less successful when tested on a wider range of soils and its scope remains in doubt (Dewar & Cooper, 1985).

In the UK, a forecast of the incidence of virus yellows has, for many years, been used in the aphid spray warning scheme. These forecasts have been updated regularly (Harrington *et al.*, 1989; Werker *et al.*, 1998). The current forecast system uses information on the severity of winter weather that might affect the over-wintering aphid vectors, crop sowing dates, the migrations of the main aphid vector *M. persicae* as measured by suction traps and the level of crop protection measures used based on seed sales (Qi *et al.*, 2004) (Table 13.3). These account for 76% of the variance in the data. However, because the seed treatments, which are now used on over 74% of UK crops (Fig. 13.4), need to be ordered in the year before use, it is impossible to change these particular crop protection measures in response to a low or high forecast. Thus most growers apply prophylactic seed treatments to control the problem.

Table 13.3 Modelling virus yellows of sugar beet in the UK.

The daily progress of the proportion of plants infected with virus yellows is described as:

$$\frac{dy}{dt} = r_p P(1-Y) + r_s Y(1-Y) \qquad \text{(Equation 1)}$$

In Equation 1, P is the proportion of plants with primary infection, Y is the plants with secondary infection, r_p and r_s are the progress rate constants for primary and secondary infection, respectively. $P = 1 - \exp(-pN)$ where p measures the number of viruliferous aphids landing on each plant per aphid caught by suction trap and N is the total aphid numbers caught up to the end of June.

To allow for a decline in the rate of disease progress due to crop development, Equation 1 is extended to the following:

$$\frac{dy}{dt} = (r_p P(1-Y) + r_s Y(1-Y))z(t) \qquad \text{(Equation 2)}$$

In Equation 2, $z(t) = \exp(-g(-te))$ where t is the date when the proportion of the diseased plants was estimated (e.g. at the end August), te is the crop emergence date and g measures the rate of decline in the rate of disease progress with plant age taken as the number of days from crop emergence $(t - te)$.

To allow for changes in past pest management practices, Equation 2 is further extended as below:

$$\frac{dy}{dt} = (r_p P(1-Y) + r_s Y(1-Y))z(t)Q(x) \qquad \text{(Equation 3)}$$

In Equation 3, $Q(x) = 1 - k/(1+\exp(-b(x - m))$ where k is the maximum efficacy in reducing r_p and r_s and reaching a midway point when a given year, x, happened to be m. b measures the rate of this change.

To allow for the effects of usage of a given new pesticide, Equation 3 is again extended further below:

$$\frac{dy}{dt} = (r_p P(1-Y) + r_s Y(1-Y))z(t)Q(x)G(x) \qquad \text{(Equation 4)}$$

In Equation 4, $G(x) = 1 - e.g.(x)$ where e is the parameter measuring the efficacy per percentage of land in use of a given new pesticide (g) in a given year (x).

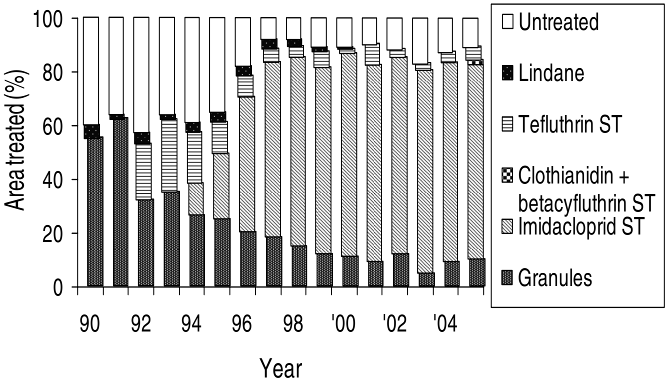

Fig. 13.4 The proportion of sugar beet treated with pesticides at sowing: 1990–2005. ST = seed treatment. Source: British Sugar Crop Survey and Crop Audit.

Crop rotation

Sugar beet is almost always grown in rotation with other crops to reduce the risk from a wide variety of weeds (including weed beet), diseases (such as rhizomania) and some pests. Rotations cannot protect crops against highly mobile pests such as aphids or birds, but can be particularly effective against relatively immobile pests with narrow host ranges (e.g. beet cyst nematode) or insect pests with at least one stage that is restricted to the soil (e.g. pygmy beetle and wireworm).

In the early years of the sugar beet industry in Germany, when it was not unusual for crops to be grown in monoculture in fields around the factories, large populations of beet cyst nematode soon built up that were impossible to control, and in many cases resulted in the enforced closure of the factories. The cause of the problem was identified as a cyst-forming nematode (Schacht, 1859) and it became clear that its limited host range and relatively high hatch rate under non-host crops (about 50% per year) meant that crop rotation could be used effectively as a control measure.

Sensible rotations can also minimize damage by other nematode pathogens. *Meloidogyne hapla* populations can be controlled by cropping with cereals, which are poor hosts (Hijink & Kuiper, 1964) whereas *M. naasi* numbers increase under cereals but decrease under potatoes (Allen *et al.*, 1970). *Nacobbus aberrans* populations decline under non-hosts such as cereals, lucerne and potatoes (Altman & Thomason, 1971). The large number of host races of *Ditylenchus dipsaci* makes this a difficult pest to control using rotations, although beet crops should not be grown after heavily-infested crops of oats, beans or onions. The wide host ranges of free-living ectoparasites, *Trichodorus* spp., *Paratrichodorus* spp. and *Longidorus* spp., mean that there are no 'safe' rotations in soils infested with these nematodes; however, grass is a particularly good host for *Longidorus* spp., and appropriate control measures should be considered for beet crops following leys on light, sandy soils.

Pygmy beetles (*Atomaria linearis*) feed and reproduce in fields of sugar beet and other chenopodiaceous crops throughout the growing season, and then over-winter in the soil, often in great numbers. If a second successive host crop is grown, the beetles start to feed on the seedlings as soon as they have germinated, and can cause virtually complete crop failure. Such disasters can be avoided by an appropriate rotation policy. Nevertheless, relatively severe damage can also be caused, especially to slow-growing crops, in intensive beet-growing areas if flights from old beet fields are sufficiently early and prolific.

Large populations of wireworms (e.g. *Agriotes* spp.) occur commonly in permanent grassland. When this is ploughed up, the wireworms feed on the below-growing parts of many subsequent arable crops (including sugar beet) and can cause extensive damage. Because of the extended life cycle of this pest, damage can occur during the 3 years after ploughing, but is usually most serious in the second year; this should be considered when planning rotations and pesticide programmes in fields at risk. Leatherjackets (e.g. *Tipula* spp.) also occur in large numbers in grassland (and possibly in crops with serious grass weed problems), especially in low-lying, wetter fields. They complete their life cycle in a single year, however, so can only damage beet crops sown in the year following ploughing.

Other cultural control methods

Several potential pest problems can be avoided or ameliorated by attention to crop hygiene and the use of appropriate cultural methods.

Crop hygiene

Elimination of over-wintering sites for pests and sources of disease (e.g. sprouting beet in cleaner–loader sites, or groundkeeper beet in other crops or set-aside land) is obviously important in controlling virus yellows. However, the removal of infested residues of previous crops can also be useful in limiting the extent of damage caused by some nematodes (e.g. *Meloidogyne* spp. and *Ditylenchus dipsaci*). Similarly, the eradication of weed hosts between beet crops can remove disease sources and increase the rate of pest population decline. Uninfested fields should be kept free from possible sources of infection by soil-borne pests such as beet cyst nematode. For example, soil from cleaner–

loader sites should be returned to fields from which it came and attention should be given to cleaning equipment, particularly contractors' machinery, coming from farms or fields in infested areas.

Seedbed preparation

The depredations of field mice occur especially on fields where seedbeds are 'cobbly' (i.e. consist of relatively large soil aggregates) and where seeds have been sown too near the surface, especially into dry soil. If pellets are left uncovered, particularly when the drill is lifted off the ground whilst turning, the mice soon learn that they contain food and move into the other areas of the field, locating even well-covered seeds by smell and digging them up along lengths of row.

Some of the ways of minimizing field mouse damage (i.e. preparing a firm, fine seedbed and ensuring that seeds are sown onto moisture at the seed furrow base) also restrict pest activity and ensure rapid plant establishment. Although compacted soil conditions should, in general, be avoided, they can impede the movement of some soil pests (e.g. free-living nematodes in sandy soils or millipedes and symphylids in silty soils); plants in fields containing these pests may grow more vigorously in areas of compaction (e.g. tractor wheelings and headlands).

Sowing date

The extent of damage caused by most sugar beet pests varies according to the developmental stage of the crop. In general, older plants with well-established root systems are less susceptible to damage than younger plants. Some pests attack relatively late in the spring or in the summer; for example beet cyst nematode, which does not hatch until soil temperatures exceed 10°C, beet fly, which, in the UK, lays its eggs on beet leaves in late April/early May and peach-potato aphids which, in the UK, are often first found on beet crops from mid to late May. These pests, or the diseases they transmit, are less damaging on very early-sown crops.

Conversely, early-sown crops, which often grow slowly during the first few weeks and remain longer in the susceptible seedling stage, are more liable to damage from pests such as springtails, wireworms and leatherjackets, which are active early in the spring. In fields at risk from damage by these pests, beet crops should not be sown until the weather prospects favour rapid emergence and early growth, or should be protected by a recommended seed treatment.

Resistant sugar beet cultivars

In general there has been more progress in breeding for resistance to sugar beet diseases (e.g. downy mildew, powdery mildew and rhizomania) than to pests, which usually have a less intimate physiological relationship with the host plant.

An exception to this is the work on beet cyst nematode, an endoparasite that induces specific tissue responses in the root resulting in the formation of transfer cells without which the nematode cannot complete its life cycle. Resistance to beet cyst nematode, based upon a hypersensitivity reaction in which juveniles within the root become surrounded by necrotic tissue, occurs in other *Beta* species, particularly those in the Section *Procumbentes* (i.e. *B. patellaris* Moq., *B. procumbens* Chr. Sm. and *B. webbiana* Moq.). The chromosome fragment bearing the gene(s) for resistance has been transferred from *B. procumbens*, via the use of monosomic addition lines, to produce diploids that are highly resistant to the nematode (Heijbroek *et al.*, 1988; Lange *et al.*, 1990). This material is now incorporated into commercial breeding lines, although reports from Germany of resistance-breaking pathotypes indicate that there are continuing problems in store for the plant breeder if resistant varieties become widely used (Müller, 1992; 1998).

Heritable resistance to *Myzus persicae* has also been reported (Lowe & Russell, 1969) and methods for field selection of resistant plants have been described (Lowe & Singh, 1985). However, the potential benefits of this partial resistance have offered insufficient inducement for its commercial development. Sugar beet varieties resistant to *Beet mild yellowing virus*, rather than to the aphids themselves are a more likely prospect in the future.

With other invertebrate pests, resistance of cultivars to spider mites is seen as the best method of controlling this pest in susceptible areas (Legrand *et al.*, 1997), and susceptible cultivars have been developed to the root maggot in the USA (Campbell *et al.*, 2000a).

Resistant catch crops

The use of trap cropping to control beet cyst nematode, i.e. planting a crop that stimulates nematode hatch and destroying it before the life cycle can be completed, was first tested over a century ago (Kühn, 1881). The drawbacks of this technique include the high cost of sowing and destroying a crop that may have no purpose other than to control nematodes, and the danger of delayed crop destruction leading to an increase in nematode population instead of a reduction.

These problems have been overcome by the use of nematode-resistant cultivars of cruciferous green manure crops. Green manures (sown in late July/early August and ploughed in 2–3 months later) have been widely used in some parts of Europe to maintain soil organic matter content, and conserve nitrogen in the topsoil. Cruciferous crops, which establish readily and grow rapidly, are well suited to this purpose but are hosts of beet cyst nematode and can cause populations to increase. Highly resistant cultivars of white mustard and oil radish have now been developed which retain the advantages of other green manures, whilst increasing the rate of decline of populations of beet cyst nematode (Steudel & Müller, 1983; Müller, 1986; Banaszak *et al.*, 1998). Significant yield increases in beet crops following catch crops have been achieved in Germany (Arndt, 2002), Italy (Tacconi & Venturi, 1991), Spain (Redondo & Villarias, 1991), the Netherlands (Heijbroek *et al.*, 1998), and the USA (Krall *et al.*, 1996; Hafez & Sundararaj, 1999).

Green manures, organic manures and straw incorporation can also reduce the effects of the soil pest complex by offering alternative foods.

Pesticides

Pesticides have been applied routinely to the sugar beet crop only since the end of the World War II, although some (e.g. lead arsenate, Paris green, derris pyrethrum and nicotine) were occasionally used long before then. A comprehensive account of pesticide usage on sugar beet would be impossible here – approved materials, timing and method of application, formulations, target species and contractual statutory regulations all vary greatly from year to year and region to region.

Apart from soil fumigants (p. 349) most sugar beet pesticides fall into five groups:

(1) Organochlorines. During the late 1940s and the 1950s materials such as DDT, gamma HCH, aldrin and dieldrin were widely used in several formulations to control a variety of sugar beet pests. However, their persistence in the environment, detrimental effects on non-target organisms (Dewar *et al.*, 1990) and accumulation in species at the end of food chains resulted either in restrictions on their use or in complete withdrawal.

(2) Organophosphates. Many organophosphates (OPs) have high mammalian toxicity, are less persistent and more selective than the organochlorines, but are still hazardous to wildlife. They were first used on the crop during the 1950s, but many have now been withdrawn from use, especially in Europe, following reviews of their ecological toxicity profiles.

(3) Carbamates. Carbamates, which, like the organophosphates, act as acetylcholinesterase inhibitors, were developed and tested during the 1960s and were widely used on the crop from the 1970s to the 1990s. They are effective against a range of nematode and arthropod pest species and have been used in a variety of formulations; however, some compounds are so toxic to mammals that they are marketed only as granules. As with OPs, some (e.g. carbofuran and aldicarb) have been or are about to be withdrawn from use in sugar beet in Europe.

(4) Pyrethroids. The synthetic pyrethroids have been used extensively on the crop. Current materials include cypermethrin, deltamethrin, fenvalerate and lambda-cyhalothrin as post-emergence insecticide sprays, and tefluthrin and beta-cyfluthrin, principally as components of seed treatments against soil pests. They are most effective against foliar pests that range

over leaf surfaces, thus coming into contact with the insecticide, but give poor control of pests such as aphids on the undersurface of leaves.

(5) Neonicotinoids. The first of this novel class of broad-spectrum pesticides, imidacloprid, was introduced in the early 1990s (1992 in France, 1994 in the UK) (Elbert *et al.*, 1990). It has since developed to be one of the highest-selling insecticides in the world for a wide variety of uses. In sugar beet, it is usually applied as a seed treatment to pelleted seed. Two further products from this group, thiamethoxam (Senn *et al.*, 1998) and clothianidin (Ohkawara *et al.*, 2002) have also now been developed for use in beet. All three chemicals have excellent systemic activity, which gives good control of sap-sucking foliar pests such as aphids and leafhoppers, as well as control of some soil pests. They do not control leaf-eating pests such as caterpillars very well, nor spider mites later in the season.

Pesticides form a vital component of almost every sugar beet grower's crop protection programme and there are few pest problems that can not be alleviated to some extent by the correct application of materials belonging to one or more of the above groups. However, problems are caused by increasingly stringent registration procedures, the appearance of pesticide-resistance in some target organisms and accelerated degradation of some materials in suppressive soils. Decisions made by growers must be based upon local regulations as well as economic considerations. The following sections outline the major formulations of pesticide available to control the most important pest species.

Baits and traps

Populations of field mice are commonly around 20/ha during the winter, falling by up to 90% during the summer (Green, 1978). Such populations can cause severe crop damage but are small enough to be controlled by breakback or baited traps. Around five breakback traps per hectare are required; these require regular inspection, resetting and protection from birds. Baited traps (3–6/ha) are probably more effective; the anticoagulant poison (e.g. warfarin or chlorophacinone) should be mixed with crushed grain or meal and 100–150 g of the mixture placed in traps that are designed to retain the poison bait, to exclude birds and larger mammals and not to roll in the wind.

Pelleted baits containing methiocarb can be applied to control damage by leatherjackets or slugs; slugs can also be controlled by pellets containing the more specific molluscicide, metaldehyde.

Seed treatments

Seed treatments to control arthropod pests have been available to some beet growers for over 40 years. Tests of gamma-HCH in the 1940s soon led to the commercial introduction of treated seed, principally to control wireworm (*Agriotes* spp.), although problems occurred because of phytotoxicity and lack of adhesion to the seed (Durrant *et al.*, 1986; Dewar *et al.*, 1988). These were partly overcome with the introduction of dieldrin, which controlled a range of soil-inhabiting arthropod pests, and could be applied safely to naked or pelleted seed. Official pressure for the withdrawal of the persistent organochlorines led to the replacement of dieldrin by the carbamate, methiocarb, which, by 1980, was used as a sugar beet seed treatment in most northern European countries. Although methiocarb was effective against pygmy beetles, it gave little protection against other members of the soil pest complex and replacements were sought almost immediately. The acceptable amount of active ingredient (a.i.) varies between countries because of phytotoxicity at higher doses. Methiocarb application rates were restricted to 2 g a.i./kg in the UK and 6 g a.i./kg in Germany, but other pesticides could be applied at relatively high rates (e.g. up to 90 g a.i./kg) with no reduction in seedling emergence or vigour. In many experiments conducted worldwide since the mid-1980s, several candidate pesticide treatments at a wide range of rates, have shown promise, including the pyrethroid tefluthrin, the carbamates carbosulfan and furathiocarb (Dewar *et al.*, 1988), and the new neonicotinoid compounds such as imidacloprid, thiamethoxam and clothianidin, which control soil pests but also have systemic action against foliar pests (Dewar, 1989a; Dewar & Read, 1990; Elbert *et al.*, 1990; Schmeer *et al.*, 1990; Dewar, 1992; Vincinaux *et al.*, 1992; Asher & Dewar, 1994; Dewar & Asher, 1994; Heijbroek & Huijbregts, 1995; Wauters & Dewar, 1996; Elfstrom, 1997; Senn *et al.*, 1998; Dewar *et al.*, 2000a; Hermann *et al.*, 2001; Meredith *et al.*, 2002; Meredith & Morris, 2003; Schmuck & Keppler, 2003). They have since become the dominant method of pest control in most countries in Europe, especially where seed is pelleted; in the UK over 74% of seed was treated with imidacloprid in 2004 (Fig. 13.4).

Pesticides, whether applied to the seeds or the seed pelleting material, can, under certain circumstances (e.g. cold, wet conditions), adversely affect plant establishment and/or growth. They are often applied prophylactically to all seeds; even if applied to selected seed lots and offered to growers as an optional treatment they will, because of the unpredictable nature of pest damage, often be used where no such damage occurs. There must therefore be very little possibility of phytotoxicity in fields not liable to pest attack. However, decisions on application rates inevitably involve a compromise between maximum efficiency against the target pest and minimum risk of phytotoxicity. These decisions are complicated by the difficulty of achieving uniform loading of pesticides because of variations in seed size and in the weight of pelleting material per seed (Durrant *et al.*, 1986; Westwood *et al.*, 1994; Dewar *et al.*, 1997). In addition there have been reports of interactions between insecticides and fungicides in the seed pellet, for example a reduction in the efficacy of hymexazol in the presence of carbamates (Asher & Payne, 1989; Heijbroek, 1989; Huijbregts & Gijssel, 1989). There can also be interactions between insecticides and herbicides when applied before the seedlings emerge; both imidacloprid and thiamethoxam have shown adverse phytotoxic effects with lenacil applied pre-emergence (Dewar & Stevens, 2003; Meredith & Morris, 2003).

Despite these problems, seed treatment is in many ways the ideal method of pesticide application. It ensures that the pesticide is localized in the rhizosphere of emerging seedlings, it enables reductions to be made to the amount of active ingredient applied per hectare and it decreases toxicity hazards to farm workers and non-target organisms (Epperlein & Schmidt, 2001; Baker *et al.*, 2002), although hazards during seed processing are increased. Improved seed treatments will give many growers the confidence to abandon the insurance use of granular pesticides, giving economic and environmental advantages. Some existing seed treatments are as effective as granules against arthropod soil pests (Dewar, 1989a; Richard-Molard, 1989; Schäufele, 1989) and the neonicotioids have replaced granular formulations of carbamates and many sprays for foliar pests, especially aphids. However, little progress has been made with seed treatments to control free-living or cyst-forming nematodes.

Granules

The main use of granules now in Europe is to control nematode pests that are unaffected by the seed treatments. They are usually applied as row treatments into the seed furrow as part of the drilling operation, although pre-drilling or post-emergence treatments of some materials are used in specific situations. Granular formulations are relatively easy to apply with an applicator. Seed furrow treatments localize the pesticide in the rhizosphere of recently germinated seedlings, the growth stage most susceptible to damage by many pest species, thus minimizing both application rates and effects on non-target organisms, although they do still have some effect on non-target organisms (Dewar *et al.*, 1990).

In the 1960s and 1970s, granular formulations of some organochlorine and organophosphate pesticides became available, for example heptachlor to control *Atomaria* (Bonnemaison & Lyon, 1968) and parathion to control *Ditylenchus dipsaci* (Graf & Meyer, 1973). However, it was the advent of the methyl-carbamate and oxime-carbamate pesticides in the 1960s and their extensive use on the sugar beet crop in the 1970s and subsequently that has been the major recent influence in commercial pest management. They have been shown to control damage by free-living nematodes (Cooke, 1989), beet cyst nematode (Griffin, 1988), arthropods of the soil pest complex (Dewar & Cooke, 1986), sugar beet root maggot (Bergen & Whitfield, 1987), and a variety of other pests (Winder & Dunning, 1986; Winder *et al.*, 1993); they can also reduce levels of virus yellows (Dewar, 1988b; 1989b) and curly top (Blickenstaff *et al.*, 1982) by controlling their insect vectors.

In the UK, granular formulations of six carbamate pesticides were approved for use on sugar beet in 1990 (aldicarb, bendiocarb, benfuracarb, carbofuran, carbosulfan and oxamyl). The area of the UK beet crop receiving one or other of these materials increased steadily between 1973 (when they were first given limited clearance for use) and 1990 (when 55% of the crop was treated), but has declined to less than 10% since the introduction of the seed treatments tefluthrin and imidacloprid in 1992 and 1994 respectively (Fig. 13.4). In addition, granular carbamates have come under increasing scrutiny from regulatory authorities because of their relatively high mammalian toxicity, and their propensity for leaching into watercourses. As a consequence, aldicarb and carbofuran are no longer approved for use in sugar beet in the UK. In future there may be no granular carbamates allowed for pest control in sugar beet.

Fumigants

Fumigants such as nicotine to control aphids and 1,3-dichloropropene-1,2-dichloropropane mixture (DD) or chloropicrin to control beet cyst nematode, were used on sugar beet crops before the 1970s, either as experimental tools or, sometimes, in commercial practice (Dunning, 1982).

Fumigation is an expensive, complicated procedure, but can give economic benefits where populations are high (Caubel & Muchembled, 1991). The efficacy of treatment can be decreased by several factors: in compacted or waterlogged soils or at low temperatures the diffusion of fumigants is restricted, in clay and peaty soils much of the toxicant is adsorbed onto mineral particles or organic matter thus increasing optimum dose rates, and in the surface layer of soil control may be inadequate because of rapid escape of fumigant to the atmosphere. Fumigants are phytotoxic and must be allowed to escape from the soil before seedlings germinate, which may delay drilling.

Low rates of fumigants, applied as row treatments at or shortly before drilling, were used commercially on a small scale to control free-living nematodes in the UK until the granular carbamate pesticides provided a more economical and convenient alternative (Cooke, 1975). However, in some other parts of Europe, fumigation is still used on the sugar beet crop as a broadcast treatment to control beet cyst nematode, especially in fields where advantages are conferred on other crops in the rotation (e.g. in potato-growing areas, where potato cyst nematode, *Globodera* spp., is also present). The most commonly used injectors have a powered roller mounted at the rear that rotates in the same direction as the machine, but faster, leaving a 'smeared' surface that is relatively impenetrable and prevents rapid escape of the fumigant. In the USA, fumigants were used in broadcast or bed applications to control beet cyst nematode or root-knot nematodes (Roberts & Thomason, 1981).

Sprays

Very few pesticide sprays are now applied to the sugar beet seedbed before drilling, but this is sometimes necessary to control epidemics of leatherjackets (e.g. with chlorpyrifos). The persistent organochlorines have now all been withdrawn because of their extreme hazard to non-target organisms. Most insecticide spray treatments are applied onto crops that have already emerged. Spray treatments are available for the control of most foliar pests but in northern Europe the usual target is the peach-potato aphid, the principal vector of virus yellows in crops not protected by systemic seed treatments. The timing of sprays is important and, in the UK, a warning scheme for growers is operated, based upon information on aphid populations (Dewar, 1994); sprays may have to be applied on several occasions and care should be taken to avoid materials that kill naturally-occurring aphid predators, such as ladybirds, lacewings or carabid beetles. The efficiency of some sprays (especially the organophosphates, carbamates and pyrethroids) is decreased by the presence of resistant aphids, which have become more prevalent in recent years (Foster *et al.*, 2002). So far no field resistance has developed to the neonicotinoids, but populations of aphids are constantly being monitored.

Beneficial organisms and biological control

Pest species are subject to attack by a range of naturally-occurring predators, parasites or diseases that can serve to decrease the severity or duration of damage to the host crop. Measures to conserve or encourage these organisms can replace or complement other control measures.

The aphids that transmit virus disease to sugar beet crops have a particularly wide range of predators, which includes the larval and adult stages of several ladybird species (e.g. *Adalia bipunctata* (L.), *A. decempunctata* (L.), *Coccinella septempunctata* (L.) (Plate 74a) and *Propylea quatuordecimpunctata* (L.)), adult and larval stages of lacewings (particularly in the Chrysopidae and Hemerobiidae) (Plates 74b,c), the larvae of several hover fly species (particularly in the genera *Platycheirus, Scaeva, Sphaerophoria* and *Syrphus*) (Plate 74d), ground beetles (Carabidae), rove beetles (Staphylinidae) and mites. The timing and selection of insecticide sprays can help to ensure that populations of these valuable allies of the sugar beet grower are not destroyed before their benefits are seen. If sprays must be used, those such as pirimicarb, which have least effect on these beneficial species, are preferable.

Parasites of aphids and other pest species include parasitic wasps (Ichneumonidae, Braconidae, Chalcidae) which lay their eggs in the host, parasitic flies (Tachinidae) which attack many species of caterpillars, parasitic nematodes (e.g. Mermithidae) that attack soil-inhabiting insects such as leatherjackets, and fungi (e.g. *Entomophthora* spp.), bacteria (e.g. *Bacillus thuringiensis*) and viruses.

Attempts to manipulate natural populations of these beneficial organisms, to introduce them into the rhizosphere or incorporate some of their genetic material directly into the crop's germplasm, have already been made (Kerry, 1988; Crump, 1991; Thomas, 1991) and will increasingly form a part of pest population management strategies in the twenty-first century.

REFERENCES

Aabdou, N. & Boulif, M. (2004) *Cassida vittata* shield beetle, a potential pest for sugar beet crops in the Gharb Region of Morocco. *Phytoma*, Ruralia, Paris, France, pp. 10–13.

Allen, M.W., Hart, W.H. & Baghott, K. (1970) Crop rotation controls barley root-knot nematode at Tulelake. *California Agriculture* **24**, 4–5.

Altman, J. & Thomason, I.J. (1971) Nematodes and their control. In: Johnson, R.T., Alexander, J.T., Rush, G.E. & Hakes, G.R. (eds) *Advances in Sugarbeet Production*. Iowa State University Press, Ames, pp. 335–370.

Andersson, S. (1984) First record of a yellow beet cyst nematode (*Heterodera trifolii*) in Sweden. *Växtskyddsnotiser* **48**, 93–95.

Armstrong, J.S., Dregseth, R.J. & Anderson, A.W. (2000) Susceptibility of sugar beet root maggot *Tetanops myopaeformis* (Diptera: Otitdae) larvae to terbufos, chlorpyrifos and aldicarb. *Journal of Sugar Beet Research* **37**, 17–25.

Arndt, M. (2002) Influence of crop rotation, chemical and biological control on the abundance of beet cyst nematodes (*H. schachtii*) and the sugarbeet yield. *Gesunde Pflanzen* **54**, 74–79.

Asher, M. & Dewar, A.M. (1994) Control of pests and diseases in sugar beet by seed treatments. In: Martin, T. (ed.) *Seed Treatment: Progress and Prospects*. BCPC Monograph No. 57, pp. 151–158.

Asher, M.J.C. & Dewar, A.M. (1997) Pests and diseases of sugar beet: a review of 1996. *British Sugar Beet Review* **65** (1), 14–19.

Asher, M.J.C. & Payne, P.A. (1989) The control of seed and soil-borne fungi by fungicides applied in pelleted seed. *Proceedings of the 52nd IIRB Congress*. pp. 179–193.

Ayala, J. (1996) Control of *Chaetocnema tibialis* (Coleoptera: Chrysomelidae) and *Onychiurus armatus* (Collembola) in spring and autumn sugarbeet with insecticides applied as pellets. *Boletin de Sanidad Vegetal*, Plagas **22**, 781–787.

Ayala, J. & Dominguez, M. (1996) Evaluation of insecticide action against *Cassida vittata* (Vill) (Coleoptera: Chrysomelidae) during the first growth stages of autumn-sown sugarbeet. *Boletin de Sanidad Vegetal*, Plagas **22**, 653–657.

Ayala, J. & Bermejo, J.L. (2001) First results of the insecticidal action of thiamethoxam on *Myzus persicae* and *Chaetocnema tibialis* in sugarbeet. *Boletin de Sanidad Vegetal*, Plagas **27**, 129–136.

Ayala, J., Perez de San Roman, C., Ortiz, A. & Juanche. J. (1996) Chemical control of *Myzus persicae* (Sulz) and *Aphis fabae* (Scop) (Homoptera: Aphididae) on sugar beet with aphicides applied at sowing and as foliar sprays. *Boletin de Sanidad Vegetal*, Plagas **22**, 731–740.

Baker, P.C., Haylock, L.A., Garner, B.H., Sands, R.J.N. & Dewar, A.M. (2002) The effects of insecticide seed treatments on beneficial invertebrates in sugar beet. *Proceedings of the British Crop Protection Council – Pests and Diseases*. 2, pp. 653–658.

Banaszak, H., Nowakowski, M., Szymczak-Nowak, J. & Ojczyk, K. (1998) Limiting of *Heterodera schachtii* Schm., diseases and weeds of sugar beet by tillage system based on mustard or radish intercrops and mulches. *Journal of Plant*

Protection Research **38**, 70–80.

Barcic, J.I., Dobrincic, R., Sarec, V. & Kristek, A. (2000) Studies on insecticide seed dressing of sugarbeet. *Agriculturae Conspectus Scientificus (Poljoprivredna Znanstvena Smotra)* **65**, 89–97.

Beaupre, C.M.S., Gray, F.A., Vincelli, P.C. & Miller, S.D. (1990) Effects of aldicarb, Rhizoctonia disease, and weeds on severity of the false root knot nematode of sugar beet. *Fungicide and Nematicide Tests* **45**, 161.

Bechinski, E.J., McNeal, C.D. & Gallian, J.J. (1989) Development of action thresholds for the sugarbeet root maggot (*Diptera: Otitidae*). *Journal of Economic Entomology* **82**, 608–615.

Beltrami, G., Piazzi, M. & Vacchi, A. (2004) How to combat defoliating noctuids in beet. *Informatore Agrario* **60**, 103–106.

Benada, J., Sedivy, J. & Spacek, J. (1987) *Atlas of Diseases and Pests in Beet*. Elsevier, Amsterdam, Oxford, New York and Tokyo.

Bergen, P. & Whitfield, G.H. (1987) Evaluation of at-planting and post-emergence treatments for control of the sugarbeet root maggot. *Journal of the American Society of Sugar Beet Technologists* **24**, 67–79.

Bichuk, Yu P., Tribel, S.A. & Prusskaya, N.D. (1986) Beet leaf beetles. *Zashchita Rastenii (Moskva)* **6**, 45–50.

Bittner, V. (2002) Sugar beet damage in Moravia and Silesia in 2002. *Listy Cukrovarnicke* **118**, 292–294.

Blickenstaff, C.C., Stander, J.R., Traveller, D.J. & Yun, Y.M. (1982) Insecticidal prevention of curly top in beets. *Journal of the American Society of Sugar Beet Technologists* **21**, 265–285.

Bongiovanni, G.C., Barbini, M. & Ansaloni, R. (1990) Results of a campaign of monitoring certain Noctuidae harmful to sugarbeet using synthetic pheromones. *Informatore Agrario* **46**, 89–99.

Bonnemaison, L. & Lyon, J.P. (1968). L'atomaire de la betterave (*Atomaria linearis* Steph.), biologie et méthodes de lutte. *Annales des Épiphyties* **18**, 401–450.

Bosch, U. & Schäufele, W.R. (1994) Zur Bekampfung von Schadlingen der Zuckerrube durch Saatgutbehandlung mit Imidacloprid. *Gesunde Pflanzen* **46**, 44–55.

Boselli, M., Curto, G.M. & Lazzari, G.L. (1991) Monitoring of the sugar beet weevil (*Temnorrhinus mendicus* Gylly) (Coleoptera: Curculionidae) and preliminary biological control trials with entomopathogenic nematodes. *Informatore Fitopatologico* **41**, 55–59.

Brown, R.A. (1981) Gappiness, sugar beet yield loss and soil-inhabiting pests. *Proceedings of the British Crop Protection Council – Pests and Diseases*. pp. 803–810.

Brown, R.A. (1982) The ecology of soil inhabiting pests of sugar-beet, with particular reference to *Onychiurus armatus*. PhD thesis, University of Newcastle-upon-Tyne.

Brown, R.A. (1984) The soil pest complex: can its damage be predicted? *British Sugar Beet Review* **52** (1), 31–32.

Brown, R.A. (1985) Effects of some root-grazing arthropods on the growth of sugar-beet. In: Fitter, A.H. (ed.) *Ecological Interactions in Soil*. Special Publication Number 4 of the British Ecological Society, pp. 285–295.

Brown, R.H. & Kerry, B.R. (1987) *Principles and Practice of Nematode Control in Crops*. Academic Press, Australia.

Campbell, L.G. (2001) Development of alternative control strategies for the sugarbeet root maggot. *Proceedings for the 31st Biennial Meeting (Agriculture) of the American Society of Sugar Beet Technologists*. Vancouver, BC, Canada, 28 February-3 March 2001, pp. 148–149.

Campbell, L.G., Anderson, A.W. & Dregseth, R.J. (2000a) Registration of F1015 and F1016 sugarbeet germplasms with resistance to the sugarbeet root maggot. *Crop Science* **40**, 867–868.

Campbell, L.G., Eide, J.D., Smith, L.J. & Smith, G.A. (2000b) Control of sugarbeet root maggot with the fungus *Metarhizium anisopliae*. *Journal of Sugar Beet Research* **37**, 57–69.

Casagrandi, M., Santi, R. & Tattini, A. (1996) Control trials against root-knot nematodes (*Meloidogyne* spp.) on sugarbeet plants for reproduction. *Informatore Fitopatologica* **46**, 55–57.

Casals, B., Brevis, A.J.C., Hepp, G.R. & Sandoval, B.C. (1999) Leafhopper species (Homoptera: Cicadellidae) associated with sugarbeet (*Beta vulgaris* L. var. saccharifera) in Nuble, Chile. *Agro-Ciencia* **15**, 189–194.

Caubel, G. (1990) Beet nematodes: combination of control methods. *Cultivar (Paris)* **279**, 54–56.

Caubel, G. & Muchembled, C. (1991) Control of *Heterodera schachtii* using nematicides or trap plants of the family Cruciferae. *Proceedings of the IIRB Congress*. 54, pp. 211–220.

Cioni, F. (2003) Spread of nocturnal leaf eating insects on sugarbeet. *Informatore Agrario* **59**, 87–89.

Clover, G.R.G., Azam-Ali, S.N., Jaggard, K.W. & Smith, H.G. (1999) The effects of beet yellows virus on the growth and physiology of sugar beet (*Beta vulgaris*). *Plant Pathology* **48**, 129–138.

Cooke, D.A. (1973) The effect of plant parasitic nematodes, rainfall and other factors on Docking disorder of sugar beet. *Plant Pathology* **22**, 161–170.

Cooke, D.A. (1975) Nematicide usage on sugar beet. *Proceedings of the 8th British Insecticide and Fungicide Conference*. pp. 127–132.

Cooke, D.A. (1976) Economics of control of Docking disorder of sugar beet. *Annals of Applied Biology* **84**, 451–455.

Cooke, D.A. (1984) The relationship between numbers of *Heterodera schachtii* and sugar beet yields on a mineral soil, 1978–1981. *Annals of Applied Biology* **104**, 121–129.

Cooke, D.A. (1987) Beet cyst nematode (*Heterodera schachtii* Schmidt) and its control on sugar beet. *Agricultural Zoology Reviews* **2**, 132–183.

Cooke, D.A. (1989) Damage to sugar-beet crops by ectoparasitic nematodes, and its control by soil-applied granular pesticides. *Crop Protection* **8**, 63–70.

Cooke, D.A. (1991) The effect of beet cyst nematode, *Heterodera schachtii*, on the yield of sugar beet in organic soils. *Annals of Applied Biology* **118**, 153–160.

Cooke, D.A. (1993) Nematode parasites of sugarbeet. In: Evans, K., Trudgill, D.L. & Webster, J.M. (eds) *Plant Parasitic Nematodes in Temperate Agriculture*. CABI Publising, Wallingford, pp. 133–169.

Cooke, D.A. & Dewar, A.M. (1992) Pests of Chenopodiaceous crops. In: McKinlay, R.G. (ed.) *Vegetable Crop Pests*. The

Macmillan Press Ltd, pp. 28–73.

Cooke, D.A. & Draycott, A.P. (1971) The effects of soil fumigation and nitrogen fertilizers on nematodes and sugar beet on sandy soils. *Annals of Applied Biology* **69**, 253–264.

Cooke, D.A. & Thomason, I.J. (1979) The relationship between population density of *Heterodera schachtii*, soil temperature and sugar beet yields. *Journal of Nematology* **11**, 124–128.

Cooke, D.A., Dunning, R.A. & Winder, G.H. (1974) The effect of nematicides, applied to the seed rows in spring, on growth and yield of sugar beet in Docking-disorder-affected fields. *Annals of Applied Biology* **76**, 289–298.

Cormack, W.F., Jarvis, P.J. & Ecclestone, P.M.J. (2004) Seed spacing and treatment for organically grown sugar beet. (BGS Occasional Symposium No. 37). Organic farming: science and practice for profitable livestock and cropping. *Proceedings of the BGS/AAB/COR Conference.* Newport, Shropshire, UK, 20–22 April 2004, British Grassland Society (BGS), Reading, pp. 208–211.

Cotten, J., Cooke, D.A., Darlington, P. & Hancock, M. (1992) Surveys of beet cyst nematode (*Heterodera schachtii* Schmidt) in England. *Annals of Applied Biology* **120**, 95–103.

Courbon, R. (1992) Potentialites de l'imidaclopride. *Phytoma* **441**, 25–27.

Crump, D. (1991) Biological control of the beet cyst nematode. *British Sugar Beet Review* **59**, 54–55.

Crump, D.H. & Irving, F. (1992) Selection of isolates and methods of culturing *Verticillium chlamydosporium* and its efficacy as a biological control agent of beet and potato cyst nematodes. *Nematologica* **38**, 367–374.

De Leij, F.A.A. & Kerry, B.R. (1991) The nematophagous fungus *Verticillium chlamydosporium* as a potential biological control agent for *Meloidogyne arenaria*. *Revue de Nématologie* **14**, 157–164.

Dewar, A.M. (1988a) Results of the co-operative trials on pesticides in pelleted seeds, 1987–1988. *Proceedings of the 51st IIRB Congress.* Brussels, Belgium, pp. 163–178.

Dewar, A.M. (1988b) Chemical control. In: *Virus Yellows Monograph.* IIRB Pests and Diseases Study Group, pp. 59–67.

Dewar, A.M. (1989a) Results of the co-operative trials on pesticides in pelleted seeds, 1987–1988. *Proceedings of the 52nd IIRB Congress.* pp. 163–178.

Dewar, A.M. (1989b) 1989 – the year of the yellow peril? *British Sugar Beet Review* **57** (1), 41–43.

Dewar, A.M. (1992) The effect of imidacloprid on aphids and virus yellows in sugar beet. *Pflanzenschutz-Nachrichten Bayer* **45**, 423–442.

Dewar, A. M. (1994) Individuals, populations and patterns in ecology. In: Leather, S.R., Watts, A.D., Mills, N.J. & Walters, K.F.A. (eds) *The Virus Yellows Warning Scheme – An Integrated Pest Management System for Sugar Beet in the U.K.* Intercept, Andover, pp. 173–185.

Dewar, A.M. (1996) The effect of soil pests on seedling root growth and yield of sugar beet. *Proceedings of the 59th IIRB Congress.* Brussels, pp. 229–238.

Dewar, A.M. & Asher, M.J.C. (1994) A European perspective on pesticide seed treatments in sugar beet. *Pesticide Outlook* June 1994, 11–17.

Dewar, A.M. & Cooke, D.A. (1986) Recent developments in the control of nematode and soil-arthropod pests of sugar beet. *Aspects of Applied Biology 13, Crop Protection of Sugar Beet and Crop Protection and Quality of Potatoes*, pp. 89–99.

Dewar, A.M. & Cooper, J.M. (1985) 'To treat or not to treat' – prospects for forecasting soil pest damage. *British Sugar Beet Review* **53** (4), 39–40.

Dewar, A.M. & Haylock, L.A. (1995) The long hot summer spawns a red menace. *British Sugar Beet Review* **63** (4), 20–22.

Dewar, A.M. & Haylock, L.A. (1996) The caterpillars return – a report of the epidemic of silver Y moth caterpillars. *British Sugar Beet Review* **64** (4), 4–6.

Dewar, A.M. & Haylock, L.A. (1997) New insecticide sprays for sugar beet. *British Sugar Beet Review* **65** (1), 37–39.

Dewar, A.M. & Read, L.A. (1990) Evaluation of an insecticidal seed treatment, imidacloprid, for controlling aphids on sugar beet. *Proceedings of the British Crop Protection Council – Pests and Diseases.* pp. 721–726.

Dewar, A.M. & Read, L.A. (1993) Efficacy of insecticide sprays against the larvae of mangold fly (*Pegomya hyoscyami*) in sugar beet. *Tests of Agrochemicals and Cultivars* No. 14, (*Annals of Applied Biology* 122 Supplement), pp. 4–5.

Dewar, A.M. & Stevens, M. (2003) Review of pests of sugar beet in 2002. *British Sugar Beet Review* **71** (1), 34–37.

Dewar, A.M. & Woiwod, I.P. (1994) Y all the caterpillars in the 1994 sugar beet crop? *British Sugar Beet Review* **62** (4), 19–20.

Dewar, A.M., Asher, M.J.C., Winder, G.H., Payne, P.A. & Prince, J.W. (1988) Recent developments in sugar-beet seed treatments. In: Martin, T.J. (ed.) *Application to Seeds and Soil.* BCPC Monograph No. 39, pp. 265–270.

Dewar, A.M., Thornhill, W.A. & Read, L.A. (1990) The effects of tefluthrin on beneficial insects in sugar beet. *Proceedings of British Crop Protection Council – Pests and Diseases*, pp. 987–992.

Dewar, A.M., Read, L.A., Hallsworth, P.B. & Smith, H.G. (1992) Effect of imidacloprid on transmission of viruses by aphids in sugar beet. *Proceedings of British Crop Protection Council – Pests and Diseases.* 3, pp. 965–972.

Dewar, A.M., Haylock, L.A. & Ecclestone, P.M.J. (1996) Strategies for controlling aphids and virus yellows in sugar beet. *Proceedings of the British Crop Protection Council – Pests and Diseases* 1, pp. 185–190.

Dewar, A.M., Westwood, F., Bean, K.M., Haylock, L.A. & Osborne, R. (1997) The relationship between pellet size and the quantity of imidacloprid applied to sugar beet pellets and the consequences for seedling emergence. *Crop Protection* **16** (2), 187–192.

Dewar, A.M., Haylock, L.A., Campbell, J., Harling, Z., Foster, S.P. & Devonshire, A.L. (1998) Control in sugar beet of *Myzus persicae* with different insecticide-resistance mechanisms. *Aspects of Applied Biology* 52, *Protection and Production of Sugar Beet and Potatoes,* pp. 407–414.

Dewar, A.M., Haylock, L.A., Bean, K.M. & Ecclestone, P.M.J. (2000a) Novel seed treatments to control soil pests of sugar beet. *Proceedings of the British Crop Protection Council – Pests* *and Diseases*. 3, pp. 907–912.

Dewar, A.M., Haylock, L.A., Bean, K.M., Garner, B.H. & Boyce, R. (2000b) The ecology and control of two-spotted spider mite, *Tetranychus urticae*, in sugar beet. *Proceedings of the British Crop Protection Council – Pests and Diseases*. 3, pp. 913–918.

Dewar, A.M., Haylock, L.A., Bean, K.M., Garner, B.H., Sands, R.J.N. & Ecclestone, P.M.J. (2001) Novel seed treatments to control aphids and virus yellows in sugar beet. *Proceedings of the British Crop Protection Council – Seed Treatment: Challenges and Opportunities*. Monograph No. 76, pp. 33–40.

Dewar, A.M., Haylock, L.A., Garner, B.H., Baker, P. & Sands, R.J.N. (2002) The effect of clothianidin on aphids and virus yellows in sugar beet. *Proceedings of the British Crop Protection Council – Pests and Diseases*. 2, pp. 647–652.

Dewar, A.M., Haylock, L.A. & Garner, B.H. (2004a) Which seed treatment? *British Sugar Beet Review* **72** (2), 26–33.

Dewar, A.M., Haylock, L.A. & Garner, B.H. (2004b) Nematodes in sugar beet: 1. Free-living nematodes. *British Sugar Beet Review* **72** (4), 9–13.

Di Vito, M. & Lamberti, F. (1977) Prove di lotta chimica contro i nematode galligeni su barbabietola da zucchero. *Naematologia Mediterranea* **5**, 31–38.

Dregseth, R.J., Boetel, M.A., Schroeder, A.J., Carlson, R.B. & Armstrong, J.S. (2003) Oat cover cropping and soil insecticides in an intergrated sugarbeet root maggot (Diptera: Otitidae) management program. *Journal of Economic Entomology* **96**, 1426–1432.

Dunning, R.A. (1961) Mangold fly incidence, economic importance and control. *Plant Pathology* **10**, 1–9.

Dunning, R.A. (1982) Pest and disease control. In: *50 Years of Sugar Beet Research*. International Institute for Sugar Beet Research, Brussels, pp. 69–93.

Dunning, R.A. & Winder, G.H. (1972) Some effects, especially on yield, of artificially defoliating sugar beet. *Annals of Applied Biology* **70**, 89–98.

Dunning, R.A., Winder, G.H. & Thornhill, W.A. (1977) Seedling grazing. *Report of Rothamsted Experimental Station for 1976*, Part 1, 54–55.

Durrant, M.J., Dunning, R.A. & Byford, W.J. (1986) Treatment of sugar beet seeds. In: Jeffs, K.A. (ed.) *Seed Treatment*. BCPC Publications, Thornton Heath, pp. 217–238.

Elbert, A., Overbeck, H., Iwaya, K. & Tsuboi, S. (1990) Imidacloprid, a novel systemic nitromethylene analogue insecticide for crop protection. *Proceedings of the British Crop Protection Council – Pests and Diseases*. pp. 21–28.

Elfstrom, K. (1997) Montur and Gaucho – new alternative seed treatments. *Betodlaren* **1**, 6–7.

El-Khouly, M.I. (2002) Biological activity of certain insecticides against the tortoise beetle, *Cassida vittata* Vill. and associated natural enemies in sugar beet fields. *Egyptian Journal of Agricultural Research Centre* **80**, 647–663.

El-Khouly, M.I. & Omar, B.A. (2002) The efficiency of some insecticides on tortoise beetle, *Cassida vittata* Vill. inhabiting sugar beet fields. *Egyptian Journal of Agricultural Research Centre* **80**, 697–708.

Epperlein, K. & Schmidt, H.W. (2001) Effects of pelleting sugarbeet seed with GauchoReg. (imidacloprid) on associated fauna in the agricultural ecosystem. *Pflanzenschutz-Nachrichten Bayer* **54**, 369–398.

Eronen, L., Knaapinen, R. & Kuhl, A. (2001) Thiamethoxam – a new sugarbeet seed treatment in Finland. Seed treatment: challenges and opportunities. *Proceedings of the British Crop Protection Council – Seed Treatment: Challenges and Opportunities*. Monograph no. 76, Farnham, pp. 197–202.

Ester, A., Arkema, M., Gruppen, R., Hazendonk, A., Huisman, M., Huiting, H.F., Rozen, K. van. & Vlaswinkel, M.E.T. (2004) Control of slugs with molluscophage nematodes. *Gewasbescherming* **35**, 1–5.

Fedorenko, V.P. (2002) Reliable protection for sugarbeet seedlings. *Zashchita i Karantin Rastenii* **4**, 19.

Foster, S.P., Harrington, R., Dewar, A.M., Denholm, I. & Devonshire, A.L. (2002) Temporal and spatial dynamics of insecticide resistance in *Myzus persicae* (Hemiptera: Aphididae). *Pest Management Science* **58**, 895–907.

Franklin, M.T. (1978) *Meloidogyne*. In: Southey, J.F. (ed.) *Plant Nematology*. Her Majesty's Stationery Office, London, pp. 98–124.

Furlan, L. & Toffanin, F. (1998) Effectiveness of new insecticides used as seed dressing (imidacloprid and fipronil) against wireworms in a controlled environment. *Atti, Giornate fitopatologiche, Scicli e Ragusa 3–7 maggio, 1998*, Universita degli Studi di Bologna, Bologna, Italy, pp. 195–200.

Gao, X. & Becker, J.O. (2002) Population development of both sexes of *Heterodera schachtii* is diminished in a beet cyst nematode-suppressive soil. *Biological Control* **25**, 187–194.

Gatineau, F., Larrue, J., Clair, D., Lorton, F., Richard-Molard, M. & Boudon-Padieu, E. (2001) A new natural planthopper vector of stolbur phytoplasma in the genus *Pentastiridius* (Hemiptera: Cixiidae). *European Journal of Plant Pathology* **107**, 263–271.

Gooris, J. & d'Herde, C.J. (1972) Mode d'hivernage de *Meloidogyne naasi* Franklin dans de sol et lutte par rotation culturale. *Revue de l'Agriculture* **25**, 659–664.

Graf, A. & Meyer, H. (1973) Bedeufung des Rübenkopfälchens (*Ditylenchus dipsaci*) in der Schweiz und seine Bekämpfungsmöglichkeiten. *IIRB Journal of the International Institute for Sugar Beet Research* **6**, 117–126.

Gray, F.A., Koch, D.W. & Krall, J.M. (1997) Comparative field reaction of sugarbeet and several cruciferous crops to *Nacobbus aberrans*. *Nematropica* **27**, 221–227.

Greco, N., Brandonisio, A. & de Marinis, G. (1982) Tolerance limit of the sugarbeet to *Heterodera schachtii*. *Journal of Nematology* **14**, 199–202.

Green, R.E. (1978) The ecology of bird and mammal pests of sugar beet. PhD thesis, University of Cambridge.

Griffin, G.D. (1981) The relationship of *Heterodera schachtii* population densities to sugar beet yields. *Journal of Nematology* **13**, 180–184.

Griffin, G.D. (1988) Nonvolatile nematicide control of *Heterodera schachtii* on sugarbeet. *Journal of Sugar Beet Research* **25**, 78–83.

Hafez, S.L. & Sundararaj, P. (1999) Exploitation of nematicidal efficacy of trap crops for the management of *Heterodera schachtii* under sugarbeet ecosystem. *International Journal* *of Nematology* **9**, 27–33.

Harper, A.M. & Whitfield, G.H. (1983) Beet leaf miner. *Agri-fax, Alberta Agriculture*. No. Agdex 622–13.

Harrington, R., Dewar, A.M. & George, B. (1989) Forecasting the incidence of virus yellows in sugar beet in England. *Annals of Applied Biology* **114**, 459–469.

Harrington, R., Parker, S., Taylor, M., Adamowicz, T., Cox, D., Foster, S., Denholm, I., Dewar, A. & Pickup, J. (2003) Trapped in 2002. *British Sugar Beet Review* **71** (1), 12–17.

Hauser, S., Stevens, M., Beuve, M. & Lemaire, O. (2002) Biological properties and molecular characterization of beet chlorosis virus (BChV). *Archives of Virology* **147**, 745–762.

Haylock, L.A. & Dewar, A.M. (2003) Mite there be a future sugar beet problem? *British Sugar Beet Review* **71** (3), 20–25.

Heathcote, G.D. & Cockbain, A.J. (1966) Aphids from mangold clamps and their importance as vectors of beet viruses. *Annals of Applied Biology* **57**, 321–336.

Heatherington, P.J. & Bolton, B.J.G. (1992) Pest control and crop establishment in sugar beet using an imidacloprid-based seed treatment. *Aspects of Applied Biology* **32**, 65–79.

Heatherington, P.J. & Meredith, R.H. (1992) United Kingdom field trials with Gaucho for pest and virus control in sugar beet, 1989–1991. *Pflanzenschutz Nachrichten Bayer* **45**, 491–526.

Heijbroek, W. (1973) Forecasting incidence of and issuing warnings about nematodes, especially *Heterodera schachtii* and *Ditylenchus dipsaci*. *IIRB Journal of the International Institute for Sugar Beet Research* **6**, 76–86.

Heijbroek, W. (1989) Interactions between pelleting material, insecticides and fungicides. *Proceedings of the 52nd IIRB Congress*. pp. 213–220.

Heijbroek, W. & Huijbregts, A.W.M. (1995) Fungicides and insecticides applied to pelleted sugar-beet seeds – III. Control of insects in soil. *Crop Protection* **14**, 367–373.

Heijbroek, W., Roelands, A.J., de Jong, J.H., van Hulst, C.G., Schoone, A.H.L. & Munning, R.G. (1988) Sugar beets homozygous for resistance to beet cyst nematode (*Heterodera schachtii* Schm.), developed from monosomic additions of *Beta procumbens* to *B.vulgaris*. *Euphytica* **38**, 121–131.

Heijbroek, W., Munning, R.G. & Swinkels, L.P.J.C. (1998) The effects of trap crops, flower mixtures and bare fallow, grown as a rotational set aside on nematodes and fungal pathogens in soil. *IIRB*. Brussels, Belgium, pp. 71–85.

Heltbech, K., Husby, J. & Hojer, P. (1999) Gaucho(R) WS-70 new high-efficacy insecticidal seed-treatment for beets. *Djf Rapport, Markburg* **10**, 237–247.

Hepp, R. & Sandoval C. (1997) Studies on yellow wilt of sugar beet (*Beta vulgaris* L. var. *saccharifera*). *Agro-Ciencia* **13** (3), 253–256.

Hermann, O., Wauters, A. & Dewar, A.M. (2001) Results of IIRB co-operative trials with insecticides in pelleted seed. *Proceedings of the 64th IIRB Congress*. Brussels, Belgium, pp. 71–85.

Hijink, M.J. & Kuiper, K. (1964) Crop rotation effects in Leguminosae due to *Meloidogyne hapla*. *Nematologica* **10**, 64.

Hill, D.S. (1987) *Agricultural Insect Pests of Temperate Regions and their Control*. Cambridge University Press.

Huijbregts, A.W.M. & Gijssel, P.D. (1989) Dosage and release patterns of insecticides and fungicides in pelleted seed. *Proceedings of the 52nd IIRB Congress*. pp. 131–143.

Hurej, M. (1986) The species composition and biology of anthomyiid flies (Diptera Anthomyiidae) occurring on sugar beet crop. *Polskie Pismo Entomologiczne* **56**, 193–207.

Hurej, J.M. & Van der Werf, W. (1993) The influence of black bean aphid, *Aphis fabae* Scop. and its honeydew on leaf growth and dry-matter production of sugar beet. *Annals of Applied Biology* **122**, 201–214.

Hurej, M., Krol, J. & Pomorski, R.J. (1994) Effects of granular insecticides or sugar-beet dressing on some sugar-beet pests and soil fauna of mites and springtails. *Polskie Pismo Entomologiczne* **63**, 183–196.

Hutchison, W.D. & Campbell, C.D. (1994) Economic impact of sugarbeet root maggot (Homoptera: Aphidiidae) on sugarbeet yield and quality in southern Minnesota. *Journal of Economic Entomology* **87** (2), 465–475.

Inserra, R.N., Vovlas, G., Griffin, G.D. & Anderson, J.L. (1983) Development of the false root-knot nematode, *Nacobbus aberrans*, on sugar beet. *Journal of Nematology* **15**, 288–296.

Jaggard, K.W. (ed.) (1989) *Sugar Beet – A Grower's Guide*. Sugar Beet Research and Education Committee, England.

Jepson, S.B. (1987) *Identification of Root-Knot Nematode* (*Meloidogyne* species). CABI Publishing, Wallingford.

Johnson, A.W. (1998) *Plant and Nematode Interactions. Vegetable Crops*. (Agronomy Series No. 36), American Society of Agronomy, Madison, 595–635.

Jones, F.G.W. & Dunning, R.A. (1972) *Sugar Beet Pests*. MAFF Bulletin 162, HMSO, London.

Jones, F.G.W. & Jones, M.G. (1984) *Pests of Field Crops*. Edward Arnold, London.

Jones, F.G.W., Dunning, R.A. & Humphries, K.P. (1955) The effects of defoliation and loss of stand upon yield of sugar beet. *Annals of Applied Biology* **43**, 63–70.

Jorritsma, J. (1985) *De teelt van suikerbieten*. Groene reeks.

Jossi, W. & Bigler, F. (1997) Occurrence and forecasting crop losses by wireworms in field crops in Switzerland. *Agrarforschung* **4**, 157–160.

Kaffka, S. & Babb, T. (2001) Pre-emergence insecticides improve seedling emergence in the Imperial Valley. *Proceedings from the 31st Biennial Meeting (Agriculture) of the American Society of Sugar Beet Technologists*. Vancouver, BC, Canada, 28 February–3 March, 2001, pp. 137–142.

Kerry, B.R. (1988) Two micro-organisms for the biological control of plant parasitic nematodes. *Proceedings of the British Crop Protection Council – Pests and Diseases*. pp. 603–607.

Kerry, B.R. (1998) Progress towards biological control strategies for plant-parasitic nematodes. *Proceedings of the British Crop Protection Council – Pests and Diseases*. 3, pp. 739–746.

Khan, M., Shahid, M. & Liaqatullah (1993) Chemical control of lepidopterous pests of sugarbeet. *Pakistan Sugar Journal* **7**, 7–10.

Kift, N.B., Dewar, A.M. & Dixon, A.F.G. (1997) The effect of plant age and infection with virus yellows on the survival of

Myzus persicae on sugar beet. *Annals of Applied Biology* **129** (3), 371–378.

Kift, N.B., Dewar, A.M., and Dixon, A.F.G. (1998a) Onset of a decline in the quality of sugar beet as a host for the aphid, *Myzus persicae. Entomologia experimentalis et applicata* **88**, 155–161.

Kift, N.B., Mellon, F.A., Dewar, A.M. & Dixon, A.F.G. (1998b) Analyses of the stomach deposit that develops in *Myzus persicae* feeding on sugar beet. *Physiological Entomology* **23**, 347–353.

Korcz, A., Olejarski, P. & Paradowska, R. (1997) Beet leaf curl in the Wielkopolska region and in Poland during 1993–1996. *Ochrona Roslin* **41**, 7–8.

Korcz, A., Olejarski, P. & Paradowska, R. (1998) The effect of Gaucho 600 FS on the beet leaf bug (*Piesma quadratum* Fieb.). *Progress in Plant Protection* **38**, 369–372.

Kornienko, A.V., Lunin, N.K., Nuzhdin, V.F., Kulikova, G.A., Ryabchinskii, A.V. & Ermokhina, I.V. (1994) Insecticides for pre-sowing treatment of seeds. *Sakharnaya Svekla* **3**, 17–18.

Krall, J.M., Koch, D.W., Gray, F.A. & Yun, LiMei. (1996) Potential of sugar beet nematode-resistant radishes and mustard for use in sugar beet rotations. *American Society for Horticultural Science*, Alexandria, USA, pp. 619–622.

Kühn, J. (1881) Die Ergebnisse der Versuche zur Ermittelung der Ursache der Rubenmüdigkeit und zur Erforschung der Natur der Nematoden. *Berichte aus landwirtschaftlichen Instituts der Universität Halle* **3**, 1–15.

Kuthe, K. (1995) Beobachtungen uber die Auswirkung verschiedener Insecktizide und Zuckerrubensaatgut auf Schadlinge und Ertrag von 1989 bis 1994 in Mittelhessen. *Gesunde Pflanzen* **47**, 139–150.

Kuthe, K. (1996) The common earwig (*Forficularia auricularia* L.), an occasional pest of sugarbeet. *Gesunde Pflanzen* **48**, 55–57.

Lane, A., Gladders, P. & Buckley, D. (2000) Pests and diseases of sugar beet. In: Alford, D.V. (ed.) *Pest and Diseases Management Handbook.* BCPC, Blackwell Science Ltd, Oxford, pp. 166–184.

Lange, W., Jung, C. & Heijbroek, W. (1990) Transfer of beet cyst nematode resistance from *Beta* species of the section *Patellares* to cultivated beet. *Proceedings of the 53rd IIRB Congress.* Brussels, pp. 89–102.

Larsson, H., Olsson, R. & Olanders, J. (1991) New cost effective cultivation techniques to improve establishment and early growth. First results from a Swedish project. *Proceedings of* the *54th IIRB Congress.* Brussels, Belgium, 20–21 February 1991, pp. 1–19.

Legrand, G. & Wauters, A. (1997) Invasion of silver Y moth caterpillars during summer 1996. *Betteravier* **31**, 42–46.

Legrand, G., Antoine, M. & Wauters, A. (1997) Presence de l'acarien jaune commun *Tetranychus urticae* Koch en culture de betterave sucrière en Belgique, en 1996 et test de sensibilité varietale de la betterave sucrière. *Mededelingen Faculteit Landbouwkundige en Toegepaste Biologische Wetenschappen Universiteit Gent*, **62**, 301–308.

Legrand, G., Demarbaix, X. & Wauters, A. (1999) Evaluation au champ de produits acaricides pour lutter contre *Tetranychus urticae* Koch en culture betteraviere en Belgique. *Mededelingen Faculteit Landbouwkundige en Toegepaste Biologische Wetenschappen Universiteit Gent*, **64**, 319–326.

Legrand, G., Wauters, A., Muchembled, C. & Richard-Molard, M. (2000) L'acarien jaune commun (*Tetranychus urticae*)(Acari: Tetranychidae) en culture de betterave sucrière en Europe: un problème nouveau. *Proceedings of the 63rd IIRB Congress.* Interlaken, pp. 245–256.

Lejealle, F. & d'Aguilar, J. (1982) Pests, diseases and disorders of sugar beet. Deleplanque et Cie, Maisons Lafitte, 167pp.

Lowe, H.J.B. & Russell, G.E. (1969) Inherited resistance of sugar beet to aphid colonisation. *Annals of Applied Biology* **63**, 337–343.

Lowe, H.J.B. & Singh, M. (1985) Glasshouse tests and field selection for heritable resistance to *Myzus persicae* in sugar beet. *Annals of Applied Biology* **107**, 109–116.

Maas, P.W.T. & Heijbroek, W. (1982) Biology and pathogenicity of the yellow beet cyst nematode, a host race of *Heterodera trifolii* on sugar beet in the Netherlands. *Nematologica* **28**, 77–93.

Maines, G., Meriggi, P., Bettini, G. & Cioni, F. (1994) Protection of the first vegetative stages of sugarbeet with the insertion of insecticide in the seed coating. *Informatore Agrario* **50**, 53–55.

Marco, V., Lopez-Olguin, J.F., Ortego, F. & Castanera, P. (1998) Restricted host range of the weevil *Aubeonymus mariaefranciscae*, a new sugar-beet pest. *Entomologia Experimentalis et Applicata* **87**, 201–207.

Meredith, R.H. & Morris, D.B. (2003) Clothianidin on sugarbeet: field trial results from Northern Europe. *Pflanzenschutz-Nachrichten Bayer* **56**, 111–126.

Meredith, R.H., Heatherington, P.J. & Morris, D.B. (2002) Clothianidin – a new chloronicotinyl seed treatment for use on sugar beet and cereals: field trial experiences from Northern Europe. *Proceedings of the British Crop Protection Council – Pests and Diseases.* 2, pp. 691–696.

Merkens, W.S.W. & Groeneweg, H. (1991) Gaucho, a new insecticide for the control of below-sea level beet beetles and aphids through treatment of sugar beet seed [Dutch]. *Gewasbescherming* **22**, 20.

Milford, G.F.J. & Lawlor, D.W. (1976) Water and physiology of sugar beet. *Proceedings of the 39th IIRB Congress.* Brussels, pp. 95–108.

Muchembled, C. (1991) Development of insecticidal treatments in beet. *Pflanzenschutz Nachrichten Bayer* **44**, 175–182.

Muchembled, C. (1999) *Tetranychus urticae* in sugarbeet crops: a new pest to watch. *Proceedings of the Fifth International Conference on Pests in Agriculture.* Paris, France, pp. 519–527.

Müller, J. (1986) Integrated control of the sugar beet cyst nematode. In: Lamberti, F. & Taylor, C.E. (eds) *Cyst Nematodes.* Plenum Press, New York and London, pp. 235–250.

