Primrose McConnell’s

The Agricultural Notebook

20th Edition

Edited by
Richard J. Soffe
Seale-Hayne
University of Plymouth
UK

Blackwell
Science
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This new edition takes *The Agricultural Notebook* into its third century. The first edition appeared in 1883. It was compiled by Primrose McConnell, a tenant farmer of Ongar Park Hall, Essex. As a student of Professor Wilson at Edinburgh University, he found ‘a great want of a book containing all the data associated with the business of farming’.

The editor is very grateful to the team that has contributed to the new edition; also to a wider group of colleagues and friends who have helped guide the content of this edition. The challenge of the changing rural scene is evident in the range of conferences currently on offer considering the future of rural areas. The editor must take a balanced view regarding which sections should be added, and which should be replaced. Thirty contributors across the rural spectrum from Scotland to Devon and Norfolk to Wales are included. We hope this reflects developments within the rural sector. New sections added include (1) a marketing perspective on diversification, (2) organic farming and (3) farming and wildlife.

Our primary aim has been to meet the needs of students studying a range of agricultural, food and rural subjects. We have received many useful comments from universities and schools across the world who have been using *The Agricultural Notebook* to teach geography and a host of related subjects – please keep in contact with us and send in your suggestions. We additionally hope it will be of value to farmers, landowners and advisors in their many roles.
Primrose McConnell: a brief biographical sketch

P.W. Brassley

‘I wish I had not been born for a hundred years to come, for there will be so many things found out after I am done with . . .’, wrote Primrose McConnell in the spring of 1906. It was typical of him: always fascinated by the latest discoveries and inventions, but concerned to test them against his own extensive knowledge and experience.

McConnell was born at Lesnessock Farm, near Ochiltree in Ayrshire, on 11 April 1856, the son and grandson of tenant farmers. After leaving Ayr Academy he was apprenticed to a Glasgow engineering firm, but subsequently, in the 1870s, went to the University of Edinburgh, which did not then offer degrees in agriculture but prepared students for the diploma examinations of the Highland and Agricultural Society. McConnell passed in 1878, and a little later also passed the certificate examinations of the Royal Agricultural Society of England. When Edinburgh eventually introduced a degree, he returned, and was the second student to be awarded the BSc in Agriculture in 1886.

The Notebook is his lasting memorial, but his writing was based on the foundation of his other activities, as farmer, scientist, engineer and inventor, traveller, lecturer and all-round man of agricultural affairs. Farming formed the foundation of his life. He first rented the 636-acre Ongar Park Hall Farm, about 20 miles from London, near Epping in Essex, initially in partnership with his father. When he began farming, half of the land was in arable, but this was in 1883, when cheap grain from the new world was beginning to make life difficult for corn producers on stiff London clays. He therefore grassed down about 200 acres and based his farming upon dairying (he had about 60 cows in milk at any one time) and feeding bullocks, heifers and sheep. In 1905 he moved. Why? ‘For the very good reason that I was losing more money than I could afford’, he wrote soon afterwards, ‘but also for various other reasons’, which in fact centred on a dispute with his landlord over how he was to be compensated for capital invested in buildings. The case went to court, and McConnell had the better of the legal arguments, but he was left with a jaundiced view of landlords. He was the owner-occupier of his new farm, North Wycke, 500 acres of land ‘as flat as a table’ near Southminster in Essex, between the Crouch and Blackwater estuaries, with ‘nothing higher than a tree or a house between me and the Ural Mountains’. When he began to farm there, it was half arable and half grass,
and he kept 80 cows, nine work horses, a pony, two dogs, three tomcats and ‘135 head of poultry of all breeds under the sun, including those that do not lay in winter’. He was understocked, he knew, but he was too short of capital to buy any more. He continued to farm there until he died in 1931.

McConnell farmed to make money, but not only to make money. Fascinated by the scientific and technical problems involved, he attempted to deal with them professionally, as befitted an agricultural graduate. He tried machine milking, found that it resulted in decreased yields, and so went back to hand milking. Then, after considering his experiences for a year or so, he wrote a detailed article for the Agricultural Gazette setting out the costs, technical details, yield changes and probable explanations, before concluding that ‘It is rather a dangerous thing to prophesy as to future inventions, and we do not know what mankind may accomplish in another generation. We may, therefore, still see a successful milking machine, but it has not arrived yet.’ He was an early advocate of milk recording and kept a Gerber fat testing machine in his dairy. He experimented with silage and he designed his own elevator. The string-binder, he thought, was the greatest invention of the nineteenth century. He had ‘an outfit of every possible kind of tool in my workshop on the farm that is likely to be of use’, and was ‘never . . . happier than when at the bench or vice’. When he wanted to try out a new plough, he would use it himself for a day, with a dynamometer between the horses and the plough. Not surprisingly, the shortcomings of farm machinery provoked some of his more vitriolic comments.