Müller, J. (1992) Detection of pathotypes by assessing the virulence of *Heterodera schachtii* populations. *Nematologica* **38**, 50–64.

Müller, J. (1998) Resistance and tolerance to beet cyst nematodes (*Heterodera schachtii*) in sugar beet cultivars. *Zuckerindustrie* **123**, 688–693.

Müller, J. (1999) The economic importance of *Heterodera schachtii* in Europe. *Helminthologia* **36**, 205–213.

Nuzhdin, V.F. (1997) Agrotechnical measures against the sugarbeet leaf beetle. *Sakharnaya Svekla* **4**, 20–21.

Ohkawara, Y., Akayama, A., Matsuda, K. & Andersch, W. (2002) Clothianidin: a novel broad-spectrum neonicotinoid insecticide. *Proceedings of the British Crop Protection Council – Pests and Diseases.* 1, pp. 51–58.

Pringas, C., Scherer, J. & Koch, H.J. (2003) Fusarium, DTR and field slugs. Higher incidence in conservation soil cultivation? *Getreide Magazin* **3**, 162–165.

Proft, M. de., Ryckel, B. de., Ducat, N., Pigeon, O. & Bernes, A. (1999) Seed treatment with thiamethoxam for the protection of sugarbeet, maize and cereals against insect pests. *Mededelingen Faculteit Landbouwkundige en Toegepaste Biologische Wetenschappen Universiteit Gent* **64**, 327–341.

Qi, A., Dewar, A.M. & Harrington, R. (2004) Decision making in controlling virus yellows of sugar beet in the UK. *Pest Management Science* **60**, 727–732.

Redondo, J. & Villarias, J.L. (1991) Degâts causes par *Heterodera schachtii* en culure de la betterave sucrière en Espagne et son controle a l'aide de plantes nematicides conduites en culture derobee. *Proceedings of the 54th IIRB Congress.* Brussels, pp. 245–262.

Richard-Molard, M. (1988) Possibilities for the utilization of tefluthrin, a new insecticide efficient against subterranean pests in seed treatments. *Proceedings of the 51st IIRB Congress.* Brussels pp. 145–162.

Richard-Molard, M. (1989) Possibilités d'utilisation de la téfluthrine, nouvel insecticide efficace contre les parasites souterrains en traitment de semences. *Proceedings of the 52nd IIRB Congress.* Brussels, pp. 153–162.

Rimsa, V. (1979) Protection of emerging sugar beet in Czechoslovakia. *Proceedings of the British Crop Protection Council – Pests and Diseases.* pp. 245–250.

Roberts, P.A. & Thomason, I.J. (1981) *Sugarbeet Pest Management: Nematodes.* University of California Division of Agricultural Sciences, Special Publication 3272.

Roebuck, A. (1932) Measurements in nature; or the toll of insect and other animal pests on the farms of Lindsey during 1932. *Presidential Address to the Lincolnshire Naturalists' Union*, Transactions of the Lincolnshire Naturalists Union, November 1932, 71–81.

Rottger, U. (1979a) Untersuchungen zur Wirtswahl der Rubenfliege *Pegomya betae* Curt. (Diptera, Anthomyidae). 1. Olfaktorische Orientierung zur Wirtspflanze. *Zeitschrift fur Angewandte Entomologie* **87** (4), 337–348.

Rottger, U. (1979b) Rearing the sugar beet miner *Pegomya betae. Entomologia Experimentalis et Applicata* **25**, 109–112.

Rottger, U. & Klingauf, F. (1978) Physiological changes in sugar-beet leaves through feeding damage by *Pegomya betae* Curt. (Diptera, Anthomyidae), with their influence on oviposition in the next generation. *Mededelingen van de Faculteit Landbouwwetenschappen Rijksuniversiteit Gent* **43**, 553–567.

Salama, R.A.K. & Elnagar, S. (1992) The tortoise beetle, *Cassida vittata* Vill. (Col., Chrysomelidae), a possible pest of sugar beet plantations in Egypt. *Journal of Applied Entomology* **113**, 88–92.

Saleh, A.Y. (1994) Insecticide tests to control the tortoise beetle, *Cassida vittata* (Vill) in sugar beet crops. *Assiut Journal of Agricultural Sciences* **25**, 197–202.

Sato, M., Tamayama, A., Sugawara, H., Shinsenji, A., Kusume, T. & Tamada, T. (1995) Application of a new insecticide 'imidacloprid' to control beet flea beetle, beet leaf miner and beet western yellow virus in Hokkaido. *Proceedings of the Japanese Society of Sugar Beet Technologists.* 37, pp. 103–113.

Schacht, H. (1859) Über einige Feinde der Rübenfelde. *Zeitschrift des Vereins für die Rübenzucker-industrie im Zollverein* **9**, 175–179.

Schäufele, W.R. (1989) Wirkung von Insektiziden am Saatgut im Vergleich zu insektizider Bodenbehandlung. *Proceedings of the 52nd IIRB Congress.* Brussels, pp. 145–151.

Schlang, J. (1989) The biological control of white beet cyst nematode (*Heterodera schachtii*) by resistant catch crops. *Proceedings of the IIRB Congress.* pp. 249–265.

Schlang, J. (1990) Erstnachweis des Gelben Rübenzystennematoden (*Heterodera trifolii*) für die Bundesrepublik Deutschland. *Nachrichten blatt des Deutsches Pflanzenschutzdienstes, Braunschweig* **42**, 58–59.

Schlang, J. (1991) Organic seed-pellet amendments for control of *Heterodera schachtii. Proceedings of the IIRB Congress.* 54, pp. 197–203.

Schmeer, H.E., Bluett, D.J., Meredith, R. & Heatherington, P.J. (1990) Field evaluation of imidacloprid as an insecticidal seed treatment in sugar beet and cereals with particular reference to virus vector control. *Proceedings of the British Crop Protection Council – Pests and Diseases.* 1, pp. 29–36.

Schmuck, R. & Keppler, J. (2003) Clothianidin-ecotoxicological profile and risk assessment. *Pflanzenschutz-Nachrichten Bayer*, Bayer AG, Leverkusen, Germany, **56**, 26–58.

Scott, R.K. & Jaggard, K.W. (1985) The effects of pests and diseases on growth and yield of sugar beet. *Proceedings of the 48th IIRB Congress.* pp. 153–169.

Senn, R., Hofer, D., Hoppe, T., Angst, M., Wyss, P., Brandl, F., Maienfisch, P., Zang, L. & White, S. (1998) CGA 293'343: a novel broad-spectrum insecticide supporting sustainable agriculture worldwide. *British Crop Protection Council – Pests and Diseases.* pp. 27–36.

Sievers, H. & Ulber, B. (1990) Field tests on the effects of organic-manure applications on *Collembola* and other small arthropods, pests of seedlings in sugarbeet stands. *Zeitschrift fur Pflanzenkrankheiten und Pflanzenschutz* **97**, 588–599.

Smith, G. (2000) Sugar beet. Root maggot control with biologicals. *Sugar Journal* **62**, 14.

Smith, H.G. & Hallsworth, P.B. (1990) The effects of yellowing viruses on yield of sugar beet in field trials, 1985 and 1987. *Annals of Applied Biology* **116**, 503–511.

Smith, R., Burtch, L.M. & Thomason, I.J. (1978) The control of root-knot nematodes (*Meloidogyne* spp.) in sugarbeets by fumigant and non-fumigant nematicides. *Journal of the American Society of Sugar Beet Technologists* **20**, 48–54.

Sosnowska, D. (2001) The role of fungi in reduction of sugar beet nematode (*Heterodera schachtii* Schmidt) population. *International Organization for Biological and Integrated Control of Noxious Animals and Plants (OIBC/OILB),* *West Palaearctic Regional Section (WPRS/SROP)*, Dijon, France, **24**, 151–156.

Steudel, W. & Müller, J. (1983) Untersuchungen und Modellrechnungen zum Einfluss pflanzenverträglicher Nematizide und nematodresistenter Zwischenfrüchte auf die Abundanzdynamik des Zuckerrübennematoden (*Heterodera schachtii*) in *Zuckerrübenfruchtfolgen. Zuckerindustrie* **108**, 365–369.

Steudel, W., Thielemann, R. & Haufe, W. (1981) Untersuchungen zur Populationsdynamik des Rübenzystenälchens (*Heterodera schachtii* Schmidt) in der Köln-Aachener Bucht. Mitt. *Biol. Bundesanst. Land-Forstwirtsch.* **199**, 1–66.

Stevens, M. & Dewar, A.M. (1996) Pest and disease problems in Chile. *British Sugar Beet Review* **64** (2), 34–38.

Stevens, M., Smith, H.G., Hallsworth, P.B., Haylock, L.A., Dewar, A.M., Devine, G.J., Harrington, R., Parker, S. & Tatchell, G.M. (1994) Detection of viruses and insecticide-resistance in sugar beet aphids caught in suction traps. *Proceedings of British Crop Protection Council – Pests and Diseases.* pp. 917–922.

Stevens, M., Smith, H.G. & Hallsworth, P.B. (1995) Detection of luteoviruses, beet mild yellowing virus and beet western yellows virus, in aphids caught in sugar beet and oilseed rape crops 1990–1993. *Annals of Applied Biology* **127**, 309–320.

Stevens, M., Hallsworth, P.B. & Smith, H.G. (2004) The effects of *Beet mild yellowing virus* and *Beet chlorosis virus* on the yield of field-grown sugar beet, 1997, 1999 and 2000. *Annals of Applied Biology* **144**, 113–119.

Szilvasi, S., Mata, O., Richard-Molard, R. & Muchembled, C. (1998) L'acarien juane sur betteraves un ravegeur de plus en plus remarquable. *Phytoma* **502**, 21–22.

Szymczak-Nowak, J. & Wasacz, E. (1998) Effectiveness of the insecticide Decis Prime 415 EC in the protection of sugar-beet. *Progress in Plant Protection* **38**, 501–504.

Tacconi, R. & Venturi, G. (1991) Agronomic methods for controlling the nematode *Heterodera schachtii* in Italy. *Proceedings of the IIRB Congress* **54**, 221–243.

Thomas, T.H. (1991) Sugar beet biotechnology. *British Sugar Beet Review* **59** (3), 5–7.

Tossens, H., Schoonejans, T., Sysmans, J., D'Hollander, R., Vermeulen, R. & Vincinaux, C. (1992) Etude de l'insecticide systemique imidacloprid en traitement des semences de betteraves sucrieres en Belgique en 1991. *Mededelingen van de Faculteit Landbouewwetenschappen, Rijksuniversiteit Gent*, **57**, 759–773.

Valloton, R. (1985) Première observation en Suisse de la 'forme spécialisée Betterave' du nématode à cyste *Heterodera trifolii* Goffart. *Revue suisse Agriculture* **17**, 137–140.

Varis, A.L. & Rautapaa, J. (1978) Mangold fly: predicting damage and the economics of control. *Annales Agriculturae Fenniae* **17**, 103–107.

Villeroy, P. & Pourcharesse, P. (1975) Development and use of Curaterr in France in recent years. *Pflanzenschutz-Nachrichten Bayer* **28**, 55–66.

Vincinaux, C., Tossens, H., Sysmans, J. & Vermeulen, R. (1992) Experimentation on sugarbeet seed treatment in 1992 with imidacloprid, a new insecticide of the nitroguanidine group. *Parasitica* **48**, 173–185.

Waters, J., Denholm, I., Harrington, R., Foster, S., Parker, S. & Dewar, A.M. (2004) Wielding the MACE – recent events regarding resistance and the peach potato aphid, *Myzus persicae. British Sugar Beet Review* **72** (1), 28–32.

Wauters, A. (1993) Rapport de l'imidacloprid comme traitement de semences en culture betteraviere en Belgique. *Mededelingen van de Faculteit Landbouwwetenschappen Universiteit Gent*, **58**, 641–651.

Wauters, A. & Dewar, A.M. (1996) The effect of insecticide seed treatments on pests of sugar beet in Europe: results of the IIRB co-operative trials with pesticides added to pelleted seed in 1991, 1992 and 1993. *Parasitica* **51** (4), 143–173.

Wauters, A. & Legrand, G. (1996) Invasion of caterpillars of the silver Y moth during the summer of 1996 (French). *Betteravier (Bruxelles)* **30** (320), 13–14.

Werker, A.R., Dewar, A.M. & Harrington, R. (1998) Analysis of virus yellows incidence in sugar beet in relation to migrations of the vector, *Myzus persicae. Journal of Applied Ecology* **35**, 811–818.

Westwood, F., Bean, K.M. & Dewar, A.M. (1994) The effect of pellet weight on the distribution of imidacloprid applied to sugar-beet pellets. In: Martin, T.J. (ed.) *Seed Treatment: Progress and Prospects.* BCPC Monograph No. 57, pp. 403–408.

Westwood, F., Dewar, A.M., Bean, K.M. & Haylock, L.A. (1997) Persistence of the selective aphicide triazamate in sugar beet in relation to its efficacy against aphids. *Proceedings of the 60th IIRB Congress.* Cambridge, UK, July 1997, pp. 585–588.

Whitehead, A.G., Fraser, J.E. & Nichols, A.J.F. (1987) Variation in the development of stem nematodes, *Ditylenchus dipsaci*, in susceptible and resistant crop plants. *Annals of Applied Biology* **111**, 373–383.

Whitney, E.D. & Duffus, J.E. (1986) *Compendium of Beet Diseases and Insects.* The American Phytopathological Society, MN.

Williams, C.T. (1995) Effects of plant age, leaf age and virus yellows infection on the population dynamics of *Myzus persicae* (Homoptera: Aphididae) on sugar beet in field plots. *Bulletin of Entomological Research* **85**, 557–567.

Williams, I.S., Dewar, A.M. & Dixon, A.F.G. (1997) The effect of host-plant induced stomach precipitate on the ability of *Myzus persicae* (Sulzer) (Hemiptera: Aphididae) to transmit sugar-beet yellowing viruses. *Bulletin of Entomological Research* **87**, 643–647.

Williams, I.S., Van der Werf, W., Dewar, A.M. & Dixon, A.F.G. (1999) Factors affecting the relative abundance of two co-existing aphid species on sugar beet. *Agricultural and Forest Entomology* **1**, 119–125.

Winder, G.H. & Dunning, R.A. (1986) Effects of row application of insecticides at sowing on leaf miner (*Pegomya betae*) injury to sugar beet. *Crop Protection* **5**, 109–113.

Winder, G.H., Dewar, A.M. & Dunning, R.A. (1993) Comparisons of granular pesticides for the control of soil-inhabiting arthropod pests of sugar beet. *Crop Protection* **12**, 148–154.

Winter, S.R. (1999) Root infestation relationship to agronomic performance and field position in furrow irrigated sugarbeet cultivar comparisons. *Journal of Sugar Beet Research* **36** (1/2), 1–13.

Wisler, G.C. & Duffus, J.E. (2000) A century of plant virus management in the Salinas valley of California, 'East of Eden'. *Virus Research* **71**, 161–169.

Yu, M.H. (1995) Identification of a *Beta maritima* source of resistance to root-knot nematode for sugarbeet. *Crop Science* **35**, 1288–1290.

Yu, M. & Lewellen, R.T. (2004) Registration of root-knot nematode-resistant sugarbeet germplasm M6–2. *Crop Science* **44**, 1502–1503.

Yu, M., Heijbroek, W. & Pakish, L.M. (1999) The sea beet source of resistance to multiple species of root-knot nematode. *Euphytica* **108**, 151–155.

Chapter 14

Weeds and Weed Control

Mike J. May and Robert G. Wilson

INTRODUCTION

Weeds have been a major problem in sugar beet since the crop was first grown in the late 1700s. At the end of the eighteenth century, Achard (1799) was already stressing the need to control weeds before the crop was sown. He also noted that once sugar beet was clear of competition from early-emerging weeds it would grow vigorously and smother weeds that germinated later. Modern weed control recommendations are still based on Achard's observations that sugar beet plants need to gain an advantage over weeds early in the season. Although tractor hoeing and hand labour are still used in many production areas, herbicides have been the primary method of weed control in sugar beet since the early 1950s (Schweizer & Dexter, 1987).

This chapter deals primarily with the principles of weed problems and weed control in sugar beet. However, the biology and ecology of major weeds in sugar beet is dealt with to the extent that they are relevant to control. Readers interested in weed biology and weed ecology are referred to the excellent works of Aldrich (1984), Gwynne and Murray (1985), Hill (1977) and Radosevich and Holt (1984).

WEEDS

Distribution and agricultural importance

Unlike insects, diseases and nematodes, weeds occur in all sugar beet fields every year, usually at populations that cause crop failure unless controlled (Jansen, 1972). Throughout the world, approximately 250 plant species have become important weeds and about 60 of these are found in the main sugar beet production regions. Approximately 70% of weeds found in sugar beet crops are broad-leaved species and 30% are grass species. Usually fewer than ten important species of weeds infest sugar beet crops on any given farm.

Two perennial weeds, *Elytrigia repens* (Fig. 14.1) and *Convolvulus arvensis*, and ten annual weeds comprise the list of major weeds in the world's sugar beet fields (Holm *et al.*, 1977). The annual broad-leaved weeds are *Amaranthus retroflexus, Chenopodium album, Matricaria recutita, Polygonum aviculare, Fallopia (Polygonum) convolvulus, Sinapis arvensis* and *Stellaria media*; annual grasses are *Echinochloa crus-galli, Poa annua*, and *Setaria viridis. C. album*, a species belonging to the same family as sugar beet, is one of the most frequently reported weeds in this crop, and sugar beet itself (growing either from groundkeepers or from seeds shed by bolters) can be a major weed problem. A more detailed list of important problem weeds is given in Table 14.1.

Biology of major weeds

Seed banks

Seed banks are reservoirs of weed seeds that may, under favourable conditions, germinate and emerge to compete with the sugar beet crop. Most agricultural soils contain large reservoirs of weed seeds, ranging from 4100 to 137 700 seeds/m^2 (Wilson, 1987; Squire *et al.*, 2003). The number and composition of weed seeds in soils vary greatly but are closely associated with climatic factors, edaphic characteristics, cropping, cultivation (tillage) and weed management practices. However, seed banks

Fig. 14.1 Sugar beet crop infested with couch grass (*Elytrigia repens*).

do have a number of similarities. Generally they are made up of numerous species, although several species may comprise 70–90% of the total seed bank (Milton, 1943). This large set may be followed by a second smaller subset of species that may comprise 10–20% of the seed reserve. A final group, accounting for only a small percentage of the total seed reserve, consists of species that are remnants of past crops (Wilson *et al.*, 1985).

Although separated by 100 km, similar seed banks have developed in Colorado and Nebraska in agricultural areas where maize (*Zea mays* L.), dry edible bean (*Phaseolus vulgaris* L.) and sugar beet were grown in rotation (Schweizer & Zimdahl, 1984; Wilson *et al.*, 1985). The dominant species in Colorado were *C. album* and *A. retroflexus*, which together accounted for 86% of the weed seed in the soil. In Nebraska, the same two species accounted for 76% of the seed bank. The second subgroup in Colorado included *Portulaca oleracea, S. viridis, Setaria glauca*, and *F. convolvulus*, which together comprised 13% of the seed bank. In Nebraska, the second subgroup was represented by *S. glauca, E. crus-galli, P. oleracea*, and *Solanum sarrachoides* and made up 22% of the seeds in the soil. These two groups together made up 99 and 98% of the seed bank in Colorado and Nebraska, respectively.

The depth of seed burial and the amount and intensity of soil cultivation are important in seed longevity. This point can be illustrated by examining the seed longevity of *C. album*. In the Burnside *et al.* (1996) experiment, *C. album* seeds germinated at a rate of 28% after burial for 17 years in undisturbed soil. In a second study, *C. album* seedling emergence was 9% after 6 years of burial in cultivated soil and 53% after 6 years of burial in undisturbed soil (Roberts & Feast, 1973).

Only a portion of the weed seed in the seed bank germinates and produces seedlings each year. In a study conducted over 22 site-years across the Midwest of the USA, average emergence each growing season ranged from 31% for *Setaria faberi*, 25% for *Kochia scoparia*, 15% for *Ambrosia artemisiifolia*, and 3% for *C. album* (Forcella *et al.*, 1997). Emergence percentages of summer annual weeds were not static from one year or site to the next. Instead, they changed annually in response to differences in soil temperature and soil moisture. For example, total seasonal emergence percentage of *S. faberi* was related positively to the first date at which average daily soil temperature at 5–10 cm soil depth reached 16°C. Thus, if the soil warmed before mid-April, secondary dormancy was induced and few seedlings emerged, whereas many seedlings emerged if the soil remained cool until June. Other species also react to soil temperature.

Many annual weed species have well-defined periods of emergence (Egley, 1986). For example, *A. retroflexus* and *C. album* have major peaks of emergence from mid-spring until early summer

Table 14.1 Common and scientific names of the most important problem weeds in sugar beet mentioned in this chapter.

Scientific name	Common name(s)
Abutilon theophrasti Medic	Velvetleaf
Agropyron repens (L.) Beauv (see *Elytrigia repens*)	
Amaranthus powellii S. Wats.	Powell amaranth
Amaranthus retroflexus L.	Common amaranth, redroot pigweed
Ambrosia artemisiifolia L.	Common ragweed
Avena fatua L.	Wild-oat
Bilderdykia convolvulus (see *Fallopia convolvulus*)	
Brassica napus L.	Rape, wild buckweed
Chamomilla suaveolens (L.) Rauschert (see *Matricaria discoidea*)	
Chenopodium album L.	Common lambsquarters, fat-hen
Cirsium arvense (L.) Scop.	Canada thistle, creeping thistle
Convolvulus arvensis L.	Field bindweed
Datura stramonium L.	Jimsonweed, thorn-apple
Echinochloa crus-galli (L.) Beauv.	Barnyardgrass, cockspur
Elymus repens (L.) Gould (see *Elytrigia repens*)	
Elytrigia repens (syn.) *Elymus repens; Agropyron repens*	Common couch, quackgrass, twitch
Fallopia convolvulus (L.) A. Löve (syn) *Bilderkykia convolvulus; Polygonum convolvulus*	Black bindweed, wild buckwheat
Galium aparine L.	Common cleaver, goosegrass
Helianthus annuus L.	Common sunflower
Kochia scoparia (L.) Schrad.	Kochia
Matricaria chamomilla L. (see *Matricaria recutita*)	
Matricaria discoidea (syn.) *Chamomilla suaveolens*	Pineappleweed
Matricaria recutita (syn.) *Matricaria chamomilla*	False chamomile, mayweed
Persicaria lapathifolium (syn.) *Polygonum lafathifoluim*	Pale persicaria
Persicaria maculosa (syn.) *Polygonum persicaria*	Ladysthumb, redshank
Physalis spp.	Groundcherries
Poa annua L.	Annual meadow-grass
Polygonum aviculare L.	Knotgrass, prostrate knotweed
Polygonum convolvulus L. (see *Fallopia convolvulus*)	
Polygonum lapathifolium L. (see *Persicaria lapathifolia*)	
Polygonum persicaria L. (see *Persicaria maculosa*)	
Polygonum spp.	Smartweeds, polygonum
Portulaca oleracea L.	Common purslane
Setaria faberi Herrm.	Giant foxtail
Setaria glauca (L.) Beauv.	Yellow foxtail
Setaria spp.	Foxtails, bristle-grass
Setaria viridis (L.) Beauv.	Green foxtail, green bristle-grass
Sinapis arvensis L.	Charlock, wild mustard
Solanum sarrachoides Sendtner	Hairy nightshade
Solanum tuberosum L.	Potato
Sonchus arvensis L.	Perennial sow-thistle
Sorghum halepense (L.) Pers.	Johnsongrass
Stellaria media (L.) Vill.	Common chickweed
Viola arvensis Murr.	Field pansy, field violet

whereas, *F. convolvulus* has a major peak of emergence from late spring until midsummer (Hill, 1977). The time of emergence of weeds in sugar beet fields plays a key role in the type of weed management programmes that must be employed (see Table 14.3).

Depth of seed burial affects germination and emergence in several ways. Seeds of 12 weed species were buried and emergence was greater from a 1 cm depth than from a depth of 20 cm (Van Rijn, 1969). Seedlings from larger seeds were generally able to emerge from greater depths.

In cultivated soils the majority of the seeds are in the upper 15 cm of soil, but they may be found throughout the cultivated depth of soil (Idris & Beshir, 1979). Wicks and Somerhalder (1971) compared the distribution of seeds in the soil profile following different methods of seedbed preparation. The first seedbed method consisted of tandem discing, ploughing, and sowing. This method left weed seed distributed in the upper 30 cm of soil, with 25% of the seeds in the upper 0–7 cm (Fig. 14.2). A second method was a reduced-tillage system called ridge sowing, which consisted of sowing maize along the previous year's maize row. Reduced tillage of the soil left 50% of the weed seeds in the upper 0–7 cm of the soil, compared to the extensively tilled soil where seeds were distributed fairly evenly through the upper 30 cm of soil. As the intensity of tillage declines, the seed bank moves closer to the soil surface. Seeds are then in a better position to germinate and interfere with crop production. Design of sowing and weed control systems in sugar beet that capitalize on the shallow seed bank can improve the effectiveness of cropping systems.

It is important to design weed management programmes that limit the renewal of seed banks. Programmes incorporating the most suitable crop rotations, herbicides and cultivation (tillage) practices play an important role in limiting the number and diversity of seeds in the seed bank. Schweizer and Zimdahl (1984) showed that the seed bank of annual weeds can decline by 96% over a 6-year period when crops are grown in rotation and efficacious herbicides are employed. An intensive system of weed management must be employed for 2–4 years where a large weed seed bank exists, but once the weed seed bank has been reduced to a low level it can be kept low with the continuous use of a moderate amount of herbicides and cultivation (tillage). However, this can sometimes conflict with environmental interests where diverse weed seedbanks are considered important for maintenance of weed populations in their own right and as a source of food for higher animals.

Seed production

Weed species that infest sugar beet fields vary greatly in their potential seed production capacity. Some examples of the potential seed production per plant are 250 for *Avena fatua*, 117 400 for *A. retroflexus*, 72 450 for *C. album*, and 7160 for *E. crus-galli* (Stevens, 1932). The actual production per plant varies greatly from year to year and depends upon factors such as interspecific and intraspecific competition, environmental conditions, the suppressive effect of herbicides and the time of emergence. In practice, weed management

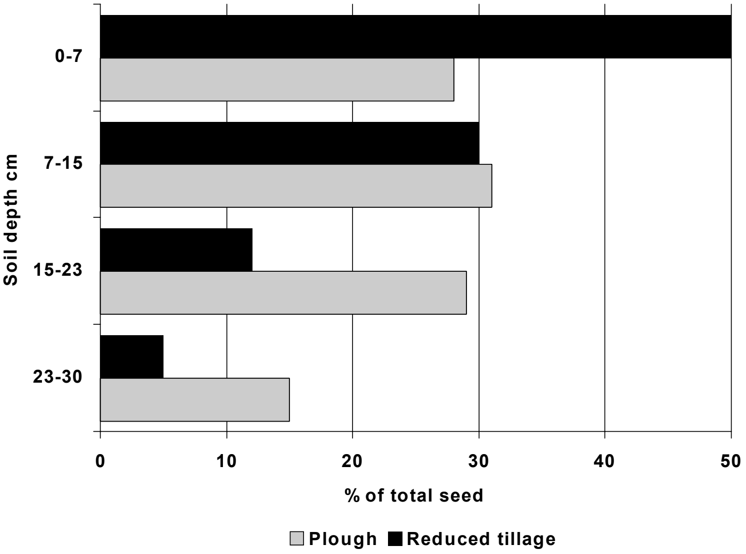

Fig. 14.2 Distribution of weed seed in the soil at different depths after seedbed preparation with a disc-plough and reduced tillage system. (Adapted from Wicks & Somerhalder, 1971.)

programmes curtail the reproductive capacity of weeds, but can never completely prevent seed production because some weeds always escape. In the future, weed seed production per unit area is more likely to increase than decrease as more emphasis is placed on organic farming, reduced-input (sustainable) agriculture and weed/crop bioeconomic modelling. In addition, it is possible that, as part of agro-environment schemes, weed refugia may be required in some European countries (Pidgeon *et al.*, 2004).

The longevity of the seed bank is dependent on the percentage of seeds that germinate and the number of weeds that produce seeds. If the rate of decay is 50% per year and no weeds produce seeds, the number of viable seeds decreases to about 2% of the original population after 6 years. If 98% of the seeds are induced to germinate each year this decline in seed population is reached after the first year, and if this rate of germination continues for 6 years without any further seed production, all seeds would be eliminated from the soil (Ennis, 1977). Clearly, increasing the rate of germination, coupled with prevention of seed production, can shorten the time needed to reduce weed populations to non-competing levels and require a balance between the reduction in inputs and leaving some natural weed seeds in the soil. Whilst farmers might tolerate some weeds if they are not causing an economic loss, there is still the old adage of '1 year's seeding, 7 years' weeding' to consider.

Effect of weeds on wildlife

Although weeds are a problem to farmers, in many countries they are also important as food and habitats for wildlife such as invertebrates, mammals and birds. In the UK, government funded Farm Scale Evaluations of genetically modified herbicide-tolerant crops showed that conventional sugar beet was an important crop for replenishment of the seed bank with seeds of spring germinating species (Heard *et al.*, 2003).

Weeds in sugar beet, especially spring germinating broad-leaved species, are a source of food for invertebrates. Groups such as Collembola may eat sugar beet seedlings depending on the availability of alternative food sources (Ulber, 1980). Although weeds are less attractive than beet to the Collembola, damage to beet seedlings was greatly reduced when there were high numbers of weeds close to the beet plants. High weed populations reduce the incidence of crop pests such as aphids (Bosch, 1987; Hani *et al.*, 1990; Dubois *et al.*, 1993). It is suggested that this can be the result of increases in the numbers of aphid antagonists, such as carabid beetles and entomophthoralean fungi (Hani *et al.*, 1990). Aphid colonization may also be reduced by a camouflaging effect of the weeds on crop plants, which makes it harder to distinguish the crop, or by olfactory confusion (Dewar *et al.*, 2003). Lower numbers of aphids can result in a decrease in the incidence of virus yellows (Hani *et al.*, 1990; Ammon *et al.*, 1996) by up to one-third (Dubois *et al.*, 1993).

Weeds may benefit birds either directly or indirectly through their effects on invertebrates. Certain birds can become pests if they graze beet seedlings, e.g. skylarks (*Alauda arvensis*) (Green, 1980). Increasing weed density reduces the tendency for skylarks to graze beet seedlings but, in the absence of other food sources, single fields with high weed populations could attract a concentration of skylarks, with a consequent increase in crop damage (Green, 1980). Other birds that graze beet include pigeons (*Columba palumbus*) and pheasants (*Phasianus colchicus*), whilst rabbits (*Oryctolagus cuniculus*) and hares (*Lepus europaeus*) also cause local damage to the foliage. Mice (*Apodemus sylvaticus*) will eat beet seed prior to its germination and in dry years, when germination is slow, damage can be severe. There is no published evidence to suggest that mice damage may be reduced by weed presence, but some agronomists believe that cover crops present at high densities can reduce the speed at which mice find seed and thereby reduce crop damage.

Not all birds use the centres of fields and some such as the yellowhammer (*Emberiza citrinella*) and grey partridge (*Perdix cinerea*) prefer the edge of fields. However, the French partridge (*Alectoris rufa*) and the skylark use the centre of the fields for foraging and nesting (Robinson & Sutherland, 2002). Arable fields are important sources of food for chicks in the form of invertebrates (Sotherton, 1992) and the number of invertebrates is related to weed presence (Dewar *et al.*, 2003).

WEED COMPETITION AND THE EFFECT OF TIME OF REMOVAL

Weeds compete with the sugar beet crop for light, nutrients and water resources. In rain-fed and irrigated geographical regions where soil water is ample and nutrients are plentiful, light becomes the prime factor around which competitive forces develop (Zimdahl, 1980; Werker & Jaggard, 1998). The most competitive are annual weeds, mostly broad-leaved species that emerge with, or shortly after, the crop, grow taller than the crop and produce dense shade. These weeds often grow to a height two to three times that of sugar beet by midsummer. Consequently, as the density of these weeds increases, light becomes more limited and root yields decrease. Figure 14.3 shows a sugar beet crop following completion of the weed control programme, where competition has not and will not reduce yield.

The extent of the decrease is dependent upon competitive ability, weed density and the length of time that weeds compete with the crop. A severe infestation present for the entire growing season may result in complete crop loss if no control measures are employed. Competition from uncontrolled annual weeds that emerge within 8 weeks of sowing or within 4 weeks of the crop reaching the two-leaf stage can reduce root yields by 26–100% (Schweizer & Dexter, 1987). Weeds that emerge 8 weeks after sowing, and particularly after the sugar beet plants have eight or more leaves, are less likely to affect yield (Scott *et al.*, 1979). Scott *et al.* (1979) estimated that once sugar beet reached the four- to six-leaves stage, weeds could reduce yields by about 1.5% per day for the next 6 weeks.

The fact that yield losses increase as weed numbers increase is self-evident. What is surprising is the low weed populations that decrease yield. Even though growers spend considerable time and money on controlling weeds, 1–5% of weeds that germinate usually survive to compete with the crop. Densities of single species of broad-leaved weeds as low as 1–12 plants/30 m of row that compete all season can reduce root yields by 6–12%; similar densities of mixed populations of weeds can reduce root yields by 11–24% (Schweizer & Dexter, 1987). Weed beet at densities of only 1 plant/m^2 can reduce root yields by 11% (Longden, 1989).

Integrated weed management systems must be implemented in order to minimize weed competition and optimize crop production and net revenues. To achieve these goals, thresholds for specific weeds and weed complexes need to be defined. Thresholds have many different interpretations and definitions (Cousens *et al.*, 1985) but they can provide information for the grower on the weed

Fig. 14.3 A sugar beet crop following completion of weed control programme.

density that must be reached before there is an economic effect. There are many considerations to be borne in mind when determining threshold values, including the effect of weeds on the yield and/or quality of the crop, seed returns to the seed bank, and cost of treatment (Cousens, 1986). Prediction of the effects of given weed populations would assist producers in making decisions on the optimum level of weed control inputs. Predictive equations to estimate yield losses in sugar beet based on weed numbers have been derived only for weed species that compete with the crop all season. *Helianthus annuus* was found to be three times more competitive than *Chenopodium album* (Fig. 14.4) and *Kochia scoparia*, and five times more competitive than *Amaranthus powellii* and *Abutilon theophrasti* (Schweizer & Lauridson, 1985). Weed numbers are less related to root yield when weeds have been treated with herbicides, and their growth has been suppressed during the growing season (Schweizer, 1981). Nevertheless, the identification and counting of seedling weeds does provide a simple and quick method of assessing the potential reduction in yield of a given weed problem.

Data on the effect of competition duration on sugar beet yield losses caused by the presence of weeds at different times provide a basis for specifying required periods of weed control. In the USA, weed problems in sugar beet are often divided into three distinct periods (Dawson, 1974). Period I occurs from sowing to thinning (when multigerm or close-spaced beet are thinned to the final stand), period II from thinning until the last cultivation or lay-by (the last time that a tractor can travel between sugar beet rows without damaging the plants), and period III after lay-by. These three periods occur in every production region, but specific dates and duration vary according to local conditions and practices. Weeds emerge in all three periods in production areas that are irrigated, but they may not emerge in all three periods in unirrigated areas. Control in one period may not affect the weeds that emerge in other periods, unless control is extended by herbicides that persist in the soil for more than one period or by cultivations which may stimulate weed emergence. In northern Europe and the USA, where most crops are grown from monogerm seed, sown to a stand and not thinned, weed management programmes are generally based upon early control of weeds (period I above) with much less emphasis on later control. Sequential herbicide treatments are used so that applications are normally affected by previous treatments.

Weed control is most difficult in period I because small sugar beet seedlings have a low tolerance to herbicides and are easily covered with soil by culti-

Fig. 14.4 *Chenopodium album* is very competitive with sugar beet.

vation. During period II, the sugar beet plants are larger and tolerate some mechanical and chemical weed control methods that cannot be used in period I. Weeds within the row constitute the major problem in periods I and II; weeds between the rows are easily controlled by cultivation. In period III, the sugar beet plants are large enough to suppress newly emerging weeds as long as the sugar beet stand is complete and vigour is normal (Dawson, 1965). Control measures are needed during period III only if the stand is incomplete or sugar beet plants lack normal vigour. Pernicious or perennial weeds may also require control during this period.

However, the ability to apply weed control methods at the so-called 'critical period' (i.e. when the removal of weed competition has the most beneficial effect on crop yield) may be limited. If weed control is to be achieved with hand labour, then growers are dependent only on the availability of labourers. However, if weed control is to be achieved primarily with herbicides, then post-emergence herbicides have to be applied at the proper growth stages of the crop and weeds, and these growth stages may not coincide with the 'critical period'. Moreover, other considerations such as the need to ensure freedom from weeds to permit efficient mechanized harvesting or prevent weed seed shed that may affect following crops, may call for a standard of weed control more rigorous than that needed simply to avoid a yield loss.

Perennial weeds such as *Cirsium arvense, Convolvulus arvensis*, *Sonchus arvensis*, and *Elytrigia repens* often infest sugar beet fields (Sullivan & Fischer, 1971). These weeds can reduce yields but their overall impact in most fields is limited because they usually are confined to small areas where their growth and development is held in check by cultivations until the crop canopy begins to close.

WEED CONTROL

Physical methods

Hand labour

When Achard (1799) wrote his first manuals for growing sugar beet the main methods used for weed control were hand pulling and hand hoeing. Hand pulling was deemed necessary when the crop was small and frail, and hand hoeing was used only after the crop had become firmly established. Hand hoeing was an essential part of sugar beet growing until monogerm seed was introduced in the 1960s. With monogerm seed there was no need to single sugar beet and, as herbicides became available and the cost of labour increased, growers in many countries relied less and less on hand hoeing as a means of weed control. Monogerm seed meant that extra care had to be taken when removing weeds that were growing very close to sugar beet plants because there was only one sugar beet plant per station and its loss would leave a large gap between plants; hand weeding ('finger weeding') was essential. However, monogerm seed did allow long-handled hoes rather than short hoes to be used much of the time. In countries or areas where labour is plentiful and cheap, hand work can still be economically viable and is still utilized (Villarias Moradillo, 1986; Schweizer & Dexter, 1987). In many countries, especially those of northern Europe, hand hoeing is an expensive practice, but it is still important on smaller holdings where family labour has a low cash cost to the grower. Hand hoeing is normally used in conjunction with tractor hoeing (cultivation) and herbicides but may be used alone where hand labour is relatively cheap. However, weather often influences the amount of hand labour that is used for weed control in the crop. If the activity of herbicides is reduced so that they are not completely effective, then manual weed control is often required (Neururer, 1985). However, this is less common in current day beet crops.

Hand labour (Fig. 14.5) is still important for the control of weed beet or bolters and, with low infestations, hand pulling is recommended and used in many countries. An alternative is to cut weed beet at soil level with a sharp spade or similar tool. When carrying out this operation before weed beet have set seed, the usual method is to pull and leave the plants in the field. Later in the season when plants begin setting seed, weed beet plants must be carried from the field (Longden, 1987).

Mechanical cultivation (tillage)

In the mid-nineteenth century Fühling (1859) referred to the use of mechanical hoes for cultivating sugar beet. These were horse-drawn (Fig. 14.6) or

Fig. 14.5 Hand hoeing and finger weeding.

ox-drawn implements that tilled the soil between the rows. Hoeing between sugar beet plants in the row and hand pulling weeds that grew too close to sugar beet plants was still necessary. However, even during the latter half of the nineteenth century, using hand labour on large areas of sugar beet was a problem because labour was in short supply (Werner, 1888).

One early cultivation method that was used for weed control in sugar beet was the stale seedbed technique. In this, a field was cultivated well before the crop was sown and then, prior to sowing the crop, the field was cultivated again to kill weeds. This technique provided some degree of weed control but is seldom used at present because it can adversely affect the seedbed, is costly and delays sowing. In countries such as the USA and in northern Europe, growers recognize that sugar beet will yield better from early sowing as long as the risk of cold periods that may kill seedlings or induce bolting of the crop plants is past. They therefore prefer to sow at the earliest opportunity, rather than make a stale seedbed. In countries where there is less pressure to sow early and soil conditions are

Fig. 14.6 A horse-drawn hoe.

good or where crops are grown organically, stale seedbed techniques can be very useful in reducing weed populations in the ensuing crop.

The use of a furrow press with the plough has become popular on lighter soils in many countries. This method leaves a form of stale seedbed that can allow the use of a pre-sowing or post-sowing contact herbicide to control early-germinating weeds prior to emergence of sugar beet seedlings.

Seedbed cultivations have a great effect on weed emergence. Cultivations make the seedbed finer (i.e. with smaller clods), and therefore more weeds emerge than from coarser seedbeds, but if the seedbed is too coarse, sugar beet emergence will also be reduced (Terpstra, 1986; see also Chapter 6). Any control method (cultivation or chemical) is more effective on small weeds than large weeds so several techniques can give effective control prior to sugar beet emergence. In most countries straight-tined harrows are used to control weeds in sugar beet seedbeds because their tines do not dig deeply into the soil. Although other tine configurations, such as the spring tooth harrow, control weeds better (Neururer, 1977) they may penetrate the seedbed too deeply, causing it to dry out and therefore result in decreased plant establishment (see Chapter 6).

Until the 1970s, the use of mechanical hoes (initially drawn by horses or oxen and later by tractors) was essential in most countries to kill weeds between sugar beet rows. Today, tractor-mounted hoes are still important in most sugar beet-producing countries. Tractor hoes are used:

- where herbicides have been sprayed in bands over the rows, and weeds between the rows still need to be controlled;
- to replace a late herbicide application, especially when weed infestations are low or some weeds are too far advanced to be properly controlled by the herbicide;
- to control difficult weeds such as weed beet and perennials; and
- to provide ditches for furrow irrigation.

The majority of hoes use fixed blades, although some use rotary blades that chop up and kill larger weeds. Powered rotary cultivators have a much slower work rate and a higher maintenance cost. Guards, discs ('cut aways') or long-nosed blades must be used early in the season to avoid smothering sugar beet seedlings with soil. However, the seedlings must not be left in a 'ridge' because of the risk of their drying out or being 'strangled' by the wind. The guards or discs need to be removed as soon as the seedlings are large enough, otherwise they will damage the older plant leaves. The tractor should be fitted with narrow wheels whenever soil conditions allow so that soil compaction near the growing roots is minimized.

Matching the hoe to the number of rows sown by the drill is essential to avoid removal of whole rows of sugar beet that do not match up properly. The exception can be where modern accurate GPS (global positioning systems) are used on drills and hoes. Increases in the width of drills have led to the development of wider hoes. This, plus the desire to travel faster, led to the development of self-steered hoes. The most common system of self-steerage is to fit a marker tine on the drill, which leaves a groove in the soil. The tractor hoe, and band sprayer when used, is fitted with a special flanged wheel that follows this groove, thus steering the hoe. Self-steered systems are able to travel at much faster forward speeds, typically 8 km/h compared with 3.5 km/h for the traditional manually steered ones (McClean & May, 1986). Other techniques rely on vision guidance and many modern systems are able to guide hoes even when some parts of the rows are missing (Tillett & Wiltshire, 2001) (Fig. 14.7).

With the advent of sugar beet tolerant to herbicides such as glyphosate and glufosinate-ammonium, there may not be a need to cultivate for weed control. Cultivation when no weeds were present had no effect on sugar beet root yield or sucrose content (Dexter *et al.*, 1999; Wilson & Smith, 1999) (Fig. 14.8). Extractable sucrose was similar between weed-free glyphosate and glufosinate-ammonium tolerant sugar beet cultivated zero, two, or five times during the growing season (Dexter *et al.*, 1999).

Chemical methods

Introduction of herbicides

The need for chemical methods of weed control became apparent as growers found it increasingly

Fig. 14.7 A tractor hoe fitted with vision guidance system (© *British Sugar Beet Review*).

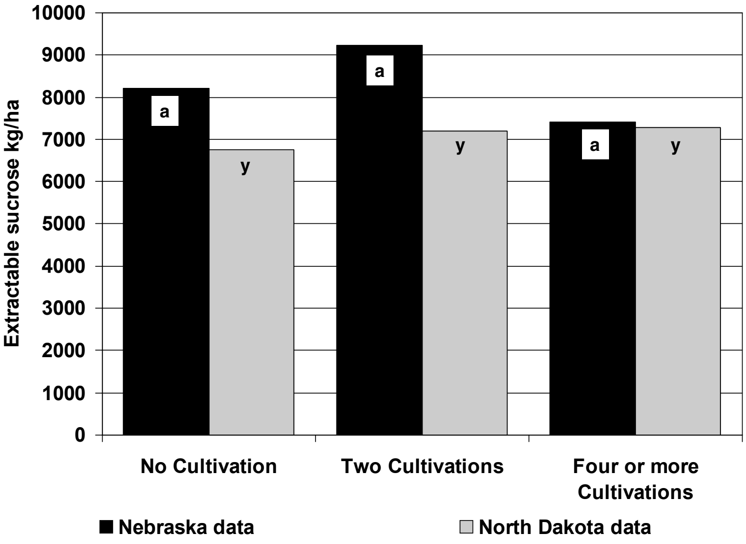

Fig. 14.8 Influence of early season cultivation on weed-free sugar beet extractable sucrose yield. Data with same letter = no significant difference (*P* = 0.05 (Data from Dexter *et al*., 1999 and Wilson & Smith, 1999).

difficult to obtain hand labour in the late nineteenth century. One of the earliest recorded uses of chemicals for weed control in sugar beet was the application of sulphuric acid in France during the 1890s (Guedon, 1928). Von Unwerth (1899) reported successful trials in Silesia using iron sulphate for weed control, although Schultz (1899) found that this chemical damaged sugar beet. Over the years there have been numerous references to the use of inorganic chemicals for weed control in sugar beet but, as with iron sulphate, many of these materials were not entirely successful. However, calcium cyanamide was used as a pre-sowing treatment for weed control (Markus, 1940). The development and use of organic herbicides was precipitated by the shortage of manual labour in the late 1930s. Pentachlorophenol (1937), propham (1946), endothal (1951) and dalapon (1954) were some of the first organic chemicals used for pre-emergence weed control in sugar beet.

In the 1960s, a number of new herbicides was evaluated for controlling weeds in sugar beet, including chloridazon (pyrazon), chlorpropham, cycloate, desmedipham, di-allate, EPTC, pebulate, phenmedipham, TCA and trifluralin. In the 1970s, diclofop-methyl, diethatyl, ethofumesate, and metamitron became available. In the 1980s, most new sugar beet herbicides were graminicides. A sulfonylurea herbicide triflusulfuron-methyl was introduced followed by other novel herbicides such as metolachlor, quinmerac, dimethenamid and clomazone. A list of the major herbicides, their uses, and the type of weeds they control is given in Table 14.2.

Table 14.2 Herbicides used in sugar beet.[1]

Herbicide	Weed type controlled
Herbicides used pre-drilling, foliar applied:	
Dalapon	grass weeds
Glufosinate-ammonium	perennial and annual grass and broad-leaved weeds
Glyphosate	perennial and annual grass and broad-leaved weeds
Paraquat	annual grass and broad-leaved weeds
Diquat (usually used with paraquat)	annual broad-leaved weeds
Herbicides used pre-drilling, incorporated:	
Chloridazon (pyrazon)	annual broad-leaved weeds
Cycloate	annual grasses and broad-leaved weeds
Di-allate	*Avena fatua*
Lenacil (organic soils only)	annual broad-leaved weeds
Metamitron	annual broad-leaved weeds
Propham	annual grasses and broad-leaved weeds
TCA	grass weeds
Tri-allate	annual grass weeds
Herbicides used between drilling and emergence, foliar applied:	
Glufosinate-ammonium	perennial and annual grass and broad-leaved weeds
Glyphosate	perennial and annual grass and broad-leaved weeds
Paraquat	annual grass and broad-leaved weeds
Diquat (usually used with paraquat)	annual broad-leaved weeds
Herbicides used between drilling and emergence, soil applied:	
Chloridazon (pyrazon)	annual broad-leaved weeds
Chlorpropham (usually used in various mixtures with fenuron, metamitron or propham)	annual broad-leaved weeds
Diethatyl	annual broad-leaved and grass weeds
Dimethenamid	annual broad-leaved and grass weeds
Ethofumesate	annual broad-leaved and grass weeds
Fenuron (usually used in various mixtures with chlorpropham and/or propham)	annual broad-leaved weeds
Lenacil	annual broad-leaved weeds
Metamitron	annual broad-leaved weeds
Metolachlor	annual broad-leaved and grass weeds
Propham (usually used in various mixtures with chlorpropham, fenuron or metamitron)	annual broad-leaved weeds
Quinmerac ~(usually in a mixture with chloridazon)	annual broad-leaved weeds

Herbicide	Weed type controlled
Herbicides for use post-emergence grass weed control, foliar applied:	
Alloxydim	annual and perennial grasses
Clethodim	annual and perennial grasses
Cycloxydiun	annual and perennial grasses
Dalapon	annual and perennial grasses
Diclofop	annual grasses
Fenoxaprop	annual and perennial grasses
Fluazifop-butyl; fluazifop-P-butyl	annual and perennial grasses
Haloxyfop	annual and perennial grasses
Quizalofop; quizalofop-P	annual and perennial grasses
Sethoxydim	annual and perennial grasses
Tepraloxydim	annual grasses
Herbicides for use post-emergence broad-leaved weed control, foliar applied:	
Clopyralid	certain broad-leaved perennial and certain annual weeds
Chloridazon (pyrazon) (usually used in tank mix with other products)	annual broad-leaved weeds
Dendritic salt	certain broad-leaved perennial and certain annual weeds
Desmedipham (usually used mixed with phenmedipham)	annual broad-leaved weeds
Dimethenamid	annual broad-leaved and grass weeds
Endothal	annual broad-leaved weeds
Ethofumesate (usually used in tank mix with other products)	annual broad-leaved and grass weeds
Lenacil (usually used in tank mix with other products)	annual broad-leaved weeds
Metamitron (usually used with adjuvant oil or in tank mix)	annual broad-leaved weeds
Metolachlor	annual broad-leaved and grass weeds
Quinmerac ~(usually used in mix with chloridazon and other herbicides)	annual broad-leaved weeds
Phenmedipham (often used in tank mix with other herbicides)	annual broad-leaved weeds
Tri-allate (usually used with phenmedipham or metamitron)	annual broad-leaved weeds
Triflusulfuron-methyl (usually used with adjuvant oil or in tank mix)	annual broad-leaved weeds
Herbicides for use as lay-by treatments, soil applied:	
EPTC	grass weeds
Trifluralin	annual broad-leaved weeds

[1] The herbicide names listed are those used by BSI, and include WSSA names in parentheses only when they differ. Not all herbicides or recommendations are available in all sugar beet growing countries and most are used in tank mix or in sequence with other herbicides listed.

Application methods

When herbicides were first introduced for sugar beet, they seldom controlled all the weeds that emerged in the crop; thus hand labour and tractor hoeing were still necessary to achieve good weed control. Later, as more herbicides became available, their costs were often so high that tractor hoeing and hand labour were used to supplement them. During the 1960s, the band sprayer played an important role because it reduced herbicide costs by applying chemicals over the sugar beet row only, while the weeds between rows were controlled by cultivation. Consequently, band sprayers were used extensively in most countries until the early 1980s to keep herbicide costs down.

Low dose techniques

In the late 1970s a low-volume, low-dose system for the control of broad-leaved weeds was adopted in many northern European countries for most post-emergence herbicide applications (Smith, 1983). This technique reduced traditional doses of the herbicide's active ingredient (a.i.) by two-thirds (e.g. 0.285 kg a.i./ha phenmedipham compared with 1.14 kg a.i./ha) in the UK and many parts of Europe (Smith, 1983). In the UK, low spray volumes were used partly so that good sprayer work rates (and hence timeliness of spraying) could be achieved, and to keep the isophorone concentration utilized in the then commonly used phenmedipham formulations at a sufficient concentration to prevent the active ingredient (phenmedipham) from crystallizing. The low spray volumes were combined with nozzles that produced fine (Southcombe *et al.*, 1997) spray droplets that ensured good spray coverage of plants. Typical spray volumes varied from country to country (e.g. 80 l/ha in the UK to 180 l/ha in Denmark). One of the main advantages of the technique was that consistently good weed control could be achieved at an economic cost to the grower. It is essential for the success of the technique that sprays are applied to cotyledon-stage weeds (Madge, 1982). This means that target weeds are small, and fine spray droplets are needed to cover them adequately. Initially, high spray pressures (e.g. five bars) were used in the UK and France to provide this fine spray, but these pressures were shown to be unnecessary so long as low volume (fine) spray nozzles were used (May, 1982); typical spray pressures are now between 2 and 4 bar. With the introduction of more new herbicides and tank mix options, spray timing could often be left until the early true leaves stage of weeds. Applications are necessary every time a new flush of weeds appears.

FAR systems in Europe (Hermann *et al.*, 1992) or micro-rate systems in the USA (Dexter *et al.*, 1997) were developed in the 1990s to reduce doses still further. The FAR system uses the principle of combining a contact herbicide (e.g. phenmedipham) 'F', an 'activator' such as ethofumesate, which will aid penetration of other herbicides into the weed 'A', and a residual component 'R'. Normally FAR treatments are a combination of phenmedipham (0.057 kg a.i./ha), ethofumesate (0.1 kg a.i./ha), a residual component (e.g. metamitron at 0.350 kg a.i./ha, lenacil at 0.088 kg a.i./ha or chloridazon at 0.350 kg a.i./ha) plus mineral or vegetable oil at 0.5 to 1.0 l/ha according to conditions. Mineral oil is often omitted from the first spray if conditions are conducive to spray damage. Treatments are applied as soon as the first weeds emerge and before true leaves appear. Typically one or two extra spray passes are necessary compared to other current systems. FAR is widely used in the Netherlands, Belgium and France but less so in other countries.

The micro-rate systems, as developed in North America, use the principle of combining desmedipham plus phenmedipham at 0.045 + 0.045 kg a.i./ha with triflusulfuron-methyl at 0.0045 kg a.i./ha and clopyralid at 0.002 kg a.i./ha plus a methylated vegetable oil at 1.5% per volume of carrier (spray volume). Treatments are applied as soon as weeds emerge and continue every 5–7 days until three or four applications have been made.

When using FAR and micro-rate systems, it is essential that spraying capacity on the farm is adequate to ensure that herbicides can be applied over the whole sugar beet area when weeds are in the optimum cotyledon stage or early true leaves for the technique employed.

Low volume band sprays

With the advent of self-steered band sprayers (Fig. 14.9), the low volumes necessary for the low-volume, low-dose technique could be adapted for band spraying (McClean, 1982). McClean & May (1986) showed that a low-dose system of band spraying could reduce chemical costs by 65%, although it required three times more man-hours than an overall spraying system. They compared a 12 m (24 row) overall sprayer with a 6 m (12 row) band sprayer and tractor hoe system; wider band sprayers and hoes would obviously reduce the time taken to spray fields, but capital costs for machinery would be greater. In the 1980s, many farmers needed to reduce their overhead costs and consequently a large proportion of them reduced the number of workers employed. As a result the extra labour required for band spraying was no longer available and growers switched from band to overall (broadcast) treatments.

To control weeds growing under sugar beet plants, many growers prefer a twin nozzle system of band spraying where a nozzle on each side of the sugar beet row is angled towards the row. This system is especially useful when sugar beet plants have four or more leaves, but requires the use of relatively high spray volumes. High spray volumes reduce the risk of nozzle blockages but care is re-

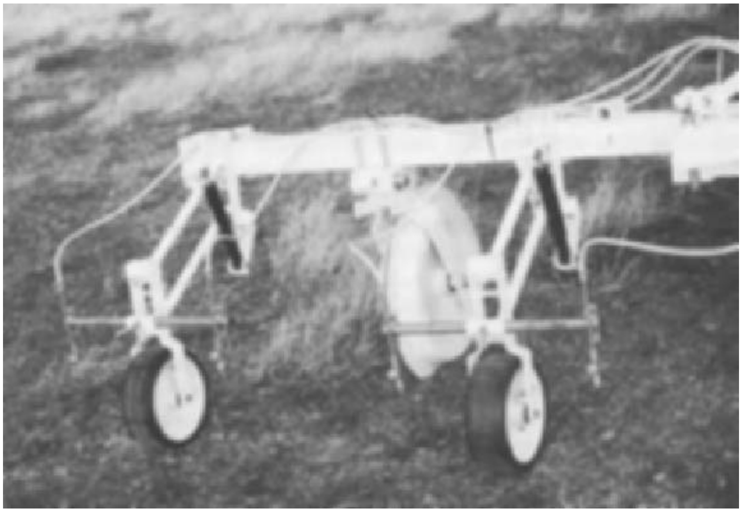

Fig. 14.9 Self-steered band sprayer.

quired to ensure that phenmedipham products do not crystallize in the tank.

The majority of herbicides are applied by the conventional hydraulic sprayer, but whether they should be applied in bands or as overall treatments depends not only on the relative costs and availability of materials and labour, but also on the weather. In wet seasons or those with few good spray days, growers may prefer the timeliness and width of the overall sprayer. In dry seasons when weeds may be harder to kill because of large amounts of wax on their leaves, band sprayers may be preferred because more use may have to be made of the tractor hoe to kill surviving weeds between the rows. Tractor hoes also perform much better in dry conditions, provided the soil is friable, because less rerooting of the weeds is likely to occur. On the other hand, finger or fine tine weeders tend to work best when the soil is moist (but not damp); under moist conditions the weeds are easier to remove from the soil, but some weeds, especially monocots can easily reroot if conditions are wet (Jones *et al.*, 1996). Other systems of mechanical weed control have been developed including specialist machines that will weed in the rows or with tines that can be used over the row once the crop is established. The cost of machines relative to herbicides means that few are used in conventional beet, but they are necessary in organic sugar beet production.

Height selective application

Weeds that grow above the sugar beet canopy can cause large yield losses (see above – Weed competition). Various selective applicators have been developed that utilize the height differential between weeds, weed beet (Fig. 14.10) and bolters and the growing sugar beet crop; typically these weeds grow to over 1 m while the crop is only about 60 cm high. Applicators, which include recirculating sprayers (McWhorter, 1970), rotating rollers (Wyse & Habstritt, 1977), rope-wick applicators (Dale, 1979) and pressure pads, are mounted above the crop canopy and spray or wipe the weeds with herbicide. Most selective applicators used in sugar beet employ glyphosate to kill weeds, weed beet and bolters. In some situations this application can damage the crop if splash or dripping occurs. However, Evans & Dexter (1981) reported that underground exchange of chemical between weed roots and sugar beet roots can also cause severe damage. Such problems have not been recorded in the UK.

The first roller applicators were relatively expensive and limited in width and were soon replaced by rope-wick applicators. These machines were cheap and deceptively simple, but they required a lot of skill and patience to set them up correctly so that glyphosate flowed through the rope in sufficient quantity to kill the weeds, yet did not drip on to

Fig. 14.10 A weed beet plant in flower, the ideal stage for weed wiping (© *British Sugar Beet Review*).

the highly susceptible sugar beet and kill it. The flow of chemical is dependent on temperature and humidity so that machines require constant adjustments to the compression fittings that alter the flow rate of chemicals as the weather changes during the day. In the 1980s the introduction of a moving rope applicator reduced the problems of continually adjusting the machines, but these applicators are relatively expensive considering the limited amount of use to which they are put on the average European farm. In the 1990s more sophisticated roller applicators were developed and are used successfully. A pressurized pad system became available in the early 2000s in which a pad is used to apply the chemical (usually glyphosate) to weeds or weed beet and liquid levels in the pads are controlled by electronic sensors. In the late 1970s, machines to electrocute weed beet were developed (Diprose & Turner, 1979; Wilson & Anderson, 1981). However, these used high voltages and so were abandoned owing to the issues associated with operators' and bystanders' safety.

Pre-sowing and pre-emergence herbicides

Two main categories of herbicides are used in sugar beet for pre-sowing and pre-emergence applications. The first comprises the non-selective contact herbicides, which are used to kill weeds before the crop emerges, and the second comprises the residual soil-applied herbicides, which are applied before or after sowing.

If a weed problem is anticipated, the decision has to be made as to whether to spray before or after sowing. If weeds are already past the cotyledon stage before sowing, and minimal cultivations are to be used that will not kill them, or the weeds may be partially buried but not killed by the drill, then non-selective contact herbicides are applied before sowing. If the application of non-selective contact herbicides can be delayed until after sowing, more weeds are likely to have emerged and been killed; however, applications must not be delayed for too long because sugar beet seedlings may be damaged or killed if herbicides are applied too close to emergence. The main contact herbicides in use around the world in this situation are paraquat (with or without diquat), glyphosate and glufosinate-ammonium. The main advantage of using non-selective herbicides prior to sugar beet emergence is that nearly all the emerged weed species, including weed beet, are controlled.

Soil-applied residual herbicides, if used prior to sowing, are usually incorporated into the soil. Incorporation must be done with care to avoid mechanical damage to the seedbed and to ensure even distribution of the herbicide throughout the top 5 cm or so of soil. Incorporation decreases the performance variability of residual herbicides by reducing the effect of weather on their activity. Incorporation is required with herbicides that volatilize and in semi-arid production areas. However, this technique is not used widely because it requires specialized implements to mix the herbicides in soil, high horsepower tractors, and incorporation may cause the seedbed to dry out.

When residual herbicides are used after sowing, they must be applied to the soil surface and, as with contact herbicides, they must be applied before sugar beet seedlings emerge or crop damage may result. However, not all residual herbicides can be incorporated because some can, in certain conditions, increase the amount of crop damage (e.g. lenacil on light soils). The advantage of soil-applied residual herbicides is that they reduce the number of weeds that emerge with the crop and often sensitize survivors to subsequent post-emergence sprays (Dexter, 1971; Duncan *et al*., 1982). Some researchers have argued that weed competition in this early period of growth does not affect yield as long as the weeds are killed later; they consider that pre-sowing or pre-emergence herbicides should not be used for ecological reasons (Meyer *et al*., 1986). However, pre-emergence herbicides are important for the majority of sugar beet growers because they reduce weed densities, complement subsequent post-emergence applications, and provide some flexibility with timing and selection of post-emergence treatments (May & Hilton, 1985).

In the 1980s the adoption of the low-dose technique of post-emergence weed control in much of northern Europe led to a change in the doses of pre-emergence herbicides used. Trials showed that the increased reliability and earlier post-emergence application of low dose sprays allowed pre-emergence herbicides for broad-leaved weed control to be used at lower doses than previously (May & Hilton, 1985). Consequently, many chemical manufacturers introduced reduced doses of their pre-emergence herbicides when these were to be followed by low dose post-emergence spray sequences. This reduction in dose, and therefore in cost, has meant that many pre-emergence herbicide applications are now seen by growers as an aid to post-emergence spraying by sensitizing weeds to post-emergence treatments and as an insurance against delayed application of post-emergence herbicides. The main pre-emergence residual broad-leaved weed control herbicides used on sugar beet crops are chloridazon (pyrazon), cycloate, diethatyl, ethofumesate, quinmerac, lenacil and metamitron. Pre-emergence residual herbicides are seldom required or used before FAR treatments.

Herbicides that may be used before sowing to control grass weeds are cycloate, dalapon, di-allate, EPTC, TCA and tri-allate. However, these graminicides, especially dalapon and TCA, while generally cheap, have been replaced in many countries by selective post-emergence graminicides which are much less likely to cause crop damage.

A large number of factors needs to be considered when selecting pre-emergence herbicides. The weed spectrum to be controlled by the treatment is of prime importance. The proposed post-emergence treatments may affect the choice of pre-emergence spray to ensure that the sequence is likely to control the complete range of anticipated weeds. Soil type and soil organic matter are major factors because they determine the products that can be used, their doses, and hence their price. Manufacturers advise against use of some sequences of herbicides because of the risk of crop damage (e.g. metamitron pre-emergence followed by lenacil post-emergence). Sequences of pre-emergence herbicides and other pesticides also can cause damage; for example carbofuran and metamitron applied to the same crop have caused phytotoxicity, although this problem is overcome by partially covering the seed before carbofuran is applied. Other herbicide and insecticides that can interact and reduce crop populations are lenacil with imidacloprid and desmedipham plus phenmedipham with chlorpyrifos.

Some situations related to wind erosion control need special care when selecting pre-emergence herbicides. Bitumen (mineral pitch) mulches and barley cover crops are two popular methods of protecting the crop against wind erosion. Bitumen mulches can decrease activity of pre-emergence herbicides (Neururer, 1984). Barley cover crops complicate weed control in sugar beet because the chosen herbicides must not kill or reduce the growth of the barley. In the UK, low doses of chloridazon (pyrazon) are the only pre-emergence treatments that do not adversely affect the growth of the barley (see Chapter 6).

Post-emergence herbicides

These can be grouped into three main categories: those used for broad-leaved weed control, those used for the control of grasses, and those used as lay-by treatments.

The herbicides used for broad-leaved weed control form the largest category and a vast number of products, tank mixes and sequences are available such that it is not possible to cover this subject in great detail. The major herbicides in this group are chloridazon (pyrazon), clopyralid, desmedipham, endothal, ethofumesate, lenacil, metamitron, phenmedipham, and triflusulfuron-methyl. In most countries where they are used, herbicides are usually applied in tank mixes with phenmedipham although metamitron is often applied with mineral or vegetable oil without phenmedipham, and clopyralid is often used alone. Sugar beet herbicides seldom have a wide enough weed control spectrum or sufficient residual activity to control all weeds, and tank mixes and sequences of different herbicides are commonly used in order to provide a broad spectrum of weed control. The activity of many post-emergence herbicides is affected by weather. For example, phenmedipham is particularly damaging to sugar beet when applied in high temperatures and high light intensities (Bethlenfalvay & Norris, 1977; Preston & Biscoe, 1982). In Austria, Neururer (1986) developed a technique using leaf discs to determine the amount of wax on leaves; the extent of wax deposition can be used as a guide to predict the sensitivity of the crop to these herbicides.

To reduce injury to sugar beet plants from tank mixes, such as phenmedipham plus ethofumesate, manufacturers have developed formulated mixtures of the materials (Marshall *et al.*, 1987). These mixtures contain smaller amounts of surfactants and formulation products than the equivalent tank mix combinations and are generally safer to the crop. Formulations of phenmedipham have also changed with less harmful solvents with reduced risk of crystallization. Herbicide solvent and formulation systems have also been changed to decrease human and environmental toxicity.

Spray additives are used to increase the efficacy of a number of broad-leaved weed control herbicides used on sugar beet to enhance the contact of spray droplets on leaves. They are especially useful under dry conditions when weeds and crop both tend to have waxy leaves. For example, metamitron is mainly active through the soil, but does have some contact activity. In most countries, therefore, metamitron is recommended with an oil additive when used as a post-emergence treatment. The major spray additives used in sugar beet crops are based on mineral or vegetable oils, but tallow amines and wetters are recommended with broad-leaved weed control herbicides in a number of countries.

Spray additives are particularly important for some of the post-emergence graminicides. Mineral oils are normally recommended with graminicides such as alloxydim, clethodim, cycloxydim, quizalofop and sethoxydim, and mineral oils or non-ionic wetters are recommended with some formulations of fluazifop-P-butyl. However, some graminicides (e.g. tepraloxydim) are now formulated with additives. Most of the post-emergence graminicides should be applied at a relatively late stage of crop growth, to give weeds enough time to develop and provide a suitable target. Graminicides, such as sethoxydim and haloxyfop, require good translocation to shoots and rhizomes if they are to give long-term control of perennial grasses such as *Elytrigia repens* (Dekker & Harker, 1985). Graminicides used in sugar beet are listed in Table 14.2.

The major herbicide used as a lay-by treatment is trifluralin, which requires incorporation into the soil with one of inter-row cultivators, harrows, or rotary hoes. It is relatively inexpensive and prevents subsequent emergence of late-emerging weeds such as *Chenopodium album* in northern Europe and *Amaranthus retroflexus*, *Echinochloa crus-galli* and *Setaria* spp. in the USA. EPTC is sometimes used as a lay-by treatment, especially if grass weeds are expected to be a late-developing problem. Metolachlor and dimethenamid have also been used as lay-by treatments and have been applied by injection through overhead sprinkler systems. Trifluralin incorporated into prepared land is often used as a herbicide before transplanted sugar beet are transplanted.

Most growers using traditional doses of herbicides follow a two-spray programme for broad-leaved weed control: typically a pre-emergence residual herbicide followed by a post-emergence herbicide. Users of the low-dose techniques usually spray three times, applying either a pre-emergence treatment followed by two post-emergence treatments or three post-emergence treatments without a pre-emergence treatment, while the FAR or micro-rate systems will require three, four or more spray passes.

Biological control

Management and manipulation of naturally occurring organisms is the basis for biological weed control and has been a component of weed management in agriculture since the mid-1800s. Where weeds have been controlled successfully, they have inhabited relatively stable ecosystems such as rangelands and aquatic sites. None of the weed species that have been controlled with biological methods is a problem in sugar beet fields.

Two basic strategies could be used in the biological control of weeds. These are the classical approach, where foreign control agents are introduced, and the augmentative or bioherbicide approach, where organisms already present in the ecosystem are increased by mass rearing or by other manipulations. Currently, neither biological control strategy is used to control weeds in sugar beet fields, and no major breakthroughs are anticipated in the immediate future. However, control of weeds in sugar beet fields with bioherbicides may be possible in the longer term.

The current bioherbicide approach employs the massive release of a biocontrol agent into specific weed-infested fields in order to infect and kill susceptible weeds (Templeton *et al.*, 1986). Several fungi, bacteria, and viruses are potential bioherbicides, although at present few fungal pathogens of weeds have been developed commercially. These two myco-herbicides are *Colletotrichum gloesporioides* ssp. *aeschynomene* (Collego, Upjohn Co., Kalamazoo, MI 49001) for control of *Aeschynomene virginica* in rice and soybean, and *Phytophthora palmivora* (Devine, Abbott Laboratories, Long Grove, IL 60047) for control of *Morrenia odorata* in citrus orchards. The success achieved with these two biocontrol agents will influence significantly the redirection of resources into biological weed control research during the next decade.

Several other fungal pathogens are under study as biological weed control agents in several crops, but not sugar beet (Charudattan & DeLoach, 1988). Five of these fungal pathogens show promise for the control of *Abutilon theophrasti*, *Chenopodium album*, *Datura stramonium*, *Echinochloa crus-galli* and *Sorghum halepense*, which can be present in sugar beet.

Several drawbacks associated with the potential use of bioherbicides include lengthy registration processes with governmental agencies, slow weed mortality or growth suppression, stringent temperature and moisture requirements for effectiveness, and a narrow spectrum of host range specificity (Khachatourians, 1986; Templeton *et al.*, 1986; Charudattan & DeLoach, 1988). One possible way of overcoming the constraint imposed by the narrow spectrum of host range is to mutate a broad-spectrum biocontrol agent so that its activity is dependent on an exogenously applied additive for target weed species; thus, once control has been accomplished, the controlling organisms will die off without the additive (Sands *et al.*, 1989).

As a consequence of the above drawbacks, and others such as commercial constraints, Jutsum (1988) considered that biocontrol will only be developed where insufficient chemical control is available, conventional chemicals are too expensive and/or governments restrict the use of chemicals. Whilst governments are placing emphasis on restricting herbicides with potential harmful effects, such as those that might contaminate groundwater, it is unlikely that many sugar beet herbicides will be affected (Knott, 2001) and so there will not be any commercial or economic pressures to develop biological agents to control weeds in sugar beet in the near future.

WEED CONTROL OUTSIDE THE SUGAR BEET CROP

In the rotation

One early method of reducing weed control requirements was to plant sugar beet for successive years. Roemer (1927) reported that this method of reducing weed populations was used in some production areas of the USA where sugar beet was grown for 7–12 consecutive years and in the Netherlands where sugar beet was grown for 3 consecutive years. However, yields were usually reduced because of a build-up of nematodes (see Chapter 13). Sugar beet monoculture is still practised in parts of some countries such as Finland. Modern experience indicates that monoculture is likely to exacerbate weed control problems by increasing the populations of some weeds that are difficult to control.

Today, rotations are always based upon economic rather than weed control considerations. However, weeds that affect sugar beet crops can be controlled successfully elsewhere in the rotation. Weed beet, growing either from groundkeepers or seeds, must be controlled in other crops where selective herbicides can be used. Perennial weeds may be killed by the use of pre-harvest applications of glyphosate wherever recommendations allow. This is especially useful when the weed is growing well in the crop but is unlikely to provide a good, growing target after the crop is harvested (e.g. volunteer potatoes in cereals). Use of glyphosate in stubbles can give useful control of emerged perennial weeds such as *Cirsium arvense*. Cultivations in stubbles will also control perennial weeds and will reduce the number of seeds in the soil (Wevers *et al*., 1986).

Volunteers from previous crops (e.g. potatoes and oilseed rape) can be troublesome in sugar beet, especially when not controlled adequately by sugar beet herbicides. Potatoes are difficult to kill when they grow from tubers although ethofumesate, in mixtures with other herbicides, or clopyralid will suppress their growth. Volunteer potatoes that grow from seeds are easier and can be killed with mixtures of phenmedipham and chloridazon (pyrazon) or by tractor hoeing. If volunteer potatoes are growing from tubers, repeated tractor hoeing is necessary to control each new regrowth or post-emergence treatment with clopyralid. Weed wiping can be used but an adequate height differential between sugar beet and potatoes exists for only a short time, if at all. If glyphosate tolerant beet are permitted in the future, control of volunteer potatoes would be simplified, costs reduced and problems of potato cyst nematode development on the volunteers reduced (Dewar *et al*., 2000). However, high levels of volunteer potato control can be achieved in cereals by the use of glyphosate (pre-harvest) or fluroxypyr (Bevis & Jewell, 1986). Volunteer oilseed rape is another problem that can occur if oilseed rape is grown in the rotation. It can be controlled with triflusulfuron-methyl but is difficult to control with other herbicides used in sugar beet, because it emerges and grows quickly past the stage at which it is sensitive to them. Oilseed rape can remain dormant in the soil for several years; in the UK it is common to find high densities suddenly appearing in sugar beet crops grown 5 years or more after the last oilseed rape crop. Oilseed rape volunteers must therefore be controlled throughout the rotation, taking particular care not to cultivate immediately after harvest of the rape crop (Pekrun & Lutman, 1998).

The crops that are grown in the rotation and the weed control measures used in them can also affect weed populations. Bray and Hilton (1975) reported that on one farm in the UK between 1950 and 1974 *Poa annua* increased in potato/cereal/sugar beet rotations, while populations of *Stellaria media* and *Polygonum aviculare* declined. The herbicides used in these crops controlled the latter two weeds but in cereals *P. annua* was not controlled, so it flourished and set seed. In the late 1970s, many cereal herbicides failed to control *Viola arvensis* and large populations of this weed are now common in sugar beet fields in the UK. Neururer (1975) surveyed weeds at four locations in Austria between 1965 and 1975 and reported that, while the total weed density had changed very little, weeds that were difficult to kill in sugar beet (e.g. *Elytrigia repens*, *Galium aparine*, *P. aviculare* and many annual grass weeds) had increased in numbers. However, in damp areas the use of residual herbicides had reduced the overall weed population.

Several experiments have demonstrated the effectiveness of controlling troublesome weeds in the crop prior to sugar beet. Controlling ALS-resistant *Kochia scoparia* at a level greater than 95% in barley resulted in an 85% reduction of *K. scoparia* density the following year in sugar beet (Mickelson *et al*., 2001). Controlling ALS resistant *K. scoparia* in barley was economical, efficacious, and reduced Kochia density in the seed bank and made ALS resistant weed control more manageable in sugar beet.

The timing of ploughing before sowing sugar beet, which is influenced by such factors as soil type and previous crop, affects weed emergence. Ploughing early in the autumn can often result in weeds emerging and growing to a large size by the time beet is sown in the spring (Wevers *et al.*, 1986).

It is obvious that weed control must be considered over the whole rotation to ensure that one weed species is not allowed to flourish and become a major problem or that an imbalance of weed species is created.

In fallow lay-by situations

There are two basic types of fallow: traditional fallow, where the land is rested for a whole year, and inter-crop fallow, where the land is rested through the autumn and winter (i.e. following the harvest of one crop and prior to sowing the next spring-sown one). Traditional fallow is no longer used in many countries because farmers cannot afford to leave a field uncropped. Where it is used for weed control, it requires repeated cultivations to kill weeds which are already growing and to stimulate weed seeds to germinate or perennial weeds to sprout. However, most cultivations are shallow, and normally it is only annual weed seeds in the top half of the plough layer that are induced to germinate and are subsequently killed.

With over-production of many crops in the 1980s governments encouraged growers to set aside land from agriculture for a period of time. In most set-aside programmes the land cannot be left clean fallow because this increases the leaching of nitrogen. Therefore, weed control must be by timely cutting, in some countries combined with a cover crop to smother weeds. In Europe, a large proportion of set-aside is sprayed with glyphosate to control weeds without harming ground nesting birds or ground-dwelling mammals. The way in which set-aside land is managed affects the type of weed population that is present when it is taken back into agriculture (Clarke & Froud-Williams, 1989).

With an inter-crop fallow, cultivations can still be used in the same way as with a conventional fallow. If the inter-crop fallow is restricted to the autumn, then only weeds that germinate during that period can be controlled. Control of autumn-germinating annuals may be of less significance for the following spring-sown crop than for the next autumn-sown one. However, this period still provides a good opportunity for the reduction of perennial weed populations and weeds such as *S. media* which germinate in both spring and autumn.

Some countries, especially members of the European Union, have considered the introduction of autumn cover crops to help prevent nitrogen leaching in nitrate sensitive areas and such techniques can also help to prevent soil erosion during winter. Killing a winter rye cover crop with glyphosate and then sowing sugar beet into the crop residue can also provide early season wind erosion protection and Wilson and Smith (1992) reported greater sugar beet populations and root yield compared to those from a conventional seedbed that was ploughed and pressed before sowing. Obviously, such cover crops will mean that cultivations cannot be used whilst the cover is present, but selection of a competitive crop will help suppress weed growth. Control of the cover crop itself before sowing of the spring crop may also cause a problem, especially on medium or heavy soils, when spring ploughing does not allow time for good weathering of soil before sowing. It is unlikely that this would be a problem in sugar beet crops tolerant to glufosinate-ammonium or glyphosate (Petersen, 2004).

HERBICIDE RESISTANCE

Crop varieties

Smith and Schweizer (1983) demonstrated that sugar beet cultivars responded differently to herbicide treatments. The differences among cultivars were apparent 45 days after sowing as herbicides reduced plant weight by 39–55%. At harvest, sugar beet had recovered from early-season injury and root yield reductions averaged 5%. Wilson (1999) found sugar beet cultivars also responded differently to mixtures of herbicides applied post-emergence. Post-emergence herbicide mixtures reduced sugar beet leaf area 10–37%, depending on crop cultivar. At harvest, root yield reductions from herbicide treatments ranged from 3 to 11%. However, the existence of herbicide × cultivar, year × herbicide, and year × cultivar interactions complicates breeding and evaluation of cultivars for herbicide tolerance based only on field experiments.

To overcome environmental variation inherent in field experimentation in any given year, scientists are developing and evaluating *in vitro* techniques for identifying genotypes with heterogeneous seedling populations that are tolerant to herbicides, and are using meristematic cloning procedures to synthesize clones that are genetically tolerant of herbicides (Smith & Moser, 1985). Hart *et al.* (1994) used somatic cell selection to develop a sugar beet breeding line tolerant to sulfonylurea herbicides. The line was tolerant to residues in soil and to post-emergence applications.

Sugar beet cultivars that are tolerant to glyphosate and glufosinate-ammonium have also been developed using genetic engineering (Moll, 1997; Read & Bush, 1998; Wilson *et al.*, 2002). Comparison of glyphosate and glufosinate-ammonium-tolerant sugar beet cultivars showed that sucrose yields were similar with the two weed control systems and that both glyphosate and glufosinate-ammonium produced less early-season crop injury than a desmedipham plus phenmedipham and triflusulfuron-methyl mixture. Enhanced early season crop vigour with genetically engineered herbicide tolerant sugar beet increases the crops ability to capture sunlight and compete with weeds. Improved weed control with these management systems diminishes the need for cultivation which, in countries where wide row spacing is used to facilitate inter-row weed control, allows row spacing to be reduced. Narrow row sowing coupled with enhanced crop vigour means earlier row closure, a crop more competitive with weeds and the potential for enhanced sucrose yield (Wilson & Smith, 1999). The reduced phytotoxicity of herbicide tolerant systems is reported as increasing yields by approximately 5% in the UK (Brants & Harms, 1998; May, 2000) and up to 15% in the USA (Kniss *et al.*, 2003). Weed control based on beet tolerant to glyphosate also offers the potential to reduce costs by about 15% (Kniss *et al.*, 2003; May, 2003).

Weeds

Many pests have demonstrated their ecological and biochemical adaptability to chemicals, some soon after they were first exposed. The discovery of insects resistant to insecticides was first reported in 1908, of plant pathogens resistant to fungicides in 1940, and of weeds resistant to herbicides (the s-triazines) in 1970 (LeBaron & Gressel, 1982). To date, 65 weed species, including 47 broad-leaved species and 18 grass species, are known to have developed biotypes resistant to triazines. Triazine-resistant weeds are common in many countries and have usually developed following the use of high rates of herbicides, the same or similar herbicides frequently, and monocultures or limited crop rotations. The first introduction of an ALS inhibitor herbicide occurred in 1982 with the introduction of the sulfonylurea, chlorsulfuron, for use in cereals. Five years after the initial use of chlorsulfuron in cereals, resistant weeds appeared (Mallory-Smith *et al.*, 1990). *Kochia scoparia*, a major weed in sugar beet in the USA has also been observed to be resistant to sulfonylurea and imidazolinone herbicides (Primiani *et al.*, 1990). The sulfonylurea herbicide triflusulfuron-methyl was developed in the USA primarily for post-emergence control of *K. scoparia*. With the advent of herbicide resistance in the weed population, *K. scoparia* control in all the major sugar beet growing areas in the USA has become extremely difficult.

Resistance to herbicides of other families is becoming more widespread. Weeds have become resistant to certain herbicides in the bipyridyl, diphenyl ether, dinitroaniline, auxin, urea, and the carbamate herbicide families and more recently, four weed species have been reported to be resistant to glyphosate (Heap & LeBaron, 2001).

Managing herbicide-resistant weeds and designing weed control programmes to reduce the development of resistance has become increasingly complex. Each strategy for sustainability of a herbicide has two components; preventing or delaying the development of resistance and mitigating resistance once it has appeared (Sammons *et al.*, 2004). Prevention practices designed to slow the development of resistance such as application rate and herbicide and crop rotation, are used widely but are difficult to evaluate for effectiveness. Since it is a formidable task to evaluate if resistance has been prevented, researchers can generally only prove that resistance has occurred. Mitigating resistance, once it has occurred, has involved using (alone or in tank mix) a herbicide that has activity on the resistant weed but has a different mode of action. It is now common in many countries to match different resistant management strategies to the mode of action of the herbicide or herbicide family that needs to be sustained.

CROP INJURY FROM HERBICIDES

Sugar beet injury can occur from herbicides applied to the crop for weed control (Table 14.3) and from herbicides that can drift or carryover in the soil (Table 14.4). Atrazine, imazethapyr, chlorsulfuron and trifluralin are examples of herbicides that can carry over from the previous crop and injure sugar beet. The risk from soil residues of herbicides is often lessened by mouldboard ploughing before sowing and consequently ploughing is often recommended on labels of many residual herbicides. Ploughing has special merit if the herbicide in question has low water solubility and therefore does not readily leach in soil. Trifluralin has a very low solubility in water (0.3 mg/l) and remains near the soil surface. By mouldboard ploughing before sugar beet sowing, trifluralin concentration in the upper 0–8 cm of soil was reduced by 76% but increased in the 15–30 cm zone of the soil profile (Wilson *et al.*, 1995). Therefore mechanical inversion of the soil diluted the trifluralin concentration in the zone where sugar beet was sown and reduced the carryover potential of the herbicide. If carryover is from a herbicide that is mobile in soil, such as atrazine (33 mg/l), mouldboard ploughing would not be effective and could increase the concentration at the soil surface by bringing atrazine that had leached into the soil profile to the surface.

The amount of herbicide carryover in soil depends on two factors; soil characteristics, such as pH, organic matter, and clay content, and herbicide characteristics such as solubility in water, sorption

Table 14.3 Herbicides utilized in sugar beet production and their effects on sugar beet and weeds.

Herbicide	Mode and site of action	Sugar beet and weed injury symptoms
Pre-plant, applied post-emergence to weeds before crop emergence		
Glufosinate-ammonium	Inhibition of glutamine synthetase	Plant foliage, especially new growth will turn yellow then brown
Glyphosate	Inhibition of EPSP synthetase	
Preplant incorporated, pre-emergence		
Cycloate Ethofumesate	Lipid synthesis inhibition	General stunting, crinkled, fused leaves. Shortened leaf mid-vein
Metolachlor	Shoot inhibition	Initial yellowing of leaf margin, affects older leaves, injured plant tissue turns brown
Metamitron Chloridazon (Pyrazon)	Photosynthesis inhibition	
Post-emergence		
Clethodim Fluazifop-P Quizalofop-P Sethoxydim	ACCase inhibition	Yellowing (chlorosis), browning of leaves emerging from grass whorl
Triflusulfuron-methyl	ALS-AHAS inhibition	General stunting, yellowing of leaves at the growing point
Clopyralid	Growth regulator – synthetic auxin	Stem elongation, twisting, leaf cupping
Chloridazon (Pyrazon) Desmedipham Metamitron Phenmedipham	Photosynthesis inhibition	Initial yellowing or brown spotting on leaves, browning of leaf margins
Post-emergence, lay-by		
Dimethenamid Metolachlor	Shoot inhibition	General stunting. Crinkled, fused leaves
EPTC	Lipid synthesis inhibition	
Trifluralin	Microtubule assembly inhibition	Root pruning

Table 14.4 Sugar beet injury symptoms associated with other crop herbicides.

Herbicide	Mode and site of action	Sugar beet injury symptoms
Amino acid synthesis inhibition		
Imazamox	ALS – AHAS inhibition	Stunting, yellowing of new growth then leaf tissue turns brown. Root pruning.
Imazapyr		
Imazaquin		
Imazethapyr		
Chlorimuron-ethyl		
Chlorsulfuron		
Diflufenican		
Metsulfuron-methyl		
Rimsulfuron		
Thifensulfuron-methyl		
Tribenuron		
Glyphosate	EPSP synthetase inhibition	New growth will yellow then turn brown.
Glufosinate-ammonium	Glutamine synthetase inhibition	
Growth regulators		
2,4-D	Synthetic auxins	Stem twisting and elongation, leaf cupping, crinkling.
MCPA		
Dicamba		
Fluroxypyr		
Picloram		
Photosynthesis inhibition		
Atrazine		Initial yellowing of leaf margins, affects older leaves more than younger leaves, injured tissue turns brown and dies.
Bentazon		
Bromoxynil		
Cyanazine		
Diuron		
Metribuzin		
Pyridate		
Simazine		
Terbacil		
Cell membrane disruption		
Acifluorfen	PPO inhibition	Affected leaves turn yellow, then brown and eventually die, sometimes water soaked or reddish coloured spotting on leaves, leaf crinkling.
Fomesafen		
Carfentrazone		
Sulfentrazone		
Photosystem I electron diversion		
Diaquat		
Paraquat		
Carotenoid biosynthesis inhibition		
Norflurazon	Phytolene desaturase inhibition	Plants turn white, often becoming translucent at the tips.
Isoxaflutole		
Mesotrione	4-HPPD inhibition	
Clomazone		

to soil particles, volatilization, and mode of chemical breakdown. The carryover potential of herbicides generally increases as soil organic matter decreases and the sand content of soil increases. The problem is further exacerbated by the fact that sugar beet are very sensitive to small quantities of herbicides used on other crops that may be present in the soil. Thus, growers must choose herbicides for crops that precede sugar beet which will not carryover in soil and affect crop growth and development.

Sugar beet are also sensitive to herbicide drift from adjacent fields. Very low concentrations of certain sulfonylurea, imidazolinone, and growth regulator herbicides can cause extensive damage to sugar beet. These same herbicides used in other crops can remain as a contaminant in the spray tank and injure sugar beet when the spray tank is used to spray pesticides on sugar beet. To prevent this, strict washing procedures are provided on the herbicide label and should be followed to ensure the herbicide is removed or deactivated (Robinson, 2002).

REFERENCES

Achard, F.C. (1799) *Ausführliche Beschreibung der Methode, nach welcher bei der Kultur der Runkelrübe verfahren werden muss.* C.S. Spener, Berlin (reprinted Akademie-Verlag, Berlin, 1984).

Aldrich, R.J. (1984) *Weed-crop Ecology – Principles in Weed Management.* Breton Publishers, North Scituate, MA.

Ammon, H.U., Dubois, D.M. & Bohren, C.H.R. (1996) Spate Unkrautbekampfung in Ruben mit Glufosinat – ein Anbauverfahren zur Nutzlingsforderung. *Zeitschrift Fur Pflanzenkrankheiten Und Pflanzenschutz – Journal of Plant Diseases and Protection* **XV**, 593–598.

Bethlenfalvay, G. & Norris, R.F. (1977) Desmedipham phytotoxicity to sugar-beets (*Beta vulgaris*) under constant versus variable light, temperature, and moisture conditions. *Weed Science* **25**, 407–411.

Bevis, A.J. & Jewell, S.N. (1986) Preliminary results from the use of chemicals or cultivations to control potato groundkeepers. *Aspects of Applied Biology 13, Crop protection of sugar beet and crop protection and quality of potatoes*, 201–208.

Bosch, J. (1987) The influence of some dominant weeds on beneficial and pest arthropods in a sugarbeet field. [German] Der Einfluss einiger dominanter Ackerunkrauter auf Nutz- und Schadarthropoden in einem Zuckerrubenfeld. *Zeitschrift fur Pflanzenkrankheiten und Pflanzenschutz* **94** (4), 398–408.

Brants, I. & Harms, H. (1998) Herbicide tolerant sugar beet. *Proceedings of the 61st IIRB Congress*. Brussels, pp. 195–204.

Bray, W.E. & Hilton, J.G. (1975) Changes over 25 years in the weed population in sugar beet grown on a Norfolk farm. *Troisième Réunion Internationale sur le Desherbage Sélectif en Cultures de Betteraves*, pp. 389–394.

Burnside, O.C., Wilson, R.J., Weisberg, S. & Hubbard, K.G. (1996) Seed longevity of 41 weed species buried 17 years in Eastern and Western Nebraska. *Weed Science* **44**, 74–86.

Charudattan, R. & DeLoach, C.J. (1988) Management of pathogens and insects for weed control in agroecosystems. In: Altieri, M.A. & Liebman, M. (eds) *Weed Management in Agroecosystems: Ecological Approaches.* CRC Press, Boca Raton, FL, pp. 245–264.

Clarke, J.H. & Froud-Williams, R.J. (1989) The management of set-aside and its implications on weeds. *Proceedings of the British Crop Protection Council – Weeds.* 2, pp. 579–584.

Cousens, R. (1986) Theory and reality of weed control thresholds. *Plant Protection Quarterly* **2**, 13–20.

Cousens, R., Wilson, B.J. & Cussans, G.W. (1985) To spray or not to spray: the theory behind the practice. *Proceedings of the British Crop Protection Council – Weeds.* 2, pp. 671–678.

Dale, J.E. (1979) A non-mechanical system of herbicide application with a rope wick. *PANS* **25**, 431–436.

Dawson, J.H. (1965) Competition between irrigated sugar beets and annual weeds. *Weeds* **13**, 245–249.

Dawson, J.H. (1974) Full-season weed control in sugarbeets. *Weed Science* **22**, 330–335.

Dekker, J. & Harker, N. (1985) Comparative efficacy of several graminicides in controlling *Elymus repens. Proceedings of the British Crop Protection Council – Weeds.* 2, pp. 471–478.

Dewar, A.M., Haylock, L.A., May, M.J., Beane, J. & Perry, R.N. (2000) Glyphosate applied to genetically modified herbicide-tolerant sugar beet and 'volunteer' potatoes reduces populations of potato cyst nematodes and the number and size of daughter tubers. *Annals of Applied Biology* **136**, 3, 179–187.

Dewar, A.M., May, M.J., Woiwod, I.P., Haylock, L.A., Champion, G.T., Garner, B.H., Sands, R.J.N., Qi, A. & Pidgeon, J.D. (2003) A novel approach to the use of genetically modified herbicide-tolerant crops for environmental benefit. *Proceedings of the Royal Society: Biological Sciences.* London, **270** (1513), 335–340.

Dexter, A.G. (1971) Weed control and crop injury from herbicide combinations used in sugarbeets. *Proceedings of the North Central Weed Control Conference.* Kansas City, MO, 26, p. 60.

Dexter, A.G., Luecke, J.L. & Bredehoeft, M.W. (1997) Microrates of post-emergence herbicides for sugarbeet. *Proceedings of the North Central Weed Science Society.* Louisville, KY, 52, p. 139.

Dexter, A.G., Rothe, I. & Luecke, J.L. (1999) Weed control in Roundup Ready™ and Liberty Link™ sugarbeet. In: *30th General Meeting of American Society of Sugar Beet Technologists* Abstracts. p. 9.

Diprose, M. & Turner, N. (1979) Electro thermal weed and bolter control. *British Sugar Beet Review* **47** (4), 31–32.

Dubois, D., Hani, A., Ammon, H.U. & Keller, S. (1993) Influence of weed control on sugar yield and the spread of yellow virus in sugar beet crops. [German] Einfluss der Unkrautbekampfung auf Ertrag und Virusbefall von Zuckerruben. *Landwirtschaft Schweiz* **6** (3), 133–138.

Duncan, D.N., Meggitt, W.F. & Penner, D. (1982) Basis for increased activity from herbicide combinations with ethofumesate applied on sugarbeet (*Beta vulgaris*). *Weed Science* **30**, 195–200.

Egley, G.H. (1986) Stimulation of weed seed germination in soil. *Reviews of Weed Science* **2**, 67–89.

Ennis, W.B., Jr. (1977) Integration of weed control technologies. In: Fryer, J.D. & Matsunaka, S. (eds) *Integrated Control of Weeds.* University of Tokyo Press, Tokyo, pp. 227–242.

Evans, R.R. & Dexter, A.G. (1981) Sugarbeet injury from glyphosate applied to redroot pigweed. *North Central Weed Control Conference.* Fargo, ND, 36, p. 19.

Forcella, F., Wilson, R.G., Dekker, J., Kremer, R.J., Cardina, J., Anderson, R.L., Alm, D., Renner, K.A., Harvey, R.G., Clay, S. & Buhler, D.D. (1997) Weed seed bank emergence across the Corn Belt. *Weed Science* **45**, 67–76.

Fühling, J.J. (1859) *Anleitung zur rationellen Kultur der Zucker- und- Futterrunkelrüben; nebst Erörterungen über die Erschroopfung des Bodens durch anhaltend fortgesetzten Zuckerrübenbau, ihre Ursachen und Vermeidung.* M. Cohen, Bonn.

Green, R.E. (1980) Food selection by skylarks and grazing damage to sugar beet seedlings. *Journal of Applied Ecology* **17**, 3, 613–630.

Guedon, P. (1928) Essai de nettoyage des betteraves par l'acide sulforique. *Bulletin de l'Association des Chimistes de Sucrerie de Distillerie et des Industries Agricoles de France et des Colonies*, Vol. 45, pp. 370–371.

Gwynne, D.C. & Murray, R.B. (1985) *Weed Biology and Control in Agriculture and Horticulture.* Batsford Academic and Educational, London.

Hani, A., Ammon, H.U. & Keller, S. (1990) Influence of weed density on aphid populations and the spread of virus yellows on sugarbeet. [German]. *Proceedings of the 53rd IIRB Congress.* Brussels, pp. 355–368.

Hart, S.E., Saunders, J.W., Penner, D. & Renner, K.A. (1994) Initial field evaluation of sulfonylurea herbicide resistant sugarbeet from somatic cell selection. *Journal of Sugar Beet Research* **31**, (3 & 4), 97–103.

Heap, I. & LeBaron, H. (2001) Introduction and review of resistance. In: Powles, S. & Shaner, D.L. (eds) *Herbicide Resistance in World Grains.* CRC Press, Boca Raton, FL.

Heard, M.S., Hawes, C., Champion, G.T., Clark, S.J., Firbank, L.G., Haughton, A.J., Parish, A.M., Perry, J.N., Rothery, P., Roy, D.B., Scott, R.J., McSkellern, M.P., Squire, G.R. & Hill, M.O. (2003) Weeds in fields with contrasting conventional and genetically modified herbicide-tolerant crops. II. Effects on individual species. *Philosophical Transactions of the Royal Society*, London, B 358, 1833–1846.

Hermann, O., De Temmerman, L. & Van Himme, M. (1992) Onkruidbestrijdring in de suikerbiet met het FAR-systeem. *De Bietplanter*, 24–27.

Hill, T.A. (1977) *The Biology of Weeds.* Edward Arnold, London.

Holm, L.G., Plucknett, D.L., Pancho, J.V. & Herberger, J.P. (1977) *The World's Worst Weeds: Distribution and Biology.* University Press of Hawaii, Honolulu.

Idris, M. & Beshir, M.E. (1979) On the distribution and dynamics of weed populations in Sudan Gezira. *Proceedings of the Symposium of Weed Research.* Sudan, **18**, pp. 15–23.

Jansen, L.L. (1972) Extent and cost of weed control with herbicides and an evaluation of important weeds, 1968. ARS-H-1. Agricultural Research Service, US Department of Agriculture, Washington, DC.

Jones, P.A., Blair, A.M. & Orson, J.H. (1996) Mechanical damage to kill weeds. *Proceedings of the 2nd International Weed Control Congress.* Copenhagen, Denmark, Department of Weed Control and Pesticide Ecology, Slagelse, Denmark, pp. 949–954.

Jutsum, A.R. (1988) Commercial application of biological control: status and prospects. In: Wood, R.K.S. & Way, M.J. (eds) *Biological Control of Pests, Pathogens and Weeds: Developments and Prospects.* Royal Society, London, pp. 247–268.

Khachatourians, G.G. (1986) Production and use of biological pest control agents. *Trends in Biotechnology* **4**, 120–124.

Kniss, A.R., Wilson, R.G., Burgener, P.A. & Feuz, D.M. (2003) Economic analysis of herbicide tolerant sugarbeet. *Proceedings of the 1st Joint IIRB–ASSBT Congress.* San Antonio, pp. 91–96.

Knott, C. (2001) The outlook for minor pesticide uses in the UK and Europe. *Pesticide Outlook.* Royal Society of Chemistry, Cambridge, UK, **12** (6), 224–228.

LeBaron, H.M. & Gressel, J. (1982) *Herbicide Resistance in Plants.* John Wiley, New York.

Longden, P.C. (1987) Weed beet: past, present and future. *International Sugar Economic Year Book and Directory.* F.O. Licht, pp. F5–F16.

Longden, P.C. (1989) Effects of increasing weed-beet density on sugar beet yield and quality. *Annals of Applied Biology* **114**, 527–532.

Madge, W.R. (1982) 'The little and often approach' for weed control in sugar beet. *Proceedings of the British Crop Protection Council – Weeds.* 1, pp. 73–78.

Mallory-Smith, C.A., Thill, D.C. & Dial, M.J. (1990) Identification of sulfonylurea herbicide-resistant prickly lettuce (*Lactuca serriola*). *Weed Technology* **4** (1), 163–168.

Markus, W. (1940) *Die Bekämpfung von Unkräutern und Schädlingen mit besonderer Berücksichtigung der Düngung mit Kalkstickstoff.* Berlin.

Marshall, J., Ayres, R.J. & Bardsley, E.S. (1987) Phenmedipham co-formulations for broadleaved-weed control in sugar beet. *Proceedings of the British Crop Protection Council – Weeds.* Brighton, 1, pp. 233–240.

May, M.J. (1982) Repeat low dose herbicide treatments for weed control in sugar beet. *Proceedings of the British Crop Protection Council – Weeds.* 1, pp. 79–84.

May, M.J. (2000) Efficacy and selectivity of RR and LL weed control techniques compared to classical weed control systems. *Proceedings of the 63rd IIRB Congress.* Interlaken, pp. 163–170.

May, M.J. (2003) Economic consequences for UK farmers of growing GM herbicide tolerant sugar beet. *Annals of Applied Biology* **142**, 41–48.

May, M.J. & Hilton, J.G. (1985) Reduced rates of pre-emergence herbicides (1982–1984). *77th Report of the Norfolk Agricultural Station*, pp. 14–21.

McClean, S.P. (1982) Developing a strategy for weed control in sugar beet. *Proceedings of the British Crop Protection Council – Weeds.* 1, pp. 91–96.

McClean, S.P. & May, M.J. (1986) A comparison of overall herbicide application with band-spraying and inter-row cultivation for weed control in sugar beet. *Proceedings of the 49th IIRB Congress.* Brussels, pp. 345–354.

McWhorter, C.G. (1970) A recirculating spray system for post-emergence weed control in row crops. *Weed Science* **18**, 285–287.

Meyer, H., Widmer, U. & Ammon, H.U. (1986) Konkurrenz der Unkräuter und Einfluss auf die Unkrautbekämpfungssysteme im Zuckerrübenbau. *Proceedings of the 49th IIRB Congress.* Brussels, pp. 263–275.

Mickelson, J.A., Particka, M.G., Flowers, N.D. & Fischer, T.A. (2001) ALS resistant Kochia management in barley-beet rotation (Experiment GN00B60). In: *Montana Agricultural Experiment Station results of weed management research conducted in South Central Montana – 2001.* p. 73.

Milton, W.E. (1943) The buried viable-seed content of a Midland calcareous clay soil. *Journal of Ecology* **31**, 155.

Moll, S. (1997) Commercial experience and benefits from glyphosate tolerant crops. *Proceedings of the British Crop Protection Council – Weeds.* 3, pp. 931–940.

Neururer, H. (1975) Changes in weed flora within the last 10 years in intensively used beet-growing districts of Austria because of modern agricultural practices. *Troisième Réunion Internationale sur le Desherbage Sélectif en Cultures de Betteraves.* pp. 309–388.

Neururer, H. (1977) Mechanical weed control with modern harrows. *Proceedings of the EWRS Symposium on Different Methods of Weed Control and their Integration.* 1, pp. 65–70.

Neururer, H. (1984) Einfluss von 'Bitumenmulch' auf den Unkrautaufgang und die Pflanzenverfügbaskeit von Bodenherbiziden. *Zeitschrift für die Pflanzenkrankheitenund Pflanzenschutz* **10**, 293–295.

Neururer, H. (1985) Warum 1985 mehr Handarbeit in der Zuckerrübe? *Pflanzenschutz* **9**, 5.

Neururer, H. (1986) Methode zur raschen Feststellung der Empfindlichkeit junger Rubenflanzen gegenuber Nachauflaufherbiziden und ihr Einsatz als sognannte 'Empfindlichkeitsprognose' in der Praxis. *Mitteilungen aus der Biologischen Bundesanstalt für Land und Forstwirtschaft* **232**, 321.

Pekrun, C. & Lutman, P.J.W. (1998) The influence of post-harvest cultivation on the persistence of volunteer oilseed rape. *Aspects of Applied Biology* **51**, 113–118.

Petersen, J. (2004) Rotary band seeding of glyphosate tolerant sugar beet into dead and living mulch. *Proceedings of the 67th IIRB Congress.* Brussels, pp. 115–129.

Pidgeon, J.D., Dewar, A.M. & May, M.J. (2004) GM beet contribute to sustainable crop production in Europe? *International Sugar Journal* **106** (1270), 542–547.

Preston, P.E. & Biscoe, P.V. (1982) Environmental factors influencing sugar beet tolerance to herbicides. *Proceedings of the British Crop Protection Council – Weeds.* Brighton, 1, pp. 85–90.

Primiani, M.M., Cotterman, J.C. & Saari, L.L. (1990) Resistance of kochia (*Kochia scoparia*) to sulfonylurea and imidazolinone herbicides. *Weed Technology* **4** (1), 169–172.

Radosevich, S.R. & Holt, J. (1984) *Weed Ecology: Implications for Vegetation Management.* John Wiley, New York.

Read, M.A. & Bush, M.N. (1998) Control of weeds in genetically modified sugar beet with glufosinate-ammonium in the UK. *Aspects of Applied Biology* **52**, 401–406.

Roberts, H.A. & Feast, P.M. (1973) Emergence and longevity of seeds of annual weeds in cultivated and undisturbed soil. *Journal of Applied Ecology* **10**, 133–143.

Robinson, T.H. (2002) Methodology of application. In: Naylor, R.E. (ed.) *Weed Management Handbook.* Blackwell Science, Oxford, pp. 199–224.

Robinson, R.A. & Sutherland, W.J. (2002) Post-war changes in arable farming and biodiversity in Great Britain. *Journal of Applied Ecology* **39**, 157–176.

Roemer, T. (1927) *Handbuch des Zuckerrübenbaues.* Parey, Berlin.

Sammons, R.D., Heering, D.C., Kinicola, N., Glick, H. & Elmore, G.A. (2004) Sustainability and stewardship of glyphosate and Roundup Ready® crops. *Weed Science* (in press).

Sands, D.C., Ford, E. & Miller, R.V. (1989) Genetic manipulation of fungi for biological control of weeds. *Weed Science Society of America Abstracts* **29**, 123.

Schultz, G. (1899) Zur Vernichtung des Ackersenfs und des Hederichs. *Landwirtschaft Zeitung für Westfalen und Lippe* **56**, 1–2.

Schweizer, E.E. (1981) Broadleafweed interference in sugarbeets (*Beta vulgaris*). *Weed Science* **29**, 128–133.

Schweizer, E.E. & Dexter, A.G. (1987) Weed control in sugarbeets (*Beta vulgaris*) in North America. *Reviews of Weed Science* **3**, 1133.

Schweizer, E.E. & Lauridson, T.C. (1985) Powell amaranth (*Amaranthus powellii*) interference in sugarbeet (*Beta vulgaris*). *Weed Science* **33**, 518–520.

Schweizer, E.E. & Zimdahl, R.L. (1984) Weed seed decline in irrigated soil after rotation of crops and herbicides. *Weed Science* **32**, 84–89.

Scott, R.K., Wilcockson, S.J. & Moisey, F.R. (1979) The effects of time of weed removal on growth and yield of sugar beet. *Journal of Agricultural Science* **93**, 693–709.

Smith, G.A. & Moser, H.S. (1985) Sporophytic-gametophytic herbicide tolerance to sugarbeet. *Theoretical Applied Genetics* **71**, 231–237.

Smith, J. (1983) Review of the post-emergence low volume, low dose application technique. *Aspects of Applied Biology 2, Pests, diseases, weeds and weed beet in sugar beet*, pp. 189–195.

Smith, G.A. & Schweizer, E.E. (1983) Cultivar X herbicide interaction in sugarbeet. *Crop Science* **23**, 2, 325–328.

Sotherton, N. (1992) The environmental benefits of conservation headlands in cereal fields. *Outlook on Agriculture* **21** (3), 219–224.

Southcombe, E.S.E., Miller, P.C.H., Ganzelmeier, H., Van de Zande, J.C., Miralles, A. & Hewitt, A.J. (1997) The International (BCPC) Spray Classification System Including a Drift Potential Factor. *Proceedings of the British Crop Protection Council.* 1, pp. 371–380.

Squire, G.R., Brookes, D.R., Bohan, D.A., Champion, G.T., Daniels, R.E., Haughton, A.J., Hawes, C., Heard, M.S., Hill, M.O., May, M.J., Osborne, J.L., Perry, J.N., Roy, D.B., Woiwod, I.P. & Firbank, L.G. (2003) On the rationale and interpretation of the Farm Scale Evaluations of genetically modified herbicide-tolerant crops. *Philosophical Transactions of the Royal Society, London*, B358, 1779–1799.

Stevens, O.A. (1932) The number and weights of seeds produced by weeds. *American Journal of Botany* **19**, 784–794.

Sullivan, E.F. & Fischer, B.B. (1971) Weed control. In: Johnson, R.T., Alexander, J.T., Rush, G.E. & Hawkes, G.R. (eds) *Advances in Sugarbeet Production: Principles and Practices.* Iowa State University Press, Ames, pp. 69–109.

Templeton, G.E., Smith, R.J. & TeBeest, D.O. (1986) Progress and potential of weed control with mycoherbicides. *Reviews of Weed Science* **2**, 1–14.

Terpstra, R. (1986) The behavior of weed seed in soil clods. *Weed Science* **34**, 889–895.

Tillett, N. & Wiltshire, J. (2001) New vision guided tractor hoe. *British Sugar Beet Review* **69** (4), 40–43.

Ulber, B. (1980) Studies on the food choice of *Onychiurus fimatus* Gisin (Onychiuridae, Collembola), a seedling pest of sugar beet. [German] Untersuchungen zur Nahrungswahl von *Onychiurus fimatus* Gisin (Onychiuridae, Collembola), einem Aufgangsschadling der Zuckerrube. *Zeitschrift fur Angewandte Entomologie* **90** (4), 333–346.

Van Rijn, P.J. (1969) The effect of soil depth on emergence of weed seedlings, in ecological aspects of weed control in cotton in the Ord River Valley. Australian *Journal of Experimental Agriculture and Animal Husbandry* **9**, 19.

Villarias Moradillo, J.L. (1986) Lutte intégrée contre les mauvaises herbes en culture betteravière en régions méditerranéenes. *Proceedings of the 49th IIRB Congress.* Brussels, pp. 287–295.

Von Unwerth (1899) *Vertilgung von Hederich. Z. d. Landw. Kammer Provinz Schlesien* **111**, 880.

Werker, A.R. & Jaggard, K.W. (1998) Dependence of sugar beet yield on light interception and evapotranspiration. *Agricultural and Forest Meteorology* **89** (3/4), 229–240.

Werner, H. (1888) Derpraktische Zuckerrübenbauer. *Leitfaden zum rationallen Anbau der Zuckerrüben.* M. Cohen, Bonn.

Wevers, J.D.A., Aarts, H.F.M. & Kouwenhoven, J.K. (1986) The effect of pre-drilling cultural practices on weed problems and control methods in sugar beet. *Proceedings of the 49th IIRB Congress.* Brussels, pp. 303–319.

Wicks, G.A. & Somerhalder, B.R. (1971) Effect of seedbed preparation for corn on distribution of weed seed. *Weed Science* **19**, 666–668.

Wilson, R.G. (1987) Biology of weed seed in the soil. In: Altieri, M.A. & Liebman, M. (eds) *Weed Management in Agroecosystems: Ecological Approaches.* CRC Press, Boca Raton, FL. pp. 25–39.

Wilson, R.G. (1999) Response of nine sugarbeet (*Beta vulgaris*) cultivars to postemergence herbicide applications. *Weed Technology* **13**, 25–29.

Wilson, R.G. & Anderson, F.N. (1981) Control of three weed species in sugarbeets (*Beta vulgaris*) with an electrical discharge system. *Weed Science* **29**, 93–98.

Wilson, R.G. & Smith, J.A. (1992) Winter wheat and winter rye cover crops for the establishment of sugarbeets. *Journal of Sugar Beet Research* 29, 1 and 2, 23–30.

Wilson, R.G. & Smith, J.A. (1999) Crop production with glyphosate tolerant sugarbeet. In: *30th General Meeting of American Society of Sugar Beet Technologists Abstracts.* p. 50.

Wilson, R.G., Kerr, E.D. & Nelson, L.A. (1985) Potential for using weed seed content in the soil to predict future weed problems. *Weed Science* **33**, 171–175.

Wilson, R.G., Shea, P.J. & Tupy, D.R. (1995) Dinitroaniline herbicide carry over to sugarbeet. *Journal of Sugar Beet Research* **32** (4), 201–213.

Wilson, R.G., Yonts, C.D. & Smith, J.A. (2002) Influence of glyphosate and glufosinate on weed control and sugarbeet (*Beta vulgaris*) yield in herbicide-tolerant sugarbeet. *Weed Technology* **16**, 66–73.

Wyse, D.L. & Habstritt, C. (1977) A roller herbicide applicator. *Proceedings of the North Central Weed Control Conference.* MO, 32, pp. 144–145.

Zimdahl, R.L. (1980) *Weed-Crop Competition: A Review.* International Plant Protection Centre, Oregon State University, Corvallis.

Chapter 15
Storage

Larry G. Campbell and Karen L. Klotz

INTRODUCTION

The primary objective of beet storage operations is to retain a high proportion of the sugar accumulated during the growing season and to prevent formation of compounds that interfere with sugar extraction while the harvested crop awaits processing. The harvested root is a living organism that must either be kept alive to maintain its physical integrity during storage, or completely frozen and processed before thawing. This task is complicated by the large mass of roots that must be handled. Roots harvested from a single hectare producing 53 t will occupy approximately 80 m^3. When this is multiplied by the 5.6 million ha in Europe, the 560 000 ha in the USA, or the 7 million ha produced worldwide (Draycott & Christenson, 2003), it becomes apparent that providing optimum controlled-environment storage facilities is not feasible, so compromises are necessary.

Production regions differ in the length of both their harvest and processing campaigns, and hence the time roots are held in storage before processing. In some Mediterranean countries and California (USA), the climate allows for extended harvests and roots are processed soon after harvest; the only stockpiling that occurs is to prevent a factory shutdown if harvest is interrupted as a result of poor weather. In other European countries, the processing campaign extends beyond harvest and may last for up to 100 days (Martens & Oldfield, 1970). After harvest, roots are stored in on-farm clamps that range in size from 100 to 1000 t. Later, the crop is delivered to a collection site or directly to the factory for processing. In most of the USA, the crop is harvested during a 2- to 4-week period in late autumn and immediately delivered to central piling stations maintained by the processors. Roots are stored outdoors in piles 5 to 8 m high, 55 to 70 m wide, and up to 400 m long. Typical processing campaigns range from 120 days in areas with moderate winters up to 250 days in northern regions with cold winters.

Sugar loss begins on the first day of storage and rapidly increases while a large portion of the crop is in storage. Although beet at the end of the storage campaign are in much poorer condition, half of the total post-harvest sugar lost may occur within the first 2 weeks (Fox, 1973), and up to 70% during the first 40 days of storage as piles are cooling down and ambient temperatures are relatively high (Wyse, 1975). In western Europe, seasonal average losses of 200 g of sugar per tonne of beet per day are considered typical. Daily losses in the first 5 days of storage are frequently three times those that occur 2–3 weeks later. In Italy, storage time is kept short because sugar losses of 1500 g/t/day are common (Martens & Oldfield, 1970; Vaccari *et al*., 1988). Reported storage losses in the Great Plains of the USA range from 18.7 to 22.5 kg sugar per tonne, with an average loss of 206 g/t/day, during a 100-day storage period. In addition to the direct loss of sugar during storage, Bichsel (1973) reported that sugar recovery rates decreased from a high of 82% in late autumn to below 70% after 130 days in storage. Factory slice rates declined by 20% over a 2-month period while the cost of producing a unit of sugar increased by 30%.

Losses incurred during storage represent a substantial decrease in revenue for the sugar industry. When multiplied over the volume of roots processed and time in storage, even small reductions in storage losses can have a significant economic impact. In many instances, close attention to details and relatively minor changes in procedures can significantly reduce losses with no, or small, increases in operating costs.

RESPIRATION

Post-harvest sugar losses occur as a result of respiration, conversion of sugar to other carbohydrates, and storage diseases. Respiration, however, is typically the major cause of post-harvest sugar loss and accounts for as much as 80% of the sugar lost during storage under ideal conditions (Wyse & Dexter, 1971b). Under actual storage conditions, the contribution of respiration to overall sugar loss is somewhat lower, since carbohydrate conversions and storage diseases become increasingly important as storage conditions deviate from the ideal. Nevertheless, respiration remains the principal cause for post-harvest sugar loss.

Respiration is the oxidative process in which cellular organic compounds are converted to carbon dioxide and water to generate metabolic substrates and energy. Harvested roots, if not frozen, respire constantly to provide the energy and carbon substrates required to maintain metabolism, heal wounds incurred during harvest and piling, and protect against pathogens. Carbohydrates are the principal substrates for respiration in plants, although amino acids, proteins, organic acids, or lipids can also be used. In sugar beet, the primary substrate for respiration is sucrose (Barbour & Wang, 1961). However, other substrates are also utilized, since the rate of carbon dioxide evolved in stored roots exceeds the rate of sugar respired (Wyse & Dexter, 1971b). The non-sugar substrates used for respiration have yet to be identified, although a decline in amino acid and protein content during storage has been documented (Wyse & Dexter, 1971b; Pavlinova *et al.,* 1979).

The overall reaction for the respiration of sugar (Equation 15.1) is accompanied by the release of 5764 kJ of energy for each mole of sugar degraded:

$$\begin{aligned}&C_{12}H_{22}O_{11} + 12O_2 + 13H_2O\\&\rightarrow 12CO_2 + 24H_2O\ (\Delta G^{o\prime} = -5764\ \text{kJ})\end{aligned} \qquad (15.1)$$

This energy is used to catalyse the phosphorylation of ADP to ATP (Equation 15.2), conserving the energy released from the oxidative breakdown of sugar in the chemical bonds of ATP.

$$\begin{aligned}&ADP^{-3} + HPO_4^{-2} + H^+\\&\rightarrow ATP^{-4} + H_2O\ (\Delta G' = 30.5\ \text{kJ})\end{aligned} \qquad (15.2)$$

However, not all of the energy released in the degradation of sugar is conserved by ATP synthesis. The complete respiration of one molecule of sugar generates 60–64 ATP molecules with a net capture of 1830–1952 kJ of energy (Siedow & Day, 2000). The remaining energy, equivalent to 11.1–11.5 kJ per gram of sugar degraded, is dissipated as heat, and can significantly contribute to warming of storage piles or clamps.

The net reaction of respiration, as described in the above equations, belies the complexity of the process. Respiration is a multistep process involving sucrolysis, glycolysis, the tricarboxylic acid cycle, electron transport and oxidative phosphorylation, and requires the transport of substrates and intermediates between three intracellular locations (Fig. 15.1). The overall stoichiometry may also differ from that presented above, since intermediates from various steps can be diverted into other biosynthetic pathways to produce amino acids, nucleotides, cell wall components, lipids, defence compounds and other metabolic intermediates. This diversion of carbon intermediates prevents the complete conversion of sugar to carbon dioxide.

Respiration begins with cleavage of sucrose into hexose sugars, creating substrates for glycolysis. In post-harvest sugar beet roots, sucrose cleavage is most likely catalysed by sucrose synthase (Pavlinova *et al.*, 1979; Echeverría, 1998; Etxeberria & Gonzalez, 2003). Sucrose synthase is a cytoplasmic enzyme that catalyses the reaction of uridine 5′-diphosphate (UDP) with sucrose, generating fructose and UDP-glucose. The fructose formed in this reaction can readily be used as a substrate for glycolysis. UDP-glucose can also be utilized as a glycolytic substrate after its conversion to glucose 1-phosphate by the cytoplasmic enzyme, UDP-glucose pyrophosphorylase. Because sucrose is stored in the vacuole (Leigh *et al.*, 1979), sucrose cleavage by sucrose synthase requires prior transport of sucrose across the tonoplast. Sucrose export from the vacuole is mediated by an ATP-dependent efflux

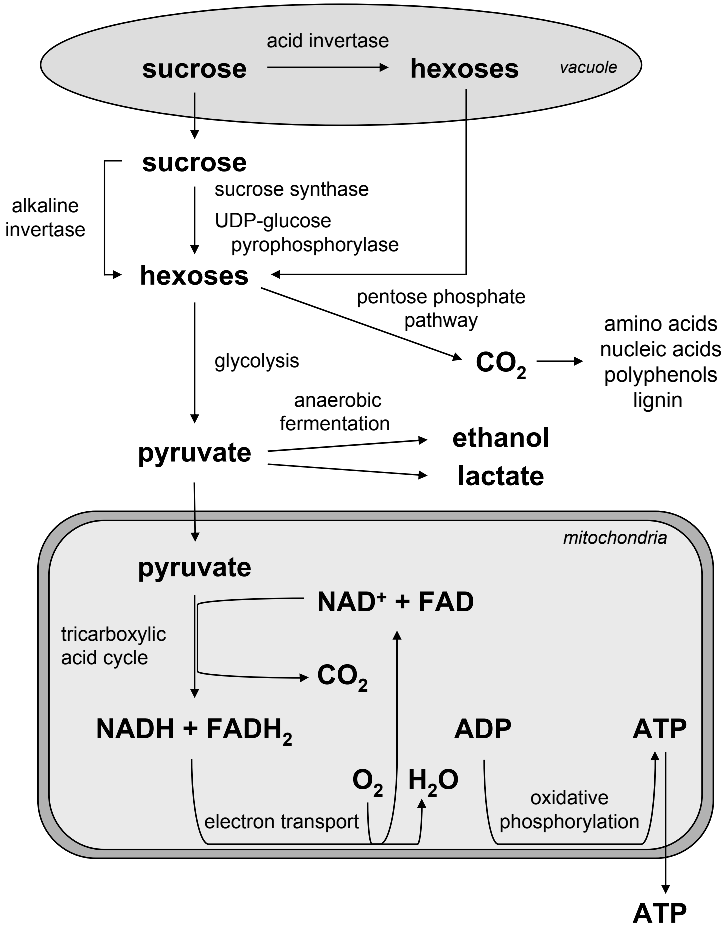

Fig. 15.1 Schematic representation of the major metabolic and transport pathways involved in the respiration of sucrose under aerobic and anaerobic conditions.

mechanism that is independent of the sucrose/H^+ antiporter that mediates sucrose import into the vacuole (Echeverría & Gonzalez, 2000).

Although current evidence supports a predominant role for sucrose synthase in sucrose cleavage, sucrolysis by alkaline and acid invertases cannot be ruled out (Wyse, 1974; Berghall *et al.*, 1997). Alkaline and acid invertases catalyse the hydrolysis of sucrose to fructose and glucose, but differ in their subcellular location and pH optimum for activity. Alkaline invertase, a cytoplasmic enzyme, is most active at the neutral to slightly alkaline conditions that occur in the cytoplasm. Acid invertase, a vacuolar enzyme, exhibits greatest activity at the acidic pH values typical of its intracellular location. Although both enzymes are present in stored roots, their activity is considerably lower than that of sucrose synthase (Berghall *et al.*, 1997; Klotz & Finger, 2004).

The hexose sugars generated by the cleavage of sucrose are primarily used as substrates for glycolysis. In glycolysis, cytoplasmic enzymes cleave and oxidize hexose sugars to form pyruvate, a three-carbon organic acid. Since carbon oxidation is coupled to the reduction of the cofactor, nicotinamide adenine dinucleotide (NAD^+), glycolysis does not require oxygen. Alternatively, hexose sugars can be oxidized by the pentose phosphate pathway. The oxidation of hexose by this pathway is incomplete, and produces one molecule of carbon dioxide for each hexose sugar entering the pathway. The remaining carbon is used to generate intermediates that can be diverted toward the synthesis of amino acids, nucleic acids, polyphenols and lignin. In sugar beet roots, both glycolysis and the pentose phosphate pathway are operational. The glycolytic pathway, however, is predominant, and has been estimated to account for 65–70% of the hexose sugars oxidized (Wang & Barbour, 1961).

The pyruvate formed in glycolysis is transported across the double membrane of the mitochondria by a pyruvate transporter and used as substrate for the tricarboxylic acid cycle (TCA). The TCA cycle oxidizes pyruvate to carbon dioxide with concomitant reduction of the nicotinamide and flavin cofactors, NAD^+ and FAD. The reduced cofactors are reoxidized by the electron transport system, a collection of mitochondrial inner membrane proteins that catalyse a multistep transfer of electrons from NADH and $FADH_2$ to oxygen. The final electron transfer in this process reduces oxygen to water and is catalysed by cytochrome *c* oxidase or alternative oxidase. Although both oxidases are present in postharvest sugar beet roots, cytochrome *c* oxidase accounts for more than 85% of the terminal oxidase activity present and is likely to be the primary enzyme catalysing this reaction (Klotz *et al*., 2003).

The final step in respiration is oxidative phosphorylation, the reaction that conserves a portion of the energy released during electron transport in the chemical bonds of ATP. In oxidative phosphorylation, ADP and inorganic phosphate are condensed to ATP by the enzyme ATP synthase. The reaction is driven by an electrochemical potential generated across the mitochondrial inner membrane during electron transport. Newly synthesized ATP is exported from the mitochondria via an adenine nucleotide carrier that exchanges mitochondrial ATP for cytoplasmic ADP. The exchange maintains a supply of ADP for continued oxidative phosphorylation reactions and releases ATP to the cytoplasm where it can be utilized.

Completion of respiration requires an adequate supply of oxygen. Low or no oxygen conditions, however, can occur during storage because of inadequate ventilation of storage piles or clamps, especially if excessive quantities of soil or plant foliage are present. Under oxygen-limiting conditions, the respiratory process terminates after glycolysis, and pyruvate, the product of glycolysis, is metabolized to ethanol or lactate by fermentation. In sugar beet roots, fermentation leading to ethanol production predominates over fermentation leading to lactate formation (Zhang & Greenway, 1994). Fermentation allows metabolism to continue under reduced oxygen conditions, but it results in large sugar losses since anaerobic respiration requires 15- to 16-fold more sucrose to generate an equivalent amount of ATP than aerobic respiration. Moreover, ethanol, the principle product of fermentation, is toxic and in sufficient quantities can lead to cell death. The oxygen concentration at which anaerobic conditions develop in sugar beet roots is temperature dependent. At 25°C, sugar beet roots become anaerobic at 5% oxygen. At lower temperatures, roots can maintain aerobic respiration at lower oxygen tensions, and roots stored at 5°C do not become anaerobic even at oxygen concentrations of 2% (Wyse, 1973a).

Respiration in plants is regulated by the availability of respiratory substrates, total respiratory activity, or the energy status of the cell. In sugar beet root, the mechanism that controls respiration has not been established, although a lack of association between respiration and respiratory activity (Klotz *et al*., 2003) or cellular energy status (Shugaev & Bukhov, 1997) suggests that respiration may be regulated by substrate availability. Possible substrates limiting respiration are oxygen, ADP and carbon substrates. In sugar beet, a positive association between respiration rate and root surface area suggests that oxygen availability may limit respiration (Stout, 1954; Wyse & Dilley, 1973). Regulation of respiration by oxygen limitation occurs when oxygen utilization by internal tissues exceeds the rate of gas diffusion through the organ. Current evidence suggests that the availability of ADP, a substrate for oxidative phosphorylation, is not limiting in sugar beet since no association between respiration rate and ADP concentration was observed in mature roots (Shugaev & Bukhov, 1997). The possible regulation of respiration by carbon substrate availability has not been examined. Carbon substrate availability is determined by the flux of carbon compounds through glycolysis and the TCA cycle.

Although the physiological mechanisms regulating respiration have not been established, many factors that influence respiration rate have been identified. Sugar beet respiration is strongly impacted by genetic factors, harvest practices, storage conditions, and disease. Storage respiration rate is determined in part by heritable factors. Differences in respiration rate of up to 250% between inbred lines and 150% between sugar beet hybrids have been attributed to genetic variation (Theurer *et al.*, 1978; Wyse *et al.*, 1978). Both additive and non-additive gene action control respiration rate, and hybrids generally have lower respiration rates than either parent.

Events occurring at harvest strongly impact storage respiration rates. Topping method, the amount of injury incurred during root harvest, transport and piling, and the overall health of the root at time of harvest affect respiration rates during short and long term storage. The method of leaf and petiole removal prior to harvest influences respiration rate, especially during short term storage. Roots defoliated with rubber flails, in which leaf and petiole tissue is removed but the taproot is left intact, respire at slightly higher rates than lightly scalped roots, in which the portion of the taproot to which living leaves are attached is removed. Topped roots, in which the crown tissue down to the lowest leaf scar is removed, respire at significantly lower rates than flailed or scalped roots (Wyse, 1978b; Wyse & Peterson, 1979; Steensen & Augustinussen, 2003). The difference in respiration rate due to topping method is greatest during the first week in storage. Respiration rate differences, however, decline with storage duration, and the impact of topping method on respiration rate after the first few weeks in storage is minimal. Topping decreases respiration, since crown tissue respires at a higher rate than the subtending root tissue (Wyse, 1978b; Klotz *et al.*, 2003). The removal of crown tissue, however, reduces root yield and facilitates the development of storage rots, negating any benefit gained from reduced respiration (Wyse, 1978b; Jaggard *et al.*, 1999). In roots defoliated by flailing, more vegetative buds remain intact than in scalped or topped roots. The greater metabolic activity of these buds and the increased frequency of leaf regrowth likely contribute to the greater respiration rate of flailed roots (Steensen & Augustinussen, 2003). Respiration rate is also greater if petiole tissue is not completely removed by flailing (Koster *et al.*, 1980).

Storage respiration rate is also influenced by the extent of root injury during harvest, transport and piling. Root injury causes respiration rate to increase within 24 hours of the injury and remain elevated for the remainder of the storage period (Dilley *et al.*, 1970; Wyse, 1978b; Wyse & Peterson, 1979). Respiration rate increases are directly related to injury severity and estimates of the magnitude of respiratory increase due to injury range from 25 to 400%, based on the type and severity of the wound and the storage conditions employed (Akeson & Stout, 1978; Wyse & Peterson, 1979; Peterson *et al.*, 1981). Root injury also impacts storage respiration by increasing the prevalence of storage diseases and generating ethylene, a promoter of respiration. Injury is a prerequisite for fungal infection by *Botrytis cinerea* Pers. Ex Fr. and *Penicillium* spp., two causal agents of storage rot (Mumford & Wyse, 1976). Without breakage of the epidermis and exposure of internal tissues, these pathogens do not establish an infection. Storage rots cause root respiration rate to increase in proportion to the severity of the infection, and infections affecting approximately 20% of the root surface have been shown to increase the respiration rate by 80–100% (Mumford & Wyse, 1976). Respiration rate is also increased by ethylene, a gas produced by many mould- and rot-causing organisms and injured plant tissues. A 25% increase in respiration rate, which persisted for at least 10 days, was observed in sugar beet roots after ethylene exposure (Dilley *et al.*, 1970). Although ethylene production in response to root injury and decay is presumed, the ability of wounded sugar beet tissue and sugar beet storage pathogens to produce ethylene has not been demonstrated.

The condition of sugar beet at time of harvest also impacts storage respiration rate. Respiration rates of roots with severe symptoms of *Aphanomyces cochlioides* Drechsl. root rot were five times those observed in healthy roots 18 days after harvest, and remained higher during 138 days of storage (Campbell & Klotz, 2003). Frost damage prior to harvest also increases storage respiration rate. Akeson (1973) reported a twofold increase in respiration rate during storage of roots exposed to frost 2 days prior to harvest, and observed an elevation in respiration rate in frost-damaged roots for the duration of storage – even though no visible symptoms of root stress were apparent.