McConnell also led a busy life away from the farm. He lectured, at various times, at the Glasgow Veterinary College (where he was appointed Professor of Agriculture at the age of 24) and Oxford and Edinburgh universities and the Essex Winter School of Agriculture (the forerunner of Writtle College), and examined at Reading, Wye and the Royal Agricultural College. He was a Fellow of the Geological Society. He was on the Council of the Dairy Show and a milking judge there, and involved with the British Dairy Farmers’ Association and the Eastern Counties Co-operative Dairy Farmers’ Association. He visited farms in Holland in 1899 and made at least two trips to North America, in 1890 and 1893, on one occasion meeting some of the Sioux who had taken part in the Custer massacre in 1876. He was also one of the pioneers in the migration of farmers from Scotland to Essex in the late nineteenth century. No sooner had he found his farm at Ongar Park Hall than he was writing articles about the potential of Essex farms for the North British Agriculturist.

And it is as a writer that he is now best remembered. ‘I began to write to the farm papers at the age of eighteen, when first learning to hold the plough’, he recalled, and he produced eleven editions of the Notebook between 1883, when he was 27, and 1930, the year before his death at the age of 75. He also wrote The Elements of Farming (1896), an elementary textbook, The Elements of Agricultural Geology (1902), The Diary of a Working Farmer (1906) and The Complete Farmer (1908), in addition to articles in the journals of the Royal Agricultural Society of England and the Bath and West Society. Later he spent many years as dairy editor of the Agricultural Gazette and editor of Farm Life.

Thus he was academically successful, and he clearly enjoyed writing. But it is also evident from his diary that he enjoyed physical work too: he writes enthusiastically of making his own cheese, digging, ploughing and broadcasting, and stooking even though the sheaves are drawing blood from his forearms. He was a teetotaller and a dissenting churchman (his wife Katherine was the daughter of a Free Church minister) who took a five-day study tour with the British Dairy Farmers’ Association as his annual holidays. He took an unsentimental attitude to landscape: ‘in a level district you get a great wide sky, and the sun shines longer’. But if this suggests the stereotypical dour Scot, then his irascibility, his sense of humour and his benevolent interest in the world around him keep breaking through, as does his pride in his family, when he mentions that his daughter Ann is an accredited dairymaid, and prints a photograph of his sons Archibald and Primrose (who was to be killed in the last days of the First World War). Farming, and thinking and writing about farming, provided him with stimulation and satisfaction. Fortunately, there was always something new to learn: ‘Agriculture is a very wide subject, and no one can master it all within the limits of an ordinary lifetime’.

Sources

Most of the material used here is taken from McConnell’s The Diary of a Working Farmer (1906) and from his obituary, published in the [Essex] Weekly News of Friday, 10 July 1931. For the latter, an enormous amount of other biographical material on McConnell, and many perceptive editorial comments, the author is indebted to Elizabeth Sellers of Chelmsford.
Contributors

Paul Brassley, BSc (Hons), BLitt., PhD.

Present appointment: Senior Lecturer Agricultural Economics, Faculty of Land, Food and Leisure, Seale-Hayne, University of Plymouth.

After reading agriculture and agricultural economics at the University of Newcastle-upon-Tyne went on to research in agricultural history at Oxford. Since his appointment to his present post at Seale-Hayne has taught agricultural economics and policy and researched agricultural history from the seventeenth to the twentieth centuries.

Peter Brooks, BSc (Hons), PhD.

Present appointment: Professor of Animal Production and Head of Research, Faculty of Land, Food and Leisure, Seale-Hayne, University of Plymouth.

Obtained degree in Animal Production and PhD from Nottingham University. Was Head of Agriculture at Seale-Hayne College (subsequently University of Plymouth) for 18 years before becoming the faculty’s Head of Research. Has researched and published extensively on the production, behaviour, management and nutrition of pigs. Current research focussed on the development of liquid feeding systems for pigs.

Adam Carter, BSc (Hons), MSc.

Previously: Lecturer in Rural Resource Management, Faculty of Land, Food and Leisure, Seale-Hayne, University of Plymouth.

Graduated in Rural Environment Studies at Wye College, University of London, before completing an MSc in Forestry at the Oxford Forestry Institute, University of Oxford. Previous experience in British silviculture and forestry extension work in Northern Sudan with Voluntary Services Overseas. Current research interests in forest ecology, silviculture and medicinal uses of forest products.

Richard Coates, FRICS, MRAC.