Storage conditions, most notably storage temperature, affect sugar beet root respiration rate and impact the amount of sugar lost during storage. Respiration rate generally declines with decreasing temperature until roots freeze and respiration stops. Roots typically freeze at –2 to –5°C (Oldfield *et al.*, 1971b; Wyse, 1978a; Milford *et al.*, 2002). The freezing temperature is determined by cellular osmotic potential, with different cells within a root freezing at slightly different temperatures. At constant temperature, root respiration rate is nearly constant and directly related to absolute temperature. Temperature fluctuations near the freezing temperature of roots, however, increase respiration rate. Transitory elevations in respiration have been observed when root temperature was raised or lowered past –1 to 0°C (Wyse, 1978a). This respiratory increase is a likely response to chilling or freezing injury since membrane permeability increases at –1 to 0°C.

Carbon dioxide and oxygen concentrations in piles and clamps can deviate from atmospheric conditions and alter root respiration rate. If ventilation is inadequate, carbon dioxide, a product of respiration, can accumulate and oxygen, a substrate for respiration, can become depleted. Carbon dioxide accumulation and oxygen depletion generally reduce respiration rate in plant products. In sugar beet roots, carbon dioxide accumulation from 0.035%, the concentration present in air, to 5% had minimal impact on respiration rate (Stout, 1954; Wyse, 1973a). Oxygen depletion, however, from the 21% present in air to 5%, reduced respiration rate by 40–75% in different studies (Stout, 1954; Wyse, 1973a). Below 5% oxygen, carbon dioxide production can increase significantly as a result of anaerobic fermentation. The oxygen concentration at which roots become anaerobic is temperature dependent as discussed above.

As a result of the influence of harvest practices, storage conditions and disease, respiration rate is not constant during storage (Fig. 15.2). Generally, respiration rate is greatest in the first 2–3 days of storage and declines during the following 1–2 weeks (Akeson, 1973; Wyse & Peterson, 1979). The high level of respiration during the first few days in storage reflects the effect of harvest and piling injury, and the higher temperature of the roots at time of harvest. During the following 1–2 weeks in storage, respiration declines as root injuries heal (Ibrahim *et al.*, 2001) and temperatures decline – weather permitting. Under ideal storage conditions, respiration rate during long term storage continues at a near constant rate for at least an additional 160 days. During this period, respiration rate is dependent primarily on storage temperature. In piles and clamps where storage conditions deviate from the ideal, fluctuations in respiration rate occur during long term storage. Injury due to freezing and thawing of roots, the development of storage rots, and the possible development of anaerobic conditions cause respiration rate to fluctuate and generally increase during pile and clamp storage.

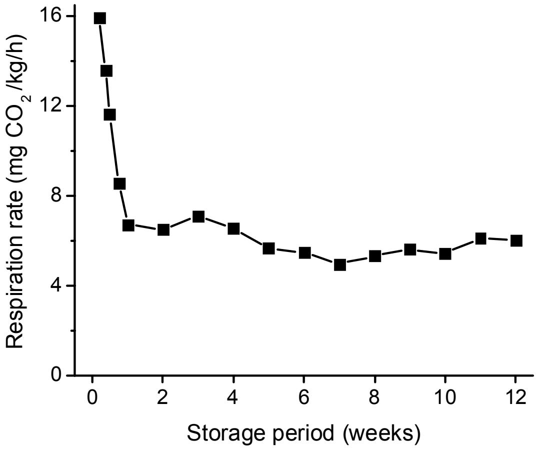

Fig. 15.2 Respiration rate of sugar beet roots during storage at 5°C. Data are the average respiration rates of 15 varieties (adapted from Wyse, 1973a).

CARBOHYDRATE IMPURITY FORMATION

In addition to respiration, post-harvest sugar loss occurs because of the formation of non-sucrose carbohydrates. Glucose, fructose, and raffinose can accumulate during storage of healthy roots, polysaccharide gums may accumulate in frost-damaged roots, and kestoses may accumulate in diseased roots. The formation of non-sucrose carbohydrates is directly responsible for a decline in root sugar content, since sugar is the substrate for their synthesis. Their impact, however, is greatest during processing, because they increase the loss of sugar to molasses and hinder processing by increasing colour formation, interfering with crystallization, and impeding filtration.

Invert sugars

The invert sugars, glucose and fructose, are present at low levels at harvest and accumulate during storage (Wyse & Dexter, 1971b; Jaggard *et al.*, 1997). Invert sugar concentrations at harvest range from 0.1 to 0.6 g/100 g of sucrose, and may increase more than fivefold during storage (Oldfield *et al.*, 1971b; Wyse & Dexter, 1971a; Jaggard *et al.*, 1997). The predominant invert sugar at harvest and throughout storage is glucose (Mahn *et al.*, 2002). Fructose is present at concentrations as much as eightfold lower than glucose at harvest, but accumulates at a greater rate during storage (Jaggard *et al.*, 1997; Martin *et al.*, 2001a). Therefore, invert concentration and the ratio of fructose to glucose typically increase during storage.

Invert sugars are formed by the enzymatic breakdown of sucrose. The reaction is catalysed by the sucrolytic enzymes, sucrose synthase, acid invertase or alkaline invertase as previously described. Both endogenous sugar beet enzymes and enzymes originating from root pathogens contribute to invert sugar formation. Invert sugar accumulation is minimal in healthy roots stored at temperatures of –1 to 5°C (Wyse & Dexter, 1971b; Wyse, 1978a; Pavlinova *et al.*, 1979). Higher storage temperatures generally increase the accumulation of invert sugars, especially when they exceed 10°C (Walker *et al.*, 1960; Wyse & Dexter, 1971a; Wyse, 1978a). The accumulation of invert sugars in healthy roots is catalysed by endogenous sugar beet enzymes and occurs when sucrolytic activity exceeds the demand for biosynthetic and respiratory substrates.

Invert sugar accumulation is influenced most by disease. Root diseases present at time of harvest or developing during storage increase invert sugar concentrations in stored roots. Storage rots increase invert sugar concentration in proportion to the severity of their infection (Mumford & Wyse, 1976; Wyse, 1978b). The impact of storage rot on invert sugar accumulation is significant, and threefold increases in invert sugar concentration have been reported in roots with as little as 15% of their surface area infected (Mumford & Wyse, 1976). The increase in invert sugars is greatest at the site of infection, but may occur in tissues removed from the infection site in severely diseased roots (Mumford & Wyse, 1976). Sucrolytic enzymes originating from the pathogen are likely to be responsible for much of the increase in glucose and fructose concentrations in infected roots (Klotz & Finger, 2004). Endogenous sugar beet enzymes may also contribute to invert sugar formation, since acid invertase expression may be induced as a wound response to infection (Rosenkranz *et al.*, 2001) and tissue degeneration may eliminate the compartmentalization that separates sucrose from sucrolytic enzymes. Diseases present at the time of harvest can also increase invert sugar accumulation during storage. Roots with severe *Aphanomyces* root rot contained 250% more fructose and 190% more glucose than uninfected roots a few days after harvest and accumulated invert sugars more rapidly during storage (Klotz & Campbell, 2002). Roots with rhizomania, the disease caused by *Beet necrotic yellow vein virus*, exhibited elevated invert sugar concentrations after 2 months in storage, although no increase in invert sugar concentration was observed at time of harvest or after 1 month in storage (Hein *et al.*, 2004).

Genetic factors and defoliation method also influence invert sugar accumulation. Threefold differences in the extent of invert sugar accumulation during storage have been attributed to genetic variation (Akeson, 1973). This variation, however, may partially be a reflection of differences in storage rot susceptibility between varieties (Wyse, 1973b). Defoliation method also affects invert sugar concentrations at harvest and during storage. Because invert sugar concentrations are three to five times greater in crown tissue than in the subtending root, topped roots have a lower invert sugar content at harvest than roots defoliated by flailing (Wyse, 1978b; Jaggard *et al.*, 1999; Mahn *et al.*, 2002). During storage, however, topped roots often accumulate greater concentrations of invert sugars than flailed roots because of the frequent development of storage rot at the wound created by topping (Wyse, 1978b). The defoliation method also affects the accumulation of invert sugars by impacting the frequency of leaf regrowth. Leaf regrowth is associated with an increased accumulation of invert sugars and is more prevalent in flailed roots than in topped roots (Wyse & Dexter, 1971a; Steensen & Augustinussen, 2003).

Raffinose

Raffinose is another non-sucrose carbohydrate that is formed during storage and contributes to post-harvest sugar loss. Raffinose is a trisaccharide composed of a galactosyl residue attached to the glucose residue of sucrose by an α-(1→6) glycosidic linkage. Its synthesis is catalysed by raffinose synthase, an enzyme that reversibly transfers a galactosyl residue from galactinol to sucrose. Galactinol, the source of the galactosyl residue, is synthesized by the cytoplasmic enzyme, galactinol synthase. Galactinol synthase condenses *myo*-inositol and UDP-galactose to form galactinol and UDP.

Raffinose is present at low levels at harvest and often accumulates during storage. Raffinose concentrations at harvest are typically in the range of 0.1–0.7 g/100 g sucrose (Brown & Wood, 1952; Martin *et al.*, 2001a). At harvest, raffinose is concentrated in the crown, where concentrations have been reported to be double those of the subtending root (Jaggard *et al.*, 1999; Mahn *et al.*, 2002). During storage, raffinose concentrations change, with the magnitude and direction of change dependent on storage conditions. In the northern USA, raffinose typically accumulates during storage, and two- to fourfold increases in raffinose content have been reported (Walker *et al.*, 1960; Wyse & Dexter, 1971a; Martin *et al.*, 2001a). In more temperate climates, raffinose concentrations may remain relatively unchanged or decline during storage (Jaggard *et al.*, 1997; Martin *et al.*, 2001a).

Raffinose concentration is dependent on genetic and environmental factors. Genetic variability influences raffinose content at harvest and its accumulation during storage. Greater than fourfold differences in raffinose content at time of harvest and twofold differences in its rate of accumulation during storage have been attributed to genetic variability (Brown & Wood, 1952; Wyse & Dexter, 1971a; Wyse, 1973b). Temperature conditions prior to harvest and during storage also influence raffinose accumulation. Low non-freezing temperatures equal to or less than 3°C are generally associated with increases in raffinose content, although the actual temperature at which raffinose accumulation begins is variety dependent (Wyse & Dexter, 1971b). At temperatures in excess of 7°C, raffinose degradation typically exceeds raffinose synthesis, and raffinose content declines. Raffinose degradation is catalysed by α-galactosidase which hydrolyses the galactosyl residue from raffinose to produce galactose and sucrose (McCready & Goodwin, 1966; Peterbauer & Richter, 2001). The raffinose content at harvest is dependent on temperature conditions before harvest. Low temperatures prior to harvest elevate raffinose concentration at time of harvest (Finkner *et al.*, 1959; Wyse & Dexter, 1971a). After storage, raffinose content is largely determined by the temperature at which the roots were stored and is independent of raffinose content at harvest (Wyse & Dexter, 1971a).

Polysaccharide gums

Polysaccharide gums can accumulate in frost-damaged roots. The polysaccharide gums, dextran and levan, are formed by bacteria that metabolize sugar released after frost injury (Oldfield *et al.*, 1971b). Dextran is a high molecular weight polymer of glucose residues linked via α-(1→6) bonds to form a linear backbone to which side chains of glucose residues are attached via α-(1→3) or α-(1→4) linkages. Dextran is synthesized from sucrose by the bacterial enzyme, dextransucrase, with the concomitant release of fructose. Levan is a high molecular weight polymer of fructose residues linked via β-(2→6) glycosidic bonds. Levan is synthesized from sucrose by the bacterial enzyme, levansucrase, with the concomitant release of glucose. Gum formation requires both freezing and thawing of tissue. Ice crystal formation during frost conditions causes membrane perforation and cell rupture. Upon thawing, cell contents leak from damaged membranes and sugar is released to bacteria present within the root, upon the root, or in adhering soil. The accumulation of significant quantities of gums occurs 3–14 days after frost damage and is preceded by an accumulation of invert sugars, whose synthesis is most likely catalysed by microbial invertases (Oldfield *et al.*, 1971b; De Bruijn, 2000). Both dextran and levan accumulation is typical in frost-damaged roots. Dextran concentration, however, is usually greater than levan concentration, although the relative amounts of the two gums are highly variable (Oldfield *et al.*, 1971b; Shore *et al.*, 1983; De Bruijn, 2000).

Kestoses

Kestose accumulation has been reported in roots with storage rots (Oldfield *et al.*, 1971b). Kestoses are trisaccharides formed by the addition of a fructose residue to sucrose. Three kestose isomers, 1-kestose, 6-kestose, and *neo*-kestose, can accumulate in roots. These isomers differ only in the location on the sucrose moiety where the fructose residue is linked. Kestose biosynthesis is catalysed by invertase. Although invertase typically hydrolyses sucrose to the invert sugars, glucose and fructose, it also possesses a fructotransferase activity that is responsible for kestose formation (Hawker, 1985). The invertase responsible for this activity is most likely of microbial origin, since kestose concentration is minimal in healthy roots. Generally, kestose accumulation during storage is of much less importance than the accumulation of other non-sucrose carbohydrates, although accumulations as great as 1.2 g/100 g sucrose have been reported in rotted roots (Oldfield *et al.*, 1971b).

STORAGE ROTS

While respiration is responsible for a substantial portion of the sucrose losses under almost all storage conditions (Wyse & Dexter, 1971b), losses attributable to storage rots are erratic, but can be considerable. During a 128-day survey, decayed tissue constituted 5065 t, or about 1.2% of the 414 425 t of sugar beet processed by a single Minnesota (USA) factory (Bugbee & Cole, 1976). The increased impurities and reducing sugars in rotted tissue, which interfere with processing, caused an estimated additional loss of 808 800 kg of sugar, for a total sugar loss of 1.3 Mkg of sugar. Losses for the following processing season were 27% those of the first year of the survey, characteristic of the year-to-year variability in storage rot losses.

Three fungi; *Phoma betae* Frank, *Botrytis cinerea* Pers. Ex Fr., and *Penicillium claviforme* Brainier; are widely recognized as storage rot pathogens (Bugbee, 1982; Bugbee, 1986). Fungi of local or lesser importance include other *Penicillium* species (Bugbee, 1975a; Bugbee & Nielsen, 1978) and species of *Aspergillus* (Halloin & Roberts, 1995), *Alternaria, Chaetomium, Fusarium, Mucor, Rhizopus, Sclerotinia, Stemphylium* (Dunning & Byford, 1982), and *Pythium* (Bugbee, 1986).

Phoma storage rot usually begins in the centre of the crown and spreads downward, often in a cone-shaped pattern, into the main taproot. Rotted tissue is black and may contain pockets lined with white mycelium (Plate 75). Spores are exuded from small black fruiting bodies (pycnidia) in a sticky, gelatinous matrix. Exposed pith tissue of topped or crowned roots is very susceptible to *P. betae* (Bugbee & Cole 1976). In general, low temperatures retard the penetration of the fungus into exposed crown tissue and higher temperatures, up to 15°C, favour rot development. *Phoma betae* strains differ in the rate they destroy beet tissue by as much as 50%, depending on temperature and storage period, (Tompkins & Pack, 1932; Cormack & Moffatt, 1961; Bugbee, 1979a). Bugbee (1973) reported a negative correlation between sugar concentration and disease severity; however, some low sugar genotypes and table beet low in sugar appeared to have some resistance to *Phoma*. The growth of *P. betae* was greater on isolated cell walls from older roots than from younger roots and the effect of cell wall material on relative growth rate was influenced by cultivar. Sucrose concentration and cell wall properties appeared to influence production of a pectolytic enzyme instrumental in pathogenesis (Bugbee, 1973; Bugbee, 1975b). Growth rate and enzyme production were enhanced when pith cells were the sole carbon source and pith cells are usually the first to decay under natural conditions.

A close association between the disease cycle and the life cycle of sugar beet (Fig. 15.3) makes *Phoma* an especially dangerous storage pathogen (Bugbee, 1982). It can be introduced to a region on infected seed (Bugbee & Cole, 1981) and, once established, it survives on crop residues in fields and adjacent to areas where beet are stored awaiting processing (Bugbee, 1986). The presence of the sexual stage of *Phoma* (*Pleospora bjoerlingii* Byford) in commercial seed production fields could lead to the development of more virulent *Phoma* strains (Bugbee, 1979a).

Botrytis storage rot can be identified by the presence of dark brown to black, round sclerotia and grey masses of spores. The 2–5 mm diameter sclerotia form in groups on dark brown to black rotted tissue (Plate 76). Spores of *B. cinerea* are disseminated by air movement (Bugbee, 1986). *B. cinerea* is widely distributed, active over a wide temperature range (Gaskill & Seliskar, 1952), and often characterized as an aggressive storage rot fungi.

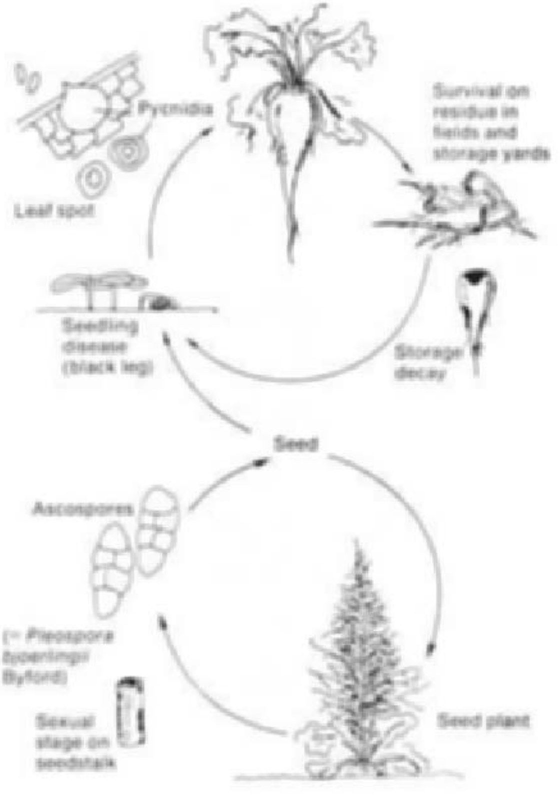

Fig. 15.3 Disease cycle of *Phoma betae* (from Bugbee, 1986).

Storage rot caused by *P. claviforme* can be identified by columnar tufts (coremia) tipped with green spore masses (Plate 77) produced on light tan to brown rotted tissue (Bugbee, 1986). *Penicillium claviforme* is less aggressive than *P. betae* or *B. cinerea*; however, extensive dissemination within a storage pile can compensate for the low pathogenicity and make *P. claviforme* more destructive than *Phoma* or *Botrytis*. *Penicillium* spores are dispersed on wind currents. Penicillium storage rot is frequently associated with wounds and can occur in conjunction with rot caused by *P. betae*. *Penicillium claviforme* is an antagonist of *B. cinerea* (Bugbee, 1976). This relationship may account for differing reports on the prevalence of *B. cinerea*. *Penicillium variabile* Sopp has been identified as a rare sugar beet storage pathogen (Bugbee, 1975a). *Penicillium claviforme*, however, is able to decay roots at lower temperatures than *P. varibile*, giving *P. claviforme* a competitive advantage under most storage conditions. Two other *Penicillium* species, *P. cyclopium* Westling and *P. funiculosum* Thom appear to be as virulent as *P. claviforme* (Bugbee & Nielsen, 1978), but are not as prevalent.

The other recognized storage rot fungi are either local problems or opportunistic organisms that are able to take advantage of unique situations. *Aspergillus fumigatus* Fresen. does not usually cause problems under normal storage conditions; however, it is capable of rapidly rotting roots following metabolic heating or composting (Halloin & Roberts, 1995). A bacterium, *Leuconostoc mesenterioides*, which produces polysaccharide gums that interfere with sugar refining is often associated with *A. fumigatus*. Under moist storage conditions, *Pythum ultimum* Trow increases in virulence and the development of rot caused by *Pythium* spp. can be retarded by dry conditions (Cormack & Moffatt, 1961). *Fusarium* spp. are relatively minor storage rot pathogens in parts of the northern USA (Bugbee & Cole, 1976) and Canada (Cormack & Moffatt, 1961), but are among the more threatening storage-rot fungi in Finland (Dunning & Byford, 1982).

Although each species of fungi has an optimum temperature for development and is active over a unique temperature range, higher temperatures generally favour rot development. Root injury before storage frequently is the most important factor determining the extent of fungal infection (Mumford & Wyse, 1976). Inoculum is abundant in the environment and frequently present in soil adhering to roots after harvest. The ability of roots to resist some rot fungi decreases over time (Bugbee, 1979b), with the difference being most apparent after approximately 80 days. Losses due to rots are not confined to the root tissue consumed by rot organisms; respiration rates double and reducing sugar concentrations triple when fungi infect only 20% of the root surface (Mumford & Wyse, 1976). The increased respiration of the rotting tissue increases temperatures, and therefore, increases sucrose loss of surrounding healthy roots.

Bacterial storage diseases rarely occur unless oxygen is depleted in a storage pile (Bugbee, 1982). Oxygen depletion is usually associated with restricted ventilation caused by excessive weeds, sugar beet leaves, or soil in the pile. In the absence of anaerobic conditions, Bugbee *et al.* (1975) found that endogenous bacteria and yeast populations increased sixfold during 150 days in storage at 5°C. A corresponding increase in invert sugar concentration depended upon the variety examined, but appeared related to relative colony count differences between the varieties. Twenty of 36 bacterial cultures isolated from root tissue were capable of hydrolysing sucrose *in vitro.*

CROP MANAGEMENT AND GROWING CONDITIONS

Crop management and environmental conditions during the growing season affect subsequent storage losses. Varietal differences in traits related to post-harvest storability have been recognized for more than 50 years (Gaskill, 1950b; Stout & Smith, 1950; Nelson, 1954). Bugbee (1978) and Campbell and Bugbee (1985) developed germplasm lines with resistance to *P. betae, B. cinerea,* and/or *P. claviforme.* Storage rot control using resistant cultivars appeared to be equal to that obtained with fungicides (Bugbee & Cole, 1979a). Inherent differences in storage respiration rate have been documented by Nelson and Wood (1950), Cole (1977), Wyse *et al.* (1978) and Akeson and Widner (1981). Polyploid lines appear to respire more slowly than diploid varieties (Stout, 1954; Martens & Oldfield, 1970). Varietal differences in raffinose (Finkner & Bauserman, 1956; Wood *et al.*, 1956) and invert accumulation during storage have been reported (Akeson & Widner, 1981). However, differences in cultivar rankings among impurity components and respiration rate, and storage time by cultivar interactions complicate the development of cultivars with improved storage characteristics (Wyse & Dexter, 1971a,b; Akeson, 1981; Akeson & Widner, 1981; Martin *et al.*, 2001a,b). Although developing cultivars with relatively low respiration rates and resistance to prevalent storage rots seems possible, incorporating additional traits into a breeding programme slows progress toward other goals or requires additional resources (Akeson, 1981; Campbell, 2005). Varietal approval criteria that exclude cultivars with substantial deficiencies in storage properties seem to be a reasonable alternative to the development of cultivars with superior storage traits.

Practices that result in uniform adequate stands not only enhance yield and quality at harvest, but also affect losses during post-harvest storage. Plant population affects root size, which in turn may affect storage respiration rate (Stout & Smith, 1950) and air flow (Tabil *et al.*, 2003b) through storage piles. Uniformly spaced plants make it easier to adjust defoliators and harvesters so that harvest losses and mechanical damage are minimized and roots are adequately cleaned. Seed infected with *P. betae* in seed production areas can be a source, but not necessarily the only or major source of inoculum for *Phoma* storage rot (Bugbee & Cole, 1981). Fungicides applied to the seed reduced this source of inoculum.

Only a few investigators have examined the effects of fertilizer management and nutrient availability on storage properties. From these, it appears that nitrogen, within the range normally recommended for commercial production, has little or no effect upon storage losses. Gaskill (1950c) found that nitrogen fertilizer reduced storage rot losses in a field moderately deficient in nitrogen. Bugbee & Cole (1986) observed an association between increased storage rot development and low clear juice purity, a quality component influenced by fertility management. Wyse and Dexter (1971a) found no relationship between nitrogen fertilizer rates and reducing sugar or raffinose accumulation during storage. Furthermore, Dexter *et al.* (1966) reported that higher quality roots deteriorated relatively slowly, even at temperatures above 10°C. These reports are consistent with the conclusion of Koster *et al.* (1980) that fertilizer levels that optimize recoverable white sugar yield at harvest also lower respiration losses.

Larmer (1937) found that applied phosphorus reduced storage rots, when phosphorus was deficient. Boron should be applied to soils lacking this element as roots of boron deficient plants deteriorate rapidly in storage (Bugbee, 1986; Draycott & Christenson, 2003). In general, a fertility programme that balances root yield and processing quality for maximum profit does not appear inconsistent with producing a product that stores well.

Diseases that occur during the growing season may increase storage respiration rates and susceptibility to storage pathogens, and hence sugar losses during storage. Roots with severe *Aphanomyces* root rot symptoms contained 90 kg extractable sugar per tonne 18 days after harvest, but 120 days later, only 34 kg/t remained (Campbell & Klotz, 2003). Comparable values for healthy roots were 152 and 125 kg/t, respectively. The effect of rhizomania (*Beet necrotic yellow vein virus*) on storage losses is less clear; however, the limited data available (unpublished) suggest that sugar losses during storage of a rhizomania susceptible cultivar are significantly higher than the losses occurring in a resistant cultivar, when rhizomania is present. Smith and Ruppel (1971) observed an association between *Cercospora* leaf spot (*Cercospora beticola* Sacc.) severity and the frequency of roots that rotted in storage. To some extent, the detrimental effects of these diseases can be minimized with the use of disease resistant cultivars, fungicides, and crop rotation.

Harvesting operations that result in clean roots with no attached leaves or petioles and minimal mechanical damage should be the goal of all producers (De Vletter & Van Gils, 1976; Cole, 1977; Houghton & Armstrong, 1994; Brown, 1998; Smith, 2001). Environmental conditions immediately preceding and at harvest can influence storage losses. Bugbee (1979b) found that low rainfall during the growing season increased the severity of *Phoma* storage rot. Dilley *et al.* (1970) reported that the effect of mechanical injury on respiration rate of beet harvested late in the season was less pronounced than for beet harvested 21 days earlier. The authors speculated that this difference was due to the relative amounts of intercellular air space and its effect on gas diffusion. Roots harvested and piled when root temperatures are high, i.e. above 13°C, will have increased initial losses as a result of high respiration rates, followed by increased development of storage rots. Low ambient temperatures and additional pile ventilation or time will be required to reach a temperature suitable for long-term storage. Frost damage to roots before they are harvested can have a substantial detrimental effect on storage. Cells of frozen tissue are disrupted, allowing leaching, exposure to micro-organisms, and eventually the formation of invert sugars and levan and dextran gums that slow processing. In Europe, processors recommend that roots frozen in the field be processed immediately, before thawing if possible (Dunning & Byford, 1982; Shore *et al.*, 1983; Milford *et al.*, 2002). In North America, roots partially damaged by frost are allowed to ‘heal’ before being defoliated, harvested, and piled (Bugbee, 1986). This healing process occurs over a few days, if temperatures are above freezing.

REDUCING MECHANICAL DAMAGE

Sugar beet harvesting and handling equipment is designed to handle large volumes of material as quickly as possible; minimizing root damage is frequently a secondary consideration. Consequently, roots are damaged by numerous impacts during harvest, handling, cleaning, and piling. This damage increases respiration rates, the loss of sucrose through leaching, and provides numerous sites for fungal invasion. Typical root injuries from harvest and piling operations include root breakage, cracking, surface abrasions, cuts, loss of small fragments, and bruising (Steensen, 1996; Wiltshire & Cobb, 2000; Brown *et al.*, 2002). Under current practices, injury sustained by roots in storage is considerable. In a study conducted in Denmark using standard harvest and piling methods, 89% of roots placed in storage were bruised, 58% experienced breakage, and 38% were cracked (Steensen, 1996).

Crowns, which comprise up to 20% of the sugar beet (Cole, 1980), have low sucrose and high impurity concentrations, compared to the true root (Cole & Seiler, 1976; Jaggard *et al.*, 1999). Hence, growers often attempt to improve quality by removing a portion of the crown (topping) as a part of the harvest operation. The negative aspects of crown removal are up to a 16% decrease in recoverable sucrose per hectare (Akeson *et al.*, 1974a; Zielke & Snyder, 1974; Steensen & Augustinussen, 2002) and increased storage losses associated with the injured tissue (Wyse, 1978b). Although clear juice purities were lower in non-topped roots at harvest, they did not decline as rapidly as in topped roots, so after storage for 180 days the purity of topped and non-topped roots were equal (Akeson *et al.*, 1974a). Crown removal is more important with lower quality roots and nitrogen fertility has a larger effect on quality than crown removal (Akeson *et al.*, 1979a). With proper nitrogen management, flailing without topping may be a viable option.

There are numerous causes of bruising, cracking, and root breakage during harvest. This damage not only increases losses during storage in colder climates, but also increases short-term losses during transit in climates where roots are processed soon after harvest (Vaccari *et al.*, 1988). A substantial portion of the damage occurs during the cleaning process, and harvester cleaning mechanisms differ in the amount of injury they cause (Parks & Peterson, 1979; Steensen, 1996; Bentini *et al.*, 2002). Most cleaning systems rely on bouncing or rolling the roots to remove dirt through impact (Peterson *et al.*, 1982) and in general, more extensive cleaning systems cause more damage. Moreover, improper harvester adjustment and operation can also increase damage to roots, while also increasing harvest losses through root breakage (Brown & Pilbrow, 1996). Additional damage, often equal to that observed during lifting and cleaning, is incurred when the roots are elevated and dropped into trucks or carts (Parks & Peterson, 1979; Brown & Pilbrow, 1996). Parks and Peterson (1979) recommended future harvesters minimize dropping, throwing, or scraping roots with moving parts of the machine, and that designers recognize that steel flights, abrupt direction changes, high internal chain speeds, onboard tanks, and fixed position booms all contribute to higher than necessary damage. Peterson *et al.* (1982) describe modifications to a conventional harvester that reduced root damage at least 60% with no increase in dirt tare.

It is widely recognized that piling and post-harvest handling damages roots (Parks & Peterson, 1979); however, roots harvested with conventional equipment often have considerable damage, complicating the evaluation of subsequent damage. Peterson *et al.* (1981) concluded that cleaning operations in harvest-piling operations are sometimes excessive. Steensen (1996) noted that damage caused when dumping on a clamp, filling the hopper of a cleaner-loader, and cleaning often negate practices that reduce damage during harvest.

Researchers wishing to quantify the negative effects of root damage have either sampled roots at various stages of harvest and handling (Cole, 1977) or attempted to simulate the damage (Akeson & Stout, 1978). Parks and Peterson (1979) describe a Bruise Index based upon number and depth of bruises and diameter of the root tip at the point of breakage. The difference between severely and moderately damaged roots in sucrose loss during 151 days of storage was equal to one-tenth of the sugar present at harvest. Electronic sugar beet that can measure and record impacts as they pass through harvesting and handling equipment have been developed (Bartlett, 1998; Biavati *et al.*, 2002). In a comparison of harvesters, results obtained using electronic beet suggested that impact intensity should be given higher priority than impact frequency in designing harvesters that minimize damage (Bentini *et al.*, 2002). De Vletter and Van Gils (1976) concluded that damaged roots lose sugar in proportion to the number of cells ruptured. Sugar leached from ruptured cells provided a substrate for fermentation and oxidation within a few hours after piling damaged beet. Losses from dropping beet on beet, or foam plastic, were approximately one-third those resulting from collisions with a hard surface.

STORAGE PILE MANAGEMENT

Minimizing sugar losses and maintaining processing quality during post-harvest storage is necessary for the long-term success of the beet sugar industry; therefore, creating the most favourable storage environment feasible is essential. Reducing temperatures to reduce respiration losses (Oldfield *et al*., 1971a) and slow fungal growth is usually the first consideration. The optimum temperature for root storage appears to be between 1.5 and 5°C. Cells may be ruptured and respiration increased upon exposure to temperatures below –2°C, and freezing water in the spaces between the roots may cause desiccation at –1°C. As a result, forced ventilation systems should be shut down when air temperatures are below –2°C, unless pile temperatures are extremely high (above 10–15°C) or the intent is to freeze the beet until processing. Some respiration continues until roots are frozen and it is recommended that piles to be deep-frozen should be reduced to at least –5°C (Wyse, 1978a). In the absence of rots, invert sugar accumulation increases as temperature increases. In contrast, raffinose accumulation is usually not a problem when temperatures are above 5°C (Wyse & Dexter, 1971a). Temperature not only affects the severity of storage rot (Tompkins & Pack, 1932), but may determine the relative prevalence of different fungi. Gaskill and Seliskar (1952) and Miles *et al.* (1977) observed that rot caused by *B. cinerea* was only slightly influenced by temperatures ranging from 5 to 30°C; whereas, rot caused by *Rhizopus* spp. was negligible at 5°C, but was more virulent than *Botrytis* at the higher temperatures. Infrared thermometers are useful for monitoring storage pile temperatures and overhead infrared photographs can be used efficiently to monitor large piles at numerous sites.

Wilting or desiccation during storage can substantially reduce extractable sugar yield and increase losses due to storage rots (Barnes *et al*., 1974; Bugbee & Cole, 1979b). Beet on or near pile surfaces, especially on surfaces exposed to direct sunlight or prevailing winds, are more vulnerable to wilting than roots in the interior of a pile. Losses due to wilting during early storage when temperatures tend to be high may equal those due to freezing and thawing cycles later, in some environments. Dexter *et al.* (1969) found extractable sugar losses in the outermost 30 cm of a pile were three times those in the interior. Damage due to wilting increased as temperature increased. A sevenfold increase in the amount of rotted tissue was associated with a 10% weight loss due to drying at 7°C (Gaskill, 1950a). Rot caused by *P. betae* was greatly accelerated by wilting when temperatures were above 10°C, but wilting had no effect on *Phoma* at lower temperatures (Cormack & Moffatt, 1961). Although dehydration is detrimental in most situations, the cooling potential of evaporation may hasten cooling (Stout, 1950). A 95–98% relative humidity is optimum for minimizing storage deterioration (Dexter *et al*., 1969), but often difficult to attain throughout a storage pile.

Forced ventilation cooling is frequently used to reduce pile temperatures, and consequently sucrose losses due to respiration and storage rots. Based upon a survey of 16 European countries, Martens and Oldfield (1970) concluded that forced ventilation reduced sugar losses by approximately 120 g/t/day. In a few countries, water was sometimes sprayed into the air that was used for ventilation to lower temperatures, when the relative humidity was below 85%. In Ireland, forced ventilation is highly recommended for large clamps in which beet will be stored for 2–6 weeks (Britton, 1984). Houghton and McMillan (1991) concluded that forced ventilation was not practical for on-farm storage in England and recommended building small clamps with relatively high surface to volume ratios to avoid overheating early in the season. Larger clamps for longer storage would be appropriate later in the harvest season when temperatures were cooler. Hansen (1950) concluded that the sugar saved by lowering temperatures from 20 to 18°C for 6–7 days was sufficient to justify the expenses associated with forced-air ventilation. Orleans and Cotton (1950) found ventilation was cost-effective when roots were stored 36 hours or less at the high temperatures, 43°C day and 28°C night, encountered during harvest in southern California. ‘Hotspots’ may develop in areas of a pile with excessive respiration rates or microbial activity. These hotspots are often caused by fermentation resulting from poor ventilation and should be removed as soon as possible to prevent damage to adjacent areas. Piling clean, non-diseased roots with minimal mechanical damage will reduce their frequency.

Although the design of ventilation systems has improved over time, based in large part on experience, some guidelines and models in the literature may offer assistance when designing new ventilation systems or modifying existing methods. Hansen (1950) outlined a method for estimating cooling rate based upon temperatures in the pile, air temperature, relative humidity, and cooling fan capacity. Tabil and co-workers characterized the thermal properties (Tabil *et al.*, 2003a) and airflow resistance (Tabil *et al.*, 2003b) of sugar beet. Airflow resistance of smaller roots (< 1200 g) was up to 1.9 times that of large roots (> 1200 g) and foreign material (soil, stones, and leaves) increased airflow resistance from 2.6 to 8.6 times that of clean roots, depending on airflow rate. The thermal conductivity of frozen roots was twice that of unfrozen roots. Jaggard *et al.* (1997) found that accumulated degree-days based upon temperatures above zero within clamps was a good indicator of sugar and yield losses during storage (Fig. 15.4) while acknowledging the difficulty of routinely determining clamp temperatures. Cannon (1950) recognized the need to reduce the heavy concentrations of trash and dirt that frequently occurred in storage piles. Moving the piler boom continuously and the piler shorter distances with each move distributed the trash and dirt more uniformly. Immediate pile levelling was suggested as a means to reduce channelling of air (Fig. 15.5) within the pile. Holdredge and Wyse (1982) developed a simulation model to estimate root temperature as a function of time and position in the pile, based on air temperature, initial pile temperature and ventilation flow rate. This model was used to compare free convection and forced ventilation in climates throughout the USA (Wyse & Holdredge, 1982) and, through an example, illustrates the utility of models in allocating limited ventilation equipment resources.

Pile coverings have been used to reduce storage losses in the large centrally located piles in the USA (McGinnis *et al.*, 1982) and the smaller clamps maintained by northern European producers. An ideal clamp covering material should protect beet from severe frost, shed water, and allow ventilation so that heat is not trapped inside the clamp (Jaggard *et al.*, 1997). A 23 cm layer of straw is a traditional clamp covering that remains an alternative, provided there is a low cost source of straw. A net under the straw will keep loose straw separate from the

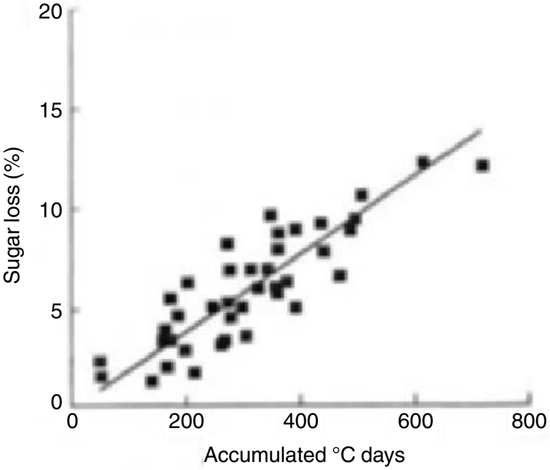

Fig. 15.4 Sugar loss as a function of accumulated heat units (°C days, with base of 0°C) during storage in England (from Jaggard *et al.*, 1997).

Fig. 15.5 Levelling piles soon after harvest reduces surface area and channelling of air within the pile (American Crystal Sugar Co.).

beet and facilitate removal (Dutton & Houghton, 1984). Woven polypropylene material provides a cost-effective, relatively durable covering (Bastow, 1983; Parry, 1989). With this and other sheeting materials, the top may be left open to allow some ventilation (Dutton & Houghton, 1984) or the covering rolled back if there is no threat of rain or frost (Britton, 1984). Old vehicle tyres anchor the covers with little risk of tearing the sheeting material; hay bales are also a common anchoring material. In Germany, a permeable insulating fleece has almost completely replaced straw as a clamp covering (Köhler & Bürcky, 2003). Akeson *et al.* (1974b) reported that over 40% of the recoverable sugar loss during storage in large piles occurred in the outer 60 cm (rim) of uncovered piles, although the rim accounts for only 17% of the pile volume. Straw coverings reduced weight loss, sugar loss, and recoverable sugar loss by 20.5, 19.6 and 23.8%, respectively, compared to non-covered piles in the Great Plains region (USA). The performance of woven polypropylene covers was inconsistent in this environment (Akeson & Fox, 1974). Applying milk of lime to pile surfaces can reduce root temperatures (Fort & Stout, 1945; Regitnig *et al.*, 2003). The milk of lime reflects sunlight and the elevated pH reduces losses from storage rots. Air inflated storage structures and plastic canopies supported by wood rafters resting on the pile top have been tried, with mixed success (Fox & Watts, 1975; Jardine & Stoller, 1975). The disadvantages of these structures – cost, susceptibility to wind damage, and the increased labour required at harvest time – make them economically feasible only when sugar prices are relatively high.

In some northern production areas, winters are cold enough to freeze the storage piles that are destined for processing late in the campaign (Moraghan, 1975; Vosper *et al.*, 1983). This permits more efficient utilization of factories by allowing campaigns of up to 250 days. In the northern Great Plains of North America, harvest is usually completed by mid- to late-October. Pile temperatures are reduced to 2°C as quickly as possible, using forced ventilation when ambient temperatures are below pile temperatures but above freezing. When outside temperatures are low enough, usually by mid-December, forced ventilation with sub-freezing air is used to freeze the beet. This typically requires 3 weeks. When ambient temperatures begin to increase in late January, all ventilation ceases (Backer *et al.*, 1979) and piles are covered with large tarpaulins (Fig. 15.6) to decrease spoilage and protect the pile from late winter rains and warm winds (Rawlings, 1997). A method of freezing roots without forced ventilation involves splitting large piles down the centre and allowing the two remaining smaller piles to freeze (Swift, 1975). The piles formed at harvest are about 66 m wide at the base. A 15 m portion is removed and processed early in the campaign, and the remaining smaller piles are left to freeze. Roots to be processed very late in the campaign (as late as mid-May), when ambient temperatures are increasing, are stored in large storage sheds (Fig. 15.7). Each shed has a capacity of 45 350–72 560 t (Rawlings, 1997). A plenum area comprised of fans, air exchangers, and instrument panels occupies 5 m along each side of the facility. The beet are piled up to 9 m high. The ceiling is insulated and louvres in the end walls allow warm air to escape. Beet typically go into storage at 10°C in October and by late December temperatures at the bottom of the pile are near –18°C, –12°C in the centre, and –7°C in the top section (Bass, 1985). Thawing prior to processing must be avoided at all costs. Although freezing reduces respiration rates and sucrose losses to very low levels, it is not with-

Fig. 15.6 Frozen pile covered with white tarpaulin to reflect sunlight while insulating pile to prevent thawing of roots near the surface (American Crystal Sugar Co.).

Fig. 15.7 Interior and exterior views of sheds used to store frozen roots for processing late in the campaign (American Crystal Sugar Co.).

out some negative aspects. For example, increased flume and washing losses occur when the surface of the root thaws during the processing of frozen roots.

Various chemical compounds, controlled atmospheres, and surface coatings have been suggested as means of reducing storage losses, but their commercial application appears to be quite limited. Karnik *et al.* (1970a,b) found that a 6% carbon dioxide – 5% oxygen concentration reduced sprouting, mould growth, and impurity concentrations at 2°C. Wyse (1973c) concluded that low oxygen concentrations of 3 to 5% reduced sucrose losses in the laboratory and suggested that the combined use of plastic coverings and mixing recycled pile air with outside air would allow the desired oxygen concentration and temperature to be obtained. Benomyl and thiabendazole controlled *Fusarium, Penicillium, Botrytis* and *Phoma*, but was not effective against *Rhizopus* in laboratory evaluations (Mumford & Wyse, 1976; Miles *et al.*, 1977; Bugbee & Cole, 1979a). Fungicide applications should be considered only when it seems likely that storage rots will cause unusually high losses (Akeson *et al.*, 1979b). Wittwer and Hansen (1951) reported that a pre-harvest foliar application of maleic hydrazide inhibited sprouting during storage. Wyse and Dilley (1973) proposed that wax coatings could reduce the internal oxygen concentration of the stored roots by increasing diffusion resistance and hence reduce respiration rate, and also desiccation.

The challenges involved in preserving the quality of the crop after harvest are, in many ways, similar to those encountered in producing the crop. The environment plays a crucial role in both, and adjustments for year-to-year variation in the weather are often necessary. The sugar losses resulting from poor storage conditions may rival the losses caused by diseases, pests, weeds, or adverse weather during the growing season. However, storage losses frequently are less obvious and therefore receive less attention. Even with the best management practices during the growing season, the roots going into storage will not always be in ideal condition and adjustments in storage pile management may be required. The detailed information included in the articles highlighted in this review, and others (McGinnis *et al.*, 1982; Vukov & Hangyál, 1985; Tungland *et al.*, 1998), can offer guidance. However, even with the most current information and technology, successful root storage requires frequent monitoring and the ability to respond to unique situations quickly. At times, management experience and a little good luck may be as valuable as anything.

REFERENCES

Akeson, W.R. (1973) Environmental factors influencing storage loss. In: Postharvest losses of sucrose in sugarbeets. *Proceedings of the Beet Sugar Development Foundation Conference*. Monterey, CA, pp. 67–75.

Akeson, W.R. (1981) Methods for estimating sucrose losses in laboratory storage tests. *Journal of the American Society of Sugar Beet Technologists* **21**, 56–73.

Akeson, W.R. & Fox, S.D. (1974) Reduction of sugar losses in sugarbeet piles with straw and plastic coverings. *Journal of the American Society of Sugar Beet Technologists* **18**, 117–124.

Akeson, W.R. & Stout, E.L. (1978) Effect of impact damage on sucrose loss in sugarbeets during storage. *Journal of the American Society of Sugar Beet Technologists* **20**, 167–173.

Akeson, W.R. & Widner, J.N. (1981) Differences among sugarbeet cultivars in sucrose loss during storage. *Journal of the American Society of Sugar Beet Technologists* **21**, 80–91.

Akeson, W.R., Fox, S.D. & Stout, E.L. (1974a) Effect of topping procedure on beet quality and storage losses. *Journal of the American Society of Sugar Beet Technologists* **18**, 125–135.

Akeson, W.R., Stout, E.L. & Fox, S.D. (1974b) Effect of pile covering on weight and sugar shrink in pile rims. *Journal of the American Society of Sugar Beet Technologists* **18**, 108–115.

Akeson, W.R., Westfall, D.G., Henson, M.A. & Stout, E.L. (1979a) Influence of nitrogen fertility level and topping method on yield, quality, and storage losses in sugarbeets. *Agronomy Journal* **71**, 292–297.

Akeson, W.R., Yun, Y.M. & Sullivan, E.F. (1979b) Effect of chemicals on sucrose loss in sugarbeets during storage. *Journal of the American Society of Sugar Beet Technologists* **20**, 255–268.

Backer, L.F., Vosper, F.C. & Bichsel, S.E. (1979) Ventilation and freezing of sugarbeet storage piles. *North Dakota Farm Research* **36** (4), 7–11.

Barbour, R.D. & Wang, C.H. (1961) Carbohydrate metabolism of sugar beets. I. Respiratory catabolism of mono and disaccharides. *Journal of the American Society of Sugar Beet Technologists* **11**, 436–442.

Barnes, M.G., Akeson, W.R. & Pence, N. (1974) Predicting sugarbeet storage losses using regression analysis. *Journal of the American Society of Sugar Beet Technologists* **18**, 182–185.

Bartlett, D.I. (1998) Development of an electronic damage analogue for sugar beet. *Aspects of Applied Biology* **52**, 185–190.

Bass, S. (1985) Pre-cooling and deep-freezing sugar beets. *Sugar y Azucar* **80** (2), 53–55.

Bastow, J. (1983) Alternative clamp covering materials. *British Sugar Beet Review* **51** (2), 29–32.

Bentini, M., Caliceti, M., Caprara, C., Gabellini, E., Tugnoli, V. & Venturi, P. (2002) Assessment of the harvesting quality on a six rows self-propelled combine harvester and a two-stage harvesting system at different working speed with an electronic beet. *Proceedings of the 65th IIRB Congress*. Brussels, pp. 367–374.

Berghall, S., Briggs, S., Elsegood, S.E., Eronen, L., Kuusisto, J.O., Philip, E.J., Theobald, T.C. & Walliander, P. (1997) The role of sugar beet invertase and related enzymes during growth, storage and processing. *Zuckerindustrie* **122**, 520–530.

Biavati, E., Bentini, M., Caprara, C., Caliceti, M. & Rondelli, V. (2002) Development of an electronic beet for evaluation of sugar beet harvesting machines. *Proceedings of the 65th IIRB Congress*. Brussels, pp. 401–406.

Bichsel, S.E. (1973) Quality losses in commercial piles: an approximate cost analysis. In: Postharvest losses of sucrose in sugarbeets. *Proceedings of the Beet Sugar Development Foundation Conference*. Monterey, CA, pp. 7–14.

Britton, J. (1984) On-farm storage of sugar beet in Ireland. *British Sugar Beet Review* **52** (3), 24–26.

Brown, R.J. & Wood, R.R. (1952) Improvement of processing quality of sugar beets by breeding methods. *Proceedings of the American Society of Sugar Beet Technologists 7.* pp. 314–318.

Brown, S.P. (1998) Quality harvesting of sugar beet. *Aspects of Applied Biology* **52**, 179–184.

Brown, S.P. & Pilbrow, J. (1996) Effective harvesting: the way to cut losses. *British Sugar Beet Review* **64** (3), 8–10.

Brown, S.P., Spackman, V. & Armstrong, M.J. (2002) Sugar beet bruising – the invisible enemy! *British Sugar Beet Review* **70** (3), 10–15.

Bugbee, W.M. (1973) Sucrose and cell walls as factors affecting Phoma storage rot of sugar beet. *Phytopathology* **63**, 480–484.

Bugbee, W.M. (1975a) *Penicillium claviforme* and *Penicillium variabile*: pathogens of stored sugar beet. *Phytopathology* **65**, 926–927.

Bugbee, W.M. (1975b) Peroxidase, polyphenoloxidase, and endopolygalacturonate transeliminase activity in different tissues of sugar beet infected with *Phoma betae*. *Canadian Journal of Botany* **53**, 1347–1351.

Bugbee, W.M. (1976) *Penicillium claviforme*: sugarbeet pathogen and antagonist of *Botrytis cinerea*. *Canadian Journal of Plant Science* **56**, 647–649.

Bugbee, W.M. (1978) Registration of F1001 and F1002 sugarbeet germplasm. *Crop Science* **18**, 358.

Bugbee, W.M. (1979a) *Pleospora bjoerlingii* in the USA. *Phytopathology* **69**, 277–278.

Bugbee, W.M. (1979b) The effect of plant age, storage, moisture, and genotype on storage rot evaluation of sugarbeet. *Phytopathology* **69**, 414–416.

Bugbee, W.M. (1982) Storage rot of sugar beet. *Plant Disease* **66**, 871–873.

Bugbee, W.M. (1986) Storage rot of sugar beet. In: Whitney, E.D. & Duffus, J.E. (eds) *Compendium of Beet Diseases and Insects*. American Phytopathological Society, St. Paul, MN, pp. 37–39.

Bugbee, W.M. & Cole, D.F. (1976) Sugarbeet storage rot in the Red River Valley. *Journal of the American Society of Sugar Beet Technologists* **19**, 19–24.

Bugbee, W.M. & Cole, D.F. (1979a) Comparison of thiabendazole and genetic resistance for control of sugar beet storage rot. *Phytopathology* **69**, 1230–1232.

Bugbee, W.M. & Cole, D.F. (1979b) The effect of root dehydration on the storage performance of a sugarbeet genotype resistant to storage rot. *Journal of the American Society of Sugar Beet Technologists* **20**, 307–314.

Bugbee, W.M. & Cole, D.F. (1981) The effect of seed infected with *Phoma betae* on rot and sucrose yield of stored sugar beet. *Phytopathology* **71**, 357–359.

Bugbee, W.M. & Cole, D.F. (1986) Sucrose content, clear juice purity and storage rot of sugarbeet. *Journal of the American Society of Sugar Beet Technologists* **23**, 154–161.

Bugbee, W.M. & Nielsen, G.E. (1978) *Penicillium cyclopium* and *Penicillium funiculosum* as sugarbeet storage rot pathogens. *Plant Disease Reporter* **62**, 953–954.

Bugbee, W.M., Cole, D.F. & Nielsen, G.E. (1975) Microflora and invert sugar in juice from healthy tissue of stored sugarbeet. *Applied Microbiology* **29**, 780–781.

Campbell, L.G. (2005) Post-harvest storage traits. In: Biancardi, E., Campbell, L.G., De Biaggi, M. & Skaracis, G.N. (eds) *Sugar Beet Breeding and Genetics*. Science Publishers Inc, Enfield, NH, pp. 122–126.

Campbell, L.G. & Bugbee, W.M. (1985) Registration of storage rot resistant sugarbeet germplasms F1004, F1005, and F1006. *Crop Science* **25**, 577.

Campbell, L. & Klotz, K. (2003) Impact of root diseases on storage. *2002 Sugarbeet Research and Extension Reports* 33. Cooperative Extension Service, North Dakota State University, pp. 254–257.

Cannon, R.M. (1950) Observations on the dehydration of beets after receiving and during storage in northern Montana. *Proceedings of the American Society of Sugar Beet Technologists 6*. pp. 642–646.

Cole, D.F. (1977) Effect of cultivar and mechanical damage on respiration and storability of sugarbeet roots. *Journal of the American Society of Sugar Beet Technologists* **19**, 240–245.

Cole, D.F. (1980) Effect of complete crown removal on quality of sugarbeets. *Journal of the American Society of Sugar Beet Technologists* **20**, 449–454.

Cole, D.F. & Seiler, G.J. (1976) Effect of crown removal on yield and quality of sugar beet roots: a grower survey. *Journal of the American Society of Sugar Beet Technologists* **19**, 131–137.

Cormack, M.W. & Moffatt, J.F. (1961) Factors influencing storage decay of sugar beets by *Phoma betae* and other fungi. *Phytopathology* **51**, 3–5.

De Bruijn, J.M. (2000) Processing of frost-damaged beets at CSM and the use of dextranase. *Zuckerindustrie* **125**, 898–902.

De Vletter, R. & Van Gils, W. (1976) Influence of the mechanical handling of sugarbeets on sugar yield in the factory. *Sugar Journal* **38** (8), 8–13.

Dexter, S.T., Frakes, M.G. & Nichol, G. (1966) The effect of low, medium and high nitrogen fertilizer rates on the storage of sugar beet roots at high and low temperatures. *Journal of the American Society of Sugar Beet Technologists* **14**, 147–159.

Dexter, S.T., Frakes, M.G. & Wyse, R.E. (1969) Damage to sugarbeet roots from various degrees of wilting at various temperatures. *Journal of the American Society of Sugar Beet Technologists* **15**, 480–488.

Dilley, D.R., Wood, R.R. & Brimhall, P. (1970) Respiration of sugarbeets following harvest in relation to temperature, mechanical injury, and selected chemical treatment. *Journal of the American Society of Sugar Beet Technologists* **15**, 671–683.

Draycott, A.P. & Christenson, D.R. (2003) *Nutrients for Sugar Beet Production: Soil Plant Relationships*. CABI Publishing, Wallingford.

Dunning, A. & Byford, W. (eds) (1982) *Pest, Diseases and Disorders of Sugar Beet*. (Translated from French). B.M. Press, Sartrouville, France.

Dutton, J. & Houghton, B. (1984) Comparison of alternate clamp covering materials. *British Sugar Beet Review* **52** (3), 38–40.

Echeverría, E. (1998) Acid invertase (sucrose hydrolysis) is not required for sucrose mobilization from the vacuole. *Physiologia Plantarum* **104**, 1217–1226.

Echeverría, E. & Gonzalez, P.C. (2000) ATP-induced sucrose efflux from red-beet tonoplast vesicles. *Planta* **211**, 77–84.

Etxeberria, E. & Gonzalez, P. (2003) Evidence for a tonoplast-associated form of sucrose synthase and its potential involvement in sucrose mobilization from the vacuole. *Journal of Experimental Botany* **386**, 1407–1414.

Finkner, R.E. & Bauserman, H.M. (1956) Breeding of sugar beets with reference to sodium, sucrose, and raffinose content. *Journal of the American Society of Sugar Beet Technologists* **9**, 170–177.

Finkner, R.E., Swink, J.F., Doxtator, C.W., Olson, R.F. & Hanzas, P.C. (1959) Changes in raffinose content and other characteristics of sugar beet varieties during six different harvest dates. *Journal of the American Society of Sugar Beet Technologists* **10**, 459–466.

Fort, C.A. & Stout, M. (1945) Whitewashing sugar beets to reduce sugar losses in storage. *Sugar* **40**, 1–6.

Fox, S.D. (1973) Economic significance of quality losses in commercial piles. In: Postharvest losses of sucrose in sugarbeets. *Proceedings of the Beet Sugar Development Foundation Conference*. Monterey, CA, pp. 15–20.

Fox, S.D. & Watts, D. (1975) Air supported 'bubble' warehouse. In: Recent development in sugarbeet storage techniques. *Proceedings of the Beet Sugar Development Foundation Conference*. Denver, CO, pp. 87–105.

Gaskill, J.O. (1950a) Effects of wilting, drought, and temperature upon rotting of sugar beets during storage. *Proceedings of the American Society of Sugar Beet Technologists 6*. pp. 653–659.

Gaskill, J.O. (1950b) Possibilities for improving storage-rot resistance of sugar beets through breeding. *Proceedings of the American Society of Sugar Beet Technologists 6*. pp. 664–669.

Gaskill, J.O. (1950c) Progress report on the effects of nutrition, bruising, and washing upon rotting of stored sugar beets. *Proceedings of the American Society of Sugar Beet Technologists 6*. pp. 680–685.

Gaskill, J.O. & Seliskar, C.E. (1952) Effect of temperature on rate of rotting of sugar beet tissue by two storage pathogens. *Proceedings of the American Society of Sugar Beet Technologists 7*. pp. 571–574.

Halloin, J.M. & Roberts, D.L. (1995) Temperature as a determining factor in the storage rot of sugarbeet caused by *Aspergillus fumigatus*. *Journal of Sugar Beet Research* **32**, 59–67.

Hansen, C.M. (1950) The distribution of air in sugar beet stock pile ventilation systems. *Proceedings of the American Society of Sugar Beet Technologists 6*. pp. 629–636.

Hawker, J.S. (1985) Sucrose. In: Dey, P.M. & Dixon, R.A. (eds) *Biochemistry of Storage Carbohydrates in Green Plants*. Academic Press, London, pp. 1–51.

Hein, W., Pollach, G. & Harzl, E. (2004) Investigations on the storage behaviour of rhizomania tolerant sugar beet varieties. *Zuckerindustrie* **129**, 161–173.

Holdredge, R.M. & Wyse, R.E. (1982) Computer simulation of the forced convection of sugarbeets. *Transactions of the American Society of Agricultural Engineering* **25**, 1425–1430.

Houghton, B. & Armstrong, M. (1994) Fragile, handle with care. *British Sugar Beet Review* **62** (3), 13–15.

Houghton, B. & McMillan, P. (1991) How to minimize losses in storage. *British Sugar Beet Review* **59** (3), 18–20.

Ibrahim, L., Spackman, V.M.T. & Cobb, A.H. (2001) An investigation of wound healing in sugar beet roots using light and fluorescence microscopy. *Annals of Botany* **88**, 313–320.

Jaggard, K.W., Clark, C.J.A., May, M.J., McCullagh, S. & Draycott, A.P. (1997) Changes in the weight and quality of sugarbeet (*Beta vulgaris*) roots in storage clamps on farms. *Journal of Agricultural Science, Cambridge* **129**, 287–301.

Jaggard, K.W., Clark, C.J.A. & Draycott, A.P. (1999) The weight and processing quality of components of the storage roots of sugar beet (*Beta vulgaris* L.). *Journal of the Science of Food and Agriculture* **79**, 1389–1398.

Jardine, G.D. & Stoller, W. (1975) Ventilated canopy storage for sugarbeets. In: Recent development in sugarbeet storage techniques. *Proceedings of the Beet Sugar Development Foundation Conference*. Denver, Colorado, pp. 68–76.

Karnik, V.V., Olson, L.E., Salunkhe, D.K. & Singh, B. (1970a) Evaluation of effects of controlled atmosphere storage on roots of sugarbeets grown at various levels of nitrogen fertilizer. *Journal of the American Society of Sugar Beet Technologists* **16**, 226–234.

Karnik, V.V., Salunkhe, D.K., Olson, L.E. & Post, F.J. (1970b) Physio-chemical and microbiological studies on controlled atmosphere storage of sugarbeets. *Journal of the American Society of Sugar Beet Technologists* **16**, 156–167.

Klotz, K. & Campbell, L. (2002) Impact of root diseases on storage: carbohydrate impurity formation. *2001 Sugarbeet Research and Extension Reports* 32. North Dakota State University Extension Service, pp. 183–185.

Klotz, K.L. & Finger, F.L. (2004) Impact of temperature, length of storage and postharvest disease on sucrose catabolism in sugarbeet. *Postharvest Biology and Technology* **34**, 1–9.

Klotz, K.L., Anderson, M.D. & Finger, F.L. (2003) Contribution of cytochrome *c* and alternative oxidase pathways to respiratory sucrose loss in postharvest sugarbeet (*Beta vulgaris* L.) roots. *Proceedings of the 1st Joint IIRB-ASSBT Congress*. San Antonio, TX, pp. 915–919.

Köhler, R. & Bürcky, K. (2003) Clamp coverings and beet cleaning. *Proceedings of the 1st Joint IIRB-ASSBT Congress*. San Antonio, TX, pp. 693–698.

Koster, P.B., Raats, P. & Jorritsmma, J. (1980) The effect of some agronomical factors on the respiration rates of sugar beet. *Proceedings of the 43rd IIRB Congress*. Brussels, pp. 109–125.

Larmer, F.G. (1937) Keeping quality of sugar beet as influenced by growth and nutritional factors. *Journal of Agricultural Research* **54**, 185–198.

Leigh, R.A., ap Rees, T., Fuller, W.A. & Banfield, J. (1979) The location of acid invertase activity and sucrose in the vacuoles of storage roots of beetroot (*Beta vulgaris*). *Biochemical Journal* **179**, 539–547.

Mahn, K., Hoffmann, C. & Märländer, B. (2002) Distribution of quality components in different morphological sections of sugar beet (*Beta vulgaris* L.). *European Journal of Agronomy* **17**, 29–39.

Martens, M. & Oldfield, J.F.T. (1970) Storage of sugar beet in Europe: report of an IIRB enquiry. *Journal of the Institute of Sugar Beet Research* **5**, 102–127.

Martin, S.S., Narum, J.A. & Chambers, K.H. (2001a) Sugarbeet biochemical changes during pile storage. Part I. Sugars. *Journal of Sugar Beet Research* **38**, 35–53.

Martin, S.S., Narum, J.A. & Chambers, K.H. (2001b) Sugarbeet biochemical changes during pile storage. Part II. Nonsugars. *Journal of Sugar Beet Research* **38**, 173–188.

McCready, R.M. & Goodwin, J.C. (1966) Sugar transformations in stored sugar beets. *Journal of the American Society of Sugar Beet Technologists* **14**, 197–205.

McGinnis, R.A., Sunderland, D.L. & Akeson, W.R. (1982) Beet storage. In: McGinnis, R.A. (ed.) *Beet-Sugar Technology*. Beet Sugar Development Foundation, Denver, CO, pp. 81–99.

Miles, W.G., Shaker, F.M., Nielson, A.K. & Ames, R.R. (1977) A laboratory study of the ability of fungicides to control beet rotting fungi. *Journal of the American Society of Sugar Beet Technologists* **19**, 288–293.

Milford, G.F.J., Armstrong, M.J. & Patchett, M. (2002) Frost damage to sugar beet – estimating the risk. *British Sugar Beet Review* **70** (3), 41–45.

Moraghan, J. (1975) Some aspects of sugarbeet storage in the USSR. In: Recent development in sugarbeet storage techniques. *Proceedings of the Beet Sugar Development Foundation Conference*. Denver, CO, pp. 221–224.

Mumford, D.L. & Wyse, R.E. (1976) Effect of fungus infection on respiration and reducing sugar accumulation of sugarbeet roots and use of fungicides to reduce infection. *Journal of the American Society of Sugar Beet Technologists* **19**, 157–162.

Nelson, R.T. (1954) Progeny test of sugar beet roots selected for low respiration rate. *Proceedings of the American Society of Sugar Beet Technologists 8 (2)*. pp. 134–136.

Nelson, R.T. & Wood, R.R. (1950) Respiration and spoilage studies employing a modification of method developed by Stout and Fort. *Proceedings of the American Society of Sugar Beet Technologists 6*. pp. 660–663.

Oldfield, J.F.T., Dutton, J.V. & Houghton, B.J. (1971a) Deduction of the optimum conditions of storage from studies of the respiration rates of beet. *International Sugar Journal* **73**, 326–330.

Oldfield, J.F.T., Dutton, J.V. & Teague, H.J. (1971b) The significance of invert and gum formation in deteriorated beet. *International Sugar Journal* **73**, 3–8, 35–40, 66–68.

Orleans, L.P. & Cotton, R.H. (1950) Commercial ventilation of beets in storage. *Proceedings of the American Society of Sugar Beet Technologists 6*. pp. 637–639.

Parks, D.L. & Peterson, C.L. (1979) Sugarbeet injury within harvesting and handling equipment. *Transactions of the American Society of Agricultural Engineering* **22**, 1238–1244.

Parry, D. (1989) Convenient clamp covering. *British Sugar Beet Review* **57** (3), 15–16.

Pavlinova, O.A., Prasolova, M.F. & Krasnoshchekova, A.K. (1979) Utilization of sucrose in sugar beet roots during the storage period and the second year of vegetation. *Soviet Plant Physiology* **26**, 416–422.

Peterbauer, T. & Richter, A. (2001) Biochemistry and physiology of raffinose family oligosaccharides and galactosyl cyclitols in seeds. *Seed Science Research* **11**, 185–197.

Peterson, C.L., Muller, E.R., Hall, M.C. & Thompson, J.C. (1981) An analysis of root damage during piling. *Journal of the American Society of Sugar Beet Technologists* **21**, 136–149.

Peterson, C.L., Thompson, J.C., Hall, M.C. & Muller, E.R. (1982) Developing concepts in low damage harvesting of sugarbeets. *Journal of the American Society of Sugar Beet Technologists* **21,** 210–220.

Rawlings, G. (1997) Storage technology easily pays for itself. *Sugar Producer* **24** (6), 8–9.

Regitnig, P.J., Nitschelm, J.J. & Llewellyn-Jones, A. (2003) Shoulder coverings for sugar beet storage piles in Alberta. *Journal of Sugar Beet Research* **40**, 188 (abstract).

Rosenkranz, H., Vogel, R., Greiner, S. & Rausch, T. (2001) In wounded sugar beet (*Beta vulgaris* L.) tap-root, hexose accumulation correlates with the induction of a vacuolar invertase isoform. *Journal of Experimental Botany* **52**, 2381–2385.

Shore, M., Dutton, J.V. & Houghton, B.J. (1983) Evaluation of deteriorated beet. *International Sugar Journal* **85**, 106–110.

Shugaev, A.G. & Bukhov, N.G. (1997) Opposite trends of seasonal changes in ADP content and respiration rate in sugar beet roots. *Journal of Plant Physiology* **150**, 53–56.

Siedow, J.N. & Day, D.A. (2000) Respiration and photorespiration. In: Buchanan, B., Gruissem, W. & Jones, R. (eds) *Biochemistry and Molecular Biology of Plants.* American Society of Plant Physiologists, Rockville, MD, pp. 676–728.

Smith, G.A. & Ruppel, E.G. (1971) Cercospora leaf spot as a predisposing factor in storage rot of sugar beet roots. *Phytopathology* **61**, 1485–1487.

Smith, J.A. (2001) Sugarbeet harvest. In: Wilson, R.G., Smith, J.A. & Miller, S.D. (eds) *Sugarbeet Production Guide.* University of Nebraska Cooperative Extension, EC01–156, Lincoln, pp. 179–188.

Steensen, J.K. (1996) Root injuries in sugar beets as affected by lifting, dumping, and cleaning. *Proceedings of the 59th IIRB Congress.* Brussels, pp. 525–532.

Steensen, J.K. & Augustinussen, E. (2002) Effect of flail topping and scalping on yield, internal quality, and storage loss in sugar beet. *Advances in Sugar Beet Research.* IIRB, 4, 125–137.

Steensen, J.K. & Augustinussen, E. (2003) Effect of rubber flail topping and scalping versus non-scalping on yield, internal quality, and storage losses in sugarbeet. *Zuckerindustrie* **128**, 100–105.

Stout, M. (1950) Heat and moisture transfer studies in relation to forced ventilation of insulated columns of sugar beets. *Proceedings of the American Society of Sugar Beet Technologists 6.* pp. 647–652.

Stout, M. (1954) Some factors that affect the respiration rate of sugarbeets. *Proceedings of the American Society of Sugar Beet Technologists 8 (2).* pp. 404–409.

Stout, M. & Smith, C.H. (1950) Studies on the respiration of sugar beets as affected by bruising, by mechanical harvest, severing into top and bottom halves, chemical treatment, nutrition and variety. *Proceedings of the American Society of Sugar Beet Technologists 6.* pp. 670–679.

Swift, E.L. (1975) Deep frozen sugarbeet storage. In: Recent development in sugarbeet storage techniques. *Proceedings of the Beet Sugar Development Foundation Conference.* Denver, CO, pp. 5–30.

Tabil, L.G., Eliason, M.V. & Qi, H. (2003a) Thermal properties of sugarbeet roots. *Journal of Sugar Beet Research* **40**, 209–228.

Tabil, L.G., Kienholz, J., Qi, H. & Eliason, M.V. (2003b) Airflow resistance of sugarbeet. *Journal of Sugar Beet Research* **40**, 67–86.

Theurer, J.C., Wyse, R.E. & Doney, D.L. (1978) Root storage respiration rate in a diallel cross of sugarbeet. *Crop Science* **18**, 109–111.

Tompkins, C.M. & Pack, D.A. (1932) Effect of temperature on rate of decay of sugar beets by strains of *Phoma betae. Journal of Agricultural Research* **44**, 28–37.

Tungland, B.C., Watkins, R.E. & Schmidt, P.V. (1998) Sugarbeet storage. In: Van der Poel, P.W., Schiweck, H. & Schwartz, T.K. (eds) *Sugar Technology.* Verlag Dr Albert Bartens, Berlin, Section 5.4, pp. 267–289.

Vaccari, G., Marzola, M.G., Mantovani, G., Bentini, M., Baralei, G. & Spettoli, P. (1988) Chemical and enzymatic changes in strongly damaged beets. *Food Chemistry* **27**, 203–211.

Vosper, F.C., Backer, L.F. & Schuler, R.T. (1983) Ventilation and freezing of stored sugar beets. *Transactions of the American Society of Agricultural Engineering* **26**, 301–304.

Vukov, K. & Hangyál, K. (1985) Sugar beet storage. *Sugar Technology Review* **12**, 143–265.

Walker, H.G., Rorem, E.S. & McCready, R.M. (1960) Compositional changes in diffusion juices from stored sugar beets. *Journal of the American Society of Sugar Beet Technologists* **11**, 206–214.

Wang, C.H. & Barbour, R.D. (1961) Carbohydrate metabolism of sugar beets. II. Catabolic pathways for acetate, glyoxylate, pyruvate, glucose and gluconate. *Journal of the American Society of Sugar Beet Technologists* **11**, 443–454.

Wiltshire, J.J.J. & Cobb, A.H. (2000) Bruising of sugar beet roots and consequential sugar loss: current understanding and research needs. *Annals of Applied Biology* **136**, 159–166.

Wittwer, S.H. & Hansen, C.M. (1951) The reduction of storage losses in sugar beets by preharvest foliage sprays of maleic hydrazide. *Agronomy Journal* **43**, 340–341.

Wood, R.R., Oldemeyer, R.K. & Bush, H.L. (1956) Inheritance of raffinose production in sugar beet. *Journal of the American Society of Sugar Beet Technologists* **9**, 133–138.

Wyse, R.E. (1973a) General postharvest physiology of the sugarbeet. In: Postharvest losses of sucrose in sugarbeets. *Proceedings of the Beet Sugar Development Foundation Conference.* Monterey, CA, pp. 47–60.

Wyse, R.E. (1973b) Influence of cultural practices and storage conditions on quality losses during storage. In: Postharvest losses of sucrose in sugarbeets. *Proceedings of the Beet Sugar Development Foundation Conference.* Monterey, CA, pp. 76–85.

Wyse, R.E. (1973c) Storage of sugarbeet roots in controlled atmospheres to conserve sucrose. *Crop Science* **13**, 701–703.

Wyse, R. (1974) Enzymes involved in the postharvest degradation of sucrose in *Beta vulgaris* L. root tissue. *Plant Physiology* **53**, 507–508.

Wyse, R.E. (1975) A physiological perspective on where we should go from here. In: Recent developments in sugarbeet storage techniques. *Proceedings of the Beet Sugar Development Foundation Conference.* Denver, CO, pp. 230–235.

Wyse, R. (1978a) Effect of low and fluctuating temperatures on the storage life of sugarbeets. *Journal of the American Society of Sugar Beet Technologists* **20**, 33–42.

Wyse, R. (1978b) Effect of harvest injury on respiration and sucrose loss in sugarbeet roots during storage. *Journal of the American Society of Sugar Beet Technologists* **20**, 193–202.

Wyse, R.E. & Dexter, S.T. (1971a) Effects of agronomic and storage practices on raffinose, reducing sugar, and amino acid content of sugarbeet varieties. *Journal of the American Society of Sugar Beet Technologists* **16**, 369–383.

Wyse, R.E. & Dexter, S.T. (1971b) Source of recoverable sugar losses in several sugarbeet varieties during storage. *Journal of the American Society of Sugar Beet Technologists* **16**, 390–398.

Wyse, R.E. & Dilley, D.R. (1973) Evaluation of wax coatings for improving sugarbeet storage. *Crop Science* **13**, 567–570.

Wyse, R.E. & Holdredge, R.M. (1982) A comparison of forced ventilation and natural convection as means of cooling sugarbeet storage piles in several geographic locations. *Journal of the American Society of Sugar Beet Technologists* **21**, 235–246.

Wyse, R.E. & Peterson, C.L. (1979) Effect of injury on respiration rates of sugarbeet roots. *Journal of the American Society of Sugar Beet Technologists* **20**, 269–280.

Wyse, R.E., Theurer, J.C. & Doney, D.L. (1978) Genetic variability in postharvest respiration rates of sugarbeet roots. *Crop Science* **18**, 264–266.

Zhang, Q. & Greenway, H. (1994) Anoxia tolerance and anaerobic catabolism of aged beetroot storage tissues. *Journal of Experimental Botany* **45**, 567–575.

Zielke, R.C. & Snyder, F.W. (1974) Impurities in sugarbeet crown and root. *Journal of the American Society of Sugar Beet Technologists* **18**, 60–75.

Chapter 16
Root Quality and Processing

John Dutton and Toon Huijbregts

INTRODUCTION

Root quality is by far the most important parameter affecting beet processing. The aim of processors, worldwide, is to produce pure sugar, at least cost, from the purchased sugar beet. Whilst the efficiency of processing can vary appreciably according to the factory equipment and the way in which it is operated, the cost of beet is everywhere the greatest manufacturing cost. Thus, the industry has recognized the overriding importance of the quality of the purchased beet towards real processing improvements and hence the industry's competitiveness.

Processors may in some countries commence their operations with harvesting and storage of the beet in the field, but in any case mechanical handling and storage are in all countries, primary stages of processing. In the next stages beet are flumed, washed and sliced into thin slices called cossettes. These are counter-current extracted (diffused) with hot water and the resulting dark, opaque raw juice, which is purified by lime/CO_2 clarification (carbonatation), yields a sparklingly clear second carbonatation filtrate. Additionally, during this carbonatation, it may be necessary to add soda ash or caustic soda if the juice 'alkalinity' is too low, or acid if it is too high. The filtrate, containing about 12–17% dissolved solids, may or may not be sulphitated to inhibit colour-forming reactions in the remainder of the process, which then involves evaporation of the 'thin' juice at high temperature to give a 'thick' juice containing 60% or more dissolved solids from which crystallization takes place under vacuum, yielding two or more crops of sugar. In general, the second and any subsequent crops of crystals are insufficiently pure to be saleable, so these are redissolved, mostly in the evaporated thick juice, giving it a higher purity and in turn, yielding a very high purity (> 99.9% sucrose) first crop sugar, which is then dried and sold.

The syrup that is separated from the last crop of sugar and from which no more sugar can be economically crystallized is called molasses. A part of this is frequently mixed with the beet pulp (the insoluble beet tissue coming from the counter-current raw juice extraction), dried and sold as animal feed (see Chapter 17); alternatively molasses is sold as an animal-feed or as a fermentation substrate in its own right.

As far as root quality relates to processing this general description should be sufficient, but for more information on sugar beet processing, reference should be made to three standard works (Vukov, 1977; McGinnis, 1982; Van der Poel *et al.*, 1998).

HISTORICAL OVERVIEW OF BEET TECHNICAL QUALITY

In order to understand what effect root quality has on processing it is certainly necessary to know the chemical constituents of beet and raw juice. Gaining this understanding was the primary objective of the former British Sugar Corporation's Research Laboratories (Carruthers, 1954; Carruthers & Oldfield, 1956; Carruthers *et al.*, 1959; 1960).

The Commission Internationale Technique de Sucrerie (CITS) also made a pioneering contribution to root quality and processing with its XIth Meeting in 1960, at which the theme was 'The Technological Value of the Sugar Beet'. In the Summary of the Proceedings, Verhaart and Oldfield (1962) drew three main conclusions (reproduced here in full with the kind permission of Dr R. Beckers, CITS Secretary-General, 195 Avenue de Tervuren, Brussels):

1. From all the factors which determine the technological value of beet, the relative proportions of crystallizable sugar and of sugar in molasses are the most important and the most studied.
2. The already-known correlation between ash content and molasses production can be improved by considering the K + Na content. Either conductometric ash or K + Na can be estimated by analysis of pressed juice or brei extracts and, because of the simplicity and rapidity of this analysis, it would be possible to take either factor into account in regard to the payment of the beet.
3. Many of the contributors thought that neither ash nor K + Na were sufficient for an exact prediction of the amount of molasses and that, for a more precise estimate, it would be necessary also to take account of either the total non-sugars, the nitrogenous constituents (particularly the amino acids), or the effective alkalinity.

Some 40 years later, these conclusions have proved to be correct. The significance of the amino acids, as well as the significance of potassium and sodium, has necessarily had to be taken into account in almost all calculations aimed at assessing the contribution of the non-sugars to the potential loss of sugar into molasses (Carruthers *et al.*, 1962; Andersen & Smed, 1963; Wieninger & Kubadinow, 1971; Reinefeld *et al.*, 1974; Devillers *et al.*, 1976; Akyar *et al.*, 1980; Hilde *et al.*, 1983; Van Geijn *et al.*, 1983; Buchholz *et al.*, 1995; Huijbregts, 1999). Sometimes reducing sugars are also taken into account (Devillers, 1988; Pollach *et al.*, 1996). However, it is concluded below that all calculations of 'theoretical molasses sugar' are, at best, only semi-quantitative.

With regard to decolorization, or rather juice and white sugar colour, pure sugar must meet very stringent standards both for reflectance whiteness and for solution colour (Mauch & Farhoudi, 1979/80), so that beet constituents giving rise to colour, e.g. reducing sugars (De Bruijn *et al.*, 1999), militate against processing efficiency firstly because colour must not contaminate the product and secondly, as indicated by Prey (1962), coloured substances are certainly melassigenic substances, which hold sucrose in solution, so that it ends up in molasses. The concept of melassigenicity is developed further below.

In their Summary, Verhaart and Oldfield refer to the importance of beet physical properties (Vukov, 1962) and also to the role of decolorization in improving crystallization (Prey, 1962), both now seen to be highly important. Thus, the book, *Physics and Chemistry of Sugar-Beet in Sugar Manufacture* (Vukov, 1977) sets out in detail the importance of the physical (or mechanical) properties of beet tissue, as well as giving full weight to its chemical composition.

Historically speaking, the role of the Institut International de Recherches Betteravières (IIRB) has also been most important in relation to the technological value of the beet (Devillers, 1982). The formation of the IIRB Study Group 'Quality and Storage' in 1971 has done much to promote international exchange between experts from all scientific disciplines. In addition, the IIRB addressed the controversial subject 'Nitrogen and Sugar-beet' with their Symposium in 1983 (IIRB, 1983). The introductory session dealt with 'The Significance of Nitrogenous Compounds in the Industrial Processing of Sugar Beet'. Later, at the 59th and 68th IIRB Congresses, sessions considered the internal and external quality of sugar beet (IIRB, 1996; 2005).

CONCEPTS OF GOOD BEET QUALITY

It is proposed in this section to highlight what the industry considers is 'good quality' and to indicate negative points. As may be deduced from the historical review, there are numerous aspects of quality. Oldfield (1974) pointed out that quality was not a single character that could be presented in a quantitative form by using a single numerical value; it was a combination of all the chemical and physical aspects of beet that lead to economy in production costs, or which affect yield in terms of sugar or of by-products, in relation to the cost of the beet. This said, everyone recognizes the paramount importance of the yield of pure sugar.

The desirability of a high sugar content was, of course, pointed out by Oldfield (1974), but along with others he was also aware of the importance of the soluble non-sugars. Oltmann *et al.* (1984) surveyed the intense activity relating to beet chemical quality and hence the potential yield of white sugar. They pointed out that even in respect of chemical quality, several different quality formulae were in use, utilizing beet laboratory or tarehouse data for potassium, sodium and amino nitrogen. Some of these are discussed below but it is important to reiterate their point that such formulae may only be used as an indication of recoverable sugar yield. As they also indicate, for better assessment of potential sugar yield (and therefore real root chemical quality) it is necessary to utilize simulated factory processing and to measure juice purities as well as particular non-sugars (Asselbergs *et al.*, 1962; Carruthers & Oldfield, 1962; Dexter *et al.*, 1967; Khelemskii & Shoikhet, 1986; Mantovani & Vaccari, 1989; Vaccari *et al.*, 1996).

Andersen and Smed (1963) made further important points with regard to juice purity and effective alkalinity. Firstly they spelt out that a change of thick juice purity from 94 to 92% with a molasses purity of 60% will mean an increase of sugar lost to molasses from 9.6% to 13.0%. This is demonstrated below, bearing in mind that juice purity is the ratio of sugar to total dissolved solids, as a percentage:

100 kg thick juice solids @ 94% purity ≡ 94 kg sugar + 6 kg non-sugar	100 kg thick juice solids @ 92% purity ≡ 92 kg sugar + 8 kg non-sugar
6 kg non-sugar in molasses @ 60% purity ≡ 9 kg sugar	8 kg non-sugar in molasses @ 60% purity ≡ 12 kg sugar
9/94 × 100 = 9.6%	12/92 × 100 = 13.0%

In this example, using 60% purity molasses, the overall melassigenic coefficient of the non-sugars is 1.5, i.e. 1.5 parts of sugar are held in molasses solution by 1 part of non-sugar. The non-sugars as a whole are therefore detrimental to quality.

The effective alkalinity is an expression of the base (alkali) remaining in excess after juice purification and is of importance to the buffer capacity of the juice and to the carbon dioxide absorption, and hence calcium elimination, in the second carbonatation stage (Brieghel-Müller & Brüniche-Olsen, 1953). It is crucial that process juices from the thin juice stage onwards do not fall below $\mathrm{pH}_{20^\circ\mathrm{C}} = 7.0$ or even 8.8, in technical thick juices, otherwise acid-inversion will occur, with sugar splitting to form invert sugar (glucose + fructose). So Andersen and Smed calculated from the main impurity parameters an 'effective alkalinity' as follows:

Effective alkalinity = 0.58 (K + Na – amino N)
– 6.8 meq/100 g of sugar

For Danish beet varieties they reported a wide range of effective alkalinities, between 0.3 and 13.7. Technologists will recognize that with invert sugar degradation alone normally yielding at least 3 meq of acid per 100 g of sugar in processing, that the latter alkalinity (13.7) is desirable, whereas the former (0.3) is totally inadequate, leading to minimal juice buffering after carbonatation and high lime salts. As will be mentioned later, further developments relating to the original concept of Andersen and Smed have followed.

Invert sugar (glucose + fructose) has been mentioned as a quality parameter and Devillers (1988) included a glucose term in his newer formula to assess 'molasses sugar' in French beet varieties. Pollach *et al.* (1996) as well as Schiweck and Burba (1993), in reviewing quality formulae, take into account reducing sugars. In factory processing, however, the basal levels of invert sugar in beet, in the range 0.3–0.6 g per 100 g sugar, are of much less concern than the levels of 1 g per 100 g sugar and above, which occur in deteriorated beet.

Other interfering substances, such as raffinose, betaine and dextran and levan and other parameters, such as beet marc, and the physical quality features, have all received less study than sugar content and the major impurities (potassium, sodium, α-amino nitrogen and invert sugar), since the 1960s, but newer constraints in regard to quality assurance and environmental matters will require more attention to some of these 'Cinderella' quality parameters in the future.

The significance of the beet enzymes, invertase, pectolytic enzymes and polyphenoloxidase, together with the whole complex chemistry of colour formation and its significance will also need more attention in the future.

Top-tare, dirt and trash accompanying the beet are very detrimental to processing (Oldfield *et al.*, 1977; De Nie & Van den Hil, 1989) and these negative quality features are considered below.

So far, in relation to factory processing, no agrochemicals used on the crop have caused problems, because of stringent measures in relation to their clearance for use. Continuing vigilance will be required to maintain this position, in order that quality assurance guarantees can be given for sugar, pulp products and molasses (Davies, 1987; Dutton, 1989).

Currently, as can be seen from the above survey, root quality covers many parameters. The grouping, by the Dutch company, Suiker Unie (De Nie & Van den Hil, 1989) of the parameters, tare, sugar content, potassium, sodium, α-amino nitrogen and frost damage into a bonus/malus payment system, represents a first attempt to combine as many quality parameters as possible, in order to determine, what they term, 'Fitness for Use'. This payment system was extended with a penalty if too much petioles and leaves are delivered. From the 1990s onwards the principles of this payment system have been used by the whole Dutch sugar industry (Suiker Unie and CSM Suiker). It should be noted that this was in the context of a wholly new contract and the details are specifically appropriate to those companies.

QUALITY PARAMETERS

Sugar content

The reasons for the apparent desirability of high sugar content were detailed by Oldfield (1974) in the context of conditions of the 1960s. In essence he pointed out that labour, capital and transport costs, together with processing losses, are all lower with higher sugar content beet. Thus, in the UK, as in many other countries, the contract with growers gives higher payments for each tonne of sugar in beet, as sugar content increases, and hence breeders have greatly increased sugar content of varieties over recent years.

Furthermore, Carruthers *et al.* (1962) had demonstrated, from the analysis of 1224 samples of beet grown in 18 different areas from 17 different varieties that high purity laboratory-clarified juice was associated with high sugar content in beet. A highly significant regression equation was obtained.

$$\text{Purity \%} = 82.8 + (0.61 \times \text{sugar content}); \quad r = 0.39$$

Thus, on average for these particular samples, beet of 17% sugar-content yielded clarified juice of 93.17% purity, whereas beet of 16% sugar-content gave a lower purity clarified juice (92.56%). The slope of the above regression equation combines the slopes of two other regression lines which were obtained by these investigators,

- Variety slope = 0.37 (purity % per 1% sugar content)
- Area slope = 0.99 (purity % per 1% sugar content)
- Combined slope = 0.61 (purity % per 1% sugar content).

Thus the incremental increase in purity associated with an increase of 1% in sugar content was smaller for changes due to these particular varieties than for changes due to agricultural effects, but the main point was that positive correlations existed in these beet from the early 1960s.

Later, however, Loilier and Bruandet (1989) pointed out that for French varieties, this traditional correlation between sugar content and purity was becoming considerably less certain. They calculated 'molasses sugar' using the Devillers (1988) formula and showed that, for four varieties tested in 1988, results contrary to the traditional positive correlation were found (Table 16.1).

The sugar contents and calculated 'molasses sugars' are expressed as percentages of the mean of all varieties tested. Thus for these four varieties, average or high sugar content is associated with low purity (i.e. high molasses sugar) whereas the low

Table 16.1 Relationship between sugar content and 'molasses sugar' of several French varieties of sugar beet (reproduced with permission of 'Sucrerie Française', Paris).

Variety	Sugar content (% of mean)	Molasses sugar (% of mean)
Sibel	99.3	96.1
Ecrin	100.1	104.7
Univers	101.6	103.1
Liza	102.5	107.0

sugar content variety, Sibel, is rather high purity (i.e. low molasses sugar). It must be concluded that in variety assessment today it may no longer be assumed that high sugar content means high juice purity (Burba & Schiweck, 1993; Burba & Jansen, 2000). As all seed breeders determine purity or impurity parameters anyway, this statement may seem superfluous, but old adages often die hard.

Other deficiencies relating to simple measurements of sugar content by polarization are well-known, but must be repeated. Firstly, sugar contents of beet measured by factory tarehouses in paying for beet will normally register approximately 0.1% sugar content in respect of raffinose, which is present in the beet (Oldfield *et al.*, 1977). Several other components with an optical rotation also affect polarization (Mauch, 1990). If beet are damaged by frost, then the high polarization on account of dextran and other dextro-rotatory substances present in such beet can lead to high polarizations equivalent to at least 1% sugar content (Shore *et al.*, 1983) and even greater for some French samples (Devillers, 1986).

Thus, sugar content determined by polarization can have marked limitations in a quality sense, for beet which are damaged. To overcome these problems, Devillers (1986) utilized enzymatic determination of sucrose (i.e. a measurement of sucrose + 66% of any kestose present) combined with measurement of the major impurities, potassium, sodium and amino nitrogen. In the future, alternatives may be high-performance liquid chromatography (HPLC) methods such as the ICUMSA Method (2002) accepted for sucrose determination in beet molasses (GS7/4/8–23), to determine the true sucrose content.

From the above it may be deduced that sugar content measurements on normal beet are a basic first step in assessing quality. However, if polarization measurements are used to improve sugar content, this may also influence the concentrations of other soluble compounds with an optical rotation. Additionally, for a proper understanding of root quality, sugar content measurement alone is insufficient. For instance, dehydration may increase sugar content without improvement of the quality. Mantovani and Vaccari (1989) have pointed out that increase in polarization of beet stored on the surface and inside beet piles in Italy at daytime temperatures of 32–34°C increased in 2–4 days by 1–2% on beet. When these polarizations on fresh weight were calculated relative to beet dry substance it was shown that in fact severe losses of sugar had occurred.

So, for quality assessment as well as the determination of the sugar content one needs to include other measurements, e.g. dry substance, non-sugars, reducing sugars, or juice purity.

Major non-sugars

Before discussing the major non-sugars, it is relevant to bear in mind that the components of beets and of the raw juices produced therefrom are quite complex. The soluble non-sugars in total represent only some 2% of the fresh weight of beet, but it is their relative distribution that is crucial to processing, some being much more important than others.

To give an idea of the complexity, Table 16.2 is a collection of numerous data reported in papers of British Sugar's Research Laboratories during their early years and is given as being obtained 'during the 1960s'. The data are given as round figures. (For information: see also Bohn (1998) and Burba *et al.* (2001), who report more recent data.)

First of all, only about 30% by weight of these total non-sugars would be removed in the carbonatation purification (1.1 g from group 2 and 2.05 g from group 3 in Table 16.2). Glutamine would be partially decomposed to yield pyroglutamic acid (PGA) and ammonia; invert sugar would be mostly degraded to acidic products and coloured substances; both unreacted glutamine, invert sugar, PGA and the invert sugar degradation products

Table 16.2 Approximate concentrations (g/100 g sugar) of non-sugars in raw juice (Source: J.V. Dutton).

Group 1 Not-removed or decomposed (D) in carbonatation		Group 2 Part-removed in carbonatation		Group 3 Removed in carbonatation	
Betaine	1.6	Citrate	0.8	Saponin	0.5
Potassium	1.2	Malate	0.2	Protein	0.5
Glutamine (D)	1.2	Sulphate	0.1	Oxalate	0.4
Invert sugar (D)	0.6			Pectin	0.3
Amino acids*	0.4			Phosphate	0.2
Raffinose	0.4			Magnesium	0.1
Nitrate	0.3			Calcium	0.05
Sodium	0.2				
Lactate	0.1				
Inositol	0.1				
Galactinol	0.1				
Chloride	0.1				
Araban	0.05				
Nucleosides**	0.05				
Totals	**6.4**		**1.1**		**2.05**

* Excluding glutamine, ** Including purines and pyrimidines.

would pass through carbonatation and so influence the rest of the process. These changes are fundamental to the acid-base balance, with the removal of anionic substances (oxalate, phosphate, citrate, malate, sulphate and pectin) releasing free base being counter-balanced by the production of acids from glutamine and invert sugar degradation. In addition, ammonia (a base), released by decomposition of glutamine, is lost by volatilization at the high temperatures during carbonatation.

Secondly, every one of the components in Table 16.2 is subject to considerable variability as mentioned by Bohn (1998).

Thirdly, in considering the importance of the non-sugars, it can be stated:

- The cations, K^+ and Na^+, together with glutamine, are both quantitatively and qualitatively important.
- All non-sugars not removed in carbonatation, representing here 6.75 g/100 g of sugar, must contribute to the loss of sugar to molasses.

Thus, not only potassium and sodium and the amino acids, but also betaine, invert sugar degradation products, raffinose, nitrate, etc., and residues of citrate, malate and sulphate must be included in considerations of melassigenicity.

In their paper to British Sugar's 15th Technical Conference, Carruthers *et al.* (1962) demonstrated that, for British factories, it was better to utilize the total non-sugars (via purity) in clarified juice to predict sugar lost to molasses. Clarified juices for purity measurement were produced from tare-house breis in simulated beet factory clarifications. They also pointed to the highly significant correlation between clarified juice purity (*CJP*) and the non-sugars, potassium, sodium and amino nitrogen determined in basic lead acetate polarization digests:

$$CJP = 97.0 - 0.0008\,(2.5\mathrm{K} + 3.5\mathrm{Na} + 10\ \text{amino N})$$

where K, Na and amino N were expressed as mg/100 g of sugar.

So they suggested that potassium, sodium and amino nitrogen measured in lead filtrates could be used as a practical quality assessment in tare-houses, because the production of clarified juices there would have been too time-consuming. Both systems (determination of *CJP* and the determination of potassium, sodium and amino nitrogen) were adopted, however, for analysis of all National Institute of Agricultural Botany (NIAB) variety trials, and determinations of clarified juice purities were only discontinued once it had been adequately demonstrated that conclusions drawn from the summated non-sugars were the same as those drawn from clarified juice purities (Willey, 1974). The term in brackets in their regression equation was called 'Measured Impurity' and is now expressed as grams per 100 g of sugar. It is used as a ranking method, for which purpose it is well justified, but, in view of the later findings of variable relationships between these major non-sugars and clarified juice purities (Last & Draycott, 1977), no attempt is made to convert 'Measured Impurity' or any combination of these non-sugars into a calculated 'molasses sugar', or into 'extractable sugar'. Last and Draycott's findings really ought to have put a stop on the development of formulae relating 'molasses sugar' to some combinations of potassium, sodium and amino nitrogen, but that has not turned out to be the case in most of Europe.

To reiterate their findings seems pertinent. They concluded, with regard to the equation of Carruthers and Oldfield above, that the constant (97.0) and slope (0.0008) have 'arbitrary values varying from site to site and within and between years, which renders calculation of clarified juice purity and absolute white sugar extraction unpractical'. Thus, the major non-sugars, potassium, sodium, and amino nitrogen cannot be related in a single regression formula to 'molasses sugar' or absolute white sugar extraction.

Reinefeld *et al.* (1974; 1986) used the following formula of Schneider *et al.* (1961) to calculate molasses purity from thick juice non-sugars (conductometric ash content, CaO, and total non-sugars):

$$P_M = 46.04 + 47.84 \times [(\text{Ash} - 2.35 \times \text{CaO})/\text{NS}]\%$$

They produced thick juices from 58 widely different beet samples by factory-simulated processing and calculated probable molasses sugars for German conditions using the above formula. Following that, they derived, by multiple regression analysis, another formula linking the beet non-sugars K, Na and α-amino N (expressed as meq/100 g of beet), and determined on the same 58 samples with calculated 'molasses sugar':

$$Z_M = 0.343(\text{K} + \text{Na}) + 0.094(\alpha\text{-N}) - 0.31$$

where Z_M = molasses sugar % beet and α-amino N* (α-N) was determined by the 'blue number' method.

In turn, 'corrected sugar content' of beet was calculated by Reinefeld *et al.* assuming a nominal factory processing loss of 0.6% sugar on beet, finally giving the formula:

$$Z_B = \text{Pol} - [0.343\ (\text{K} + \text{Na}) + 0.094\alpha\text{-N}) + 0.29]$$

where Z_B = 'corrected sugar content' (% beet).

This formula was then adopted as the official criterion for judging beet quality in Germany (Oltmann *et al.*, 1984). Nowadays the use of Schneider's formula for calculating molasses purity from selected thick juice non-sugars has not been confirmed by direct measurements (Buchholz *et al.*, 1995) and is therefore no longer recommended.

In France, Devillers *et al.* (1976) introduced their formula for 'molasses sugar', this time from factory measurements:

$$\text{Molasses Sugar (\% beet)} = 0.124\text{K} + 0.117\text{Na} + 0.408\alpha\text{-N}$$

where K, Na and α-N were expressed as mmoles/100 g of beet.

The relative importance given by these authors to potassium and sodium, compared to α-amino nitrogen, is quite different from those of Reinefeld *et al.* Thus, Devillers *et al.* (1984) and Reinefeld *et al.* (1986) each advanced arguments, supportive of their own weightings given to the factors, by which potassium, sodium and α-amino nitrogen are multiplied. However, such differences as found are wholly in keeping with the findings of Last and Draycott (1977) mentioned above. Moreover, in 1988 Devillers modified the formula to:

$$\text{Molasses Sugar (\% beet)} = 0.14(\text{K} + \text{Na}) + 0.25(\alpha\text{-N}) + 0.50$$

In 1995, Buchholz *et al.* repeated the work of Reinefeld *et al.* and arrived at a totally different official German formula for 'molasses sugar', which was close to that of Devillers in 1988. It was:

$$SMV = 0.12w'_{\text{K + Na}} + 0.24w'_{\alpha\text{-N}} + 0.48$$

where *SMV* = standard molasses loss in % on beet and w' = amount of substance in mmol/100 g beet.

This is in agreement with the so-called Rendement Concept mentioned below, currently published by Burba and Harling (2003).

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*α-amino nitrogen was determined by a 'blue-number' method instead of the ninhydrin/hydrindantin method used for amino nitrogen by Carruthers *et al.* (1959). Slightly different answers are obtained on beet extracts; thus the ninhydrin/hydrindantin method reacts with γ-amino butyric acid which is, like all amino acids, detrimental in processing because of Maillard colour formation (Carruthers *et al.*, 1963), but it also reacts with any small amount of ammonium ion present, which should not be included (today noxious nitrogen includes ammonia nitrogen from amides because of environmental reasons), because ammonia is volatilized during processing. Moreover, some laboratories now determine amino nitrogen fluorimetrically (see below) using the method of Burba and Georgi (1975/1976) and this does also include γ-amino butyric acid. However, no one has shown any practical significance attaching to these methodological differences, within the contexts of melassigenesis or alkalinity coefficient, although some attention has been given to the analytical differences (Glattkowski & Märländer, 1993; Obradovic *et al.*, 1997).

The movement away from reliance solely on potassium, sodium and α-amino nitrogen as the major non-sugars affecting 'molasses sugar' and alkalinity was started by Akyar *et al.* (1980). For Turkish conditions (quite different from those of northern Europe) they introduced a term for invert sugar into their formula for 'corrected sugar content' (meaning the extractable sugar content of the beet), Z_B:

$$Z_B = \text{Pol} - [0.19\ (\text{K} + \text{Na}) + 0.274\alpha\text{-N} + 1.145I + 0.576]$$

where I = g invert sugar per 100 g beet.

Ruiz Holst *et al.* (2003) confirmed the importance of invert sugar under Mediterranean conditions.

Whilst it is correct, as intended by Akyar *et al.* (1980) and Ruiz Holst *et al.* (2003), to include invert sugar when considering factory beet, the significance of an invert sugar term is not generally deemed to be so great for the analysis of beet trials e.g. of varieties. The exception to this was in France, where Devillers (1988) proposed that a glucose term be included in the latest IRIS (Institut de Recherches de l'Industrie Sucrière) formula for determining 'molasses sugar':

$$\text{Molasses Sugar (\% beet)} = 0.14\ (\text{K} + \text{Na}) + 0.25\alpha\text{-N} + 3.3G + 0.30$$

where K, Na and α-N are given as millimoles per 100 g beet and G = g glucose per 100 g beet.

A rather different approach was taken in Austria (Wieninger & Kubadinow, 1971; Pollach, 1984a; 1989), where, because of concern about evaporator corrosion in the 1960s, an alkalinity coefficient (*AC*) was determined from these major non-sugars (expressed as millimoles per 100 g of sugar) as follows:

$$AC = \text{K} + \text{Na}/\alpha\text{-N}$$

Wieninger and Kubadinow stated that the alkalinity coefficients must not fall below 1.8 if the thick juice were not to fall to below $\text{pH}_{20} = 8.6$ (and hence cause corrosion at the high temperatures of evaporation). This concept is similar to that of Andersen and Smed who also wished to ensure adequate juice alkalinity. In Austria the alkalinity coefficient was used to grade beet and mix them in proportions that would ensure adequate resultant factory alkalinities. As reported by Pollach, this was the first-utilized system of grower advice. '*AC* less than 1.8 = grower over-fertilization with N = alkali addition in the factory'. The beet laboratories set up in Austria for these analyses also calculated 'molasses sugar', using the relationship found for Austrian molasses:

$$\frac{\text{Millimoles of sugar}}{\text{Millimoles of K} + \text{Na}} = 1.02 \pm 0.024$$

This is an old relationship with the concept originating from Dedek (1927) and which, as opposed to being fundamental (one molecule of sucrose per atom of potassium or sodium) is certainly, as suggested by Henry *et al.* (1961) and Pollach *et al.* (1996), entirely empirical. Nevertheless it was ultimately used in Austria to determine calculated 'molasses sugar' on beet of $AC > 1.8$ and formed the basis of the quality premium payment applied to growers' beet there, since 1978. For beet of $AC < 1.8$, 'molasses sugar' was calculated from the α-amino nitrogen. Later this concept of *AC* was dropped, because alkalinity coefficients as low as this were no longer found. 'Molasses sugar' on all samples was determined by the formula:

$$(\text{mmol K} + \text{Na}) \times 0.86 \times 0.342\ \text{g}/100\ \text{g beet}$$

The factor 0.86 was derived from the factor 1.02, above, multiplied by 0.845 to allow for the fact that extraction of potassium and sodium into raw juice is on average 84.5% of the amount that is extracted into the basic lead acetate polarization digests.

The advent of rhizomania-infected beet in Austria led to changed views and a new quality approach (Pollach *et al.*, 1991) and ultimately to a new quality formula (Pollach *et al.*, 1996) for calculating 'molasses sugar' (*Sm*):

$$Sm = 0.11 \times \text{K} + 0.09 \times \text{Na} + 0.30 \times \alpha\text{-N} + 0.46$$

Hein *et al.* (1994) and Pollach *et al.* (1996) also recognized that for correctly assessing 'molasses sugar' the alkalinity reserves need to be taken into account. This has been touched upon earlier where the findings of Andersen and Smed (1963) were reported. Wieninger and Kubadinow (1971) also applied an alkalinity 'coefficient' to Austrian beet and Van Geijn *et al.* (1983) applied a limit value of 17 mmoles α-N/100 g sugar above which a correction for added sodium (from soda to increase pH) had to be applied to Dutch beet. In addressing this, Schiweck and Burba (1993) found that for South German beet, for an exact ionic balance, the weight of K + Na had to exceed that of α-amino N by 3.6 ± 0.2 mmoles/100 g beet.

Therefore, in one of the latest 'molasses sugar' formulae, Huijbregts (1999) applies an alkalinity correction when (K + Na – amino N) is less than 3.5 mmoles/100 g beet, giving the formula:

$$Sm = 0.142 \times (\text{K} + \text{Na}) + 0.2 \times \text{amino N} + 0.7$$

rather than:

$$Sm = 0.342 \times (\text{K} + \text{Na})$$

when (K + Na – amino N) is greater than or equal to 3.5 mmoles/100 g beet.

It will be noted that the latter formula is quite similar to that used in Austria from 1971 to 1991, except for omission of the factor of 0.86 allowing for the different extractions of K + Na into raw juice and lead acetate solution.

Huijbregts (2003) compared the application of the Devillers (1988), Buchholz *et al.* (1995), Pollach *et al.* (1996) and his own (1999) formulae to the beet sample data published by Buchholz *et al.* (1995) and found a general parallelism between the results for 'molasses sugar' thus confirming that the formulae can only indicate 'molasses sugar' rather than being a true measure of it. All of this confirms the findings of Last and Draycott (1977) in comparing the diverse relationships existing between clarified juice purity and the major non-sugars: potassium, sodium and amino nitrogen.

Here, it is relevant to point out that originally betaine was included by Carruthers *et al.* (1962) in their 'impurity value' and the correlation obtained between clarified juice purity (CJP) and impurity value, made up of potassium, sodium and amino nitrogen was greatly improved by its inclusion (with betaine, $r = {}^{-}0.95$; without betaine, $r = {}^{-}0.86$). However, at the time the determination of betaine did not lend itself to tarehouse analysis, so betaine was never included. In 1993, Burba and Schiweck did include betaine (w'_{Be}) and raffinose (w'_{Ra}) in their formula for determining 'molasses non-sugar value':

$$m_{\text{NZW}} = 0.92 \times w'_{\text{K}} + 0.75 \times w'_{\text{Na}} + 0.84 \times w'_{\alpha\text{-N}} + 1.15 \times w'_{\text{Be}} + 4.95 \times w'_{\text{Ra}}$$

However, the more general application of this formula does not seem to have been taken up so far.

For attempts to introduce the soluble organic nitrogen of aluminium sulphate filtrates (closely correlated with the noxious nitrogen in thick juices) instead of a summation of amino nitrogen, betaine nitrogen and other nitrogen containing compounds, see Burba (1996). In 1998, Burba published an outlook on perspectives and limits of current beet quality evaluation.

Recently, Burba and Harling[†] (2003) introduced the Rendement Concept as an alternative means for establishing beet quality formulae. The Rendement Concept is essentially based on fixed molar ratios of sucrose and selected non-sucrose compounds (K + Na and soluble N) in technical molasses, termed Rendement Factors. As shown by Burba and Harling, the known molar ratios (taken as 1.0 or calculated from molasses data available or experimentally determined) allow a simple assessment of the amount of sucrose lost to molasses, if conventional tarehouse analyses for polarization, potassium, sodium, and soluble nitrogen are available. However, because at present standard beet analysis in the tarehouse does not cover total soluble nitrogen, it is required to use a regression for calculating total soluble nitrogen in molasses from α-amino nitrogen in beets. Furthermore, transition of sucrose and non-sucrose compounds from beet to thick juice is not complete, because fractions are lost during the manufacturing process. These losses can be considered by employing transition factors and a correction factor for amide saponification.

Rendement Formulae are similar to existing quality formulae based on regressions, proving their correctness and allowing for the first time a sugar technological interpretation of their coeffi-

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[†] The authors thank Drs M. Burba and H. Harling for their contribution to this section.

cients. Burba and Harling conclude, that the Rendement Concept can be universally employed for a fast and cost-efficient calculation of beet quality formulae.

Reducing sugars

Glucose and fructose are the principal reducing sugars in beet that will be discussed in relation to processing, although Burba and Nitzschke (1973) have reported that the reducing sugar galactose is also present (see also Lieker *et al.*, 1994).

The equimolar mixture of glucose and fructose, referred to as ‘invert sugar’, is obtained from sugar (sucrose) by acid or enzyme (invertase) hydrolysis:

$$\begin{array}{ccccc} & & \text{acid} & \multicolumn{2}{c}{\text{Invert sugar}} \\ \text{sucrose} + & \text{water} & \rightarrow & \text{glucose} + & \text{fructose} \\ 342\text{ g} & 18\text{ g} & \text{or enzyme} & 180\text{ g} & 180\text{ g} \end{array}$$

Whilst sucrose is quite stable under normal processing conditions, glucose, fructose and galactose, having reactive free carbonyl $(> C = 0)$ groups, are not. Thus Oldfield (1957) and later Degeest and Debroux (1987) found that formic and acetic acids were produced from invert sugar in carbonatation and Shore (1957) showed that lactic acid represented almost half of the total acid produced in degradation of invert sugar by lime at 80°C (as in carbonatation).

In fresh beet, Burba and Nitzschke (1973) found glucose levels to be generally more than double those of fructose and, in a later paper, Schiweck and Büsching (1974) reported glucose:fructose ratios in campaign beet of between 1.5:1 and 1.7:1, so the statements commonly used which refer to ‘invert sugar’ in beet are, in the strictest sense, incorrect. From the point of view of processing quality, however, it is known that the normal total reducing sugar content of fresh beet is usually in the range 0.2–0.6 g/100 g sugar and, within the industry, this is referred to as ‘invert sugar’ or ‘invert’. Smed (1992) reported significantly different invert sugar levels in topped roots of different varieties. Thus the lowest contained 463 mg/100 g sugar, while the highest contained 556 mg/100 g sugar.

Vukov and Hangyál (1985) pointed out that pathological processes, such as mechanical damage, wilting, freezing and microbiological damage, greatly add to invert sugar accumulation via enzymic reactions as mentioned below. Oldfield *et al.* (1971) also showed the dramatic effects both of freezing and thawing and of mould damage on invert sugar levels in beet. Smed (1992) also reported on very severe invert formation in beet which had been frosted and then allowed to thaw.

Because of the severe accompanying effects on colour formation (Fig. 16.1) and therefore on white sugar production, Oldfield *et al.* (1971) considered basing a tarehouse rejection procedure upon the rapid determination of invert sugar, with a rejection limit of 2.0 g invert sugar/100 g sugar (Shore *et al.*, 1983). This has been used by British Sugar but latterly visual assessment of split beet has been preferred.

Oldfield *et al.* (1971) stressed that the invert sugar level in roots is only a guide to juice colour, it is not wholly responsible for it; other substances, polyphenols, beet polysaccharides and beet protein degradation products (Clarke *et al.*, 1989), are also major contributors to the juice colour. They did, however, establish that invert sugar is the primary

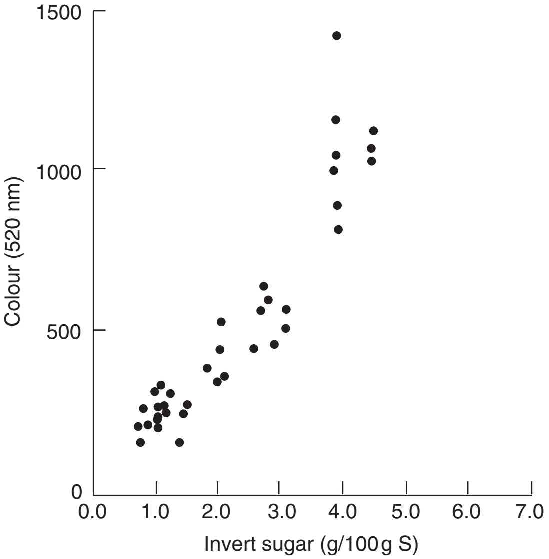

Fig. 16.1 Relationship between invert sugar of raw juice and colour of second carbonatation filtrate (from Oldfield *et al.*, 1971, reproduced with permission of the International Sugar Journal, Tunbridge Wells, TN1 2UN, England).

cause of increased lime salts, causing evaporator scaling and necessitating very high usage of sodium carbonate (soda ash) in the factories to maintain juice $pH_{20} \geq 7.0$.

The chemistry of glucose and fructose breakdown and especially its contribution to colour formation, particularly in the Maillard reaction with amino acids, are matters of continuing research (Reinefeld *et al.*, 1978; De Bruijn *et al.*, 1987; 1999), as also is the whole complex question of juice and sugar colour (Kofod Nielsen *et al.*, 1979; Reinefeld *et al.*, 1982; Shore *et al.*, 1984a; Broughton *et al.*, 1987; Bobrovnik & Rudenko, 1988). The Commission Internationale Technique de Sucrerie formed a sub-committee to consider the subject of colour, because of uncertainties relating to it. Christodoulou *et al.* (1988) reported to the sub-committee that, for Greek beet and juices, not only invert sugar, but also the major non-sugars, potassium, sodium and amino nitrogen, provide both indicators of melassigenesis and of thin juice colour. Their concept that coloured substances are melassigenic reflects the same points raised by Prey (1962) and Zaorska (1979).

In conclusion, invert sugar is an undesirable quality parameter because:

- At the basal level in beet it breaks down in carbonatation to yield acids and some colour. Both are melassigenic and any corrective sodium carbonate added by the factory to minimize lime salts and to maintain $pH_{20} > 7.0$ is melassigenic.
- At higher levels, it represents sugar lost and greater acid and colour production. In British Sugar white sugar cannot easily be produced when invert sugar in beet exceeds 2.0 g/100 g sugar.

Betaine

Betaine is a neutral nitrogenous substance, (carboxymethyl) trimethyl ammonium hydroxide, inner salt. It is related to the amino acids but, unlike them, it has no free (and therefore reactive) amino-group.

Table 16.2 shows that, in the 1960s, betaine was the most prevalent single non-sugar in raw juice. The same is probably true today but interest in betaine by the industry has tended, until recently, to be quite low for three main reasons:

(1) Betaine has been considered to be inert in processing. It also has a melassigenicity of 1.17 (Devillers *et al.*, 1984), which is slightly lower than the average 'melassigenicity' of all non-sugars of 1.5, for a nominal molasses purity of 60.
(2) Bosemark and Arvidsson (1964) suggested that varietal variations in the level of betaine were such that it was unnecessary to include it in assessing varieties. The 'impurity value' of Carruthers and Oldfield (1962), calculated from K + Na + amino N, was considered by them to be sufficiently precise.
(3) Betaine measurement was somewhat tedious, until an HPLC separation method for the determination of betaine (Bourlet, 1998) was developed under the auspices of ICUMSA.

However, some information has been published indicating that betaine is not inert in processing. Bobrovnik *et al.* (1984) have reported that betaine (% sucrose) decreased from raw juice to thick juice and betaine (% non-sugars) decreased from thick juice to molasses in the Yagotin experimental factory in Russia. These authors report loss of betaine in the presence of invert sugar and sucrose under alkaline conditions at 110°C with the formation of an absorbance peak at 335 nm, indicative of melanoidin colour formation. These results were obtained with high betaine concentrations and K. Fares (Université Cadi Ayyad, Morocco, 2004, personal communication) has other evidence that, at normal betaine levels, no colour formation nor degradation occurs. This matter would therefore bear further study in the future.

As regards melassigenicity, betaine levels in British molasses in 1987–1988 and 1988–1989 were in the range 4.5–6.0%. French levels were similar (J.-P. Lescure, SNFS Services Techniques, France, 1989, personal communication), and Czech levels (Stechova *et al.*, 1988) ranged slightly wider (4.0–7.1%). Assuming:

(a) that 1.17 g sugar is held in molasses per 1 g betaine;
(b) 3.3% molasses on beet;

then the losses of sugar to molasses at the extremes of the widest range were:

- 4.0 g betaine/100 g molasses = 0.154% sugar on beet;
- 7.1 g betaine/100 g molasses = 0.274% sugar on beet.

From this calculation it may be deduced that for every 1 Mt of European beet sliced, between 1500 and 2700 t of sugar could not be crystallized because of the presence of betaine. The real losses could be higher if the views of Bobrovnik *et al.* (1984) that betaine is degraded and involved in colour formation are true.

With regard to varietal variation, Trzebinski *et al.* (1985) reported that breeding lines with a high sugar content tended to contain more betaine. Rearick *et al.* (1993), in testing 25 varieties, found that betaine content showed some correlation (r about 0.7) with the sucrose content. Moreover, Beringer *et al.* (1986) found that betaine levels were significantly correlated with both potassium and sucrose accumulation; they concluded that betaine has a role as a cytosolic osmoticum in sugar beet tissue. Smed *et al.* (1996) reported effects on betaine by irrigation, year/site, variety, fertilizers and topping. Hoffmann *et al.* (2002) found the proportion of betaine to decrease with an increasing proportion of α-amino nitrogen. Beiss (1994), however, reported no connections found between betaine contents and other beet parameters. Beiss did however find a higher betaine content in the beet crowns and towards the end of the growing period, as well as after increased nutrient supply (nitrogen, potassium, sodium), insufficient water supply, and at a low plant density. Beiss also reported that betaine was lowered by rhizomania infestation and in bolted beet. Without irrigation, Kenter and Hoffmann (2002) found sugar and α-amino nitrogen contents temporarily increased as a result of summer drought, whilst the betaine content remained elevated until final harvest.

There is no doubt that betaine is the main soluble non-sugar in beet and its level appears to be correlated with sugar content. Confirmation of this has just come from Kenter and Hoffmann (2004), who concluded that high sucrose concentration could only be achieved by simultaneously maintaining the osmotic balance in the cells by betaine accumulation. One way of overcoming its melassigenic influence is to remove it by chromatographic separation and then to market it (as a provitamin it is widely used in the food, animal feed and pharmaceutical industries). Some beet sugar companies are already so treating low green syrup to extract betaine as described by Paananen and Kuisma (2000). The sucrose-rich fraction from the separation is returned to processing.

Raffinose‡

Raffinose is α-D-galactosyl sucrose. It interferes adversely with the crystallization of sucrose in the sugar end (Mantovani & Fagioli, 1964). Because of its high polarization value relative to sucrose, it also leads to errors in the estimation of sucrose by polarization (Gruszecka, 2000).

Raffinose levels in beet will increase between two- and fourfold with long cold storage (Wyse & Dexter, 1971).

By splitting it with the enzyme melibiase, or α-D-galactosidase (Yamane, 1971), an additional yield of sugar (sucrose) could be obtained:

$$\underset{504\text{ g}}{\text{raffinose}} + \underset{18\text{ g}}{H_2O} \xrightarrow{\text{Melibiase}} \underset{342\text{ g}}{\text{sucrose}} + \underset{180\text{ g}}{\text{galactose}}$$

The galactose which is produced during this hydrolysis behaves rather like glucose.

Such enzyme processes were at one time utilized in Japan, where recovery of sucrose from molasses, either by the Steffen process or by demineralization, was practised (K. Sayama, Nippon Beet Sugar Mfg Co Ltd, Japan, 1989, personal communication). It was necessary to break down the raffinose because it follows the sucrose stream; at levels of, say, 5% on sucrose (which are found in these processes). Raffinose has a dramatic effect on both sucrose crystallization rate and sucrose crystal morphology (Smythe, 1967; 1971; Obara *et al.*, 1976–1977; Vaccari *et al.*, 1986). As little as 2 g of raffinose per

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‡ The authors acknowledge with thanks the helpful comments of Mr Senba, Nippon Sugar Manufacturing Company Limited and Dr Fujihira, Japan Sugar Refiners' Association, in finalizing this section.

100 g water in sucrose solution of 1.10 supersaturation approximately halved the crystallization rate compared with that achievable with pure sucrose at the same supersaturation (Mantovani & Fagioli, 1964). Raffinose was shown to cause this interference by being incorporated into the crystal structure (see also Schiweck & Büsching, 1970) and causing the shape of the sucrose crystals to change to a needle-like form. Shah and Delavier (1974) indicated that this morphological change created difficulties in separating the mother liquor from the crystals, so making sugar-end operations difficult and losing more sugar in molasses.

The main enzyme process in Japan utilized a mould *Mortierella vinaceae* var. *raffinose utiliser* (Obara *et al*., 1976–1977). This technique has now been replaced by a chromatographic separation (Sayama *et al*., 1992) but has not been adopted in countries other than Japan where raffinose levels are of the order of 1 g/100 g sugar in the final boiling (compared with at least five times that level in Japan).

This chromatographic separation yields crystalline raffinose and also yields sucrose, which is recycled, together with betaine which is also crystallized and marketed. Raffinose has a major food use associated with promoting the proliferation of bifidobacteria in the human intestinal microflora; this is expected to expand its market rapidly (Sayama *et al*., 1992).

Dextran and levan

The most serious factory processing problems can arise from the presence of dextran gum, which occurs in frost-damaged beet (Atterson *et al*., 1963; Oldfield *et al*., 1975; Shore *et al*., 1983; De Nie *et al*., 1985; De Bruijn, 2000). Reinefeld (1975) considered that levan gum is also involved in similar processing problems.

Neither dextran nor levan is present in healthy beet, but both are readily formed by the action of micro-organisms, which are present in beet tissue once cell-rupture occurs, releasing sugary liquid. Such cell-rupture occurs most frequently as a result of the freeze-thaw cycle. Microbiological degradation of sugar may start after thawing, especially at relatively high temperatures (Heijbroek & Huijbregts, 1984). Deep-freezing of beet is the preferred method of storage in parts of the USA (Bichsel, 1988), and similar practices are used in the colder regions of the countries of the former USSR (Vukov & Hangyál, 1985).

Dextran and levan are also formed in beet stored under anaerobic conditions (Shore *et al*., 1983), but in most European countries beet are usually stored with adequate ventilation, and any dextran and levan gums are usually present only in beet that have been frozen and then allowed to thaw. Beet losses in the UK were particularly severe in 1962–1963 when 300 000 t of beet, unharvested by Christmas, were locked in the ground by severe weather and rendered unprocessable. The UK is particularly vulnerable and has often been unprepared (Oldfield *et al*., 1980) but similar problems have, of course, occurred in other countries (Skogman, 1971; Devillers *et al*., 1974; De Nie *et al*., 1985; Grabka & Wasiak, 1996; De Bruijn, 2000).

The carbonatation stage of the factory process is often brought almost to a standstill by the inability to filter the fine calcium carbonate precipitate, which is formed in the presence of the high-molecular-weight gums (principally dextran). Dextran must not exceed approximately 75 mg/l of raw juice (De Bruijn, 2000), otherwise these filtration difficulties will occur. Dextran in beet can be determined by thin-layer chromatography (Schneider, 1979) or, by a gel filtration method (Sayama & Kamata, 1988) in about 2 hours, but these methods are inappropriate at the factory's beet reception area, so visual methods have been devised (Shore *et al*., 1983; De Nie *et al*., 1985). Plates 78 and 79 show the guide used by British Sugar for acceptance or rejection with beet showing any gumminess as in G/F and E, being rejected, whereas J is accepted and D is only accepted if it is to be processed directly, without further storage in the factory yard.

Because it is impossible to detect all frost-damaged beet, factories must incur additional costs to process those that do enter the factory. Shore *et al*. (1983) estimated an additional cost of £100 000 for a special calcium carbonate to assist in the filtration of juice from between 250 000 and 500 000 t of beet in 1981–1982, which would probably have been rejected in earlier years. This cost is attributable to dextran only, but there would have been many other additional costs related to the overall deteriorated state of these beet. Burroughs and Wones (2003) have also proposed adaptations of the carbonatation to make it possible to process frost damaged beet.

In the Netherlands (De Nie *et al.*, 1985; De Nie & Van den Hil, 1989) the two sugar companies have attempted to exclude frosted beet from their factory sites because of the resultant increase in the biological oxygen demand (BOD) load in their effluents. Financial penalties are therefore applied where such beet are detected in delivered loads.

In Japan, dextran problems in the factory process were first countered by using an enzyme, dextranase. This operates only in cool raw juice (~60–65°C) and so cannot be used in factories that have hot raw juice. De Bruijn (2000) reported that CSM's circulation juice temperature had to be reduced from 80 to 65°C in order to avoid thermal inactivation of the NOVO 50L dextranase being used. Barfoed and Mollgaard (1987) have also used dextranase in Denmark. However, such treatments are add-on costs to processing that ought often to be avoidable.

Enzymes

The enzymes of importance for the processor are those that lead to sugar loss, breakdown of the beet tissue or colour formation. These three groups of enzymes (which are not mutually exclusive) are listed below:

1. sugar loss enzymes: acid and neutral invertases (Oldfield *et al.*, 1969; Burba & Nitzschke, 1980; Klotz & Finger, 2001a), sucrose synthase (Dutton *et al.*, 1961; Wyse, 1982; Vukov & Hangyál, 1985; Vaccari *et al.*, 1988; Sakalo & Tyltu, 1997); all of these enzymes (Knyazev *et al.*, 1995; Berghall *et al.*, 1997; Klotz & Finger, 2001b; 2002);
2. tissue breakdown enzymes: pectolytic enzymes (Vukov & Hangyál, 1985);
3. colour precursor enzymes: tyrosinase (Gross & Coombs, 1975), polyphenoloxidases (Vukov & Hangyál, 1985; Nezam El-Din, 1996).

The sugar-loss enzymes are the most important. Vaccari *et al.* (1988) perceived the possible involvement of all three enzymes in sugar loss during storage, and others (Knyazev *et al.*, 1995; Berghall *et al.*, 1997; Sakalo & Tyltu, 1997; Klotz & Finger, 2001b) have also invoked some or all of these enzymes, but the biochemical mechanisms of sugar storage loss are still not completely understood (Vukov & Hangyál, 1985). Gibriel *et al.* (2003) proposed treatment of stored roots with sodium metabisulphite, which reduced the loss of sugar by invertase activity. Acid invertase is involved in sugar loss during processing, when beet cossettes are allowed to fall below killing temperatures of about 70°C (Oldfield *et al.*, 1979a). In many countries, as part of heat economy strategies, the temperature of cossettes is being raised only gradually (Degeest & Debroux, 1987; Dodd, 1989) and therefore it is probable that sugar losses due to beet acid invertase will be increasing. Such losses will also be increased as crown tare or green matter levels increase. On the other hand, in their experiments with electroporation and alkaline extraction of beet, Frenzel *et al.* (2003) found that invertase activity was suppressed and this led to a high raw juice purity.

Pectolytic enzymes are operational during beet storage and Vukov and Hangyál (1985) have found them to be correlated with the physical properties of the roots. The consequences of pectin breakdown are not fully understood. However, Fares *et al.* (2003) have studied pectin breakdown in processing. Galacturonic acid was measured in extraction and thin juices to assess pectin breakdown under the hot alkaline conditions of purification. Its presence in the juice increased colour formation and negatively affected the ionic balance. More studies in this area would seem to be called for.

The complexity of colour formation was discussed above. The role of tyrosinase and polyphenoloxidases in the darkening of raw juice is well-established (Gross & Coombs, 1975; Kofod Nielsen *et al.*, 1979), but Buchholz and Mikhael (1989) did find that, with incomplete substrate oxidation, these enzymes can cause the formation of soluble melanins, which could explain the phenomenon of unusual juice darkening, after purification. It may be therefore that the role of these enzymes will assume a greater significance in the future, unless the electroporation of beet prior to extraction (Frenzel *et al.*, 2003) takes over, in which case alkaline extraction would come into its own and the significance of all enzymic activity in processing would diminish.

As far as breeding is concerned, it should be noted from the work of Leigh *et al.* (1979), that high sucrose was associated with low activity of acid-invertase in the vacuoles of beet tissue.

Marc

Marc is usually thought of as the insoluble part of the beet root. However, much of it (except the cellulose, lignin and some ash) is partially water-soluble, albeit with difficulty, so this definition is somewhat imprecise. Claassen (1916) devised a method of extracting sugar from brei, using hot water in a simulation of the factory diffusion process, and leaving the marc. By dictionary definition, marc is the whole residuum (e.g. marc de pommes = pomace) and therefore includes any ash component. Nevertheless some investigators refer to marc as the insoluble matter **minus** the ash; such marc figures will be referred to here as 'marc-ash'.

Marc is the second most valuable product in the sugar beet after sugar. It forms the beet pulp, utilized either as animal feed, or, more recently, as a human dietary fibre (see Chapter 17). From a beet quality point of view, where processors have purchased the pulp rights, it is desirable that the marc should be as high as possible. The composition of beet marc is shown in Table 16.3. Other authors (Silin, 1964; McCready, 1966) have also reported marc analyses which are generally in agreement with these data.

Vukov (1977) stated that the relationship between marc content and cutting resistance of sugar beet was a loose one; hence a higher marc content did not imply a higher cutting resistance. Vukov and Hangyál (1985) pointed out that during storage, enzymatic transformation of insoluble protopectin into soluble pectin occurs, so that the total amount of marc is reduced. Also, pectin and mineral substances solubilize so that the relative cellulose content increases; parallel to this the cutting resistance of the tissue increases, because this is a function of the cellulose and lignin content of the marc (Vukov, 1977). This implies that slicing resistance, and therefore cossette quality, may be worse with stored beet as a result of solubilization of marc components. These links between chemical components and physical properties and the effects of solubilization of such components on juice purification are subjects requiring further investigation.

Table 16.3 Composition of beet marc (%) (reprinted from Vukov & Hangyál, Sugar Beet Storage, *Sugar Technology Reviews* **12**, 1985, 143–265, with permission from Elsevier).

Composition of beet marc	%
Pentosans	24–32
Pectins	24–32
Cellulose	22–30
Lignin	3.0–6.0
Crude protein	4.5–5.5
Encrusted mineral substances	4.0–4.5

Some concern was expressed at reductions in marc levels that have occurred since 1980. Huijbregts obtained results for marc-ash in Dutch beet between 1976 and 1989, as shown in Fig. 16.2.

Environmental factors (e.g. soil and/or weather conditions) are very important in affecting marc, which is also reduced by high rates of nitrogen fertilizer and by increases in the weight of individual roots (Huijbregts, 1986; Beiss, 1988; Huijbregts *et al.*, 1996a). Differences are also found between varieties (Huijbregts *et al.*, 1996a; Bloch & Hoffmann, 2004). Huijbregts (1986) found higher levels of marc in the old polyploid variety Kawepoly than in some newer monogerm varieties (e.g. Monohil, Regina, Bingo and Bella). More recently, Kenter and Hoffmann (2004) have demonstrated that a high sucrose concentration is accompanied by a high marc at different locations. It is assumed that a high sucrose concentration in sugar beet can only be achieved by forming the optimal cell structures to obtain the optimal cell volume for sugar storage. Furthermore, Bloch and Hoffmann (2004) also found that marc accumulation was positively correlated with sucrose concentration.

Because the levels of marc in the crowns may be 6.0–7.7% compared with only 4.0–5.5% in the topped roots (Beiss, 1988), variations in the amount of crown tissue will also influence marc levels.

The traditional method of measuring marc is very time-consuming, and this has restricted in-

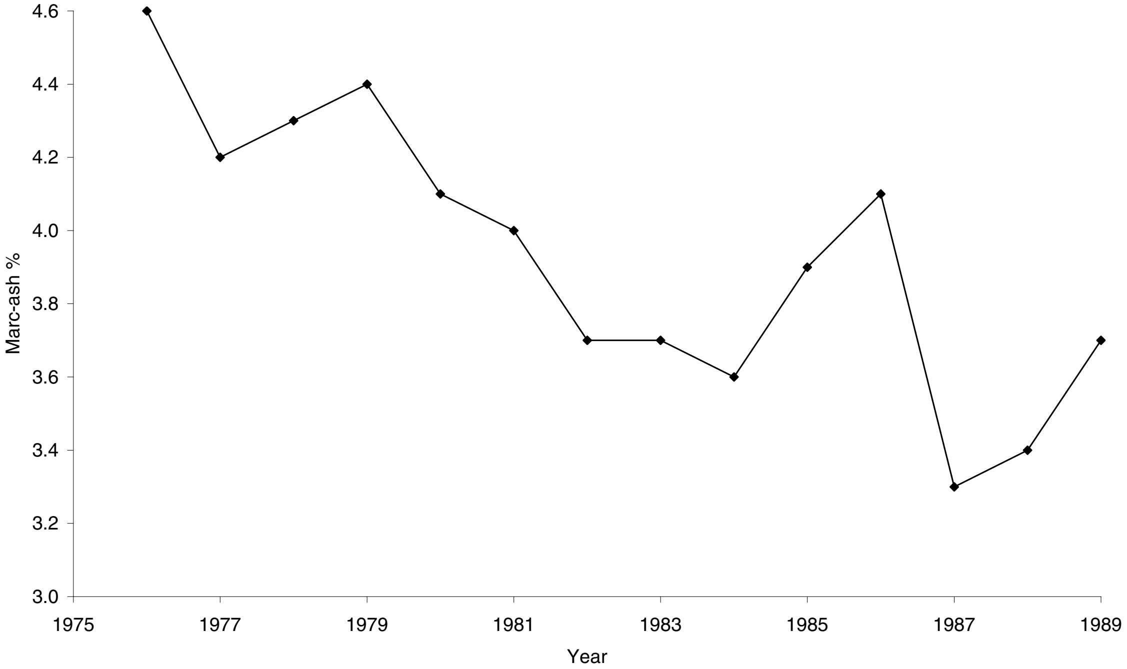

Fig. 16.2 Changes in 'marc-ash' of Dutch sugar beet, 1976–1989 (Source: A. W. M. Huijbregts).

vestigations of its variability. The IRS in the Netherlands has developed an alternative method using near infra-red (NIR) analysis (Huijbregts *et al.*, 1996a).