Present appointments: Buildings officer to the Anglican Church Schools of Papua New Guinea
Was Sole Principal of Rural Design Consultancy, Lemprice Farm, Budleigh Salterton, Devon. (now rtd)

Chartered Building Surveyor and Land Agent with a special interest in design in the countryside – both in agricultural, construction and other rural building projects. Forty years’ experience in field including 18 years as Resident Building Surveyor to Clinton Devon Estates. Only designer to have won the coveted CLA Farm Buildings Award four times. Principal contributor of articles in Countryside Building, the journal of the Rural Design and Building Association (Chairman 2000–2001).

R.A. Cooper, CDA (Hons), NDA, MSc, PhD.

Present appointment: Principal Lecturer, Animal Production, Faculty of Land, Food and Leisure, Seale-Hayne, University of Plymouth.

Taught animal production at Shropshire Farm Institute before moving to University of Malawi as lecturer in animal husbandry and assistant farms director. Joined Seale-Hayne in 1974 following MSc at Reading University and completed PhD on interactions between growth promoters and reproductive physiology in ewe lambs in 1982. Main research interests in aspects of goat production, particularly in milking does, and in water intake studies.
John Eddison, BSc, PhD, CBiol, MIBiol.

Present appointment: Principal Lecturer, Applied Ethology, Faculty of Land, Food and Leisure, Seale-Hayne, University of Plymouth.

Graduated in Zoology from Leeds University and then conducted PhD research at Aberdeen University into the effect of environmental variation on ecological communities. Post-doctoral research followed at the Edinburgh School of Agriculture investigating the grazing behaviour and ecology of hill sheep. Took up his position in 1983 and now has a number of research projects on the behaviour and welfare of farm animals.

Tim Felton, LLb (Hons) of the Middle Temple, Barrister at Law.

Present appointment: Senior Lecturer, Law and Business Management, Faculty of Land, Food and Leisure, Seale-Hayne, University of Plymouth.

After reading law at Leeds University was called to the Bar of the Middle Temple. Following a period of legal practice he took up a career in practical farming and obtained a Diploma in Farm Management from Seale-Hayne. Prior to taking his present position he was share farming a mixed dairy, arable and beef farm at Tiverton, Devon of 185 hectares. Particular interests include access to the countryside and employment law issues in the rural environment.

David Fuller

Present appointment: Agriculture Colleges Liaison Officer, Royal Society for the Protection of Birds (RSPB), Sandy, Bedfordshire.

Has held the above post since its creation in 1997. Prior to working for the RSPB he spent over 33 years in the Ministry of Agriculture, Fisheries and Food (MAFF), administering many of the grant and subsidy schemes in East Anglia, Yorkshire and Lancashire. He also spent several years in Whitehall on policy work and in particular the development of the Environmentally Sensitive Areas (ESAs) scheme. He is a keen ornithologist and licenced bird ringer and carries out bird survey work on farmland in his local area of Norfolk.

Michael P. Fuller, BSc, PhD.

Present appointment: Reader in Crop Improvement and Acting Head of Department, Department of Agriculture and Food Studies, Faculty of Land, Food and Leisure, Seale-Hayne, University of Plymouth.

Graduated from Leicester University and then completed a PhD at the Welsh Plant Breeding Station, Aberystwyth (now IGER) on Frost Resistance in Grasses. Previous appointments: Leeds University and Sports Turf Research Institute; was visiting Professor to Angers University and is a Visiting Fellow of Exeter University. Current research interests include ice nucleation and resistance to frost; growth and development of cauliflowers and plant tissue culture.

Anita J. Jellings, BSc (Hons), PhD (Cantab).

Present appointment: Principal Lecturer, Faculty of Land, Food and Leisure, Seale-Hayne, University of Plymouth.

Read Applied Biology at the University of Bath and completed a PhD at the University of York investigating constraints on photosynthetic capacity. Current interests are centred on sustainable agricultural systems.

J.A. Kirk, BSc, PhD.

Present appointment: Principal Lecturer, Animal Production, Faculty of Land, Food and Leisure, Seale-Hayne, University of Plymouth.

Spent nine years farming before reading agriculture with agricultural economics at the University College of North Wales, Bangor. Postgraduate research on the growth and development of Welsh Mountain lambs led to a PhD. Current research interests are the growth and development of animals and the improvement of meat quality.

Nicolas H. Lampkin, BSc (Hons), PhD.

Present appointment: Senior lecturer, Agricultural Economics, Institute of Rural Studies, University of Wales, Aberystwyth.

Graduated in agricultural economics from University of Wales, Aberystwyth, followed by PhD research on the economics of conversion to organic farming. Subsequent research has focused on the financial performance of organic farming and the role of organic farming in the development of the Common Agricultural Policy. Currently co-ordinator of organic agriculture teaching and research at IRS and director of Organic Centre Wales. Author/editor of Organic Farming (Farming Press) and the Organic Farm Management Handbook (UWA/EFRC).