Physical properties

Two quantifiable physical properties of primary importance in processing are: (1) resilience; (2) resistance to cutting. Morphological properties, such as fanginess and the depth of the groove are considered later because their most significant effects are on dirt removal and consequent root damage.

The physical resilience of beet roots is very important to both grower and processor because it affects the degree of breakage and bruising damage, and the subsequent leaching or microbial catabolism of sugar in harvesting, storage, transport and fluming. Vukov (1977) and Vukov and Hangyál (1985) used the modulus of elasticity of pieces of tissue from fresh and stored beet to characterize them and place them into one of four broad categories (Table 16.4). They stated that with loss of beet mass by dehydration there is a change in the turgid state of the beet and in the elasticity of the tissue.

Experience tells us that fresh beet are usually more brittle than beet that have been stored, even for quite short periods. De Vletter and Van Gils (1976) quantified this in their studies of sugar loss from whole beet that had been damaged by various

Table 16.4 Influence of water loss on the modulus of elasticity (reprinted from *Sugar Technology Reviews*, Vol. 12, 1985, pp. 143–265, Vukov & Hangyál 'Sugar Beet Storage', with permission from Elsevier).

Loss of mass – mainly of water (%)	Designation	Corresponding turgidity	Modulus of elasticity (MN/m^2)
0–4	Brittle	Fresh	7.0–14.0
4–10	Elastic	Desiccated	4.2–7.0
10–20	Soft	Wilted	1.8–4.2
> 20	Very soft	Very wilted	< 1.8

heights of fall, and found that losses were 1.6 times greater with fresh beet than with stored beet.

Peterson and Hall (1983) studied the injury inflicted on commercial and experimental cultivars of sugar beet by a drop-impact device. Damage caused by a 2 kg weight of 6 cm diameter falling from heights of 43 or 57 cm was assessed by measuring the maximum vertical and horizontal widths and the maximum depth of bruises inflicted on whole beet. Significant differences were found between cultivars, but there was no correlation between bruising damage and sugar content.

In assessing damage susceptibility of sugar beet, Van Swaaij *et al.* (2003) expressed elasticity as a Pendulum Index (PI), i.e. the percentage of beet that absorb less energy at the second impact than at the first impact of a pendulum. A lower absorption at the second impact means that the beet tissue has been changed during the first impact. A high PI correlates with high elasticity, and expectations were, with lower damage susceptibility. Though this was not established, some significant findings were made. Thus, the elasticity of beet tissue showed a consistent decrease from September to November and elasticity decreased with increasing nitrogen fertilizer usage. These authors concluded that many factors affecting damage interact and the assessment of damage susceptibility in terms of surface damage and tip breakage is still quite variable.

Sugar losses due to mechanical damage are considerable. In the Netherlands, where 5 Mt of beet are processed annually, De Vletter and Van Gils (1976) estimated that if ‘average practice’ were changed to ‘good practice’, 3.6 kg sugar/t beet could be saved. Also, Houghton and Armstrong (1994) summarized the financial losses accruing from dropping beet onto beet or onto concrete, under UK conditions.

Resistance to cutting is a physical property of key importance to the processor in the slicing station. The ease with which sugar diffuses out of cossettes is positively correlated with their thinness, but the cossettes must have sufficient strength and flexibility to withstand the pressures and turbulent movement in diffusers (Vukov, 1977; Dreibholz, 1996). Silin (1964) devised a number, expressed as metre length of cossettes per 100 g, which should be as large as possible, commensurate with cossette stability. This becomes less achievable as beet tissue deteriorates and becomes softer, so that thicker slices must be cut to prevent their later disintegration in diffusion, pressing and drying. However, it is detrimental to slicing if beet tissue is woody, because fibrous tissue blunts the slicing knives and they have to be changed more frequently. This can primarily be controlled by removing bolted beet from the crop. Vukov’s classification of various resistances to cutting is given in Table 16.5.

Whilst resistance to cutting is a useful initial concept, Drath *et al.* (1984), opted for a modified way of measuring ‘resistance to slicing’ using a Frank tensile testing machine, Type 81558, fitted with a knife instead of the normal descending punch, which they used to determine flexural testing ‘to-the-breaking-point’ of beet tissue samples. With this equipment they were able to quantify the following parameters:

- the breaking value, in Newtons (N), of test pieces of tissue;
- the maximum deflection (mm) by the movement of the descending punch from the point where it contacted the sample until failure;
- the slicing resistance (N/cm); being the force necessary for the knife to cut through samples with a slicing length of 3 cm.

They found good correlation between their slicing resistances and Vukov’s cutting resistances determined in various samples. However, they preferred their own method for determining flexural properties, because, in the action of force to break the sample, both the elastic and plastic properties are

Table 16.5 Sugar beet grading based on the resistance to cutting (reproduced with the kind permission of Ir. Peter Vukov, H-7400 Kaposvár, Hungary).

Resistance to cutting (N/cm)	Designation
< 8	Soft
8–14	Normal
14–18	Suberized
18–30	Woody
> 30	Extremely woody

involved, whereas in Vukov's procedure only the elastic property is involved.

The studies by Drath *et al.* (1984) were prompted by repeated difficulties due to beet breakage at the Plattling factory in Germany in the period 1975–1977, and their field experiments showed that higher rates of nitrogen fertilizer (250 and 350 kg N/ha) gave beet of worse mechanical properties than lower rates (150 kg N/ha and below). The breaking load, in particular, provided a characteristic value, and they concluded that cossettes from beet tissue with a breaking load of < 600 N were more difficult to process in diffusion.

More work was carried out at Plattling by Cronewitz (1977), who compared cossette qualities and their processing consequences during two periods in the 1976 campaign. In the October period, beet having tissue breaking-loads of about 680 N were processed and in the November period beet with tissue breaking-loads of about 590 N were processed. Much more fine pulp material was produced from the low than the high breaking-load beets (16% versus 6%) with the following consequences:

- additional diffusion draft;
- worse pulp pressing;
- loss of pulp as dust;
- higher bacterial infection in the pulp circuit; and
- lower white sugar yield resulting from solubilization of pulp solids.

The estimated financial loss was about DM 1m (€511 300) for 1 Mt of beet sliced, although this did not include the inevitably increased yard losses or additional effluent treatment costs.

In another study, Cossairt (1979) made photographic comparisons of cross-sections of piles of cossettes having structural rigidity with those made up of cossettes from soft, limp roots; the former provided an open porous bed whereas the latter exhibited a lack of openness and produced plugging of the diffusion screens. He emphasized that pectin modification processes as well as loss of water are involved in tissue softening, a point confirmed by Vukov and Hangyál (1985) who established significant correlations between the activities of pectolytic enzymes and the modulus of elasticity, the fragility and the degree of injury of sugar beet roots.

Drath *et al.* (1984) reported that beet breaking at lower loading (< 600 N) contained more amino nitrogen and more sodium; additionally they noted a tendency, though not statistically significant, for positive effects on mechanical properties from magnesium and/or calcium fertilization. Despite this work, and that of Vukov and Hangyál (1985) the links between chemical or biochemical properties and physical properties seem somewhat unresearched. Whilst other studies have been made of the physical properties of beet in relation to Italian (Vaccari *et al.*, 1981) and Polish (Bieluga & Bzowska-Bakalarz, 1980; Ostrowska & Wzorek, 1980) conditions, there is no doubt that further attention should be given towards improving the physical properties of beet.

As well as these 'mechanical' properties, the diffusion coefficient, which affects the efficiency of extracting sugar from cossettes (Vukov, 1977) and is, for example, adversely influenced by wilting, also warrants further research, such as that by Genie (1994) and Walerianczyk (1994).

Tare

Top tare

There have been many studies of the quality of the crowns of beet, some of which were reviewed by Devillers (1982; 1984). Two points of importance emerge:

(1) the quality of the crowns is always worse than the quality of the topped roots;
(2) for optimum storage, there may be different topping requirements for different countries (Vukov & Hangyál, 1985).

The following requirements for crown quality assessments should be met:

- Crowns for analysis must be prepared in a way that can be achieved by currently available harvesters. In particular, they should retain the short vascular strands that Carruthers *et al.* (1966) could not force off by hand.
- Properly clarified juices should be prepared and juice purities determined (Oldfield *et al.*, 1977).

- If clarified juice purities cannot be determined, then quality assessment should not be based simply upon potassium, sodium and amino nitrogen. Jaggard *et al.* (1999) studied the distribution of several additional quality parameters between different beet parts (scalp, crown, root and tail). It is not possible to predict molasses sugar from any formula combining these major non-sugars, and with crown tissue this becomes an even more difficult problem because:
  - (a) invert sugar and betaine are more concentrated in crown tissue (Winner & Feyerabend, 1971) and therefore must be included in quality assessment;
  - (b) raffinose is present in crown tissue at approximately double the level present in the root (O'Connor, 1984);
  - (c) invertase activity is higher in the crown than in the root and very much higher in petioles and leaves (Kursanov, 1967);
  - (d) there are higher levels of polyphenols (melanin colour precursors) in the crown than the root (Kofod Nielsen *et al.*, 1979).

Because of these difficulties, in most countries the crown tissue (i.e. that which is above the lowest leaf scar) is regarded as tare and is not paid for by the processor.

For storage, beet should be either topped or not, according to the agricultural advice given in individual countries. In the UK, post-harvest temperatures are usually high enough to allow beet with crowns to sprout, which increases storage losses (Oldfield *et al.*, 1981). Where beet have been frozen before harvest, topping is necessary to remove frost-damaged crowns.

Dirt and trash

Dirt and trash are obviously negative quality features for the processor, but they should also be regarded as such by the growers. In the 52nd Winter Congress of the IIRB, Fauchère (1989) identified the reduction of dirt tares as being one of ITB's main concerns. Excessive dirt and trash are well known to cause high losses during short-term storage in growers' clamps, for example, but less well known, are the costs to growers of delivering organic matter and nutrients in soil tare, which are valued in France at fr.18 (€2.7) per tonne of tare (Soignet, 1981). The errors in determining clean beet weight are also increased as dirt tare increases (Devillers, 1986). The total costs to the French beet industry have been estimated at fr.87.5 (€13.3) per tonne of dirt and trash (Bouquery & Guérin, 1986).

Most processors are faced with the following problems associated with dirt and trash:

- increased losses in yard storage due to overheating (Oldfield *et al.,* 1979a);
- breakage and bruising of beet resulting in sugar loss and effluent loading; production of tails, particularly with fangy beet, in washing to remove the dirt: such tails cause more fine pulp in slicing (Vukov, 1977);
- separation and treatment of soil residue and treatment of the liquid effluent load.

It has also been suggested that residual dirt that is not removed in the washers results in increased usage of slicer knives and, where it has a high clay content, is responsible for higher sugar losses in carbonatation (Oldfield *et al.*, 1977).

De Nie and Van den Hil (1989) estimated the factory costs of dirt as being 28 Dutch guilders (€13) per tonne of soil. Suiker Unie, as part of their new contract package, started charging the growers 22 guilders (€10) per tonne of delivered dirt, in the hope that this would encourage dirt removal at the farm if it could be achieved at less cost. Hoogerkamp (1993) refers to a 'dirt tare contribution arrangement' being introduced in the Netherlands. More recently, Van der Linden (1996) estimated the handling costs relating to soil removal as 46m guilders (€21 million) for the Dutch factories. He investigated cleaning technology in an attempt to decrease the amount of soil tare by 80%, e.g. lifting principles that did not compress soil onto beet and that consequently decreased the amount of soil adhering to the beet. Cleaning systems such as compressed air, brushes, stars and axial rollers were compared with conventional systems such as turbines and augers. These different systems decreased clay soil tare by 50% and sandy soil tare by 80%. All this technology was appropriate for beet harvesters and cleaner loaders. During the 65th

IIRB Congress attention was paid to techniques for soil tare reduction by breeding techniques (Gram & Jorgensen, 2002), by cultural practice (Koch, 2002) and by harvesting techniques (Guiraud de Willot & Lévèque, 2002; Van der Linden, 2002). Steensen (2002) studied the balance between reduction of soil tare and root injuries.

FACTORS INFLUENCING QUALITY

Introduction

Many varietal, environmental and agronomic factors influence beet quality; for example 28 were listed by Vukov (1977). Huijbregts *et al.* (1996b) presented an overview of agronomic factors on sugar, potassium, sodium and α-amino nitrogen and Smed *et al.* (1996) on raffinose, reducing sugars, glutamine, betaine and phosphate. They concluded that, although year and site are important factors influencing beet quality, the farmer may improve the quality of the beet by optimal fertilization, choice of varieties, optimal plant population, prevention of stress conditions, control of pests and diseases, way of topping and harvest and storage under optimal conditions. Some of those that have the greatest influence on the quality parameters already mentioned are discussed below.

Climate

Because of the heterozygotic nature of its heritable characteristics, sugar beet is readily adaptable to different environmental factors, including climate. However, climatic conditions can affect the properties of the beet roots (Glattkowski & Märländer, 1994).

In general, if the crop is sown early with favourable climatic and soil conditions, it will produce good quality roots. Van der Beek and Huijbregts (1986) highlight the importance of early sowing and favourable weather conditions in relation to the 'extractabilities' of crops grown in the Netherlands from 1982 to 1985. Conversely early sowings combined with cold weather may cause vernalization, with consequent increases in cutting resistance.

Drought and high temperatures during growth also have adverse effects on root quality, raising levels of individual amino acids, other nitrogen compounds and invert sugar (Carruthers *et al.*, 1960; Vukov, 1977; Oldfield *et al.*, 1979b). In this regard, the difference between the qualities of 'northern European' beet and 'Mediterranean' beet needs to be mentioned (Christodoulou & Hadjiantoniou, 1990; Noé & Mantovani, 1996; Fares *et al.*, 1994; 1996a). Apart from the quality-lowering by the formation of high levels of invert sugar due to the high temperatures during harvesting and storage, 'Mediterranean' beet have higher levels of sodium and α-amino nitrogen, as shown in Table 16.6.

Fares *et al.* (1994) point to even higher levels of these two non-sugars in Moroccan beet and conclude that factors other than the dosage of nitrogen fertilizer play a part in this phenomenon (e.g. climate and soil type). This seems to be something requiring further research.

Another key climatic factor with respect to beet quality is undoubtedly frost and the often irregular timing of its occurrence (Devillers *et al.*, 1974). All sugar beet companies have programmes to minimize damage by frost, and it is incumbent upon growers to follow any advice and observe any regulations that have this objective (Shore *et al.*, 1982; Davies, 1987; De Nie & Van den Hil, 1989).

Table 16.6 Beet analyses 1992–2002.

Country	Sugar content (°Z)	K (mmol/100 g beet)	Na (mmol/100 g beet)	α-amino-N (mmol/100 g beet)
S Germany[1]	17.33	4.33	0.58	1.85
UK[2]	17.15	4.18	0.69	1.49
N Italy[3]	15.21	4.40	1.91	2.85
Greece[4]	14.02	4.48	2.61	2.71

Data kindly supplied by: 1. H-J Puke, Südzucker; 2. G Parkin, British Sugar; 3. G Pezzi, Comprensorio di Minerbio e Ostellato; 4. D Hadjiantoniou, H.S.I.

Variety

Oltmann *et al.* (1984) considered that the sugar content of current varieties had neared an upper limit so, for further quality improvement, it would be better to try to reduce the levels of impurities. Subsequently, Kerr and McCullagh (1989) reported marked reductions in the levels of the major non-sugars, potassium, sodium and, particularly, amino nitrogen, in British varieties. The situation has, however, become more complicated with the newer search for rhizomania-resistant varieties in all countries (e.g. ITB, 2002; Kerr, 2003; Srba & Hakaufová, 2003).

Jansen and Burba (2001) in reviewing breeding progress in the German national lists tests report that, despite the genetically-fixed negative correlation between yield and sugar content, the latter has increased by about 5% since the mid-1970s. Even more evident has been the progress in the reduction of the alkali content (K + Na) by about 35%. Moreover, α-amino nitrogen has decreased by 50%. These authors conclude that some 20% of the resulting decline in thick juice non-sugars has been due to less nitrogen fertilizer application, while around 80% can be attributed to progress in breeding. For the future, they suggest that the ionic balance is crucial, which will require that alkalinity reserves are maintained, along with further reductions in α-amino nitrogen.

The observation by Leigh *et al.* (1979) that high sucrose in vacuoles was associated with low acid-invertase activity will be an important consideration for processors seeking heat economy, though the development of routine testing methods for acid-invertase may present difficulties.

The developments in breeding rounder beet (Mesken, 1984; Coe & Theurer, 1987; Theurer, 1989) are important steps in helping the industry to overcome the problems associated with high dirt tares. Working along these lines, Hilleshog (2004) have reportedly developed a variety, Bandit, with a much reduced root groove. The Dutch list of varieties gives information about dirt tare (De Nie & Van den Hil, 1989), which is important for grower and processor alike.

One thing missing from breeding programmes, which if introduced would benefit the whole industry, is the application of routine physical tests to help to ensure that new varieties combine resilience with good slicing properties.

Fertilizer

During the 1980s, great efforts were made by all companies to curb the excessive use of nitrogen fertilizer. In spite of all the information on nitrogen usage (Dutton & Turner, 1983; IIRB, 1983; Schepers & Saint-Fort, 1988; Saint-Fort *et al.*, 1990), the application of excessive amounts continued to be a great problem for processors. It not only increases most of the major non-sugars, in particular α-amino nitrogen (Wiklicky, 1971; Burba *et al.*, 1984), resulting in lower crystallizable sugar (Devillers, 1982) and alkalinity, but it also has detrimental effects on sugar content and marc (Wieninger & Kubadinow, 1973), invert sugar, lime salts and colour (Reinefeld & Baumgarten, 1975), raffinose (Burba & Nitzschke, 1973) and the physical strength of beet tissue (Bürcky *et al.*, 1978; Drath *et al.*, 1984).

It also threatened the environment, not only as nitrates, which can leach into drinking water, but also as ammonia which is the principal volatile nitrogenous product coming from beet juice processing (from glutamine breakdown) and which, as a highly odoriferous gas, would need to be reduced in factory emissions (Huisman *et al.*, 1987).

Within the UK, tarehouse measurements of α-amino nitrogen were instituted, coupled with a grower-advisory system to control excessive applications (Shore *et al.*, 1984b). As can be seen in Table 16.7, this UK system has been completely effective, by more than halving the α-amino nitrogen levels in British beet since 1990. In other countries, some different means of control of nitrogen fertilizer are also being effectively employed (Herlihy & Hegarty, 2001; Horn & Fürstenfeld, 2001). According to Draycott *et al.* (2003), in the UK the nitrogen application to the beet crop has reduced from 160 kg N/ha to 105 kg N/ha over the last 25 years, thus largely solving the 1970s problem of excessive usage.

The only other fertilizer warranting comment as far as beet quality is concerned is that of salt (sodium chloride). This is applied to the crop in order to increase yield and it is reported that 73%

Table 16.7 Average sugar contents and α-amino-N levels in British beet (1990–2002).

Year	Sugar content (°Z)	α-amino-N (mg/100 g sugar)
1990	17.20	211
1991	17.49	171
1992	17.01	137
1993	16.84	107
1994	16.96	135
1995	16.47	168
1996	18.04	132
1997	17.17	163
1998	17.34	125
1999	17.16	117
2000	17.10	92
2001	17.16	78
2002	17.38	88

Data kindly supplied by G Parkin, British Sugar plc.

of the 1999 UK crop received sodium, mainly as salt (Dutton, 2000). However, Jarvis *et al.* (2003) point out that 50% of the UK beet crops grown on clay soils and 25% of those grown on peat/organic soils receive agricultural salt, even though both soils probably contain sufficient readily-exchangeable potassium to meet the crops' needs.

On the one hand, salt reportedly lowers juice purity (0.37 ± 0.19 units) and increases sodium, potassium, chloride and total nitrogen levels in the juices (Carruthers *et al.*, 1956). On the other hand, in field trials to study the effects of KCl and NaCl applications to beet, Farley and Draycott (1975) concluded that, although the concentrations of potassium and sodium respectively in the beet juice were increased, there were proportionate decreases in α-amino nitrogen levels, giving a nil effect on calculated purity; no weighting was given to the chloride, however. NaCl is, of course, highly melassigenic, its coefficient being almost double that of sodium glutamate or pyroglutamate (Devillers *et al.*, 1984). Thus, salt applications might be more detrimental to the processor than was suggested by Farley and Draycott; their effects on beet quality should surely be measured in future trials.

There is a suggestion of improvements to mechanical properties of beet from magnesium and/or calcium fertilization (Drath *et al.*, 1984) and calcium is also claimed to confer benefits to pulp (Jones, 1988). These effects also require further investigation.

Other agronomic factors

General agronomy

The effects of many agronomic factors, such as plant population, cultivations and irrigation on yield, sugar content and juice purity are well researched. However their effects on dirt tare, root physical properties (such as those described by Peterson & Hall, 1983, or Drath *et al.*, 1984) and morphology (e.g. variabilities in heights of crowns above soil level, or root fanginess) are little understood and require further investigation. Some work has, however, been reported by Kamil *et al.* (2000) on studies of the morphological characteristics of ten cultivars during 1996/1997.

Diseases during crop growth

Most beet diseases result in lower sugar content (Vukov, 1977), and if the non-sugars taken up by the beet do not change, juice purities from diseased plants will therefore be lower than from healthy plants. In some cases, however, the non-sugars do change, for example Oldfield *et al.* (1977) found a doubling of amino nitrogen in plants infected with virus yellows compared with uninfected plants. There is a report of virus yellows increasing the content of reducing sugars (Vukov, 1977) and in the UK in 1974, when there was 76% virus yellows infection nationally, levels of invert sugar in trial beet were 1.0 g invert/100 g sugar, which is higher than normal (P.J. Last, Broom's Barn Experimental Station, UK, 1989, personal communication). Other changes in processing quality are dependent upon the timing of virus yellows infection (Heijbroek, 1988).

There are also reports of substantial increases in invert sugar caused by downy mildew (Vukov, 1977), and particularly noticeable increases in sodium (Pollach, 1984b; Bertuzzi & Zavanella, 1988) in the case of rhizomania infection. Pollach utilized a concomitant smaller increase in potassium together with a decrease in α-amino nitrogen to compute a 'rhizomania signal' for use in detect-ing rhizomania-infected beet during conventional Austrian analyses, whereas the Italian authors relied solely on the beet sodium levels.

The more recent occurrences of Rhizoctonia root rot (Puscasu & Caraba, 1999; Benker, 2000; Rysánek, 2002) have resulted in beet of very poor quality. Thus, as reported by Bruhns *et al.* (2004), such infected beet yielded juices having poor filtration characteristics, increased hardness and the need for soda ash. Juice colours were also higher, as were the sugar losses to molasses. The only current counter-measure seems to be to identify and sort severely affected beets and reject them, as well as ensuring that all beet from severely affected areas are processed as soon as possible.

Agrochemicals

It is increasingly necessary, for quality assurance of products and for the sale of molasses for animal feed and fermentation, to ensure that there are no residues of agrochemicals (particularly of pesticides) in the beet to be processed. If such products are used according to manufacturers' recommendations there should be no problems (Oien, 1989; Wevers, 2001). However, continued research on residues is called for, such as that by Richard-Molard and Morel-Krause (2003) and Kucharski (2003). Additionally, the rates, for example, of herbicide applications need careful scrutiny (Paradowski & Adamczewski, 2002) as does further consideration of the alternative of mechanical weed control (Tugnoli, 2000).

Harvesting and topping

For satisfactory storage and processing of beet roots it is necessary to remove at least the scalp and all green material; harvested roots should also have low dirt tare and minimal bruising and breakage. The IIRB, through its Harvest Mechanization Sub-group, recognises these requirements, which were the main subject of its 47th Winter Congress introduced by Pichenez (1984).

A development that had implications for the processor was the introduction of harvesting equipment such as the skew-bar topper, which leaves profiled crowns on the beet roots (Breay, 1986). Sugar beet crowns, even if they are scraped with a knife to expose white tissue, are of distinctly lower quality than the remainder of the root (Zielke, 1973). Therefore, although such equipment improves the quality of delivered crowns and increases the tonnage of delivered beet, it would, if widely used, lengthen the processing campaign and cause a general reduction in root quality. In those climates where beet may be frosted in the ground, clean topping to remove completely all frosted crown material will always be necessary.

From the processor's point of view, it is desirable to minimize dirt tares, and initiatives to clean the beet on the farm are to be encouraged (Vigoureux, 1989) though careful handling is necessary (Van Swaaij *et al.*, 2003); alternatively, some processors have introduced charges for cleaning (see above under Dirt and trash). Of course cleaning and handling roots can damage them, with a resultant loss of extractable sugar. Such damage has been largely underestimated, but is of greatest concern and has received most attention where crops are harvested at higher temperatures, for example in Italy and Morocco (Mantovani, 1981; Vaccari *et al.*, 1981; Mantovani & Vaccari, 1989; Fares *et al.*, 1996b).

Storage

Chapter 15 is devoted to storage, and excellent reviews of the current state of knowledge regarding storage as it affects processing quality have been written by Devillers (1982) and Vukov and Hangyál (1985).

Despite the publication of such reviews and numerous advisory articles, storage of roots on the farm is still a chore, so that practice often falls short of what is desirable. As a result there have been unnecessarily high losses due to frost damage and overheating. Factory storage, too, often leaves a lot to be desired, and some factory beet-handling systems were not designed with a view to minimizing sugar losses in the yard.

Jaggard *et al.* (1997) studied the changes in weight and quality of beet stored in farm clamps. Rates of sugar loss and the relationship with handling and mechanical damage have been addressed by Tschernjawskaja and Chelemski (1997), Houghton and Hopkinson (1998) and Hopkinson and Jaggard

(2001), while Berghall *et al.* (1997) have considered the actual enzymatic and microbial mechanisms by which sugar is lost.

Specific questions, which are often asked by growers and for which precise answers cannot always be given include:

- What should be done with harvested beet covered in sticky mud?
- Beet must be kept cool, but how cool? Freezing must certainly be avoided in any case, but Vukov and Hangyál (1985) advise against storage below $^{+}4$°C.
- Are effective mould-control chemicals available and, if so, when should they be used?

One possible solution to the first point above is the adoption of indoor beet storage (Pettit, 1996). Alternatively, in parts of Germany, piles are covered with woven polypropylene material to dry the beet, as well as reducing the storage losses (Günther, 1995). A major problem in the UK arises from the development of 'hot spots' caused by accumulations of dirt and trash in large piles (Oldfield *et al.*, 1979a). A proposed solution was to modify yard storage methods, and this has resulted in British Sugar's general adoption of flat pad storage.

A final requirement for better storage is the maintenance of good root quality: higher levels of invert sugar production have been noted in beet grown with higher levels of nitrogen fertilizer (Vukov & Hangyál, 1985) and more storage rot has been seen in beet roots which give low clarified juice purities (Bugbee & Cole, 1986). Zahradnicek (1996) has considered the doses and strengths of lime needed to counteract various rots.

Factory beet handling

Damage to roots during factory handling leads to quality loss through two routes:

(1) rupture of cell tissue, leaching of contents and access by micro-organisms;
(2) production of tails, which degrade and leach more rapidly than whole roots, so that they must either be discarded or put into the process to give poor yields of sugar at high cost (Broughton *et al.*, 1995).

The study of De Vletter and Van Gils (1976) focused the attention of the sugar companies on to the question of yard losses arising from mechanical damage. The review of Martens and Oldfield (1970) suggests that extended storage at the factory or in intermediate storage piles will make the losses even worse.

In Germany, symposia on beet handling equipment were reported in *Zuckerindustrie* in 1979 and 1987. The latter report described the current state-of-the-art regarding unloading, cleaning, silo design, mobile bridges and delivery belts, ventilation, recovery and wet beet elevation (Gerlach, 1987; Hartmann, 1987; Kugel, 1987; Lippe, 1987). See also: BMA Sugar Division (1995). In the USA, Mielke (1989) reported the upgrading of the beet handling system at a 4000 t/day factory. The estimated cost benefits accruing from tails-savings, labour and electricity savings, and improved slice and extraction have more than covered the investments; so one company at least has reduced the quality loss identified in (2) above.

Beet cleaning methods were discussed in the 1987 German symposium, and by Vukov and Hangyál (1985) who reported different findings in relation to 'dry' and 'wet' cleaning before storage. The use of polymers to assist in solids removal in wet beet handling is considered by Fuentes *et al.* (2001). With cost reduction a priority, such studies will undoubtedly become more important.

EVOLUTION OF BEET QUALITY

The changes in thick juice purities that occurred in Austria and France between 1963 and 1979 were discussed by Devillers (1982). There were steady falls in purities until 1971 in Austria and up until 1976 in France, which were attributed to the excessive use of nitrogenous fertilizers, the widespread growing of high-yield/low-purity varieties and mechanical harvesting. In both countries quality began to improve some 5 years after the initiation of research work and because of a wider interest in this aspect of sugar beet production.

Similar changes occurred in other beet-growing countries, possibly stimulated by the realization that improvement in quality is necessary to ensure survival of the beet sugar industry in competition with cane sugar and other sweeteners. For example, in Hungary average sugar content fell to 11.5% by 1975–1976, owing primarily to excessive nitrogen fertilization, because payment for beet was made solely on a weight basis; this situation gradually improved once payment on a sugar-content basis was introduced (Vigh, 1984). In Japan, the quality of roots delivered to the Nippon Beet Sugar Company has improved after payment for sugar content was introduced in 1986, with a juice purity increase after carbonatation of the order of 2 units, to 92% (K. Sayama, Nippon Beet Sugar Mfg Co Ltd, Japan, 1989, personal communication).

The Austrian experience is perhaps the best-known; it began with concern about the loss of alkalinity and evaporator corrosion in the 1960s. As a result of the programme introduced there, juice purities were increased by more than 3 units over about 15 years to approximately 94.5%. However, this programme was expensive, with the capital cost of the soil-testing laboratory at Tulln being around 30m Austrian schillings (€2.2 million) (G. Pollach, Zuckerforschungs-Institut, Austria, 1989, personal communication).

Other ways of improving juice purity have been used elsewhere. For example, Südzucker AG in Germany have a quality premium system, based on the formula of Reinefeld *et al.* (1974) up to 1996 and on the new Braunschweig formula (Buchholz *et al.*, 1995) since, in addition to the EU basic payment system, which has resulted in a juice purity increase of between 3 and 4 units since it was instituted in 1978/1979 (H.-J. Puke, Südzucker AG, Germany, 2004, personal communication). The Dutch systems (Huijbregts, 1999) and the American Crystal system (Hobbis *et al.,* 1982) also base payments upon tarehouse measurements of potassium, sodium and amino nitrogen. With the American Crystal system there has been a general trend in increasing beet quality since its inception (C. Hotvedt, American Crystal Sugar Company, USA, 2004, personal communication). In the Netherlands, K + Na as well as amino nitrogen have reduced by over 40% in the period 1983–2002 (Van Swaaij & Maassen, 2005).

However, although these non-sugar measurements are useful in improving beet quality by consultation with the farmer, they have limitations for predicting factory juice quality (Uhlenbrock, 1973; 1992). Consequently many companies use tarehouse non-sugar measurements for advisory purposes only (Jensen *et al.*, 1983; Shore *et al.*, 1984b; Melin *et al.*, 1989; R. Mesnard, Generale Sucrerie, France, 1989, personal communication). Today, however, in Denmark, the only tarehouse quality measurements are those of sugar content and dirt tare (O. Hansen, Danisco Sugar, Denmark, 2004, personal communication).

In France, tarehouse measurements have been interpreted in relation to the soil 'nitrogen balance' theory of Professor Hébert (ITB, 2001); this was done by the collaboration of growers, processors and research institutions in 'quality circles'. In the UK it was decided to focus initially simply upon amino nitrogen levels in growers' beet (Shore *et al.*, 1984b), with nitrogen prediction and modelling (Pocock *et al.*, 1988) coming later as fine-tuning. In both countries, average thick juice purities improved by 1 unit between 1984 and 1988. These improvements were brought about partly by average reductions in nitrogen fertilizer usage of about 30 kg N/ha in each country (Turner, 1989; J.-P. Lescure, SNFS Services Techniques, France, 1989, personal communication), and partly by improvements in varieties. Oreel (1991), in an article written for Italian growers, discusses the Austrian and Dutch payment systems and their effects on improving beet quality, and hence industrial efficiency, against a background of possible beet price reductions in the future. The call for such systems, designed to obtain the highest possible quality at least cost, will undoubtedly gather pace. However, as this paper points out, with variable soil types, beet prices will vary accordingly, so that the implementation of equitable beet prices based upon 'extractable' sugar as well as applying universal penalties for dirt tares, could prove difficult in countries where beet are grown on widely varying soil types.

In the USA as well, juice quality improvements are being obtained at American Crystal (see above), and a report on one factory stating that diffusion juice purity had increased by more than one percentage point (Melin *et al.*, 1989). Since 1989, within the same company (M. Law, Imperial Sugar Company, USA, 2004, personal communication), there has been a steady improvement in juice purity as a result of a multifaceted approach, involving nitrogen fertilizer management, irrigation and variety development (purity and low crown tare).

With regard to other quality features, there are reports of improvements in the removal of green material from beet in Denmark (R.F. Madsen, De Danske Sukker Fabrikker, Denmark, 1989, personal communication), and in dirt tare in Germany (Buchholz & Schliephake, 1989). This improvement in Germany has continued, with dirt tare being reduced to an average of 8.5% from 1991 to 2002 (H.-J. Puke, Südzucker AG, Germany, 2004, personal communication). In Denmark, a bonus/malus system on dirt tare has been agreed by which there is a deduction in price for delivery of dirty beet and a premium for delivery of clean beet (O. Hansen, Danisco Sugar, 2004, personal communication). However, in general there does not seem to have been as much progress in quality areas such as enzymes, marc and physical properties as in those areas which have been seen to be of primary importance in the last 40 years (i.e. juice components influencing the yield of crystalline sugar).

CONCLUSIONS

The sugar content of roots is the most important quality parameter for the processor. However, information on sugar content must normally be supported by information on non-sugars and, in some cases of dehydration and dry matter content.

A physiological sugar-content limit may almost have been reached and breeders have therefore aimed to produce roots with lower non-sugar contents, although with respect to this, the following points should be made:

- There may be a lower limit for levels of amino acids, which after all are essential to plant growth. Moreover, the problem of excessive alkalinity may arise if glutamine is reduced more than potassium and sodium (Oldfield *et al.*, 1970). Evaporation and sugar-end operations are hampered by very high pH. Fortunately, in the last 30 years the alkalinity content (K + Na) has also decreased considerably.
- Reducing sugars, betaine and raffinose should be included in quality assessments more regularly.

In considering processability, it should be emphasized that the complexity of beet stored at high temperatures, deteriorated beet or crown tissue, relative to normally topped roots, is such that proper clarified juices ought to be prepared for purity measurement, instead of trying to deduce a purity from measurements of individual non-sugars (Jorritsma & Oldfield, 1969). Similarly, it should be recognized that potassium, sodium and α-amino nitrogen data can do no more than give an indication of molasses sugar; accurate estimates can only be made using purities of thick juices. The search for better formulae to express molasses sugar from the major non-sugars would be unnecessary if automatic purity meters now used in sugar factories were adapted to suit the requirements of breeders and field trials also.

In the future, as well as improving the estimates of non-sugars, more attention should be given to improving physical properties, tare and fertilizer practices, particularly with salt and possibly with calcium and magnesium. Environmental concerns will increase, and genetic engineering to produce, for example, herbicide-resistant sugar beet (D'Halluin, 1989), will need to demonstrate that the pulp produced is still suitable for animal feed (Savary *et al.*, 2004).

Processors will continue to investigate more cost-effective procedures to yield sugar products, e.g. whether to subject the beet to prior electroporation (Frenzel *et al.*, 2003; Schultheiss *et al.*, 2004) but such investigations will require close scrutiny of all aspects of quality. Studies of beet-growing in hotter climates and the special requirements with regard to agronomy and storage (Christodoulou & Hadjiantoniou, 1990; Fares *et al.*, 1994; Noé & Mantovani, 1996) will help to ensure satisfactory processing quality under such conditions. Research efforts will continue to improve the quality of sugar beet roots, and therefore the cost-effectiveness of processing. This is vital to ensure the survival of the beet sugar industry in the face of increasing competition from cane sugar and alternative sweeteners.

REFERENCES

Akyar, O.G., Cagatay, M., Kayimoglu, E., Özbek, A. and Titiz, S. (1980) Über die Beziehung zwischen dem bereinigten Zuckergehalt und der chemischen Zusammensetzung der Zuckerrübe. *Zuckerindustrie* **105**, 457–465.

Andersen, E. & Smed, E. (1963) The chemical composition of sugar beets and the effective alkalinity and the sugar loss in molasses. In: *Comptes Rendus de la XIIme Assemblée Générale de la Commission Internationale Technique de Sucrerie.* Paris, pp. 395–406.

Asselbergs, C.J., Van der Poel, P.W., Verhaart, M.L.A. & De Visser, N.H.M. (1962) Rohsaftgewinnung im Laboratorium zum Studium des technischen Wertes der Zuckerrübe, I: The technological value of the sugar beet. *Proceedings of the XIth Session of the CITS.* Frankfurt, 1960, Elsevier, Amsterdam, pp. 78–93.

Atterson, A., Carruthers, A., Dutton, J.V., Hibbert, D., Oldfield, J.F.T., Shore, M. & Teague, H.J. (1963) Changes in beet after freezing and storage. Paper presented to the *16th Annual Technical Conference.* British Sugar Corporation Ltd.

Barfoed, S. & Mollgaard, A. (1987) Dextranase solved dextran problems in DDS beet sugar factory. *Zuckerindustrie* **112**, 391–395.

Beiss, U. (1988) Influence of some factors on marc content of sugar beet. *Zuckerindustrie* **113**, 1041–1048.

Beiss, U. (1994) Zum betaingehalt der Zuckerrübe. *Zuckerindustrie* **119** (2), 112–117.

Benker, M. (2000) Rhizoctonia-Rübenfäule – Welchen Beitrag können resistente Zuckerrübensorten zur Kontrolle der krankheit leisten. *Zuckerindustrie* **125** (9), 693–697.

Berghall, S., Briggs, S., Elsegood, S.E., Eronen, L., Kuusisto, J.O., Philip, E.J., Theobald, T.C. & Walliander, P. (1997) The role of sugar beet invertase and related enzymes during growth, storage and processing. *Zuckerindustrie* **122** (7), 520–530.

Beringer, H., Koch, K. & Lindhauer, M.G. (1986) Sucrose accumulation and osmotic potentials in sugar beet at increasing levels of potassium nutrition. *Journal of the Science of Food and Agriculture* **37**, 211–218.

Bertuzzi, S. & Zavanella, M. (1988) Determiazione di K, Na, azoto alfa-amminico in zuccherificio. Implicazioni technologiche ed agronomiche. *L'Industria Saccarifera Italiana* **81**, 135–138.

Bichsel, S.E. (1988) An overview of the US beet sugar industry. In: Clarke, M.A. & Godshall, M.A. (eds) *Chemistry and Processing of Sugarbeet and Sugarcane.* Elsevier, Amsterdam, pp. 1–8.

Bieluga, B. & Bzowska-Bakalarz, M. (1980) Mechanical properties of sugar beets. *Roczniki Nauk Rolniczych, C (Technika Rolnicza)* **74** (4), 63–79.

Bloch, D. & Hoffmann, C. (2004) Genotyp bedingte Entwicklung von Mark, Betain und Saccharose in Zuckerrüben. In: *Proceedings of the 67th IIRB Congress.* Brussels, pp. 369–374.

BMA Sugar Division (1995). From one single source: machinery and equipment for the beet yard. *BMA Information* **33**, 14–16.

Bobrovnik, L.D. & Rudenko, V.N. (1988) The latest on colorants in beet sugar manufacture. *Pishchevaya Promyshlennost* **2**, 47–48.

Bobrovnik, L.D., Voloshanenko, G.P. & Kirichenko, V.A. (1984) Betaine degradation and its influence on colour of sugar solutions. *Sakharnaya Promyshlennost* **9**, 23–26.

Bohn, K. (1998) Composition of sugarbeet and sugarcane and chemical behavior of constituents in processing. In: Van der Poel, P.W., Schiweck, H. & Schwartz, T. (eds) *Sugar Technology.* Verlag, Dr A. Bartens, Berlin, pp. 115–151.

Bosemark, N.O. & Arvidsson, M. (1964) Comparisons between different methods of beet quality assessment. In: *Proceedings of the 27th IIRB Congress.* Bruxelles, pp. 275–296.

Bouquery, J.-M. & Guérin, B. (1986) Le coût de la tare dans la filière betterave-sucre. *Sucrerie Francaise* **127**, 16–21.

Bourlet, P. (1998) In: *Proceedings of the 22nd Session, ICUMSA.* pp. 305, 307–311.

Breay, H.T. (1986) A growing interest in skew bar topping. *British Sugar Beet Review* **54** (3), 47–48.

Brieghel-Müller, A. & Brüniche-Olsen, H. (1953) Neuere Gesichtspunkte zur zweiten Saturation. *Zucker* **6**, 443–446.

Broughton, N.W., Sargent, D., Houghton, B.J. & Sissons, A. (1987) The inclusion of colour and ash components in UK beet white sugar. In: *Comptes Rendus de la XVIIIme Assemblée Générale de la Commission Internationale Technique de Sucrerie.* pp. 101–132.

Broughton, N.W., Sargent, D., Theobald, T.C. & Gaughan, F. (1995) The optimum use of tails from beet processing. *Zuckerindustrie* **120** (3), 219–224.

Bruhns, M., Lemmes, R. & Schick Jr., R. (2004) Verarbeitungseigenschaften von Rhizoctonia-geschadigten Rüben. *Zuckerindustrie* **129** (2), 105–111.

Buchholz, K. & Mikhael, I. (1989) Model experiments on enzymic browning. *Zuckerindustrie* **114**, 558–561.

Buchholz, K. & Schliephake, D. (1989) On the 1988 campaign and new technological developments. *Zuckerindustrie* **114**, 275–290.

Buchholz, K., Märländer, B., Puke, H., Glattkowski, H. & Thielecke, K. (1995) Neubewertung des technischen Wertes von Zuckerrüben. *Zuckerindustrie* **120** (2), 113–121.

Bugbee, W.M. & Cole, D.F. (1986) Sucrose content, clear juice purity and storage rot of sugarbeet. *Journal of the American Society of Sugar Beet Technologists* **23**, 154–161.

Burba, M. (1996) Der Schädliche Stickstoff als Kriterium der Rübenqualität. *Zuckerindustrie* **121**, 165–173.

Burba, M. (1998) Perspectives and limits of current beet quality evaluation. *Zuckerindustrie* **123**, 365–374.

Burba, M. & Georgi, B. (1975/1976) Die fluorometrische Bestimmung der Aminosäuren in Zuckerrüben und Zuckerfabriksprodukten mit Fluoreszamin und o-Pthalaldehyd. *Z. Zuckerindustrie* **25**, 667–673 and **26**, 322–329.

Burba, M. & Harling, H. (2003) Qualitätsbewertung von

Zuckerrüben mit festen Saccharose/Nichtsaccharose-Verhältnissen (Rendementfaktoren) aus Melassen. *Zuckerindustrie* **128**, 233–242, 508–513, 745–750.

Burba, M. & Jansen, R. (2000) Geschichte, gegenwärtiger Stand und künftige Perspektiven der Qualitätszüchtung bei Zuckerrüben. *Zuckerindustrie* **125**, 591–602 (part 1), 803–814 (part 2).

Burba, M. & Nitzschke, U. (1973) Stoffwechselphysiologische Untersuchungen an Zuckerrüben während der Vegetationszeit. III: Glucose, fructose, galactose und raffinose. *Zucker* **26**, 356–365.

Burba, M. & Nitzschke, U. (1980) Nachweis und Eigenschaften der Saccharose Spaltenden Enzyme der Zuckerrübe. *Zuckerindustrie* **105**, 149–155.

Burba, M. & Schiweck, H. (1993) Nichtzuckerbilanz und Ionenbilanz im Dicksaft als Grundlagen einer Qualitätsbewertung von Zuckerrüben – Teil 2. *Zuckerindustrie* **118**, 921–936.

Burba, M., Nitzschke, U. & Ritterbusch, R. (1984) Die N-Assimilation der Pflanze unter besonderer Berücksichtigung der Zuckerrübe. *Zuckerindustrie* **109**, 613–628.

Burba, M., Junghans, E., Wöhlert, W. & Eggers, W. (2001) Die automatisierte Rübenanalytik als Grundlage der Qualitätszüchtung bei Zuckerrüben. *Zuckerindustrie* **126**, 606–618.

Bürcky, K., Beiss, U., Winner, C., Drath, L. & Schiweck, H. (1978) Versuch zur Bedeutung des Nährstoffangebotes für die Qualität der Zuckerrübe. II: Stickstoff und Kalium. *Zuckerindustrie* **103**, 190–200.

Burroughs, P.A. & Wones, S.J. (2003) The effect of frost damaged beet and other factors on Dorr 2nd carbonatation juice particle size distribution. *International Sugar Journal* **105**, 342–349.

Carruthers, A. (1954) Studies in the chemistry of sugar beet processing. *Paper presented to the 7th Annual Technical Conference.* British Sugar Corporation Ltd.

Carruthers, A. & Oldfield, J.F.T. (1956) Pectin and polysaccharides in beet juices and molasses. *Paper presented to the 9th Annual Technical Conference.* British Sugar Corporation Ltd.

Carruthers, A. & Oldfield, J.F.T. (1962) Methods for the assessment of beet quality. In: The technological value of the sugar beet. *Proceedings of the XIth Session of the CITS.* Frankfurt, 1960, Elsevier, Amsterdam, pp. 224–248.

Carruthers, A., Oldfield, J.F.T. & Teague, H.J. (1956) A comparison of the effects on juice quality of nitrate of soda, sulphate of ammonia and salt. In: *Proceedings of the 19th IIRB Congress.*

Carruthers, A., Dutton, J.V., Oldfield, J.F.T., Shore, M. & Teague, H.J. (1959) The composition of sugar beet and chemical changes occurring during processing. *Paper presented to the 12th Annual Technical Conference.* British Sugar Corporation Ltd. Also (in German) *Z. für die Zuckerindustrie* (1960), **10**, 350–354.

Carruthers, A., Dutton, J.V., Oldfield, J.F.T., Shore, M. & Teague, H.J. (1960) Juice composition in relation to factory performance. *Paper presented to the 13th Annual Technical Conference.* British Sugar Corporation Ltd.

Carruthers, A., Oldfield, J.F.T. & Teague, H.J. (1962) Assessment of beet quality. *Paper presented to the 15th Annual Technical Conference.* British Sugar Corporation Ltd.

Carruthers, A., Dutton, J.V. & Oldfield, J.F.T. (1963) Chromogenic reducing substances in molasses. *International Sugar Journal* **65**, 297–301, 330–334.

Carruthers, A., Oldfield, J.F.T. & Teague, H.J. (1966) The influence of crown removal on beet quality. *International Sugar Journal* **68**, 297–302.

Christodoulou, P. & Hadjiantoniou, D. (1990) Experiences of juice purification with beets of Mediterranean origin. *Paper presented to the British Sugar plc Technical Conference.* Eastbourne.

Christodoulou, P., Hadjiantoniou, D. & Zountsas, G. (1988) The influence of melassigenic factors on the colour formation of thin juice. *Zuckerindustrie* **113**, 973.

Clarke, M.A., Godshall, M.A., Blanco, R.S. & Perret, G.T. (1989) Beet sugar colorant: recent studies. *Zuckerindustrie* **114**, 709–713.

Claassen, H. (1916) Der Markgehalt der Rüben und seine Bestimmung. *Zeitschrift des Vereins der deutschen Zuckerindustrie* **66**, 359–370.

Coe, G.E. & Theurer, C. (1987) Progress in the development of soil-free sugarbeets. *Journal of the American Society of Sugar Beet Technologists* **24**, 49–56.

Cossairt, G.W. (1979) Beet storage and the factory processes. In: *Proceedings of the 20th Regional Meeting of the American Society of Sugar Beet Technologists.* pp. 44–70.

Cronewitz, T. (1977) Die technologische Bedeutung der mechanischen Qualität der Zuckerrübe. *Paper presented to the Sudzücker Spring Conference.* 17pp.

Davies, J. (1987) Quality assurance – what it means to British Sugar. *British Sugar Beet Review* **55** (1), 2–3.

De Bruijn, J.M. (2000) Processing of frost-damaged beets at CSM and the use of dextranase. *Zuckerindustrie* **125** (11), 898–902.

De Bruijn, J.M., Van der Poel, P.W., Kieboom, A.P.G. & Van Bekkum, H. (1987) Reactions of monosaccharides in aqueous alkaline solutions. In: *Comptes Rendus de la XVIIIme Assemblée Générale de la Commission Internationale Technique de Sucrerie*, pp. 1–25.

De Bruijn, J.M., Struijs, J.L.M. & Bout-Diederen, M.E.F. (1999) Sucrose degradation and color formation. *Zuckerindustrie* **124** (1), 28–33.

Dedek, J. (1927) Der Ursprung und das Wesen der Melasse. *Zeitschrift des Vereins der deutschen Zuckerindustrie* **77**, 495–561.

Degeest, J. & Debroux, J. (1987) Historique du Controle de l'Etat Sanitaire de la Diffusion RT. In: *Comptes Rendus de la XVIIIme Assemblée Générale de la Commission Internationale Technique de Sucrerie.* Ferrara, pp. 509–534.

De Nie, L.H. & Van den Hil, J. (1989) Beet quality: technological and economical values and a payment system. *Zuckerindustrie* **114**, 645–650.

De Nie, L.H., Van der Poel, P.W. & Van de Velde, M.H. (1985) Sugar beet and frost damage in the Netherlands – a successful approach to prevent the delivery of frozen beet. *Zuckerindustrie* **110**, 37–42.

Devillers, P. (1982) Quality and storage. In: *50 Years of Sugar Beet Research.* IIRB, Bruxelles, pp. 113–125.

Devillers, P. (1984) Qu'est-ce la qualité? Facteurs de qualité influencés par la mécanisation. In: *Proceedings of the 47th*

IIRB Congress. pp. 165–211.

Devillers, P. (1986) Qualité des betteraves et rentabilité de la filière betteraves-sucre. *Sucrerie Française* **127**, 7–11, 13–44.

Devillers, P. (1988) Prévision du sucre mélasse. *Sucrerie Française* **129**, 190–200.

Devillers, P., Gory, P. & Loilier, M. (1974) Le gel du 2 décembre 1973. *Sucrerie Française* **115**, 393–406.

Devillers, P., Detavernier, R., Gory, P., Loilier, M. & Roger, J. (1976) Peut-on prévoir le sucre mélasse à partir de dosages simples effectués sur betteraves? *Sucrerie Française* **117**, 437–448.

Devillers P., Detavernier, R. & Roger, J. (1984) Nouvelles mesures de pouvoirs mélassigènes. *Sucrerie Française* **125**, 181–192.

De Vletter, R. & Van Gils, W. (1976) Influence of the mechanical handling of sugarbeets on sugar yield in the factory. *Sugar Journal* **38** (8), 8–13.

Dexter, S.T., Frakes, M.G. & Snyder, F.W. (1967) A rapid and practical method of determining extractable white sugar as may be applied to the evaluation of agronomic practices and grower deliveries in the sugar beet industry. *Journal of the American Society of Sugar Beet Technologists* **14**, 433–454.

D'Halluin, K. (1989) Herbicide resistant sugarbeets by genetic engineering. In: *Proceedings of the 52nd IIRB Congress*. pp. 283–288.

Dodd, J. (1989) The coupling of a countercurrent cossette mixer with a RT diffuser. *Zuckerindustrie* **114**, 140–141.

Drath, L., Strauss, R. & Schiweck, H. (1984) Untersuchungen über die mechanischen Eigenschaften von Zuckerrüben. II: Einflussfaktoren auf die Bruchfestigkeit von Rüben. *Zuckerindustrie* **109**, 993–1007.

Draycott, A.P., Townshend, C., Fisher, S. & Johnson, P. (2003) Sugar beet production in nitrate vulnerable zones. *British Sugar Beet Review* **71** (1), 18–21.

Dreibholz, E. (1996) A review: knife sharpening can affect diffuser draft and sugar loss. *Sugar Journal* **58** (10), 29–30.

Dutton, J.V. (1989) Substances in British beet molasses which may be harmful to fermentation. *Zuckerindustrie* **114**, 483.

Dutton, J.V. & Turner, F. (1983) Correcting excessive use of nitrogen: beet amino-N measurements. *British Sugar Beet Review* **51** (2), 15–17.

Dutton, J.V., Carruthers, A. & Oldfield, J.F.T. (1961) The synthesis of sucrose by extracts of the root of the sugar beet. *Biochemical Journal* **81**, 266–272.

Dutton, M. (2000) Rock salt for sugar beet – where does it come from? *British Sugar Beet Review* **68** (4), 37–38.

Fares, K., Zaki, A., Aissaoui, N., R'Zina, Q. & Mauch, W. (1994) Productivitié et teneurs en sodium et en potassium de la betterave sucrière méditérranéenne. *Industries Alimentares et Agricoles*, 7–8, 422–427.

Fares, K., Aissaoui, N., Zaki, A., R'Zina, Q. & Mourou, Y. (1996a) Réflexions sur la qualité interne de la betterave sucrière en Maroc, similitudes avec quelques pays méditerranéens. In: *Proceedings of the 59th IIRB Congress*. pp. 423–444.

Fares, K., Aissaoui, N., R'Zina, Q., Mourou, Y. & Chernane, H. (1996b) Evaluation of the consequences of field storage of sugar beet under Mediterranean climate. In: *Proceedings of the 20th General Assembly of CITS*. Munich, Germany, pp. 170–184.

Fares, K., R'Zina, Q., El Amrani, M., Crepeau, M.-J. & Thibault, J.-F. (2003) Extraction and degradation of polysaccharides from sugar beet roots under factory conditions. *Zuckerindustrie* **128**, 243–249.

Farley, R.F. & Draycott, A.P. (1975) Growth and yield of sugar beet in relation to potassium and sodium supply. *Journal of the Science of Food and Agriculture* **26**, 385–392.

Fauchère, J. (1989) Réduction de la tare-terre. In: *Proceedings of the 52nd IIRB Congress*. pp. 65–78.

Frenzel, S., Michelberger, Th. & Witte, G. (2003) Electroporation for the treatment of sugar beet cells. Part 2: Experience from trials in laboratory and technical scale. In: *CITS Proceedings*. Madrid, pp. 217–227.

Fuentes, O., Hatch, R.O., Emmons, J. & Grzemski, A.S. (2001) Benefits for a beet handling system by polymer assisted mud removal in a flume clarifier. In: *Proceedings 31st Biennial Meeting (Operations) of the American Society of Sugar Beet Technologists*. Vancouver, Canada, pp. 161–170.

Genie, G.V. (1994) Juice extraction by diffusion. *International Sugar Journal* **96** (1144), 124–128, 160–162.

Gerlach, K. (1987) Neuerungen im Hofbereich. *Zuckerindustrie* **112**, 788–791.

Gibriel, A.Y., Madkour, M.H.F., Abd El-Razik Aly, F. & Hozayen, A.M. (2003) Effect of some chemical treatments on the change of technological characteristics of sugarbeet roots during storage. *Arab Universities Journal of Agricultural Sciences* **11** (1), 303–314.

Glattkowski, H. & Märländer, B. (1993) Transformation of values of amino-N in sugar beet for application in the Reinefeld formula using aluminium sulphate as clarification and a fluorimetric method for amino-N determination. *Zuckerindustrie* **118**, 247–249.

Glattkowski, H. & Märländer, B. (1994) Zur Frage der Beeinflußbarkeit von Ertrag und Qualität beim Anbau von Zuckerrüben durch pflanzenbauliche Maßnahmen. Teil 1: Ertragsparameter und Melassebildner. *Zuckerindustrie* **119**, 570–575.

Grabka, J. & Wasiak, T. (1996) Purification of raw juice from sugar beet of poor quality. In: *Proceedings of the 20th General Assembly of CITS*. Munich, pp. 468–475.

Gram, N.H. & Jorgensen, A.B. (2002) Reduction of soil tare through breeding techniques. *Proceedings of the 65th IIRB Congress*. Bruxelles, pp. 99–106.

Gross, D. & Coombs, J. (1975) Enzymic colour formation in beet and cane juices. In: *Comptes Rendus de la XVme Assemblée Générale de la Commission Internationale Technique de Sucrerie*. pp. 295–308.

Gruszecka, H. (2000) Proba okreslenia wplywu rafinozy na wyniki rachunku technicznego cukrowni. *Gazeta Cukrownicza* **108** (7), 122–125.

Guiraud de Willot, D. & Lévèque, E. (2002) Harvesters and reduction of soil tare. In: *Proceedings of the 65th IIRB Congress*. Bruxelles, pp. 129–138.

Günther, I. (1995) Reduzierung von Lagerverlusten durch unterschiedliche Abdeckung der Rübenmieten. In: *Proceedings of the 58th IIRB Congress*. pp. 453–471.

Hartmann, H. (1987) Rübenentladung – Rübenlagerung. *Zuckerindustrie* **112**, 786–788.

Heijbroek, W. (1988) The effect of virus yellows on yield and processing quality. In: *Virus Yellows Monograph.* International Institute for Sugar Beet Research, Brussels, pp. 27–35.

Heijbroek, W. & Huijbregts, A.W.M. (1984) Some factors affecting frost damage to sugar beets. In: *Proceedings of the 47th IIRB Congress.* Bruxelles, pp. 35–52.

Hein, W., Pollach, G. & Rösner, G. (1994) Beurteilung der Alkalitätsreserven von Zuckerrüben. *Zuckerindustrie* **119**, 15–21.

Henry, J., Vanderwijer, R, and Pieck, R. (1961) The technical value of sugarbeets in 1960. *Paper presented to the 14th Annual Technical Conference.* British Sugar Corporation Ltd.

Herlihy, M. & Hegarty, T. (2001) Prediction of nitrogen inputs for sugar beet: an evaluation of soil tests and soil management criteria in arable soils. *Rural Environmental Series-TEAGASC.* No. 31.

Hilde, D.J., Bass, S., Levos, R.W. & Ellingson, R.F. (1983) Grower practices system promotes beet quality improvement in the Red River Valley. *Journal of the American Society of Sugar Beet Technologists* **22** (1), 73–88.

Hilleshog (2004) Root with real shape. In: *Eastern Daily Press*, 26 June 2004.

Hobbis, J., Kysilka, J. & Holle, M. (1982) Design and operating characteristics of a new beet quality measuring system. *La Sucrerie belge* **101**, 49–59.

Hoffmann, C., Mahn, K. & Marlander, B. (2002) Einfluss von Genotyp und Umwelt auf die Zusammensetzung des Schadlichen Stickstoffs in Zuckerruben. *Zuckerindustrie* **127** (10), 784–791.

Hoogerkamp, D. (1993) Research on dirt tare in the Netherlands. *Journal of Sugar Beet Research* **30** (1/2), 101.

Hopkinson, I. & Jaggard, K. (2001) Sugar beet storage – the science. *British Sugar Beet Review* **69** (3), 7–9.

Horn, D. & Fürstenfeld, F. (2001) Nitrogen fertiliser recommendation for sugar beet according to the EUF soil testing system. In: Plant nutrition: food security and sustainability of agro-ecosystems through basic and applied research. *Fourteenth International Plant Nutrition Colloquium.* Hannover, Germany, pp. 746–747.

Houghton, B. & Armstrong, M. (1994) Fragile. Handle with care. *British Sugar Beet Review* **62** (3), 13–15.

Houghton, B.J. & Hopkinson, I.P. (1998) Sugar beet storage technology. *Aspects of Applied Biology* **52**, 191–198.

Huijbregts, A.W.M. (1986) Marc content in brei. *Paper presented to the Meeting of the International Institute for Sugar Beet Research Study Group 'Quality and Storage'.*

Huijbregts, A.W.M. (1999) New Dutch sugar recovery formula for sugar beet. *Zuckerindustrie* **124**, 698–701.

Huijbregts, A.W.M. (2003) Technical quality assessment of sugar beet in Europe. In: *Proceedings of the 1st Joint IIRB–ASSBT Congress.* San Antonio, TX, pp. 451–459.

Huijbregts, A.W.M., De Regt, A.H. & Gijssel, P.D. (1996a) Determination of some quality parameters in sugar beet by near infra-red spectrometry. *Communications in Soil Science and Plant Analysis* **27** (5-B), 1549–1560.

Huijbregts, A.W.M., Glattkowski, H., Houghton, B.J. & Hadjiantoniou, D. (1996b) Effect of agronomic factors on parameters used in formulas to estimate extractable sugar in sugar beets. In: *Proceedings of the 59th IIRB Congress.* Bruxelles, pp. 353–368.

Huisman, B.C., De Nie, L.H., Peters, H.J. & Van der Poel, P.W. (1987) Odour emission and control in the Dutch sugar industry. In: *Comptes Rendus de la XVIII^{me} Assemblée Générale de la Commission Internationale Technique de Sucrerie.* Ferrara, pp. 571–597.

ICUMSA (2002) Method GS7/4/8–23. In: *ICUMSA Methods Book*, 1994, with 1998, 2000, 2003 and 2005 Supplements. Verlag Dr A.Bartens, Berlin.

IIRB (1983) Symposium '*Nitrogen and Sugar Beet*'. International Institute for Sugar Beet Research, Brussels.

IIRB (1996) Internal quality and external quality. In: *Proceedings of the 59th IIRB Congress.* Brussels, pp. 309–462, 463–548.

IIRB (2005) Beet quality. In: *Proceedings of the 68th IIRB Congress.* Maastricht (in press).

ITB (2001) La fertilization azotée, synthèse des experimentations. Méthode du bilan, quel gain pour l'utilisateur. *Le betteravier français* **764**, 17–19.

ITB (2002) Comptes rendus des travaux effectués en 2002. *ITB.* Paris, France.

Jaggard, K.W., Clark, C.J.A., May, M.J., McCullagh, S. & Draycott, A.P. (1997) Changes in the weight and quality of sugar beet (*Beta vulgaris*) roots in storage clamps on farms. *Journal of Agricultural Science* **129** (3), 287–301.

Jaggard, K.W., Clark, C.J.A. & Draycott, A.P. (1999) The weight and processing quality of components of the storage roots of sugar beet (*Beta vulgaris* L.). *Journal of the Science of Food and Agriculture* **79**, 1389–1398.

Jansen, R. & Burba, M. (2001) Progress in sugar beet quality by breeding. In: *Proceedings of the 64th IIRB Congress.* Bruges, Belgium, pp. 195–204.

Jarvis, P., Milford, G., Armstrong, M. & Barraclough, P. (2003) Recent research on Potassium and Sodium recommendations for sugar beet. *British Sugar Beet Review* **71** (4), 4–9.

Jensen, V., Marcussen, C. & Smed, E. (1983) Nitrogen for sugar beet in Denmark, research and its utilisation. In: Symposium *'Nitrogen and Sugar-Beet'.* International Institute for Sugar Beet Research, Brussels, pp. 305–316.

Jones, G.C. (1988) Cossette pretreatment and pressing. *International Sugar Journal* **90**, 157–163, 167.

Jorritsma, J. & Oldfield, J.F.T. (1969) 1. Effect of sugar beet cultivation and extent of topping on processing value. *Journal of the International Institute for Sugar Beet Research* **3** (4), 226–240.

Kamil, M.M., Salem, S.A., El-Mansy, H.A., Moustafa, B.M. & Ghazal, G.A. (2000) Physico-chemical and technological studies on sugar beet roots. *Nahrung* **44** (4), 264–271.

Kenter, C. & Hoffmann, C. (2002) Ertrags- und Qualitätsentwicklung von Zuckerrüben in Abhangigkeit von Temperatur und Wasserversorgung. *Zuckerindustrie*, **127** (9), 690–698.

Kenter, C. & Hoffmann, C. (2004) Marc and betaine of sugar beet in relation to sucrose concentrations during the growing season. In: *Proceedings of the 67th IIRB Congress.* Brussels, pp. 375–380.

Kerr, S. (2003) The march of progress continues with new varieties. *British Sugar Beet Review* **71** (2), 8–16.

Kerr, S. & McCullagh, S. (1989) Report on the 1988 NIAB variety trials. *British Sugar Beet Review* **57** (2), 11–15.

Khelemskii, M.Z. & Shoikhet, A.L. (1986) About methods and techniques for predicting possible yields of crystalline sugar in relation to the chemical composition of the beet to be processed. *Sakharnaya Promyshlennost* **8**, 41–42.

Klotz, K.L. & Finger, F.L. (2001a) Activity and stability of a soluble acid invertase from sugarbeet roots. *Journal of Sugar Beet Research* **38** (2), 121–137.

Klotz, K.L. & Finger, F.L. (2001b) Biochemical properties of three sugarbeet sucrolytic enzymes and their implications for postharvest sucrose loss. *Proceedings 31st Biennial Meeting of the American Society of Sugar Beet Technologists*. Vancouver, pp. 222–225.

Klotz, K.L. & Finger, F.L. (2002) Contribution of invertase and sucrose synthase isoforms to sucrose catabolism in developing sugarbeet roots. *Journal of Sugar Beet Research* **39** (1/2), 1–24.

Knyazev, V.A., Sakalo, V.D., Shvetsova, L.A., Fen', S.A. & Styltu, A. (1995) Sucrose losses in unfavourable storage conditions (Russian). *Sakharnaya Svekla* **10**, 16–17.

Koch, H.J. (2002) Cultural practice effects on soil tare. *Proceedings of the 65th IIRB Congress*. Bruxelles, pp. 107–116.

Kofod Nielsen, W., Madsen, R.F. & Winstrom-Olsen, B. (1979) Investigations on colour formation in juices and sugar. In: *Comptes Rendus de la XVI Assemblée Générale de la Commission Internationale Technique de Sucrerie*. pp. 743–777.

Kucharski, M. (2003) Influence of herbicide and adjuvant application on residues in soil and plant of sugar beet. *Journal of Plant Protection Research* **43** (3), 225–232.

Kugel, F. (1987) Rübenhofanlagen. *Zuckerindustrie* **112**, 783–786.

Kursanov, A.L. (1967) Les bases biochimiques de la translocation et de l'accumulation du saccharose chez la betterave sucrière. *Journal of the International Institute for Sugar Beet* **2** (3), 162–183.

Last, P.J. & Draycott, A.P. (1977) Relationships between clarified beet juice purity and easily-measured impurities. *International Sugar Journal* **79**, 183–185.

Leigh, R.A., ap Rees, T., Fuller, W.A. & Banfield, J. (1979) The location of acid invertase activity and sucrose in the vacuoles of storage roots of beetroot (*Beta vulgaris*). *Biochemical Journal* **178**, 539–547.

Lieker, H.-P., Burba, M. & Thielecke, K. (1994) Bestimmung von Monosacchariden in mit Aluminiumsulfat geklärten Rübenbrei-Digeraten. *Zuckerindustrie* **119**, 639–642.

Lippe, R. (1987) Planung und Ausführung von Rübenhöfen. *Zuckerindustrie* **112**, 781–783.

Loilier, M. & Bruandet, D. (1989) Réflexions sur la présentation des résultats variétaux. *Sucrerie Française* **130**, 89–93.

Mantovani, G. (1981) La conservazione delle bietole ferite. *L'Industria Saccarifera Italiana* **74**, 93–97.

Mantovani, G. & Fagioli, F. (1964) Untersuchungen über die Saccharose kristallisation in Gegenwart von Raffinose. *Zeitschrift für die Zuckerindustrie* **14**, 202–205.

Mantovani, G. & Vaccari, G. (1989) The beet technological value and storage conditions (Abstract). *Journal of Sugar Beet Research* **26**, A 16.

Martens, M. & Oldfield, J.F.T. (1970) Storage of sugar beet in Europe; report of an IIRB enquiry. *Journal of the Institute for Sugar Beet Research* **5**, 102–128.

Mauch, W. (1990) General Subject 6. Beet. In: *Proceedings of the 20th Session ICUMSA*. pp. 79–91.

Mauch, W. & Farhoudi, E. (1979/80) Quality factors in commercial white granulated sugar. *Sugar Technology Reviews* **7**, 87–171.

McCready, R.M. (1966) Polysaccharides of sugar beet pulp. A review of their chemistry. *Journal of the American Society of Sugar Beet Technologists* **14**, 260–270.

McGinnis, R.A. (1982) *Beet-sugar technology*. Beet Sugar Development Foundation, Fort Collins.

Melin, D.C., Lind, D.W. & Murdock, D.E. (1989) Effect of quality improvement at Sidney, Montana (abstract). *Journal of Sugar Beet Research* **26**, A 17.

Mesken, M. (1984) A contribution of plant breeding to a good quality harvesting of sugar beets. In: *Proceedings of the 47th IIRB Congress*. pp. 381–382.

Mielke, R.A. (1989) Handling the sugar beet. *Paper presented to the 25th General Meeting of the American Society of Sugar Beet Technologists*.

Nezam El-Din, A.M.M. (1996) Chemical and technological studies on sugar beet roots. *Egyptian Journal of Food Science* **24** (1), 1–14.

Noé, B. & Mantovani, G. (1996) Resultats de l'Enquete sur la Qualité Interne de la Betterave Sucriere. In: *Proceedings of the 59th IIRB Congress*. pp. 329–342.

Obara, J., Hashimoto, S. & Suzuki, H. (1976–1977) Enzyme applications in the sucrose industries. *Sugar Technology Reviews* **4**, 209–258.

Obradovic, S., Kabic, D., Curcic, R., Radivojevic, S., Milic, M., Karadzic, V., Grbic, J. & Dosenovic, I. (1997) Comparison of fluorimetric and 'blue number' methods for the determination of α-amino-nitrogen in aluminium sulfate filtrates from sugar beet. *Zuckerindustrie* **122**, 706–711.

O'Connor, L.J. (1984) The influence of level of topping, N-fertilization, plant density and row width on sugar beet yield and quality, and crown tissue production. *Proceedings of the 47th Winter Congress of the International Institute of Sugar Beet Technologists*. pp. 383–403.

Oien, S. (1989) Environmental policy and the consequences for growing sugar beet – actual situation, legislation and developments in the near future. In: *Proceedings of the 52nd IIRB Congress*. pp. 1–10.

Oldfield, J.F.T. (1957) The formation of volatile organic acids in factory juices and the estimation of these acids by gas-liquid chromatography. In: *Proceedings of the Xth General Assembly of CITS*. pp. 56–66.

Oldfield, J.F.T. (1974) Quality requirements for economic processing in the factory. In: *Proceedings of the 37th IIRB Congress*. Bruxelles, Session II, Report No. 2.

Oldfield, J.F.T., Dutton, J.V., Grierson, D., Heaney, R.K. & Teague, H.J. (1969) Effet du soutirage et de l'inversion sur la qualité du jus dans les diffuseurs de betteraves. *La Sucrerie belge* **88**, 69–80.

Oldfield, J.F.T., Shore, M. & Senior, M. (1970) Thick juice pH control by cation exchange. *International Sugar Journal* **72**, 323–327, 355–359.

Oldfield, J.F.T., Dutton, J.V. & Teague, H.J. (1971) The significance of invert and gum formation in deteriorated beet. *International Sugar Journal* **73**, 3–8, 35–40, 66–68.

Oldfield, J.F.T., Dutton, J.V., Teague, H.J. & Williams, E.L.

(1975) Effect of dextran on second carbonatation filtration. In: *Comptes Rendus de la XVmeAssemblée Générale de la CITS*. pp. 229–249.

Oldfield, J.F.T., Shore, M., Dutton, J.V., Houghton, B.J. & Teague, H.J. (1977) Sugar beet quality – factors of importance to the UK Industry. *International Sugar Journal* **79**, 37–43, 67–71.

Oldfield, J.F.T., Shore, M., Dutton, J.V. & Teague, H.J. (1979a) Assessment and reduction of sugar losses in beet sugar processing. In: *Comptes Rendus de la XVIme Assemblée Générale de la Commission Internationale Technique de Sucrerie*. pp. 431–469.

Oldfield, J.F.T., Shore, M., Dutton, J.V. & Teague, H.J. (1979b) Association between juice quality and factory performance in 1976 and 1977. *La Sucrerie belge* **98**, 35–46.

Oldfield, J.F.T., Shore, M., Dutton, J.V. & Houghton, B.J. (1980) Are your beet safely gathered in? *British Sugar Beet Review* **48** (4), 40–42.

Oldfield, J.F.T., Shore, M., Dutton, J.V. & Houghton, B.J. (1981) Agricultural factors affecting beet respiration rates. *La Sucrerie belge* **100**, 249–255.

Oltmann, W., Burba, M. & Bolz, G. (1984) Die Qualität der Zuckerrübe, Bedeutung, Beurteilungskriterien und züchterische Massnahmen zu ihrer Verbesserung. *Advances in Plant Breeding* 12, Verlag Paul Parey, Berlin und Hamburg.

Oreel, T. (1991) La bieticoltura moderna europea. Come affrontera I'Italia la situazione? *L'Industria Saccarifera Italiana* **84**, 131–137.

Ostrowska, D. & Wzorek, H. (1980) Physical properties of sugar beet roots. *Gazeta Cukrownicza* **88**, 218–221.

Paananen, H. & Kuisma, J. (2000) Chromatographic separation of molasses components. *Zuckerindustrie* **125** (12), 978–981.

Paradowski, A. & Adamczewski, K. (2002) Evaluation of change of weed control technology in sugar beet in the last 15 years (Polish). *Biuletyn Instytutu Howdowli I Aklimatyzacji Roslin* **222**, 271–277.

Peterson, C.L. & Hall, M.C. (1983) Effect of cultivar on impact resistance of sugarbeets. *Zuckerindustrie* **108**, 1162–1165.

Pettit, D. (1996) Indoor beet storage: planning for profit. *British Sugar Beet Review* **64** (4), 14–15.

Pichenez, J. (1984) Mécanisation de la recolte et qualité de la betterave. In: *Proceedings of the 47th IIRB Congress*. Brussels, pp. 269–274.

Pocock, T., Milford, G. & Armstrong, M. (1988) The nitrogen nutrition of sugar beet: progress in research towards site-specific fertiliser requirements. *British Sugar Beet Review* **56** (3), 41–44.

Pollach, G. (1984a) Development and utilisation of quality criteria for sugar beet in Austria. *Paper presented to the 27th Technical Conference*. British Sugar plc.

Pollach, G. (1984b) Versuche zur Verbesserung einer Rizomania – Diagnose auf Basis konventioneller Rübenanalysen. *Zuckerindustrie* **109**, 849–853.

Pollach, G. (1989) Qualitá: esperienza austriache. In: *Report of the Congress 'Bietola: Obiettivo Qualitá – Strategie per conciliare esigenza agricole e industriali'*. Salsomaggiore, pp. 21–27.

Pollach, G., Hein, W., Rösner, G. & Berninger, H. (1991) Assessment of beet quality including rhizomania-infected beet. *Zuckerindustrie* **116**, 689–700.

Pollach, G., Hein, W. & Rösner, G. (1996) Definition of the 'internal quality' of sugar beet. *Zuckerindustrie* **121**, 332–344.

Prey, V. (1962) Probleme der Zuckerrübenanalyse. In: The technological value of the sugar beet. *Proceedings of the XIth Session of the CITS*. Frankfurt, 1960, Elsevier, Amsterdam, pp. 283–290.

Puscasu, A. & Caraba, C. (1999) Brown rot – a new sugar beet disease in Romania (Romanian). *Analele Institutului de Cercetari pentru Cereale Protectia Plantelor* **30**, 35–39.

Rearick, D.E., McKay, C. & Simantel, G. (1993) Betaine content of sugarbeet varieties. *Journal of Sugar Beet Research* **30** (1–2), 112.

Reinefeld, E. (1975) Discussion of paper 'Effect of dextran on second carbonatation filtration'. In: *Comptes Rendus de la XVme Assemblée Générale de la CITS*. p. 247.

Reinefeld, E. & Baumgarten, G. (1975) Verarbeittungseigenschaften der Zuckerrübe in Abhängigkeit vom Stickstoffangebot. *Zucker* **28**, 61–65.

Reinefeld, E., Emmerich, A., Baumgarten, G., Winner, C. & Beiss, U. (1974) Zur Voraussage des Melassezuckers aus Rübenanalysen. *Zucker* **27**, 2–15.

Reinefeld, E., Bliesener, K.-M. & Kunz, M. (1978) Über die Reactivität von Glucose und Fructose bei der Carbonylamino-Reaktion in technischen Zuckersäften. *Zuckerindustrie* **103**, 20–28.

Reinefeld, E., Bliesener, K.-M., Brandes, E. & Borrass, V. (1982) Contribution to the knowledge of colour formation in sugar beet juices. *Paper presented to the 26th Technical Conference*. British Sugar plc.

Reinefeld, E., Emmerich, A., Burba, M. & Possiel, M. (1986) Zur Bewertung der Qualität von Zuckerrüben nach dem Bereinigten Zuckergehalt, insbesondere zur Gewichtung der einbezogenen Stoffklassen. *Zuckerindustrie* **111**, 730–738.

Richard-Molard, M. & Morel-Krause, É. (2003) Recherche de résidus de produits phytosanitaires dans les betteraves sucrières: résultats encourageants d'une étude régionale dans le centre. *Phytoma* **561**, 52–53.

Ruiz Holst, M., Dominguez, F.M., Burba, M., Dominguez, P., Elias, P. & Diener, G. (2003) Assessment of the technical quality of sugarbeet in Southern Spain. *Zuckerindustrie* **128**, 879–887.

Rysánek, P. (2002) Rhizomania and rhizoctonia root rot of sugar beet-two diseases with increasing importance in the Czech Republic (Czech). *Listy Cukrovarnické a Reparské* **118** (5/6), 125–127.

Saint-Fort, R., Frank, K.D. & Schepers, J.S. (1990) Role of nitrogen mineralization in fertilizer recommendations. *Communications in Soil Science and Plant Analysis* **21** (13–16), 1945–1946.

Sakalo, V.D. & Tyltu, A.S. (1997) Enzymes of carbohydrate metabolism in sugar beet roots in the course of short-term storage under unfavourable conditions. *Russian Journal of Plant Physiology* **44** (1), 70–76.

Savary, B.J., Hicks, K.B., Fishman, M.L., Hotchkiss, A.T. & Liu, L. (2004) Sustainable technologies and valuable new polysaccharide-based products from sugar beet pulp. *2004*

SPRI Conference on Sugar Processing Research. Atlanta, pp. 80–86.

Sayama, K. & Kamata, T. (1988) Analysis of dextran in beet sugar factory with dextranase, part 2: Determination by gel filtration method. *Proceedings of the Research Society of Japan Sugar Refinery Technologists* **36**, 59–67.

Sayama, K., Kamada, T., Oikawa, S. & Masuda, T. (1992) Production of raffinose: a new byproduct of the beet sugar industry. *Zuckerindustrie* **117** (11), 894–899.

Schepers, J.S. & Saint-Fort, R. (1988) Comparison of potential mineralizable nitrogen using electroultrafiltration and four other procedures. In: *Cost Reduction and Environmental Protection, vol. 2*. EUF Symposium 1988, Mannheim.

Schiweck, H. & Burba, M. (1993) Abschätzung der Alkalitätsreserven von Zuckerrüben aus der Ionenbilanz von Dicksäften. *Zuckerindustrie* **118**, 241–246.

Schiweck, H. & Büsching, L. (1970) Raffinose in Zuckerrüben und Zuckerrohrprodukten. *Zucker* **23**, 405–409.

Schiweck, H. & Büsching, L. (1974) Das Verhalten von Glucose und Fructose während der Zuckerfabrikation. *Zucker* **27**, 122–128.

Schneider, F. (1979) *Sugar Analysis: ICUMSA Methods*. International Commission for Uniform Methods of Sugar Analysis, Verlag Dr A. Bartens, Berlin.

Schneider, F., Emmerich, A., Reinefeld, E., Walter, E. & Kelm, W. (1961) Auswirkung der Nichtzuckerstoffe de Rübe, insbesondere auf die Melassebildung. Part 1. *Zucker* **14** (1961), 208–212.

Schultheiss, C., Bluhm, H.-J., Mayer, H.-G., Sack, M. & Kern, M. (2004) Principle of electroporation and development of industrial devices. *Zuckerindustrie* **129**, 40–44.

Shah, T.H. & Delavier, H.J. (1974) Study of the influence of some non-sucrose substances on habit modification of crystallised sucrose. *Zeitschrift für die Zuckerindustrie* **24**, 27–31.

Shore, M. (1957) The formation of lactic acid in relation to sugar loss. In: *Proceedings of the Xth General Assembly of the Commission Internationale Technique de Sucrerie*. pp. 196–202.

Shore, M., Dutton, J.V. & Houghton, B.J. (1982) Beet losses again? *British Sugar Beet Review* **50** (3), 20–22.

Shore, M., Dutton, J.V. & Houghton, B.J. (1983) Evaluation of deteriorated beet. *International Sugar Journal* **85**, 106–110, 136–139.

Shore, M., Broughton, N.W., Dutton, J.V. & Sissons, A. (1984a) Factors affecting white sugar colour. *Sugar Technology Reviews* **12**, 1–99.

Shore, M., Broughton, N.W., Dutton, J.V. & Bowler, G.I. (1984b) Nitrogen fertiliser control by amino-nitrogen measurements. *Paper presented to the 27th Technical Conference*. British Sugar plc.

Silin, P.M. (1964) *Technology of beet-sugar production and refining*. Israel Program for Scientific Translations, Jerusalem.

Skogman, H. (1971) Some aspects on the 1970 frost beet campaign in Sweden. *Proceedings of the XIVth General Assembly of the Commission Internationale Technique de Sucrerie*. pp. 307–319.

Smed, E. (1992) The influence of the variety and the ecological factors on the invert sugar content in the sugar beet. *Invertsukker-Kolloqvium*, Holeby.

Smed, E., Huijbregts, A.W.M., Hadjiantoniou, D. & Vallini, G. (1996) Influence of agronomic factors on non conventional parameters of the internal quality of sugar beet. In: *Proceedings of the 59th IIRB Congress*. Bruxelles, pp. 385–389.

Smythe, B.M. (1967) Sucrose crystal growth. III: Relative growth rates of faces and their effect on sucrose crystal shape. *Australian Journal of Chemistry* **20**, 1115–1131.

Smythe, B.M. (1971) Sucrose crystal growth. *Sugar Technology Reviews* **1**, 191–231.

Soignet, G. (1981) Le coût de la terre. *Info betterave GS Culture CFS Agriliaisons* **38**, 1–3.

Srba, V. & Hakaufová, L. (2003) Sugar beet varieties registered in 2003 (Czech). *Listy Cukrovarnické a Reparské* **119** (2), 47–49.

Stechova, A., Svobodova, L., Korcakova, S. & Kadlec, P. (1988) Determination of betaine in sugar factory samples. *Listy Cukrovarnicke* **104** (6), 121–124.

Steensen, J.K. (2002) Balance between reduction of soil tare and root injuries. *International Sugar Journal* **104** (1240), 171–176.

Theurer, C. (1989) Progress and performance in development of smooth root sugarbeet varieties (abstract). *Journal of Sugar Beet Research* **26**, A 25.

Trzebinski, J., El-Rakabawy, N. & Labedzka, E. (1985) Effect of mineral fertilization and genetic variability on the content of betaine in sugar beet plants. *Biuletyn Instytutu Hodowli i Aklimatyzacji Roslin* **158**, 91–99.

Tschernjawskaja, L.I. & Chelemski, M.S. (1997) Zuckerverluste bei der Lagerung und Verarbeitung von Zuckerrüben-Teil 1: Untersuchungen zur Bestimmung der Rübenmasse- und Zuckerverluste bei der Rübenlagerung. *Zuckerindustrie* **122** (6), 440–446.

Tugnoli, V. (2000) Utilizzi alternativi della bieticoltori per un reddito piu elevato. *Informatore Agrario* **56** (48), 35–39.

Turner, F. (1989) Amino nitrogen story update. *British Sugar Beet Review* **57** (3), 31.

Uhlenbrock, W. (1973) Beet constituents and prediction limits for beet quality. *Zucker* **26**, 469–478.

Uhlenbrock, W. (1992) Comparison of beet quality predictions. *Proceedings CITS Scientific Committee*. Bratislava, Slovakia, 15–17 June 1992, p. 22.

Vaccari, G., Accorsi, C.A. & Mantovani, G. (1981) Danneggiamento della bietola e sue implicazioni industriali. *L'Industria Saccarifera Italiana* **74**, 153–161.

Vaccari, G., Mantovani, G., Squaldino, G., Aquilano, D. & Rubbo, M. (1986) The raffinose effect on sucrose morphology and kinetics. *Sugar Technology Reviews* **13**, 133–178.

Vaccari, G., Marzola, M.G., Mantovani, G., Bentini, M. & Baraldi, G. (1988) Chemical and enzymatic changes in strongly damaged beets. *Food Chemistry* **27**, 203–211.

Vaccari, G., Dosi, E., Mantovani, G. & Reggiani, M. (1996) A new approach to evaluating the industrial quality of beet. *International Sugar Journal* **98** (1165B), 3–8.

Van der Beek, M.A. & Huijbregts, A.W.M. (1986) Internal quality aspects of sugar beet. *Proceedings of the Fertiliser Society*. No. 252, London.

Van der Linden, J.P. (1996) Reducing soil tare of sugar beet with 'novel' cleaning technology. In: *Proceedings of the 59th*

IIRB Congress. Bruxelles, pp. 499–505.

Van der Linden, J.P. (2002) Cleaning techniques and reduction of soil tare. In: *Proceedings of the 65th IIRB Congress*. Bruxelles, pp. 139–148.

Van der Poel, P.W., Schiweck, H. & Schwartz, T. (1998) *Sugar Technology*. Verlag Dr Albert Bartens KG, Berlin.

Van Geijn, N.J., Giljam, L.C. & De Nie, L.H. (1983) α-amino-nitrogen in sugar processing. In: *Proceedings of the Symposium 'Nitrogen and Sugar-Beet'*. IIRB, Bruxelles, pp. 13–25.

Van Swaaij, A.C.P.M and Maassen, J. (2005) *Bietenstatistiek 2004*. IRS report 05P01.

Van Swaaij, A.C.P.M., Van der Linden, J.P. & Vandergeten, J.-P. (2003) Effect of growth conditions and variety on damage susceptibility of sugar beet. *Zuckerindustrie* **128** (12), 888–891.

Verhaart, M.L.A. & Oldfield, J.F.T. (1962) A summary of the proceedings. In: The technological value of the sugar beet. *Proceedings of the XIth Session of the CITS*. Frankfurt, 1960, Elsevier, Amsterdam, pp. 1–8.

Vigh, A. (1984) Experiences in raising the processing quality of beet in Hungary. *Listy Cukrovarnicke* **100** (11), 259–262.

Vigoureux, A. (1989) *IIRB Agronomy Study Group: 1988 Report of the Mechanisation Sub-group*. International Institute for Sugar Beet Research, Brussels.

Vukov, K. (1962) Die mechanischen Eigenschaften der Zuckerrübenwurzel. In: The Technological Value of the Sugar Beet. *Proceedings of the XIth Session of the CITS*. Frankfurt, 1960, Elsevier, Amsterdam, pp. 291–305.

Vukov, K. (1977) *Physics and Chemistry of Sugar-Beet in Sugar Manufacture*. Elsevier Science Publishers, Amsterdam.

Vukov, K. & Hangyál, K. (1985) Sugar beet storage. *Sugar Technology Reviews* **12**, 143–265.

Walerianczyk, E.W. (1994) The thermal factor in the process of sugar extraction (Polish). *Gazeta Cukrownicza* **102** (9), 165–169.

Wevers, J.D.A. (2001) A scoring method to evaluate the environmental contamination of chemical crop protection treatments, applied to weed control in sugar beet. In: *Proceedings 31st Biennial Meeting (Agriculture) of the American Society of Sugar Beet Technologists*. Vancouver, Canada, pp. 116–119.

Wieninger, L. & Kubadinow, N. (1971) Beziehungen zwischen Rübenanalysen und technologische Bewertung von Zuckerrüben. In: *Comptes Rendus de la XIVme Assemblée Générale de la Commission Internationale Technique de Sucrerie*. Bruxelles, pp. 523–538.

Wieninger, L. & Kubadinow, N. (1973) Die Stickstoffdüngung und ihre Auswirkung auf technologische Qualitatsmerkmale der Zuckerrübe. *Zucker* **26**, 65–70.

Wiklicky, L. (1971) The processing quality of sugar beet. *Zucker* **21**, 667–672.

Willey, L.A. (1974) Trials of commercial varieties of sugar beet. *British Sugar Beet Review* **42** (2), 82–86.

Winner, C. & Feyerabend, I. (1971) A contribution to morphology and technical value of the sugar beet crown. *Zucker* **24**, 35–43.

Wyse, R.E. (1982) The sugarbeet and chemistry. In: *Beet-sugar Technology*. 3rd edn, Beet Sugar Development Foundation, Fort Collins.

Wyse, R.E. & Dexter, S.T. (1971) Effect of agronomic and storage practices on raffinose, reducing sugar and amino acid content of sugarbeet varieties. *Journal of the American Society of Sugar Beet Technologists* **16**, 369–383.

Yamane, T. (1971) The decomposition of raffinose by α-galactosidase. An enzymatic reaction applied in the factory-process in Japanese beet sugar factories. In: *Comptes Rendus de la XIVme Assemblée Générale de la Commission Internationale Technique de Sucrerie*. pp. 187–194.

Zahradnicek, J. (1996) Physiological and biochemical aspects of beet storage and fundamentals of its protection (Czech). *Listy Cukrovarnické a Reparské* **112** (11), 333–338.

Zaorska, H. (1979) Diminution of sugar losses in molasses and the increase in crystallisation rate due to the decolorisation of thin juice. In: *Comptes Rendus de la XVIme Assemblée Générale de la Commission Internationale Technique de Sucrerie*. pp. 655–668.

Zielke, R.C. (1973) Yield, quality and sucrose recovery from sugarbeet root and crown. *Journal of the American Society of Sugar Beet Technologists* **17**, 332–344.

Chapter 17

Co-products

Janice I. Harland, Calvin K. Jones and Chuck Hufford

INTRODUCTION

The sugar beet crop, when harvested and processed for the production of sugar, yields a number of co-products that can be used as animal feeding stuffs, and can provide a useful supply of forage for livestock. The processing of sugar beet roots results in the production of two more valuable feeds: sugar beet pulp and beet molasses. The latter may be further processed by fermentation to alcohol or ion exclusion to yield additional potential feedstuffs. These products may be used separately or combined and they may be dried or otherwise processed in a variety of ways to produce a range of high-quality animal feeds. This chapter outlines the analysis, feeding value and optimal feeding rates of these products, and their significance in livestock nutrition.

SUGAR BEET ROOTS

Sugar beet roots provide a valuable livestock feed and may be used as such when circumstances prevent the harvest of the crop for the production of sugar. By either lifting the root to the field surface and pasture feeding or lifting and transporting the root to grind and commingle with other more dry feedstuffs (e.g. cotton burs) a palatable feedstuff can be prepared and cause salvage of an otherwise 'lost' crop.

SUGAR BEET TOPS

Sugar beet tops may comprise just the sugar beet leaves or a combination of the leaves and crowns, depending on the type of harvester used; in this chapter the expression 'tops' will be used to denote a combination of leaves and crowns. Prior to the sugar beet root harvesting operation (lifting) a separate procedure is used to remove the sugar beet top from the root. This procedure is more commonly performed by a defoliator, which shreds tops prior to a scalping procedure causing the removal of the crown portion of the sugar beet plant. A less common practice is to 'save' the tops by use of an implement that removes a crown portion with the top intact, then gently conveys this material into a row upon the field surface. Tops can provide a cheap fodder for a variety of farm livestock; they may be fed either fresh or wilted, or they may be ensiled for use throughout the winter feeding season. The weight of tops is roughly equivalent to the weight of roots but varies with time of harvest, growing season and variety. In the UK, the maximum top yield, which generally occurs during September, is around 50 t/ha (5–6 t/ha dry matter).

Fresh or wilted tops can be grazed as is in the field, the usual practice when they are being fed to sheep or cattle, or they can be carted from the field for feeding. Tops which are to be ensiled should be harvested with equipment that allows their direct collection at topping in order to minimize soil contamination. There are four main requirements for the production of good beet top silage:

(1) Ensuring that tops are wilted, in order to reduce effluent and aid compaction in the silo or pit;
(2) Keeping soil contamination to a minimum;
(3) Locating the silo or pit for proper effluent disposal;
(4) Filling the silo or pit correctly, to ensure exclusion of air.

Tops should be windrowed in the field and allowed to wilt to 60–65% moisture before ensiling.

Detailed investigations into the ensiling of sugar beet tops were carried out by Nuttall and Stevens (1983), who reported effluent losses of 194–333 l/t. The first effluent was observed within 2 days of filling the silo and most of the loss took place during the first 7 days. The use of acid silage additives had little effect on effluent production or silage quality. Sugar beet top silage has a density of 1.25–1.3 t/m^3 (0.7–0.8 m^3/t).

Analysis and feeding value

Tops are an excellent source of protein, vitamin A, and carbohydrates. Sugar beet leaves normally contain 12–14% dry matter (DM), and leaves and crowns 16–18% DM. With fresh tops there is also a variable amount of surface water that must be taken into account when assessing their feeding value. The extent of soil contamination is also a major determinant of the feeding value of sugar beet tops. In wet harvesting conditions, up to 25% of the DM may be silica from soil, which greatly decreases the digestibility and metabolizable energy content of the tops (Table 17.1).

Table 17.1 Effect of different amounts of silica present on digestibility (D-value) and metabolizable energy (ME) of beet top silage.

	Silica (% in DM)	D-value	ME (MJ/kg DM)
Clean fresh tops	5	65	10.1
Good beet top silage	15	57	8. 8
Moderate beet top silage	25	49	7.6

Typical analyses of fresh and ensiled sugar beet leaves and leaves plus crowns are shown in Table 17.2. Fresh beet tops and top silage are both very palatable and may be fed to all ruminants. On an energy basis 10 kg beet top silage is equivalent to 1.5 kg barley. In the USA, tops are considered slightly inferior to alfalfa haylage or corn silage for beef cattle, but are equivalent to alfalfa haylage or corn silage for sheep.

Feeding sugar beet tops

Beet top silage is best fed in combination with other feeds.

Dairy cows

Sugar beet tops should be introduced gradually into the diet when they are fed to dairy cows. Suggestions that tops lead to milk taint are thought to be largely anecdotal, and in an extensive study carried out on 444 farms in Sweden, tops had no effect on milk quality, hygiene, taste or smell (Andersson *et al.*, 1980). The recommended rate of feeding is 20 kg/head during early and mid-lactation, although greater amounts may be fed to cows which are either in late lactation or dry.

Table 17.2 Analysis of fresh and ensiled sugar beet tops.

	Fresh		Ensiled	
	Leaves	Leaves plus crowns	Leaves	Leaves plus crowns
DM (%)	12–14	14–16	16–18	15–19
pH			3.8–4.0	3.8–4.2
	Concentration in dry matter			
Crude protein (%)	14–16	13–15	14–18	12–16
Silica (%)	5–15	5–13	10–25	7–25
ME* (MJ/kg DM)	8.5–10.0	8.0–9.5	8.0–9.5	7.8–9.2
D-value	55–65	55–65	50–60	50–60

* Metabolizable energy

Beef cattle

Numerous studies have been carried out at Norfolk Agricultural Station on the feeding of sugar beet tops to beef cattle (e.g. Nuttall & Stevens, 1983). Fresh tops can be fed *ad lib* to cattle from 300–350 kg liveweight.

Maynard and Knaus (1959) published in *Beets and Meat* 3rd revised edition, 'depending on age, from 4 kg for calves to 15 or even 20 kg maximum feed for older beef cattle or dairy cows. It is advisable to feed some long forage such as straw or alfalfa hay with beet-top silage.'

Silage fed with 2–3 kg/head/day high energy concentrate can lead to liveweight gains of 0.9–1.3 kg/head/day and even at lower levels of concentrate supplementation (1.25 kg/head/day) reasonable rates of liveweight gain have been reported in Hereford × Friesian cattle. Large quantities of top silage can be fed with no apparent digestive disturbances or effect on carcass conformation.

Sheep

Sheep are normally fed on sugar beet tops in the field after harvest. Initially, they should be allowed to graze only for a limited period to avoid too high a consumption before the appropriate bacterial population has established in the rumen. After approximately 10 days they can safely graze *ad lib* without any adverse effect. An average stocking rate is 125–175 ewes/ha.

Sugar beet silage can be fed to lactating ewes or fattening sheep. The normal feeding rate is 3–5 kg fresh weight/head. For lambs, Maynard and Knaus recommended that a daily ration for lambs should consist of from 0.75 to 2 kg.

Pigs

Pigs can only utilize sugar beet leaves to a limited extent. In a trial carried out by Smits and Haaksma (1980) only 55% of the crude protein (CP) and 70% of the organic matter (OM) of sugar beet leaves was digestible. Beet leaves should therefore only be used sparingly in pig diets.

SUGAR BEET PULP

After harvesting, sugar beet roots are delivered to the factory, where they are washed and sliced into strips called cossettes (which resemble thin potato slices). The cossettes are mixed with hot water and the sugar is extracted by diffusion. The sugar in solution goes forward for the production of sugar crystals, while the spent cossettes, known as wet pulp, form the basis of various valuable animal feeds. The wet pulp may be sold directly to the farmer or may be passed through heavy presses that squeeze out nearly all the surplus water to produce pressed pulp. The pressed pulp may also be sold to the farmer for feeding fresh or ensiling, or it may be dried to produce dried plain sugar beet pulp. In some countries the pressed pulp is mixed with molasses and then dried to produce dried molassed sugar beet pulp (feed).

The dried molassed feeds are particularly popular in the UK and in Ireland as well as in the USA and Japan, and full details of their analysis and feeding value are given below. Dried sugar beet pulp may be sold as shreds, (the loose form) or pelletized. The pelletized form is conducive for transporting greater distances from the beet sugar producing facility.

Characterization of sugar beet pulp

Sugar beet pulp normally enters the feeding system as one of the following three products which differ only in DM content:

	Dry matter (%)
Wet pulp	6–12
Pressed pulp	18–30
Dried plain sugar beet pulp	87–92

Wet pulp

The low dry matter content of wet pulp means that it is rather fluid in nature, and therefore difficult to handle and store. It can be fed fresh to ruminant livestock and pigs, where its major attributes are its energy and digestible fibre content.

Wet pulp is extensively produced and used in Denmark, where it is usually fed in combination with other fodders grown on the farm. If wet pulp is to be ensiled, it is preferable to use a pit silo, which will contain the product more successfully. No silage additive is necessary because the high sugar content ensures a good fermentation.

Pressed pulp

Pressed pulp is produced by all beet sugar facilities worldwide and is a very popular feed with livestock farmers in close proximity to production. Like wet pulp, its major attributes are its energy and digestible fibre content. However, the higher density of these components, a result of the lower moisture content, make it more suitable for high-performance animals.

Pressed pulp, if fed fresh, should be used within 5–7 days, as mould will grow on any surface exposed to air, causing spoilage. This spoilage occurs more rapidly in warm, humid conditions where immediate ensilage is recommended.

Ensilage of pressed pulp

Good ensilage of pressed pulp requires attention to detail. However, if precautions are taken, losses from the ensiling process are minimal. The major points to take account of are:

- The silo should be well sited and drained, preferably with a concrete pad as a base.
- The ensiling should be filled as quickly as possible.
- The pressed pulp should be compressed, if possible during the filling of the silo to exclude all air.
- The silage should be covered immediately with polythene and weighted down thoroughly to exclude all air from the surface of the pulp.
- When opened, the area of the silage face should be kept to a minimum to prevent secondary fermentation.

Provided these conditions are adhered to, good quality silage results, and over 90% of the original pressed pulp DM can be recovered from the clamp (Harland, 1981a). The density of pressed pulp silage is around 1 t/m^3.

Pressed pulp does not usually require a silage additive, as its sugar content of 6–12% is adequate to ensure good fermentation. It very quickly becomes infected by *Lactobacillus* which leads to a rapid production of lactic acid, causing a fall of pH to 3.6–4.2, and stabilizes the silage. Butyric pressed pulp silage is rare, since fermentation normally proceeds rapidly, and lactic acid is predominant.

Occasionally when pressed pulp is ensiled, the resulting silage is greasy in texture. This is due to the breakdown of some of the more fibrous components so that the structure collapses (Haaksma, 1988). It is thought that this breakdown is caused by the action of thermophilic bacteria because pressed pulp, particularly if it has a relatively low DM content, is a very poor conductor of heat and high temperatures can build up within the clamp. 'Greasy' silages are less acceptable to livestock and their handling may be more difficult. In a well-fermented silage, it is possible to come across football-sized balls of grey-green mould. The reason for their production is unclear, but they are best avoided when feeding to livestock.

Dried plain sugar beet pulp

When dried, sugar beet pulp is a very stable feeding stuff, which can be either used directly or stored for up to a year without any adverse effect on its feeding value. It is normally produced as 8 mm pellets, which are convenient for use in automatic bulk handling systems. The un-pelleted form, referred to as 'shreds' provides a stable feed for customers close to the beet sugar factory. The density of the shreds is one-third that of pellets, so transporting great distances may be costly. Pressed pulp and dried pulp have similar feeding values on a dry matter basis and the choice of product depends on which is the more compatible with the feeding system in operation.

Analysis and feeding values of sugar beet pulp

Sugar beet pulp provides animals with both energy, derived primarily from the structural carbohydrate of the beet, and digestible fibre. Animals do not contain the necessary enzymes to break down the fibre and release energy, but the micro-organisms, primarily bacteria, which live in their digestive tracts do. It is these bacteria in the fore-stomach (rumen) of cattle and sheep (ruminants) and in the hind-gut of pigs and horses (monogastrics) that render the fibre available to the host animal. The fibre in sugar beet root crops is not mature and so not extensively lignified. It comprises approximately one-third pectin, one-third hemicellulose and one-third cellulose, so that it can be almost completely digested by bacteria. Stern and Metwally (1990), state, with regard to the nutritive value of sugar beet pulp for ruminants, that although beet pulp has a high fibre content, it is an excellent digestible energy source for ruminants because of the type of carbohydrate associated with the cell wall fraction.

It is the high pectin content of beet pulp that provides a readily available source of energy for microbial protein synthesis in the rumen. This is important because under most feeding practices there is a need for readily-available energy to help the rumen bacteria make efficient utilization of rumen ammonia (see, for example, studies of Hristov and Ropp, 2003, with high fibre diets including sugar beet pulp). The resulting microbial protein synthesized comprises a substantial part of the protein entering the small intestine (60–85% of total protein). Additional protein required by ruminants is provided by dietary protein which leaves the rumen undegraded (also referred to as bypass protein or digestible undegraded protein (DUP)). There is some evidence that beet pulp is a good source of bypass protein, although the content of protein is fairly modest at 90–120 g/kg DM.

The sugar beet fibre is highly digestible, almost 90% in both ruminants (Ewing, 1997) and pigs (Longland *et al.*, 1987a,b), giving sugar beet pulp an important role in feeding regimes by increasing the fibre level of the diet without reducing the energy density.

This combination of high energy and fibre places sugar beet pulp in a unique position amongst feed ingredients. The comparative feeding values typically assigned to dried molassed sugar beet feed and dried plain sugar beet pulp are given in Table 17.3.

Table 17.3 Nutritive value of dried molassed sugar beet feed and dried plain sugar beet pulp.

	Dried molassed sugar beet feed	Dried plain sugar beet pulp
Dry matter	87–90%	87–90%
	Concentrations in dry matter	
Ether extract (g/kg)	4	4
Total sugar (g/kg)	140–300	65
Neutral detergent fibre (g/kg)	305	350
Acid detergent fibre (g/kg)	180	220
NCDG (g/kg)	840	870
Total ash (g/kg)	85	68
ME ruminants (MJ/kg DM)	12.5	12.5
FME (mg/kg DM)	12.3	12.4
Digestible energy pigs (MJ/kg DM)	13.1	13.2
ME poultry (MJ/kg DM)	5.8	3.5
Crude protein (g/kg)	110	100
ERDP (0.2), (0.5), (0.8) (g/kg)	6.4, 4.9, 4.5	6.9, 5.5, 4.6
DUP (0.2), (0.5), (0.8) (g/kg)	2.6, 3.8, 4.5	1.8, 3.3, 3.8
Calcium (g/kg)	0.95	0.8
Phosphorus (g/kg)	0.15	0.3
Magnesium (g/kg)	0.15	0.25

Source: Ewing (1997), NCGD – Neutral Cellulase Gamanase Digestibility, ME – metabolizable energy, FME – fermentable metabolizable energy, ERDP – Effective rumen degradable protein, DUP – Digestible undegrable protein.

Feeding sugar beet pulp

Sugar beet pulp is primarily used as an energy source in livestock rations. However, it has also been suggested that the digestibility of poor quality forage diets for ruminants, such as those based on straw or hay, could be enhanced by the inclusion of sugar beet pulp. The pulp increases the number and variety of fibre-digesting bacteria in the rumen, resulting in more extensive digestion and utilization of all fibre in the ration. This has enabled the intake of straw by sheep to be increased from 414 to 505 g DM/day (Silva & Orskov, 1985). Studies by the Aberdeen group also demonstrated that dried plain sugar beet pulp fed at high levels with ammonia-treated straw had a less depressing effect than barley on straw digestibility (Fahmy *et al.*, 1984).

Recently it has been suggested that the inclusion of sugar beet pulp in cereal mixes fed with grass silage also improves overall utilization of the diet; the resulting balance of carbohydrates leads to higher rumen microbial output and rumen pH is buffered leading to optimization of events in the rumen.

Sugar beet pulp can therefore improve both the digestibility and the intake of forage such as straw, with more recent research demonstrating that total intake and output of modest quality grass silage can also be enhanced. See for example, the effect of the partial substitution of grass silage with pressed pulp (Humphries *et al.*, 2003).

Harvesting and/or poor ensiling conditions when grass silage is being made often leads to silage quality being compromised with the consequent need to feed more concentrates. Part of this effect is considered to be due to the development of a solid mass of digesta in the rumen, with loss of the normal layered or biphasic stratification of rumen contents. Under such conditions, rumen motility, rate of forage digestion and voluntary feed intake will be compromised. Mertens (1997) stressed that chemical definition of dietary fibre such as neutral- (NDF) or acid-detergent (ADF) fibre content was an inadequate description of the fibre content of a diet as it affects rumen function and animal performance. Consequently he proposed both effective NDF (eNDF; ability of a feed to replace roughage with no negative effect on milk fat content) and physically effective NDF (peNDF; a measure of the physical properties of fibre as it stimulates chewing activity and development of the biphasic stratification of rumen contents) as additional descriptors of the physical characteristics of dietary fibre.

Humphries *et al.* (2003) compared a control ration based on grass silage and concentrates (60:40 DM basis) with three treatments based on 10, 20 and 30% pressed pulp inclusion. Pressed pulp caused marked improvements in total DM intake with a significant ($P < 0.05$) increase at the highest level of inclusion (control, 13.8; 30% pressed pulp (PP3), 19.4 kg/d; $P < 0.05$), associated with increases in NDF and ADF intake of 29 and 14% respectively. The effective DM degradability of grass silage nor rate of passage of the silage were significantly affected although a non-significant decline in rate of degradation was observed as pressed pulp inclusion levels increased. In contrast, chewing activity was significantly ($P < 0.05$) affected by inclusion of pressed pulp in the ration with both increased bolus chewing time (47.1 vs. 50.3 secs/bolus) and chews per bolus (49.6 vs. 54.5). In addition, a marked reduction in rumen mat density (control, 51.1; PP3, 45.3 bar) was observed.

The authors concluded that part replacement of modest quality grass silage with pressed pulp provided an improved rumen environment more conducive to the efficient utilization of ingested fibre and indicated a highly beneficial role for pressed sugar beet pulp in the ration of lactating dairy cows. In addition these results support the contention that dietary fibre should be assessed in both physical and chemical terms.

Dairy cows

It is generally assumed that equal dry matter intakes of pressed and dried pulp behave similarly when fed to livestock. In one of the few comparative trials that have been carried out, dairy cow performance was not affected when 5 kg/day DM was fed in either form, although it was shown that protein degradability, at 0.07 and 0.60 for dried and pressed pulp respectively, differed greatly (Hemingway *et al.*, 1986a). Pulp protein availability in the rumen seemed to be significantly altered by drying, although it was unclear whether this was of practical significance. The pulp intake represented approximately 25% of the total DM intake in this experiment, but a markedly lower contribution to overall CP intake.

The different forms of feed had no effect on milk production or composition, although cows fed pressed pulp had lower DM intakes in early lactation and therefore were in a more negative energy balance initially and lost more weight (De Visser & Tamminga, 1987).

Clearly, 25% of the DM intake of dairy cows can satisfactorily be fed as sugar beet pulp (Steg *et al.*, 1985), which can also increase the energy density of rations, particularly those based on poorer quality forage.

Beef cattle

Sugar beet pulp is an attractive feed for beef cattle and, although a supplement of protein and mineral/vitamin mix is generally required, it may comprise the major proportion of the diet. When finishing beef cattle were fed on up to 40 kg/day pressed pulp, equivalent to 10 kg/day DM and representing over 80% of the total DM intake, they grew well, with liveweight gains of 1.2–1.5 kg/head/day (Harland, 1981b). Bulls from 297 to 621 kg liveweight had similar liveweight gains when they fed *ad lib* on pulp in either pressed or dried form (0.75 kg DM/100 kg body weight) with a protein concentrate. There was no significant difference in performance between the groups fed pressed pulp and those fed dried pulp (Boucque *et al.*, 1984).

Pressed pulp fed to calves from the age of 3 months was palatable and well accepted by all animals, and had no adverse effect on growth or efficiency of liveweight gain (Nuttall, 1981).

Sheep

Growing and fattening lambs can utilize a large proportion of sugar beet pulp in their diet. When up to 81% of the cereal of a lamb-fattening diet was replaced by dried beet pulp, liveweight gain was similar to the control diet and the efficiency of utilization of the diet and the carcass quality, tended to improve (Theriez & Brun, 1983).

Lambs fed dried beet pulp pellets gained faster and more efficiently than lambs fed an equivalent amount of DM from pressed or wet beet pulp. Lambs fed more beet pulp (33% of dietary DM) gained faster but not more efficiently than lambs fed less beet pulp (15% of dietary DM) (Stern & Metwally, 1990).

Pigs

Traditionally, it was believed that pigs could make only limited use of fibrous feeds. However, there is now considerable evidence demonstrating that growing pigs can utilize 15% pressed or dried pulp in the diet without adversely affecting growth or efficiency of energy utilization (Longland *et al.*, 1987a,b; Smits & Sebek, 1987; Haaskma, 1988). Furthermore, Low *et al.* (1990) and Edwards *et al.* (1991) have shown that 15% dried sugar beet pulp was efficiently utilized by piglets of only 3 weeks old.

It has been shown that the efficiency of utilization of sugar beet pulp non-starch polysaccharides (NSP) in growing pigs increases with its prolonged inclusion in its diet. Longland *et al.* (1993) suggested that a period of 3–5 weeks was required for maximal digestion to take place.

An additional benefit identified by Longland *et al.* (1991), was that the eating quality of pork from animals fed sugar beet pulp has superior properties. Kreuzer *et al.* (2002) also demonstrated that cholesterol levels were lower in blood and muscle from pigs fed sugar beet pulp and suggested that pork from these animals could be beneficial to human health.

Breeding sows can utilize fibre more efficiently than growing pigs, and levels of up to 40% sugar beet pulp have been successfully incorporated in sow diets (Smits & Sebek, 1987; Edwards *et al.*, 1989; Close *et al.*, 1990).

In trials where 0, 3.75 or 7.5 kg of pressed pulp were included in the diet of sows, the consumption of water, provided *ad lib*, decreased as the pressed pulp consumption increased (Haaksma, 1988; Fig. 17.1). The decreased water intake also led to reduced slurry production, which is an important environmental consideration, particularly in countries such as the Netherlands. A reduction in nitro-

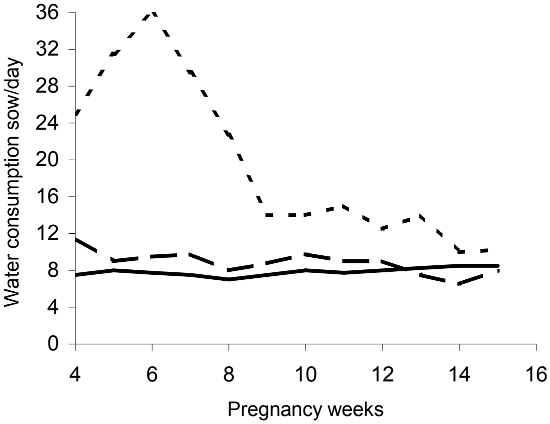

Fig. 17.1 Average water consumption (feed and drink water) in l/sow/day when pressed pulp is fed: 7.5 kg pressed pulp (continuous line); 3.75 kg pressed pulp (long dashed line); 0 kg pressed pulp (short dashed line).

gen omissions was a further environmental benefit reported when sugar beet pulp was included in the fibrous component of grower pig diets (Canh *et al.*, 1998; Zervas & Zijlstra, 2002).

Additional benefits from including sugar beet pulp in sow diets include increased food intake during lactation, higher piglet weights at birth, faster growth of piglets and improved satiety of sows during pregnancy when feeding is restricted (Edwards *et al.*, 1989; Close *et al.*, 1990).

Clearly, moderate levels of sugar beet pulp (up to 15% of DM intake) can successfully be included in the diet of growing pigs, with higher levels (up to 40% of DM intake) being suitable for breeding sows.

Horses and ponies

Since the 1990s a number of studies has evaluated the role that sugar beet pulp can play in the diet of horses and ponies.

The research of Hyslop and Cuddeford (1999), established basal parameters for the inclusion of unmolassed sugar beet pulp is the diet of equids. It was recommended that sugar beet pulp is soaked prior to feeding and the soaked feed can act as a partial forage replacer in diets for equids at a rate of approximately 200 g/kg total diet DM. This level is equivalent to approximately 300 g/day per 100 kg pony liveweight of dried sugar beet pulp prior to soaking. At this level of intake, total dry matter intake of the animal is maintained.

In a further study by Hyslop (2002), the critical level of sugar beet pulp inclusion was established by assessing the level at which there was a statistically significant reduction in voluntary food intake. Inclusion levels from 0 to 800 g/kg DM were evaluated in Welsh Cob ponies. There was a progressively reduced voluntary food intake of 35% as intake of beet pulp increased. Energy content of the diet increased, but digestible protein content declined, as the level of beet pulp increased, reflecting its feed values. The critical level of beet pulp inclusion required before a statistically significant reduction in feed intake occurred lay between 320 and 480 g/kg DM.

Using an *in sacco* technique, which involves the use of porous synthetic bags that are placed in the equine stomach to assess the rate of disappearance of the various components, it has been established, (Hyslop, 2003) that 160 g/kg DM disappear in the stomach; 411 g/kg DM disappear in the small intestine and 90 g/kg DM disappear in the colon of equids. The extent of caecal fermentation reported for sugar beet pulp is far greater than seen for other fibrous foods, such as hay soya hulls or naked oats.

Other uses of sugar beet pulp

Sugar beet pulp has been used as a palatable, fibrous food ingredient for human consumption. The inclusion of sugar beet fibre in the diet of healthy volunteers has resulted in significant physiological changes, such as reductions in the levels of both postprandial plasma glucose and blood cholesterol (Morgan *et al.*, 1988). The physiological effects of eating Beta Fibre have been reviewed by Harland (1989; 1993).

Pet food manufacturers have also included sugar beet pulp in their formulations for many years. The addition of beet pulp provides the fibrous filler (bulking agent), plus pectin, for many of their formulations. Sunvold *et al.* (1995), suggested that moderately fermentable dietary fibre sources, such as beet pulp, promote excellent stool characteristics without compromising nutrient digestibility in dogs, and may promote gastrointestinal tract health by optimizing short chain fatty acid production.

SUGAR BEET MOLASSES

Beet molasses is the residual syrup from the processing of sugar beet from which no more sugar can be crystallized by conventional means. Additional sugar can be realized by further processing through ionic separation technology. This technology has been installed adjacent to many of the beet sugar factories within the USA. It is a viscous black liquid that is primarily used as an animal feed or for fermentation purposes. In the factory, it is 80–85% brix and of high viscosity. This makes handling at ambient temperatures difficult, so it is normally diluted to 72–75% DM for sale and use on farm or in feed mills.

Analysis and feeding value of sugar beet molasses

The chemical composition reported for beet molasses is highly variable. This is demonstrated by Table 17.4, which shows the analyses given in a number of different feedstuff tables. Most of the recent figures suggest a protein digestibility of around 77% and DM digestibility of around 90%, indicating that beet molasses can be well utilized by ruminant livestock.

The protein composition of molasses comprises three main fractions: 27% betaine, 33% amino acids and 35% uncharacterized. It is believed that it is these nitrogenous components that give beet molasses its characteristic earthy flavour and smell.

The major component of the dry matter of beet molasses is sucrose, which comprises approximately 50% as sold. There are also small quantities of reducing sugars and raffinose, and the final main component, apart from nitrogen, is ash. Potassium and sodium are the main minerals present, and their relatively high contents (55 g/kg and 11 g/kg respectively) may cause diarrhoea in livestock if fed in large amounts. The vitamin content of beet molasses is low and does not contribute significantly to livestock requirements.

Accurate assessments of the feeding value of beet molasses are difficult to achieve. They are generally determined by difference, because the beet molasses can only be incorporated into the diet at moderate rates (approximately 20%).

In USA commercial practice, it is considered that beet molasses is a high-energy feed capable of replacing 70% of the same weight of corn. The maximum dietary level is restricted to 10–15% for cattle, the major beet molasses consumer in the USA.

In sheep fed 20% beet molasses, a digestible energy (DE) value of 13.5 MJ/kg DM has been derived. However, Steg and Van der Meer (1985) derived the considerably higher value of 14.9 MJ/kg

Table 17.4 Dry matter (DM), ash and crude protein (CP) content of beet molasses and its digestibility according to feed tables.

	DM (g/kg)	Ash (g/kg DM)	CP	DM, Digestibility	CP (%)
UK[1]	750	90	69	79	34
UK[2]	763	136	117	88	77
France[3]	775	103	116	89	60
Denmark[3]	770	137	99	94	71
Netherlands[3]	764	140	110	90	65
Netherlands[3]	803	148	90	92	76
Federal Republic of Germany[3]	770	131	108	86	58
USA	770	106	87	79	57

[1]MAFF (1986), [2]Givens D I, ADAS Feed Evaluation Unit, Drayton, England (1983) (personal communication), [3]Steg & Van der Meer (1985).

DM when 15% or 30% beet molasses was included in a hay-based test diet. A review of the literature (Harland, 1988) suggests that, at moderate levels of inclusion (approximately 10%), the energy value of beet molasses is similar on a dry matter basis to that of cereals, so the higher value of Steg appears to be the closer predictor of livestock performance.

Feeding levels of sugar beet molasses

Dairy cows

Beet molasses is used primarily as a palatable source of energy. It is generally included in the diet at levels of 10–15%, which seems to have no adverse effects. Higher levels may result in the development of off-flavours in the milk, probably due to the breakdown of betaine to triethylamine (which has a fishy taste). However, provided adequate long forage is kept in the diet, this does not appear to be a problem in practice.

The use of beet molasses in concentrates fed to dairy cows has been investigated (Table 17.5), as it has been suggested that the supplementary simple sugars can improve microbial protein synthesis (Newbold *et al.*, 1988). Levels of beet molasses equivalent to 140 g/kg DM intake have been shown to increase the food intake of dairy cows, although performance was similar in terms of milk quality and yield (Newbold *et al.*, 1989). The benefits of this system need further quantification before the widespread use of this feeding regime can be recommended.

Table 17.5 Effect of beet molasses inclusion in sugar beet feed compared with barley in lactating dairy cow rations (from Sutton *et al.*, 1988).

	Beet molasses inclusion (g/kg)			
Parameter	0	400	Barley	SE
Sugar in SBF (%)	6	22		
Milk yield (kg/day)	25.9	24.4	26	0.71
Milk fat (g/kg)	37.9	39.4	36.4	1.11
Milk fat (kg/day)	0.98	0.96	0.95	
Milk protein (g/kg)	28.7	29.9	30	0.38
Milk protein (kg/day)	0.74	0.73	0.78	

Growing/finishing ruminants

With beef cattle it is the sugar level that determines the amount of beet molasses which can be included in the diet. This is because at higher levels of inclusion the micro-organisms capable of sugar fermentation increase, with the result that butyric acid production in the rumen increases and propionic acid production decreases. It has been suggested that, regardless of the animal's efficiency of utilization of each acid, it may be physiologically unable to tolerate high butyrate levels. Higher butyrate concentration may lead to the production of ketone bodies and decrease the efficiency of energy utilization for growth and fattening.

The inclusion of urea in the diet may enhance propionate production and decrease the levels of ketogenic and higher volatile fatty acids, leading to a more efficient utilization of beet molasses for fattening.

When a significant level of beet molasses is fed to cattle, a proportion of the diet needs to be in the form of roughage to facilitate rumen outflow. In trials, alfalfa hay was marginally superior to oat straw chaff and cotton lint in this respect (Beveridge & Leng, 1981).

In trials in which steers weighing initially 400 kg were fed from 0.6 to 2.4 kg beet molasses per 100 kg of liveweight daily, there were no adverse effects on health even at the highest levels of inclusion. Performance in terms of liveweight gain was poorer than predicted, but it improved as the proportion of molasses in the diet increased (Ruiz *et al.*, 1980). Karalazos and Swan (1976) concluded that beet molasses could comprise up to 20% of the dietary dry matter of mixed cereal and forage rations without adversely affecting ruminant livestock performance or depressing total diet digestibility. This conclusion is confirmed by studies that indicate that diets containing beet molasses had higher DM digestibility, increased levels of microbial nitrogen in the small intestine and high efficiency of microbial nitrogen synthesis. The inclusion of beet molasses increased the pH range in the rumen and was associated with a decreased lag time of both hay and silage DM degradation (Hutitanen, 1988).

In a recent trial, Boland *et al.* (2004) included 0, 3, 6, or 9% molasses in a complete grower finisher diet for early-weaned Texel lambs. Feed intake reduced at the higher levels of molasses inclusion, although growth rate was unaffected. However of major practical significance was the condition of the fleece; faecal material adhered to the fleece when 6–9% molasses was fed and the cleanliness of lambs was below levels considered acceptable by the abattoir. These authors considered that while performance was not compromised, the higher levels of inclusion were unacceptable in the final finishing phase of intensively reared indoor lambs.

It appears that up to 20% beet molasses can be included in both forage and mixed diets of beef cattle with no adverse effect on growth and performance. However, with more stringent European Union requirements on the cleanliness of finished animals presented at abattoirs, it may be advisable to feed lower levels of molasses in the final finishing phase of intensively reared stock.

Horses

Some years ago it was reported that the safe level of beet molasses inclusion in the diet of horses was 10.0–16.5% (Morrison, 1936). More recently, however, recommended feeding levels have been considerably lower than this.

Experiments at the Warwickshire College of Agriculture investigated levels of beet molasses inclusion in both forage (hay) based diets and cereal diets. A cross-section of horses and ponies was introduced over a period of time to beet molasses up to a maximum level of 1 kg/head/day. The levels of beet molasses achieved and sustained for a period were, on average, equivalent to 10% of intake. At higher levels of beet molasses intake, water intake increased and faeces sometimes became soft, although this was not severe enough to cause distress to the horses (S. Pillner & J.I. Harland, 1986, unpublished observations).

It does not seem possible to include in modern-day rations of horses and ponies the large amounts of beet molasses recommended by Morrison (1936), although levels of up to 10% are probably quite acceptable.

Non-ruminants

With both pigs and poultry, the level of beet molasses inclusion in the diet is usually limited because of the risk of soft faeces or diarrhoea. This is generally thought to be due to the high levels of potassium and sodium, rather than simply the level of sugar.

Ewing (1963) suggested that it was the alkaline salts that gave beet molasses a laxative effect in poultry. However, Cuervo *et al.* (1972) concluded that in cane molasses non-mineral substance(s) cause the laxative effect. It has been suggested that if this is also the case in beet molasses, either the oligosaccharide, raffinose or nitrogenous compounds may be responsible.

Beet molasses has been fed to growing chicks and laying hens at levels of 10% and 20% respectively without any adverse effect on performance (Keshavarz *et al.*, 1980). Up to 34.5% beet molasses could be incorporated in poultry diets, provided the amino acid and mineral profiles of diets containing substantial quantities of beet molasses were correctly balanced (Waldrup, 1981). However, at these high levels faeces were sticky, which may present disposal problems in some intensive systems. For laying hens, the performance is less susceptible to high levels of beet molasses inclusion; no adverse comment on inclusion levels of up to 15% was reported following a taste panel of test eggs, although at 20–30% inclusion levels, the eggs received lower scores whilst still maintaining an acceptable rating (Waldrup, 1981). It is concluded that up to 10% beet molasses can be included in poultry diets.

For pigs, a safe level of inclusion is 5% in growing pig diets and 10% in finishing pig diets (Yany & Lee, 1982). Higher levels may be fed, although soft, dark-coloured faeces may be a problem in some intensive systems.

Other uses for sugar beet molasses

Beet molasses is often used as a silage additive. The addition of sugar to low-quality grass improves fermentation by maximizing the availability of the lactobacillus. Typically, 2.5% sugar (equivalent to 5.0–7.5% beet molasses) needs to be added for successful ensiling of grass, although the usual addition rates are somewhat higher, at 7.5–15% beet molasses. The actual rate required depends on the sugar and moisture content of the grass. Although beet molasses is difficult to handle in some systems, it has the advantage of being non-corrosive and safe.

A number of liquid feeds are based on beet molasses, most of them containing a source of protein and a vitamin/mineral supplement. These liquids may be used to improve the palatability of low-quality feeds, such as straw and hay.

Beet molasses may be incorporated into solid feed blocks that contain a variety of other nutrients to provide a suitable and convenient feed for remote locations. They are used extensively in hill locations in the UK, and on range land in the USA.

Another major outlet for beet molasses is in the compound feed industry where it is included in many formulations, typically at levels of 5–10%. The main advantages of including beet molasses are:

- increased energy density;
- improved palatability;
- reduced dustiness;
- improved throughput, with consequent cost reductions;
- improved physical quality of the product;
- masking of less palatable ingredients;
- cost effectiveness.

In conclusion, beet molasses is primarily used as either a feed ingredient or a fermentation substrate. Its energy value and palatability are its main benefits when fed to livestock, which usually respond positively to a 10% inclusion of beet molasses in their diet. Traditionally, the direct use of beet molasses on farm has been limited by difficulties in the physical handling of the product. However, the widespread availability of blends has largely overcome this problem.

The fermentation industry is another large user of beet molasses and the remaining fermentable sugars in beet molasses are an excellent source of growth in bakers yeast production. Beet molasses is typically used in combination with cane molasses, the ratio depending on their relative prices and availability. Beet molasses is generally preferred as it has a lower ash content, which reduces the waste matter flow. Other fermentation uses for beet molasses include the production of monosodium glutamate, lysine and citric acid.

Beet molasses is a good source of betaine, which acts as a methyl donor and can replace part of the animal's requirement for the amino acid methionine. In recent times, betaine has been purified from beet molasses and is used in monogastric and fish diets; its role in metabolic processes was recently reviewed by Craig (2004).

An additional liquid co-product results from the desugaring of beet molasses. The use of chromatographic separation allows the factory to extract the majority of the sucrose remaining in beet molasses and creates another liquid co-product, desugared molasses. This product ranges in dry matter from 50 to 70% with crude protein ranging from 7 to 20% and total sugars in the 13–20% range. It is used extensively in liquid feed production as a lower cost substitute for cane molasses and, in some areas, is added to beet pulp as a binding agent.

MOLASSED SUGAR BEET PULP (FEED)

Dried molassed pulp or molassed pressed pulp are manufactured in several European countries plus the USA. However, given the relative high value for beet molasses for industrial and desugaring applications, the production of and/or the percentage of beet molasses applied to sugar beet pulp is declining.

These products are produced by mixing pressed pulp with warm beet molasses in the beet sugar factory. The resulting product is either sold directly for use on the farm as molassed pressed pulp, or dried in shredded form and then pelletized to produce sugarbeet pellets (6–8 mm diameter). Although no significant reaction takes place during the drying process, the reactions between the sugar and proteins which have the advantage of slowing the release of energy from beet molasses in the rumen of cattle and sheep, but the disadvantage of rendering some of the protein unavailable to monogastric animals. The dried product may contain from 5 to 20% beet molasses.

In the UK, the dried feed typically contains 20% sugar. In other countries the sugar content may be higher, as in Sweden, or lower, as in Germany. The ratio of beet molasses to pulp can alter the nutritional characteristics of the product, for example by influencing the ratio of rapidly available to slowly available energy.

Molassed pressed pulp

Molassed pressed pulp is not widely available and usually contains a very low level of beet molasses. Increasing the beet molasses content increases lactic acid production in the silo and reduces organic matter loss (Kamphues *et al.*, 1983) and in the UK, relatively high levels of beet molasses are used. The storage and handling characteristics of molassed pressed pulp are very similar to those of pressed pulp and so will not be detailed further.

Little experimental work has been carried out on this product specifically. However, according to MAFF (1986) its energy, protein and digestible organic matter in dry matter (DOMD) values are 12.2 MJ/kg DM, 123 g/kg DM and 831 g/kg DM respectively.

In one of the few experiments comparing pressed pulp with molassed pressed pulp, milk yields of dairy cows fed 5 kg/day DM as pressed pulp were significantly higher than those from animals fed on molassed pressed pulp (21.6 kg/day compared with 20.8 kg/day). The fat concentration however, was significantly higher in milk from the cows fed on molassed pressed pulp (41.2 g/kg compared with 39.5 g/kg). The net yield of fat was similar in both feeding regimes (0.85 and 0.86 kg/day for pressed pulp and molassed pressed pulp respectively) and milk protein yield was not significantly different (Hemingway *et al.*, 1986a,b). The addition of beet molasses appeared to alter the partition of energy by the animal, although the overall effect on performance was minimal. However, there are situations where the production of a lower volume of higher solids milk would be more cost effective within the present European Union milk quota scheme.

In conclusion, substantial quantities of molassed pressed pulp may be fed to ruminant livestock, with levels of up to 25% of DM intake giving good results. It is possible that higher levels could be incorporated into the diet without any adverse effect on performance.

Dried molassed sugar beet feed

Analysis

The typical analysis of dried molassed sugar beet feed (DMSBF) is given in Table 17.3. It is generally assumed that DMSBF has an energy value that is similar to that of barley, and when used on farm it is often substituted on a one-for-one basis. Like dried plain sugar beet pulp, the major contribution which DMSBF makes to livestock nutrition is as a source of energy, in this case rapidly available energy from sugar and more slowly available energy from digestible fibre. In addition, its sugar content makes it a very palatable feed, and in many feeding situations it may be the only concentrated feed which is given.

DMSBF is fed both to ruminant livestock and to simple-stomached animals such as pigs and horses. It is a stable product, which can be stored in cool, dry conditions for up to a year without any adverse effect on its feeding value.

Dairy cows

Early work in which DMSBF was included in dairy cow rations produced the fundamental information that demonstrated that DMSBF and barley were equivalent, and for all practical purposes could replace each other on a weight-for-weight basis. It also demonstrated that high levels of DMSBF could safely be fed to dairy cows: intakes of 9.07 kg were recorded in Ayrshire cows, and there was no need to soak the product prior to feeding (Castle *et al.*, 1966; Castle, 1972). Up to 10 kg/day DMSBF have been fed to dairy cows with no adverse effect on performance (Lees *et al.*, 1982), however in commercial practice, typically amounts of 2–4 kg DM are included in the ration of lactating dairy cows.

While it is clear that DMSBF is a suitable feed for dairy cows, investigations have focused on determining whether it has significant advantages over cereal or starchy feeds. The three main aspects, that have been investigated are: milk quality and nutrient partition during lactation; forage intake and substitution rate; optimizing health and rumen performance.

By looking at each area in greater detail, it can be seen that DMSBF tends to increase the concentration of milk fat, with little or no effect on milk protein and lactose production, thereby leading to an overall improvement in milk quality (Hemingway *et al*., 1986a,b; Sutton *et al*., 1988; Table 17.5). Starchy compounds increase milk yield and milk proteins, whereas fibrous concentrates enhance milk fat production and yield (Sutton *et al*., 1985). In maize silage-based diets, fed as total mixed rations the effect of DMSBF inclusion was studied in lactating Friesian-Holsteins in a 4 × 4 Latin, square design experiment (Phipps *et al*., 2003). DMSBF replaced 0 to 180 g/kg DM cracked wheat in the mix. The optimal rate of inclusion was 120 g/kg DM; at this level milk yield and quality was maximized.

Hence, choice of feed type can manipulate milk quality and thereby maximize the returns by enhancing milk quality to better meet the requirements of the milk sales contract.

There are reports that diets based on sugar beet pulp led to higher milk production and greater body weight loss in dairy cows, indicating that nutrient partition is strongly in favour of milk synthesis (Tyrrell *et al*., 1973; Lees *et al*., 1982). However, a subsequent study (Beever *et al*., 1988) was unable to confirm this finding, but the trial was confounded by differing energy intakes, and the energy balance was not measured until week 11 of lactation.

Research carried out at the Hannah Dairy Research Institute on substitution rates of forages has shown that the higher the digestibility of the forage, the higher the substitution rate. This is particularly the case with starchy supplements. Four silages with CP levels of 237, 182, 149 and 131 g/kg DM and DOMD of 770, 760, 690 and 600 g/kg DM respectively were fed with a supplement based on either barley or DMSBF. With the highest quality silage, DM intake using the DMSBF based supplement was 11% greater than the intake when the supplement was based on barley. With the other silages no significant differences were recorded (Anon., 1984).

In one series of trials with starchy or fibrous concentrates, average daily silage DM intake was increased by 0.7–1.0 kg when concentrates included sugar beet feed (Thomas *et al*., 1984), whereas, in a separate comparison, there were no differences in silage DM intakes between dairy cows fed 10 kg concentrate based on barley and those based on sugar beet feed (Mayne & Gordon, 1984). Nevertheless, on balance, fibrous concentrates and DMSBF in particular do appear to increase the DM intake of forage in lactating dairy cows by approximately 0.7–1.0 kg/head/day. There is some evidence that this effect is most marked in early lactation (Beever *et al*., 1988).

The role that sugar beet pulp can play in rumen ‘conditioning’ has been discussed above.

It has further been suggested that a benefit of fibre-based concentrates is an improvement in hoof health. Anecdotal reports seem to confirm this, although few studies have been sufficiently long in duration to confirm this experimentally. In one of the few reported studies, Livesey *et al.* (2003) found no difference in hoof horn haemorrhages between heifers fed on concentrates containing 50% starch or beet pulp, although impaired hoof health is usually more prevalent in multiparious cows.

In conclusion, it is clear that DMSBF is a good feed for dairy cows. It can be included in the diet at levels up to 40% DM intake; in commercial practice levels of 10–20% of DM intake are more usual. Its inclusion often results in an increase in milk fat concentration and/or yield, and increased forage DM intake, although further research is required to determine whether its inclusion could lead to a significant reduction in lameness.

Calves

Traditionally, calves have been introduced to hay or other long forage at an early stage to encourage rumen development, but intake is generally low and highly variable, and growth rate varies proportionally. An alternative approach is required, and several experiments have demonstrated that the inclusion of roughage into a compound is beneficial (Thomas & Hicks, 1983; Williams *et al*., 1987).

The roughage that was incorporated was usually straw, and although good levels of intake were maintained, rumen pH values were higher and molar proportions of acetate and butyrate were increased while propionate levels were decreased (leading to more stable conditions within the rumen), performance in terms of liveweight gain was not improved. This was thought to be due to the decrease in net energy intake as a result of the inclusion of low-digestibility forage.

Another aspect of forage inclusion that has received little attention is the intestinal buffering promoted by the non-starch polysaccharide in the plant cell walls. Lucerne (alfalfa) has considerable buffering capacity, as has sugar beet pulp, which exhibits a substantial ability to exchange cations from the fibre matrix with H^+ ions produced during fermentation, resulting in a moderated rumen ecosystem (McBurney *et al.*, 1983).

In investigations of practical calf diets, Williams *et al.* (1987) demonstrated that by replacing varying amounts of rolled barley by sugar beet pulp and citrus pulp, DM intake was linearly increased ($P < 0.05$). In a later series of experiments, DM intake improved by as much as 0.3 kg/day when barley was replaced by DMSBF; liveweight gain was increased by 0.1 kg/day from 0.72 kg/head/day for cereal-based diets to 0.82 kg/head/day for DMSBF-based diets. The optimal range of DMSBF inclusion was 5–15% of the diet DM (Frost *et al.*, 1989).

Beef cattle

The feeding of DMSBF to beef cattle is a long-established practice. In intensive systems, the substitution of cereal by DMSBF generally leads to similar performance in terms of liveweight gain, although feed conversion efficiency is generally impaired at higher levels of DMSBF inclusion (Frost, 1989). The optimal range of DMSBF inclusion is around 15–25% of DM intake.

In semi-intensive systems, DMSBF and barley were compared as supplements to grass silage in the fattening phase of rearing beef steers. Similar performances were obtained when the supplements were fed at 4 kg/day, but DMSBF performance was poorer when the supplements were fed at only 2 kg/day. The inclusion of 200 g fishmeal at the lower level of concentrate supplementation led to similar performance with DMSBF and barley (Kay & Harland, 1988).

Sheep

Research with growing and fattening lambs has followed similar lines to that with beef cattle, although the findings are generally more positive with regard to the use of DMSBF in either intensive or forage-based systems.

In investigations of several combinations of DMSBF and barley in fattening lamb rations, a 25% substitution was optimal in terms of carcass yield and protein content (Galbraith *et al.*, 1989). At higher levels of inclusion (approximately 75%) the efficiency of converting dietary energy into carcass gain was poorer with DMSBF than with barley. This was attributed to heat production associated with carcass protein deposition being higher with DMSBF than with barley, possibly because of futile substrate cycles within the tissue (Scollan *et al.*, 1988), resulting in less energy being available for fat deposition (Emmans *et al.*, 1989). This finding may explain the positive response in performance when fishmeal was given to semi-intensive beef cattle fed DMSBF as a supplement to grass silage, as discussed above. Richardson *et al.* (2000) investigated the effect of providing lamb diets synchronous, in terms of hourly energy and protein supply provided from diets based on DMSBF or cereal. The lambs fed DMSBF-based diets retained more nitrogen, but resulted in a lower microbial protein synthesis. There was no benefit from providing dietary synchrony.

DMSBF appears to offer potential for manipulating carcass composition, but the mechanisms involved clearly require further investigation.

In forage-based systems, lambs have finished more efficiently when given a supplement of DMSBF than when given a cereal-based concentrate (Minter & Tempest, 1987). Similarly, the diet of pregnant and lactating ewes has been successfully supplemented with DMSBF (Dove *et al.*, 1985; Robinson, 1985).

There is no doubt that DMSBF can successfully comprise 15–40% of the DM intake of growing, finishing and breeding sheep. At higher levels there may be less efficient performance if protein levels are limiting.

Pigs

The ability of pigs to utilize fibrous feeds has received considerable attention recently. It is now apparent that pigs can use sugar beet pulp very efficiently. Similar or even better results have been recorded for pigs fed DMSBF (Longland *et al.*, 1987a,b; Bulman *et al.*, 1989; Kay *et al.*, 1990; Table 17.6).

Clearly the inclusion of 15–25% DMSBF in the diet of pigs from 15–90 kg liveweight leads to a performance similar to that from conventional cereal-based diets, in terms of liveweight gain and improved feed conversion efficiency. Leaner carcasses are produced, and there is some evidence of improved eating qualities of the meat as assessed by a taste panel.

For growing and fattening pigs, the optimal level of inclusion appears to be 15–20% of the feed DM (Table 17.6). For breeding sows, the DMSBF recommendations closely follow those given previously for plain sugar beet pulp, with good performance from levels of up to 40% of DM intake.

Other livestock

In investigations of lactating goat rations, concentrates based on either 70% DMSBF or 70% barley have been compared. No differences were recorded in total DM intake or milk yield, although the yields of milk fat and protein were marginally higher for the DMSBF-fed goats. However, none of the differences was significant and it was concluded that DMSBF and barley support similarly high levels of hay intake and milk production in dairy goats (Sutton & Mowlem, 1989).

For many years, a small quantity of soaked DMSBF was an accepted part of horse rations. During the mid-1980s, trials were carried out at Warwickshire Agricultural College; in the first series of trials, DMSBF at a level of 25% of the concentrate DM had no adverse effects on the horses' condition and ability to do work. In a second series of trials, DMSBF was used as a forage substitute, replacing hay on the basis of 1 kg DMSBF being equivalent 1.5 kg hay. The maximum intake of soaked DMSBF fed was 2.5 kg/day (dry weight), which was 25% of the total DM intake. Consumption of this large volume was very slow, and a more appropriate recommendation for practical purposes is 15% of DM intake (S. Pillner & J.I. Harland, 1987, unpublished observations).

The use of DMSBF in poultry diets is at present limited but, with this exception, the product is widely used in many sectors of livestock farming, as a highly palatable, recognized source of digestible fibre and energy.

Summaries of the recommended levels of inclusion are given in Table 17.7.

Table 17.6 Effect on liveweight gain and feed conversion efficiency (FCE) of feeding 10–25% dried molassed sugar beet feed to pigs.

Pig liveweight (kg)	Level of DMSBF	Liveweight gain compared with control (g)	FCE compared with control (kg)	FCE† significance	Reference
18–77.5	15	67	0.12	NS	Longland *et al.*, 1987a
18–77.5	15	7	–0.06	NS	Bulman *et al.*, 1989
15–35	15	30	–0.11	S	Kay *et al.*, 1990
35–90	15	8	0.1	NS	Kay *et al.*, 1990
35–90	20	34	0.26	S	Kay *et al.*, 1990
35–90	25	–2	0.13	NS	Kay *et al.*, 1990
7–15 *	15	–31	0.08	NS	Low *et al.*, 1990
7–15	10	24	0.04	NS	Edwards *et al.*, 1991
7–15	15	–20	–0.01	NS	Edwards *et al.*, 1991

* Unmolassed sugar beet, † S = significant, NS = not significant.

Table 17.7 Recommended inclusion rate of DMSBF in livestock rations (%).

Livestock	Inclusion of DMSBF in experimental diets	Commercial feeding rate
Pigs		
Growing pigs	10–20	5–10
Breeding sows	10–45	5–20
Poultry		
Poultry breeding and fattening	0–5	0–5
Cattle		
Dairy cows	10–50	10–20
Calves up to 3 months	5–25	5–15
Fattening cattle 3–18 months	15–30	15–30
Sheep		
Lactating ewes	10–40	10–40
Growing/fattening lambs	10–40	10–40
Goats		
Lactating and fattening	10–30	10–30
Horses		
Ponies, horses	5–20	5–15

Enhancement of silage

As long ago as 1975, the inclusion of DMSBF into herbage silage was recommended to capture silage effluent and improve the nutrient density (Dulphy & Demarquilly, 1975). This use of DMSBF was not exploited commercially for over a decade, but interest was renewed in the late 1980s, due largely to concern over the polluting properties of silage effluent and an increase in the number of farm pollution prosecutions. This was particularly the case in the UK and Eire, where low dry matter grass is frequently ensiled without wilting, resulting in a high effluent production.

Silage effluent is readily digestible by ruminant livestock and pigs and is a rich source of soluble nutrients, energy in the form of organic acids, and protein as simple nitrogenous compounds. It also contains significant quantities of minerals, the most important of which are calcium, phosphorus, potassium and magnesium. The use of DMSBF in clamps of grass silage helps to retain some of this valuable and nutritious feed.

Research carried out at British Sugar plc has shown that DMSBF absorbs up to three to four times its own weight as effluent. In these trials and others (Bastiman & Altman, 1985), the optimum level of DMSBF inclusion ranges from 15 kg/t of grass at 25% DM to 85 kg/t of grass at 15% DM.

The addition of DMSBF leads to stable fermentation, with the resulting silage usually being higher in DM and energy and lower in ammonia N and total CP content. The overall yield of silage is increased because of the reduced effluent losses and reduced fermentation losses. When silage produced in this way was fed to finishing beef cattle (predominantly Charolais cross weighing approximately 400 kg at the start of the experiments), liveweight gain was enhanced, compared with similar grass ensiled alone but fed with a loose supplement of DMSBF (Table 17.8). The higher level of liveweight gain was due partly to increased DM intake of silage and partly to improved efficiency of utilization of the diet (Jones & Jones, 1988; Hyslop *et al.*, 1989).

Further studies using DMSBF as an absorbent in forage maize silage (Bell *et al.*, 2000) have also indicated positive benefits in terms of silage quality and containment of effluent, as well as improved dairy cow performance when compared to grass silage alone or grass plus maize silage.

In the UK, the absorption and silage enhancing properties of DMSBF have been utilized in the development of Grainbeet. Grainbeet comprises the moist spent grains from breweries and DMSBF usually in the ratio of 5:1. The two ingredients are ensiled together and the resulting high-energy, high-protein moist feed is a versatile feed for all

Table 17.8 Liveweight gain and feed intake data of beef cattle fed silage with or without DMSBF incorporated.

	Control silage	Silage plus 50 kg/t DMSBF
Autumn cut silage		
Liveweight gain (LWG) (kg/day)	0.87	0.96
Silage DM intake (kg/day)	6.63	8.37
Net feed conversion (kg feed intake/kg LWG)	9.09	8.72
Spring cut silage		
Liveweight gain (LWG) (kg/day)	1.12	1.21
Silage DM intake (kg/day)	6.53	7.10
Net feed conversion (kg feed intake/kg LWG)	7.13	5.87

ruminants. It has been fed as a partial concentrate replacer for dairy cows, a forage extender when mixed with straw, as a complete finishing diet for beef animals and lambs and as a concentrate replacer for ewes (for further details see the Grainbeet Handbook, 1999).

BEET VINASSE

Beet vinasse or, as it is called in the UK, condensed molasses solubles, is not produced directly from the sugar beet crop but results when beet molasses has been fermented. As a consequence it contains only a small amount of sugar. The DM consists primarily of crude protein and ash. For a review of its feeding value and use in livestock rations see Haaskma and Vecchiettini (1988).

CONCLUDING REMARKS

Feeds produced from the various parts of the sugar beet crop are highly versatile and valuable sources of digestible fibre and energy, primarily for ruminant livestock but also for pigs, horses and a large range of other livestock and pets. Sugar beet leaves are primarily a source of protein and can supplement or replace other forages in the diet of ruminant livestock. Sugar beet root fibre is highly digestible and its composition – in broad terms a third cellulose, slightly more than a third hemi-cellulose and slightly less than a third pectin – give it unique properties that make it suitable for a wide range of both ruminant and non-ruminant animals.

With the increasing interest in the health-promoting properties of feeds, as opposed to their nutritional contribution, the role that sugar beet feed can play in promoting hoof health, a healthy digestive tract and producing foods from livestock with improved qualities requires further investigation.

REFERENCES

Andersson, I., Inger, K., Nilson, L. & Hans-Uno, J. (1980) Influence of feeding and other environmental factors on cell counts and quality of milk with special regard to the influence of sugar beet tops. *Report 78*. Department of Animal Husbandry, Swedish University of Agricultural Science, Uppsala, pp. 1–8.

Anon. (1984) Sugar supplements and high protein silages. In: *Hannah Research 1984*. Hannah Research Institute, Ayr, Scotland.

Bastiman, B. & Altman, J.F.B. (1985) Losses at various stages in silage making. *Research and Development in Agriculture* **2**, 19–25.

Beever, D.E., Sutton, J.D., Thomson, D.J., Napper, D.J. & Gale, D.L. (1988) Comparison of molassed and unmolassed sugar beet feed and barley as energy supplements on nutrient digestion and supply in silage fed cows. *Animal Production* **46**, 490.

Bell, J.F., Roberts, D.J. & Leach, K.A. (2000) The effect of feeding forage maize ensiled with sugar beet pulp (Pulp'n' Maize) to dairy cows. *Proceedings British Society of Animal Science Annual Meeting 2000*. Scarborough, p. 148.

Beveridge, R.A. & Leng, R.A. (1981) The effects of forage on rumen fluid volume and outflow in cattle given molasses based diets. *Tropical Animal Production* **6**, 5–10.

Boland, T.M., Keane, N., Callan, J.J., Quinn, P.J. & Crosby, T.F. (2004) The effect of molasses inclusion on the cleanliness and performance of early-weaned Texel lambs. *Proceedings British Society of Animal Science Annual Meeting 2004*. York, p. 102.

Boucque, C.V., Flems, L.O., Cottyn, B.G. & Buysse, F.X. (1984) Ensiled pressed sugar beet pulp or dried sugar beet pulp pellets as feed for beef bulls. *Revue de l'agriculture* **37**, 635–647.

Bulman, J.C., Longland, A.C., Low, A.G., Keal, H.D. & Harland, J.I. (1989) Intake and performance of growing pigs fed diets containing 0, 150, 300 or 450 kg molassed or plain sugar beet pulp. *Animal Production* **48**, 626.

Canh, T.T., Sutton, A.L., Aarnink, A.J., Verstegen, M.W., Schrama, J.W. & Bakker, G.C. (1998) Dietary carbohydrates alter the fecal composition and pH and the ammonia emission from slurry of growing pigs. *Journal of Animal Science* **76**, 1887–1895.

Castle, M.E. (1972) A comparative study of the feeding value of dried sugar beet pulp for milk production. *Journal of Agricultural Science, Cambridge* **78**, 371–377.

Castle, M.E., Drysdale, A.D. & Watson, J.N. (1966) The effect of feeding dried sugar beet pulp on the intake and production of dairy cows. *Journal of Dairy Research* **33**, 123–128.

Close, W.H., Pettigrew, J.E., Sharpe, C.E., Keal, H.D. & Harland, J.I. (1990) The metabolic effects of feeding diets containing sugar beet pulp to sows. *Animal Production* **50**, 559–560.

Craig, S.A. (2004) Betaine in human nutrition. *American Journal of Clinical Nutrition* **80**, 539–549.

Cuervo, C., Bushman, D.H. & Santos, E. (1972) The effect of deionization and drying of cane molasses and their laxative action in chickens. *Poultry Science* **51**, 821–824.

De Visser, H. & Tamminga, S. (1987) Influence of wet versus dry by product ingredients and addition of branched chain fatty acids and valerate to dairy cows. 1: Feed uptake, milk production and milk composition. *Netherlands Journal of Agricultural Science* **35**, 27–30.

Dove, H., Milne, J.A., Lamb, C.S., McCormack, H.A. & Spence, A.M. (1985) Effect of fibre in compound feeds on the performance of ruminants. In: Haresign, W. & Cole, D.J.A. (eds) *Recent Advances in Animal Nutrition*. Butterworth, London, pp. 113–129.

Dulphy, J.P. & Demarquilly, C. (1975) Inclusion of sugar beet pulp in grass silage: use by dairy cows. *Bulletin Technique, Centre de Recherches Zootechniques et Veterinaires de Theix* **22**, 45–52.

Edwards, S.A., Njotu, B.A. & Fowler, V.R. (1989) Evaluation of fibrous by product foods for the pregnant sow using antibiotic suppression to measure degree of fermentation. *Animal Production* **38**, 642.

Edwards, S.A., Taylor, A.G. & Harland, J.I. (1991) The inclusion of sugar-beet pulp in diets for early-weaned piglets. *Animal Production* **52**, 599–600.

Emmans, G.C., Cropper, M., Dingwall, W.S., Brown, H., Oldham, J.D. & Harland, J.I. (1989) Efficiencies of use of the metabolical energy front foods based on barley or sugar beet feed in immature sheep. *Animal Production* **48**, 634–635.

Ewing, W.N. (1997) *The FEEDS Directory – Vol 1*. Context Publications, Heather, England, pp. 102–103.

Ewing, W.R. (1963) *Poultry Nutrition*, 5th edn. Ray and Ewing Co., Pasadena, CA.

Fahmy, S.T.M., Lee, N.H. & Orskov, E.R. (1984) Digestion and utilisation of straw. 2: The effect of supplementing ammonia-treated straw with different nutrients. *Animal Production* **30**, 75–81.

Frost, A.I. (1989) The effect of dietary substrate on the stimulation of appetite and rumen function in young calves. PhD thesis, University of Aberdeen, Scotland.

Frost, A.I., Innes, G.M. & Williams, P.E.V. (1989) Effects of replacing rolled barley with either molassed sugar beet feed or lucerne meal in the complete diets for young calves. *Animal Production* **48**, 630.

Galbraith, H., Mandebvu, P., Thompson, K.J. & Franklin, M.K. (1989) Effects of diets differing in the proportion of sugar beet pulp and barley on growth, body composition and metabolism of entire male lambs. *Animal Production* **48**, 652.

Grainbeet Handbook (1999). Trident Feeds, PO Box 11, Oundle Road, Peterborough, UK, pp. 2–8.

Haaksma, J. (1988) Application and value of by products from the sugar and alcohol industry in animal nutrition. *Proceedings of the 29th British Sugar Technical Conference*. **3** (3), pp. 13–18.

Haaksma, J. & Vecchiettini, M. (1988) Beet vinasse a protein source in animal nutrition. In: *Proceedings of the 51st IIRB Congress*. Brussels, Belgium, pp. 315–332.

Harland, J.I. (1981a) Pressed pulp the feed for the eighties. *British Sugar Beet Review* **49** (1), 26–27.

Harland, J.I. (1981b) Pressed pulp the feed to put on pounds and save £s. *British Sugar Beet Review* **49** (3), 47–49.

Harland, J.I. (1988) The feeding value and future use of molasses. In: *Proceedings of the 51st IIRB Congress*. Brussels, Belgium, pp. 267–281.

Harland, J.I. (1989) Beta fibre: a positive route to lower cholesterol. In: *Proceedings of Food Ingredients Europe*. Porte de Versailles, Paris, pp. 204–205.

Harland, J.I. (1993) Beta Fibre: a case history. *International Journal of Food Sciences and Nutrition* **44** (1), S87–S96.

Hemingway, R.G., Parkins, J.J. & Fraser, J. (1986a) Sugar beet pulp products for dairy cows. *Animal Feed Science and Technology* **15**, 123–127.

Hemingway, R.G., Parkins, J.J. & Fraser, J. (1986b) A note on the effect of molasses inclusion in sugar beet pulp on the yield and composition of the milk of dairy cows. *Animal Production* **42**, 417–420.

Hristov, A.N. & Ropp, J.K. (2003) Effect of dietary carbohydrate composition and availability on utilization of ruminal ammonia nitrogen for milk protein synthesis in dairy cows. *Journal of Dairy Science* **86**, 2416–2427.

Humphries, D.J., Sutton, J.D., Cockman, D.M., Witt, M.W. & Beever, D.E. (2003) Pressed sugar beet pulp as an alternative fibre source for lactating dairy cows. *Proceedings British Society of Animal Science Annual Meeting 2003*. York, p. 9.

Hutitanen, P. (1988) The effects of barley, unmolassed sugar beet pulp and molasses supplements on organic matter, nitrogen and fibre digestion in the rumen of cattle given a silage diet. *Animal Feed Science and Technology* **20**, 259–278.

Hyslop, J.J. (2002) Voluntary feed intake, apparent digestibilities and nutritive values in ponies given *ad libitum* access to complete pelleted diets containing different levels of unmolassed sugar beet pulp. *Proceedings British Society of Animal Science Annual Meeting 2002*. York, p. 32.

Hyslop, J.J. (2003) Partitioning degradation of feeds between different segments of the equine digestive tract. *Proceed-*

ings British Society of Animal Science Occasional Meeting 2003, Emerging Equine Science, 15–16 September 2003. RAC, Cirencester, England, pp. 18–19.

Hyslop, J.J. & Cuddeford, D. (1999) Soaked unmolassed sugar beet pulp as a partial forage replacer in equine diets when ponies are offered grass hay *ad libitum*. *Proceedings British Society of Animal Science Annual Meeting 1999.* Scarborough, p. 140.

Hyslop, J.J., Offer, N.W. & Barber, G.D. (1989) Effect of ensilage method on storage, dry matter loss and feeding value of malt distillers grain (draff). *Animal Production* **48**, 664.

Jones, R. & Jones, D.I.H. (1988) Effect of incorporating molassed sugar beet in grass silage. *Proceedings of the 29th British Sugar Technical Conference.* **3** (4), pp. 7–30.

Kamphues, J., Dayen, M. & Meyer, H. (1983) Silage from pressed sugar beet pulp with different contents of molasses in the fattening of cattle. *Wirtschaftseigene Futter* **29**, 110–127.

Karalazos, A. & Swan, H. (1976) The nutritional value for sheep of molasses and condensed molasses solubles. *Animal Feed Science and Technology, 1977*, 2, 143–152.

Kay, R. & Harland, J.I. (1988) Fishmeal supplementation of sugar beet feed or barley based concentrates for finishing beef cattle fed grass silage diets. *Animal Production* **46**, 525.

Kay, R., Simmon, H. & Harland, J.I. (1990) The use of molassed sugar beet feed in growing pig diets and the effect of inclusion rate on subsequent performance. *Animal Production* **50**, 591.

Keshavarz, K., Dale, N.M. & Fuller, L.P. (1980) The use of non protein nitrogen compounds, sugar beet molasses and their combinations in growing chick and layer rations. *Poultry Science* **59**, 2492–2499.

Kreuzer, M., Hanneken, H., Wittmann, M., Gerdemann, M.M. & Machmuller, A. (2002) Effects of different fibre sources and fat addition on cholesterol and cholesterol-related lipids in blood serum, bile and body tissues of growing pigs. *Journal Animal Physiology and Animal Nutrition (Berl)* **86**, 57–73.

Lees, J.A., Garnsworthy, P.C. & Oldham, J.D. (1982) The response of dairy cows in early lactation to supplements of protein given with rations designed to promote different patterns of rumen fermentation. *British Society of Animal Production*, occasional publication **6**, 157–159.

Livesey, C.T., Metcalf, J.A. & Laven, R.A. (2003) Effect of concentrate composition and cubicle bedding on the development of hoof haemorrhages in Holstein heifers after calving. *Veterinary Record* **152**, 735–739.

Longland, A.C., Low, A.G., Keal, H.D. & Harland, J.I. (1987a) The digestibility of growing pig diets containing dried molassed or plain sugar beet pulp. *Proceedings of the Nutrition Society* 47, 103A.

Longland, A.C., Low, A.G., Keal, H.D. & Harland, J.I. (1987b) Dried molassed and plain sugar beet pulp in diets of growing pigs. *Proceedings of the Nutrition Society* 47, 102A.

Longland, A.C., Wood, J.D., Enser, M.B., Carruthers, J.C. & Keal, H.D. (1991) Effects of growing pig diets containing 0, 150, 300 and 450 g molassed sugar-beet feed per kg on carcass and eating quality. *Animal Production* **52**, 559–560.

Longland, A.C., Low, A.G., Quelch, D.B. & Bray, S.P. (1993) Adaptation to the digestion of non-starch polysaccharide in growing pigs fed on cereal or semi-purified basal diets. *British Journal of Nutrition* **70**, 557–566.

Low, A.G., Carruthers, J.C., Longland, A.C. & Harland, J.I. (1990) Performance and digestibility of non starch polysaccharides in cereals or sugar beet pulp in pigs of 3–8 weeks. *Animal Production* **50**, 589.

MAFF (1986) Ministry of Agriculture, Fisheries and Food Standing Committee on Tables of Feed Composition. *Feed Composition.* Chalcombe Publications, Marlow, Bucks., pp. 40–48.

Maynard, E.J. & Knaus, K.D. (1959) *Beets & Meat*, 3rd edn. (revised).

Mayne, C.S. & Gordon, F.J. (1984) The effect of type of concentrate and level of concentrate feeding on milk production. *Animal Production* **39**, 65–76.

McBurney, M.I., Van Soest, P.J. & Chase, L.E. (1983) Cation exchange capacity and buffering capacity. *Journal of the Science of Food and Agriculture* **34**, 910–916.

Mertens, D.R.(1997) Creating a system for meeting the fiber requirements of dairy cows. *Journal of Dairy Science* **80**, 1463–1481.

Minter, C.M. & Tempest, W.M. (1987) Supplementation of silage for finishing lambs. *Animal Production* **44**, 483.

Morgan, L.M., Tredger, J.A., Williams, C.A. & Marks, V. (1988) Effects of sugar beet fibre on glucose tolerance and circulating cholesterol levels. *Proceedings of the Nutrition Society* 47, 185A.

Morrison, F.B. (1936) *Feeds and Feeding.* Morrison Publishing, New York, pp. 394–399.

Newbold, C.J., Thomas, P.C. & Chamberlain, D.G. (1988) Effect of dietary supplements of sodium bicarbonate on the utilisation of nitrogen in the rumen of sheep receiving a silage based diet. *Journal of Agricultural Science, Cambridge* **110**, 383–386.

Newbold, C.J., Thomas, P.C. & Chamberlain, D.G. (1989) A note on the effects of the method of inclusion of sodium bicarbonate and diet composition on the intake of diet based on silage by dairy cows. *Animal Production* **48**, 611–615.

Nuttall, M. (1981) *Feeding pressed pulp to beet cattle.* Publication 81/10 Norfolk Agricultural Station, Morley, Norfolk.

Nuttall, M. & Stevens, D.B. (1983) Beef cattle, the production of sugar beet top silage and its use in a finishing ration 1975–1980. In: *Norfolk Agricultural Station, 75th Annual Report.* pp. 45–55.

Phipps, R.H., Jones, A.K., Beever, D.E. & Witt, M.W. (2003) Effect of the incremental replacement of cereal grain with sugar beet feed on lactational performance of high yielding cows offered maize-silage based diets. *Proceedings British Society of Animal Science Annual Meeting 2003.* York, p. 128.

Richardson, J.M., Sinclair, L.A. & Wilkinson, R.G. (2000) The effects of sequence feed allocation within the day on microbial protein production and diet digestibility in lambs fed barley or sugar beet based diets. *Proceedings British Society of Animal Science Annual Meeting 2000.* Scarborough, p. 96.

Robinson, J.J. (1985) Energy and nitrogen in the feeding of the lactating ewe. In: *Proceedings of the 36th Annual Meeting of the European Association of Animal Production*, NS2.1. pp. 1–2.

Ruiz, N.I., Klee, G.G. & Fuentes, V.R. (1980) Fattening of bullocks on diets based on high levels of sugar beet molasses. *Agricultura Technica* **40**, 85–94.

Scollan, N.D., Brisbane, J.R. & Jessop, N. (1988) Effect of diet and level of intake on the activities of acetyl CoA synthetase and acetyl CoA hydrolase in ovine adipose tissue. *Proceedings of the Nutrition Society* 47, 168A.

Silva, A.T. & Orskov, E.R. (1985) Effect of unmolassed sugar beet pulp on the rate of straw degradation in the rumen of sheep given barley. *Proceedings of the Nutrition Society* 44, 8A.

Smits, B. & Haaksma, J. (1980) The digestibility and feeding value of beet leaf silage for pigs. *Report IVVO* **35**, 12.

Smits, B. & Sebek, L.B.J. (1987) The nutritive value of pressed pulp silage for growing pigs and breeding sows. *Report IVVO* **183**, 1–53.

Steg, A. & Van der Meer, J.M. (1985) Differences in chemical composition and digestibility of beet molasses. *Animal Feed Science and Technology* **13**, 83–91.

Steg, A., Van der Honing, Y. & De Visser, H. (1985) Effect of fibre in compound feeds on the performance of ruminants. In: Haresign, W. & Cole, D.J.A. (eds) *Recent Advances in Animal Nutrition*. Butterworth, London, pp. 113–129.

Stern, M.D. & Metwally, H.M. (1990) *Nutritive Value of Sugar Beet Pulp for Ruminants*, University of Minnesota.

Sunvold, G.D., Fahey, Jr. G.C., Merchen, N.R., Titgemeyer, E.C., Bourquin, L.D., Bauer, L.L. & Reinhart, G.A. (1995) Dietary fiber for dogs: IV. In vitro fermentation of selected fiber sources by dog fecal inoculum and in vivo digestion and metabolism of fiber-supplemented diets. *Journal of Animal Science* **73**, 1099–1109.

Sutton, J.D. & Mowlem, A. (1989) A comparison of barley and molassed sugar beet feed for Saanen goats in early lactation. *Animal Production* **48**, 653.

Sutton, J.D., Bines, J.A., Napper, D.J. & Morant, S.V. (1985) Starch:fibre ratio of concentrates of dairy cows. *Animal Production* **44**, 469.

Sutton, J.D., Daley, S.R., Haines, M.J. & Thomson, D.J. (1988) Comparison of dried molassed and unmolassed sugar beet feed and barley at two protein levels for milk production in early lactation. *Animal Production* **40**, 533.

Theriez, M. & Brun, J.P. (1983) Utilisation of dehydrated pulp by fattening lambs. *Bulletin Technique, Centre de Recherches Zootechniques et Veterinaires de Theix* **54**, 27–30.

Thomas, C., Aston, K., Daley, S.R., Hughes, P.M. & Bass, J. (1984) The effect of composition of concentrate on the voluntary intake of silage and milk output. *Animal Production* **38**, 519.

Thomas, D.B. & Hicks, C.-E. (1983) A note on the optimum level of roughage inclusion in the diet of the early weaned calf. *Animal Production* **36**, 299–301.

Tyrrell, H.F., Moe, P.W. & Bull, L.S. (1973) Energy value of cracked corn and dried beet pulp fed to Holstein cows. *Journal of Dairy Science* **56**, 1384.

Waldrup, P.W. (1981) Use of molasses and sugars in poultry feeds. *World Poultry Science Journal* **37**, 193–202.

Williams, P.E.V., Fallon, R.J., Innes, G.M. & Garthwaite, P. (1987) Effects on food intake rumen development and liveweight of calves of replacing barley with sugar beet citrus pulp in a starter diet. *Animal Production* **43**, 367–375.

Yany, Y.K. & Lee, P.K. (1982) Effect of cane molasses and glutamate fermentation and liquor as feed ingredient and feed efficiency of growing fattening pigs. *Journal of Taiwan Livestock Research* **15**, 9–16.

Zervas, S. & Zijlstra, R.T. (2002) Effects of dietary protein and fermentable fiber on nitrogen excretion patterns and plasma urea in grower pigs. *Journal of Animal Science* **80**, 3247–3256.

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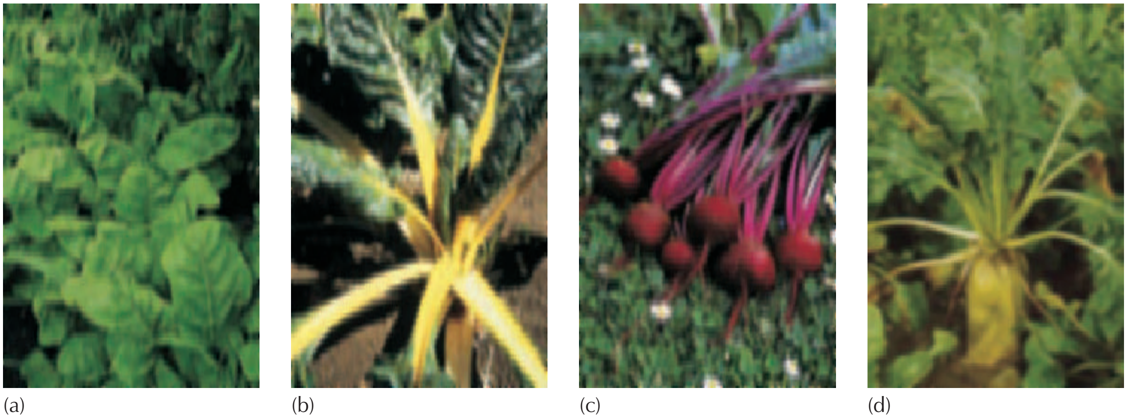

(a) (b) (c) (d)


(e)

Plate 1 Diversity of crops within *Beta vulgaris* ssp. *vulgaris*: (a) Spinach (or leaf) beet. The leaves are eaten boiled as a vegetable. (b) Swiss chard. The petioles and mid-ribs eaten boiled as a vegetable. Other chard cultivars are also available with red, orange or purple petioles, sometimes grown purely as garden ornamentals. (c) Garden beet (beetroot or red beet). The roots are eaten as a salad vegetable. Most have globe-shaped roots, others have flattened or tapering roots, some novelty orange and white-rooted forms are grown in gardens. (d) Fodder beet showing root protruding above soil level. This is used purely as animal feed. (e) Sugar beet, of which the roots are used for sugar extraction and the tops are used as stock feed in some situations. Plates (a) to (c) © S. E. Marshall & Co. Ltd.

Plate 2 Wild sea beet *Beta vulgaris* ssp. *maritima* growing in its natural habitat, here along the strand-line of a salt marsh on the north Norfolk coast (UK). © Sally Francis.

Plate 3 Leaf number 24 from plots without (left) and with (right) nitrogen fertilizer. Deficiency causes uniform yellowing, no green veining and much reduction in size.

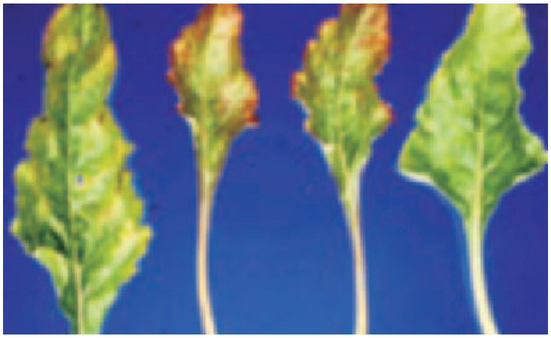


Plate 4 Leaves of plants from plots given no phosphorus fertilizer for many years. Typical purple coloration – not to be confused with herbicide toxicities.

Plate 5 Mature leaf showing potassium deficiency with brown necrosis around the margins and chlorotic lobes between the veins.

Plate 6 Unmistakeable pale yellow chlorosis and black necrosis caused by magnesium deficiency on the maturing crop.

Plate 7 Calcium deficiency causing hooding and blackening of leaves of all ages.

Plate 8 A sight as yet rarely seen – sulphur deficiency in a field-grown crop.

Plate 9 Symptoms of boron deficiency not surprisingly known as 'heart-rot'.

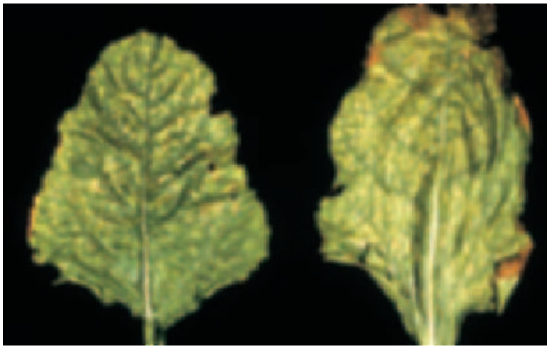


Plate 10 Unique symptoms of manganese deficiency causing yellow spotting followed by translucent necrosis.

Plate 11 Iron deficiency symptoms which appear sporadically on a few plants scattered amongst many without any symptoms.

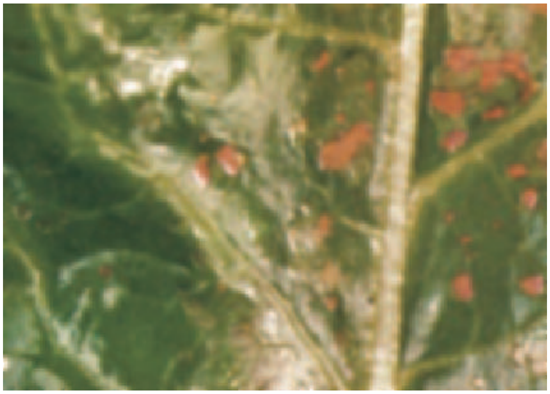


Plate 12 Zinc deficiency induced in sand culture, rarely seen in the field.

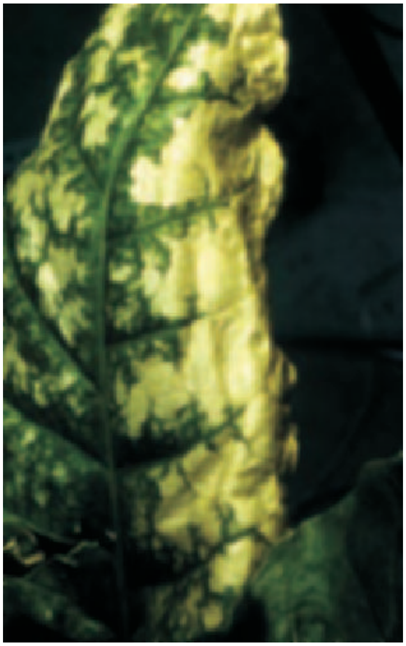


Plate 13 Copper deficiency on a mature leaf.

Plate 14 Field symptoms of rhizomania in a non-tolerant variety in the UK.

Plate 15 Severe attack of rhizomania in Alsace, France at the end of July, in a non-tolerant variety.

(a) (b)

Plate 16 (a) Longitudinal section of a sugar beet taproot infected with *Beet necrotic yellow vein virus*. (b) Detail of necrosis and tumour-like symptoms on the root.

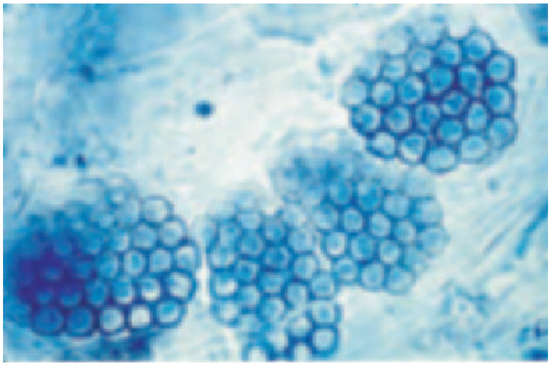


Plate 17 Resting spores of *Polymyxa betae*, the vector of *Beet necrotic yellow vein virus*.

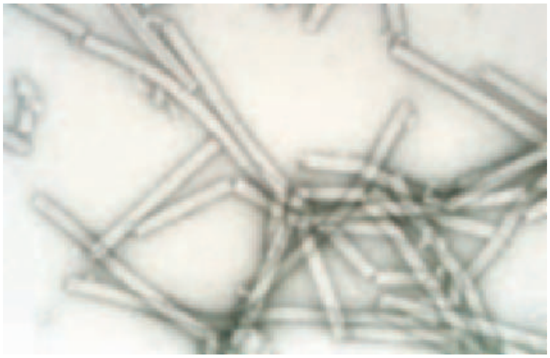


Plate 18 Particles of *Beet necrotic yellow vein virus* observed under the electron microscope.

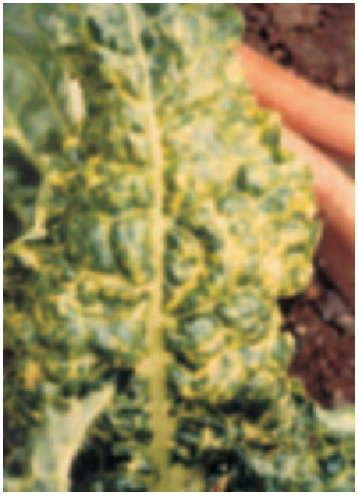


Plate 19 Yellow vein leaf symptoms of the *Beet necrotic yellow vein virus* P-type on a systemically infected sugar beet from the Pithiviers region (France).

Plate 20 Symptoms of *Beet soil-borne mosaic virus*: slight leaf distortion, light green or yellow blotches, faint overall mottling, and light yellow vein banding.

Plate 21 Symptoms of *Beet oak-leaf virus*: 'watermark' oak-leaf patterns on leaf.

Plate 24 Symptoms of *Beet mild yellowing virus* (left) and *Beet chlorosis virus* (right).

Plate 22 Symptoms of *Beet distortion mosaic virus*: leaf distortion, mottling, and roughened light green areas.

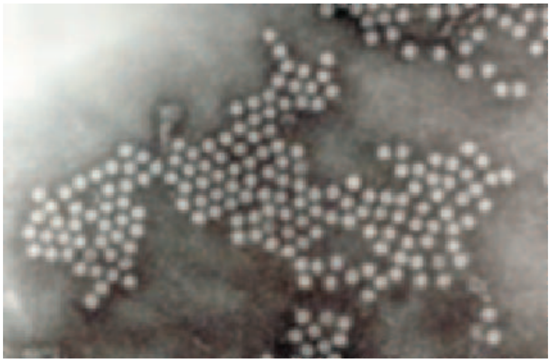


Plate 25 Particles of *Beet mild yellowing virus*.

Plate 23 Aerial view of sugar beet field infected with virus yellows.

Plate 26 Sugar beet breeding material showing resistance to *Beet mild yellowing virus* (right).

Plate 27 Symptoms of *Beet yellows virus*.

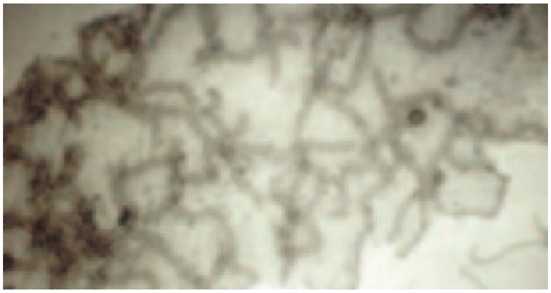


Plate 28 Particles of *Beet yellows virus*.

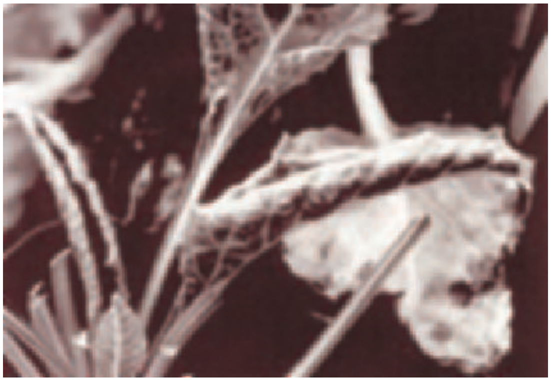


Plate 29 Symptoms of *Beet curly top virus*: dwarfing, crinkling, and leaf rolling.

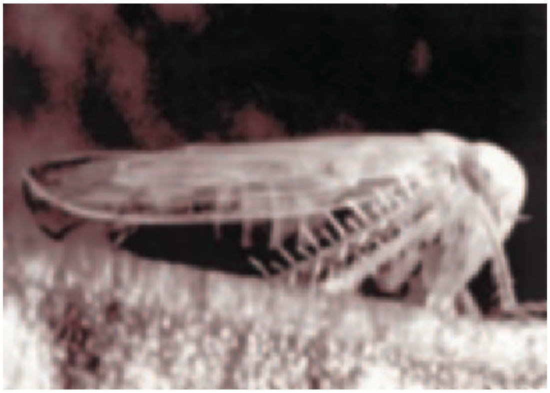


Plate 30 The beet leafhopper, *Circulifer tenellus*.

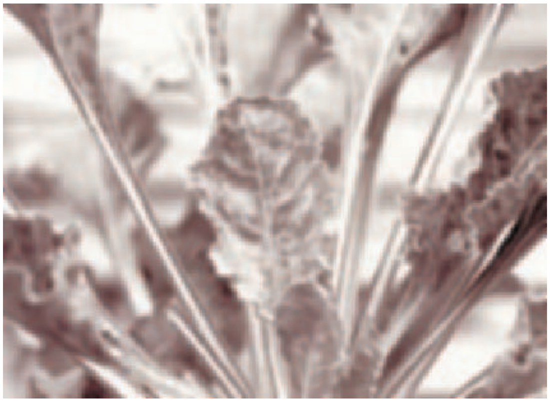


Plate 31 Symptoms of *Beet mosaic virus*.

Plate 32 Symptoms of *Beet yellow net virus*: chlorosis of the veinlet network.

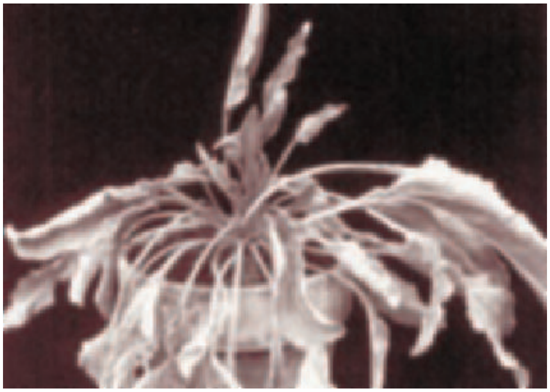


Plate 33 Symptoms of *Beet yellow stunt virus*: twisting and stunting of leaves.

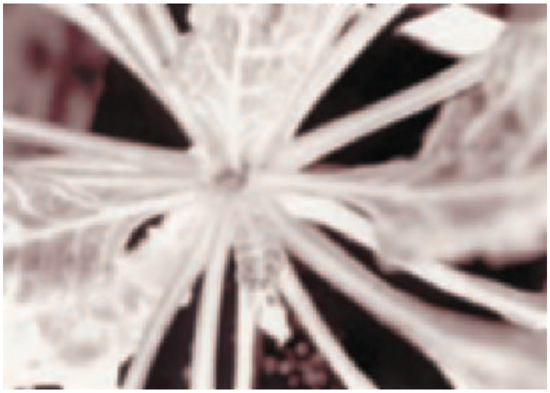


Plate 34 Symptoms of *Beet yellow vein virus*: dwarfing and vein yellowing on young leaves.

Plate 35 The sweet potato whitefly, *Bemisia tabaci*.

Plate 36 Symptoms of *Lettuce infectious yellows virus*.

Plate 37 Seedlings attacked by *Aphanomyces cochlioides*.

Plate 38 Seedlings infected with *Pythium ultimum*.

Plate 39 Lateral root proliferation caused by *Rhizoctonia solani*.

Plate 40 Symptoms of cercospora leaf spot.

Plate 41 Powdery mildew (*Erysiphe betae*) infection.

Plate 42 Younger leaves exhibiting symptoms of downy mildew (*Peronospora farinosa* f. sp. *betae*).

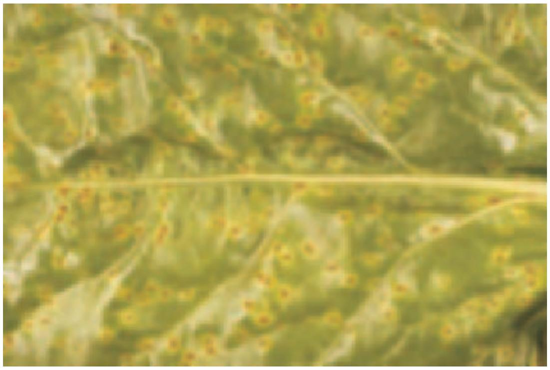


Plate 43 Rust (*Uromyces beticola*) pustules surrounded by yellow haloes.

Plate 44 Beet rust (*Uromyces beticola*).

Plate 45 Ramularia leaf spot (*Ramularia beticola*).

Plate 46 Foliar lesions caused by *Phoma betae*.

Plate 47 Alternaria leaf spot (*Alternaria alternata*) on leaves infected with virus yellows.

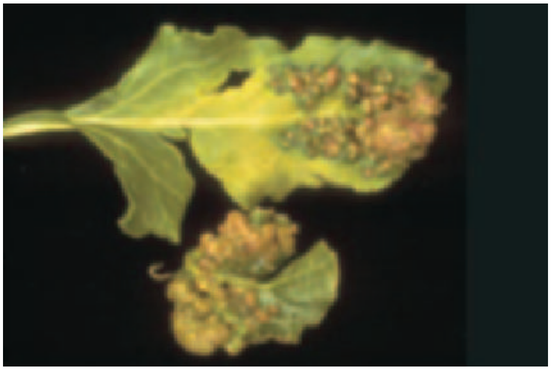


Plate 48 Beet tumour galls produced by *Urophlyctis leproides* (courtesy E. G. Ruppel, USDA-ARS, USA).

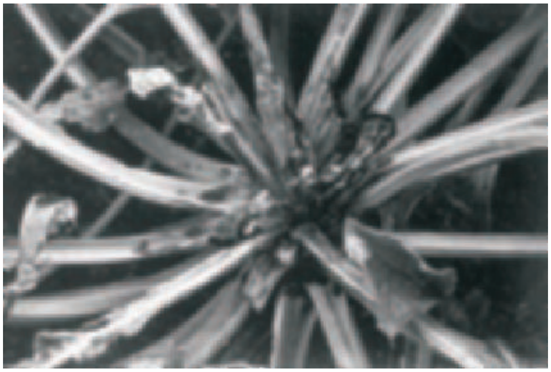


Plate 49 Rhizoctonia foliar blight caused by *Rhizoctonia solani* (courtesy E. G. Ruppel, USDA-ARS, USA).

Plate 50 Root rot caused by *Aphanomyces cochlioides* (courtesy E. G. Ruppel, USDA-ARS, USA).

Plate 51 Rosette of dead leaves associated with rhizoctonia root rot.

Plate 52 Black rot and cracking caused by *Rhizoctonia solani*.

Plate 53 Violet root rot (*Rhizoctonia crocorum*).

Plate 54 Phymatotrichum root rot: root colonized by *Phymatotrichum omnivorum* (courtesy W. Bugbee, USDA-ARS, USA).

Plate 55 Tip rot caused by *Rhizopus* sp. under conditions of excessive moisture (courtesy E. G. Ruppel, USDA-ARS, USA).

Plate 56 Southern sclerotium rot: roots attacked by *Sclerotium rolfsii* (courtesy J. Ayala Garcia, AIMCRA, Spain).

Plate 57 Root crowns invaded by *Fusarium culmorum* following severe wilting.

Plate 58 Fusarium yellows: interveinal foliar yellowing caused by root infection with *Fusarium oxysporum* f. sp. *betae*.

Plate 59 Chlorosis of one-half of the leaf lamina; a typical symptom of wilt caused by *Verticillium* spp. (courtesy B. Holtschulte, KWS, Germany).

Plate 60 Necrotic vascular tissue colonised by *Erwinia carotovora* ssp *betavasculorum*.

Plate 61 Bacterial leaf spot caused by *Pseudomonas syringae* pv. *aptata*.

Plate 62 Crown gall developing on root infected with *Agrobacterium tumefaciens*.

Plate 63 Common scab (*Streptomyces scabies*).

Plate 64 Symptoms of yellow wilt caused by an aphid-transmitted, rickettsia-like organism.

Plate 65 Discoloration of vascular tissues symptomatic of the planthopper transmitted Basses Richesses (low sugar syndrome).

Plate 66 Damage to sugar beet seedlings by stubby root nematodes (*Trichodorus* spp. and *Paratrichodorus* spp.).

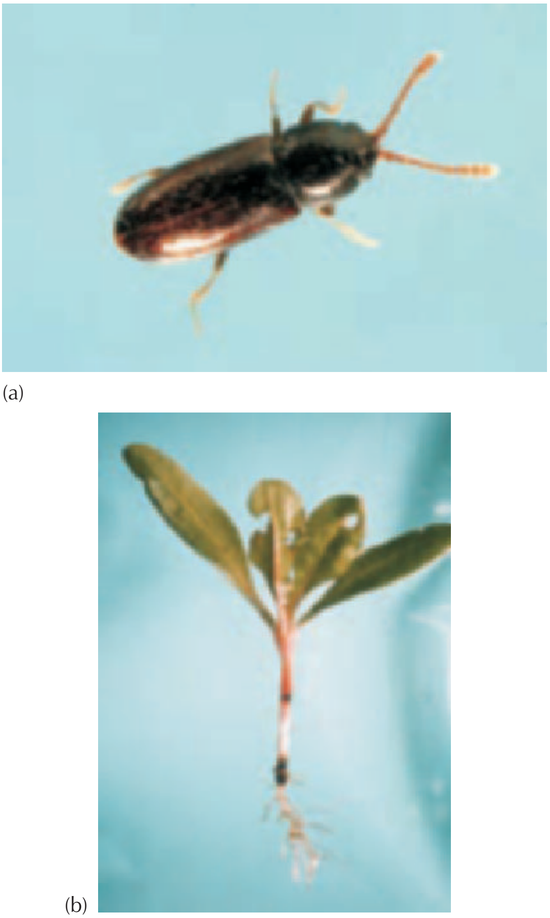


Plate 67 Pygmy beetle (*Atomaria linearis*) (a) and damage to sugar beet seedling (b).

Plate 68 Damage to sugar beet seedling by wireworms (*Agriotes* spp.).

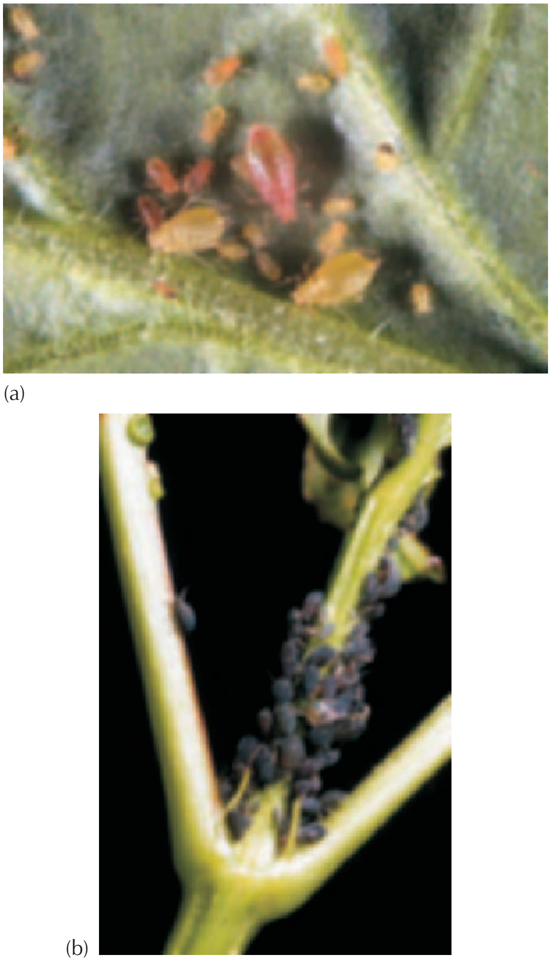


Plate 69 Aphids on sugar beet; the peach-potato aphid (*Myzus persicae*) (a); the black bean aphid (*Aphis fabae*) (b).

Plate 70 Capsid (*Lygocoris pabulinus*) feeding on sugar beet petiole.

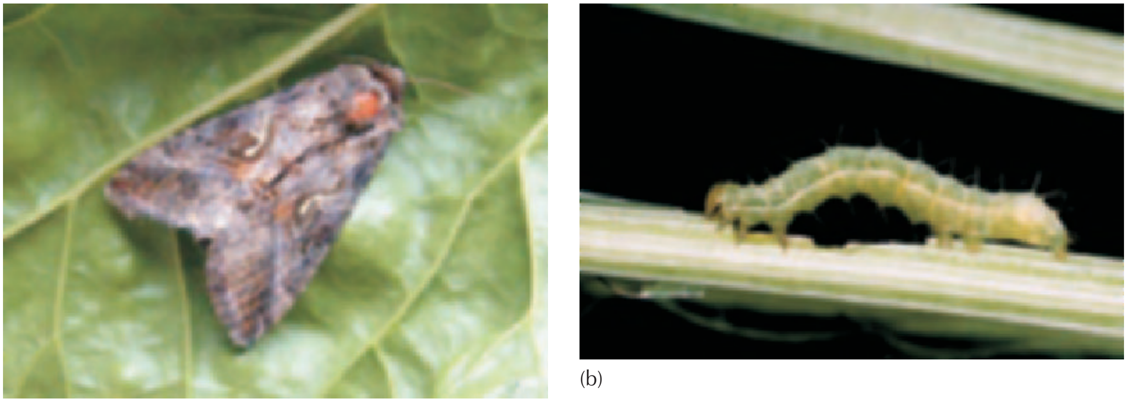
(a)

(b)

(c)

(d)

Plate 71 Beet fly (*Pegomya hyoscyami*) adult (a), eggs (b), and larva (c); the characteristic damage to leaves (d) caused by the feeding activity of the leaf-mining larvae.



(a)

(b)

Plate 72 Silver Y moth (*Autographa gamma*) adult (a) and larva (b).

(a)

(b)

Plate 73 Two-spotted spider mite (*Tetranychus urticae*) adult (a) and the damage caused by a severe infestation (b).

(a)

(b)

(c)

Plate 74 Beneficial insects. Several species of insects are predators of sugar beet pests (particularly aphids) and can effectively reduce pest populations. Some of the more important of these predators are ladybirds (a, seen with an apterous *Myzus persicae*), lacewings, adult (b) and larva (c) and hoverfly larvae (d).

(d)

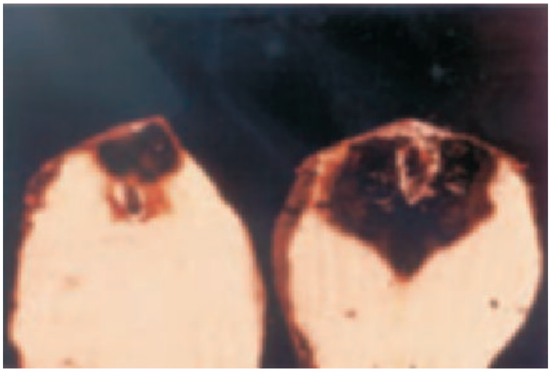


Plate 75 Storage rot caused by *Phoma betae* indicating its typical progression downward from crown (W. M. Bugbee).

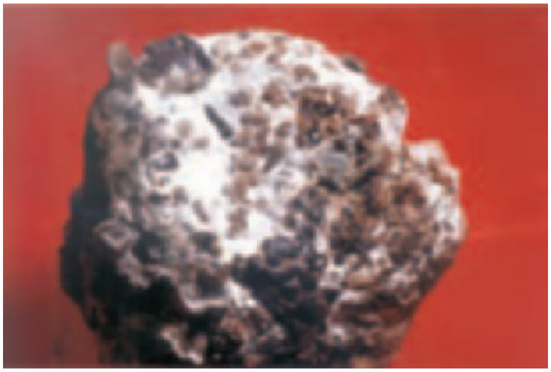


Plate 76 Round brown to black, hard masses of fungal growth on root surface, characteristic of storage rot caused by *Botrytis cinerea* (W. M. Bugbee).

Plate 77 Rot caused by *Penicillium claviforme* illustrating unique columnar tufts (coremia) tipped with green spore masses (W. M. Bugbee).

Plate 78 Healthy sugar beet roots (J, above) and roots that have been frozen in the ground (G) with top section gumming (F) (reproduced with permission of the International Sugar Journal).

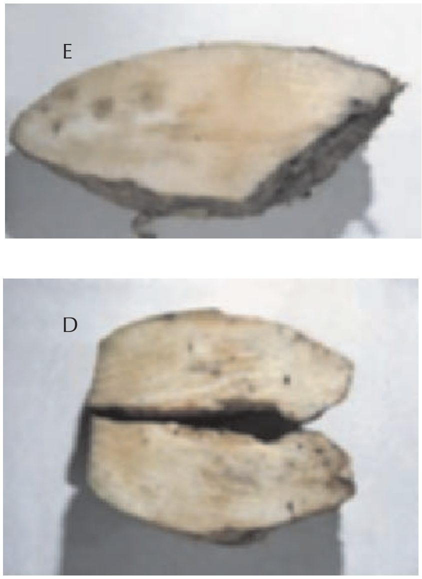


Plate 79 Sugar beet roots frozen after harvesting: gumming (E, above); thawed but not gumming (D, below) (reproduced with permission of the International Sugar Journal).