A. Langley, BSc, MSc, HNC (Building), ND AgrE, MIAgrE.

Present appointment: Lecturer, SAC, Edinburgh.
After two years involvement with potato cultivation investigations at the National Institute of Agricultural Engineering (Scottish Station), joined SAC in 1974 as a Mechanisation Adviser, covering all aspects of mechanisation and specialising in cultivations, irrigation and crop storage. Focused on lecturing from 1990 and covered a range of topics including crop storage and processing, field production equipment and waste management. Also involved in organising and co-ordinating national machinery field demonstrations.

Tony G. Marangos, BSc (Hons), PhD, CBiol, MIBiol, RNutr.

Present appointment: Principal, Nutrition Solutions, Consultant Nutritionist, Burnham House, Fairfield Road, Shawford, Winchester, Hampshire, SO21 2DA

Educated at Reading and London Universities where he gained a PhD. Since then has held senior technical (nutrition) and marketing positions in the animal feed and supply industry. In 2000, after 25 years, began his own independent nutrition consultancy, Nutrition Solutions, and now advises national and international organisations.

D.J. Mattey, MIagrE, MIOSH, MWeldI.

Present appointment: Consultant, International Labour Organisation (ILO) Training Centre (Turin); and The International Social Security Association (Geneva) Former HM Chief Inspector of Agriculture for HSE, and Regional Director (Midlands)

Robert E.L. Naylor, BSc (Hons), PhD, DSc, CBiol, FIBiol.

Present appointment: Partner in Trelareg Consultants specializing in crops and environment and Honorary Professor in Crop Science and Protection at the University of Aberdeen.

Spent 30 years at Aberdeen University teaching crop physiology, weed science, seed science and rural biodiversity and researching in specialist areas of these topics. On Board of Editors of Seed Science and Technology and Crop Protection. Senior Editor for Journal of Agricultural Science. Edited a new edition of the Weed Management Handbook for the British Crop Protection Council. Author of over 100 research papers and book chapters.

R.M. Orr, BSc, PhD, MIBiol.

Present appointment: Senior Lecturer, Faculty of Land, Food and Leisure, Scale-Hayne, University of Plymouth. Read agriculture with animal science at the University of Aberdeen. Postgraduate research at Edinburgh University on appetite regulation led to a PhD. Teaching and research interests include food quality and nutrition.

H.E. Palmer

Formerly Farm Woodland Consultant, Scottish Agricultural College

Graduated in Agriculture from the University of Reading and completed an MSc in Forestry and its relation to land use at the Oxford Forestry Institute, University of Oxford. Wide experience in temperate forestry and farm woodland management, and has worked as a woodlands adviser and consultant on farms and estates in Scotland for 12 years. Member of the Institute of Chartered Foresters.

Robert Parkinson, BSc (Hons), MSc, PhD, MILT.

Present appointment: Principal Lecturer, Soil Science, Faculty of Land, Food and Leisure, Scale-Hayne, University of Plymouth.

Studied at Leeds and Reading Universities before taking up a post as Research Officer at Birkbeck College, University of London, working on soil water dynamics and agricultural drainage. This research subsequently led to the award of PhD. Current research interests include nutrient management in agricultural systems, bio-waste recycling and composting, and soil/hydrological controls on the reconstruction of species-rich grassland.

John I. Portsmouth, NCP, NDP, DipPoult, NDR, FPH.

Present appointment: Managing Director, JP Enterprises, Consultant Nutritionist, Tremene, Maenporth Hill, Falmouth, Cornwall.

Began his own private consulting service in 1991 following some 30 years in animal nutrition and animal health industry. Author of several books and many technical articles on poultry nutrition and management. Specialist subjects are calcium metabolism in laying hens and micro-nutrient requirements of poultry. In 1988 given a distinguished service award for services in nutrition to the UK poultry industry.

David Sainsbury, MA, PhD, BSc, MRCVS, FRSH, CBiol, FIBiol.

After a period of research and lecturing at the Department of Veterinary Hygiene, Royal Veterinary College, London, until 1993 worked at the Department of Clinical Veterinary Medicine, University of Cambridge in the Division of Animal Health. Main interests have been concerned with the health and well-being of farm livestock especially under intensively managed conditions. Author of five textbooks and some 130 scientific papers.

R.W. Slee, MA, PhD, Dip Land Economy.

Present appointment: Senior Lecturer Rural Economics, Department of Agriculture, University of Aberdeen.

Before moving to Aberdeen in 1989, spent over 10 years as a lecturer at Seal-Hayne Faculty, University of Plymouth. Has written widely on rural economic change, including contributions to The Changing Countryside (eds J. Blunden and N. Curry, Croom Helm, 1985) and A Future for Our Countryside (eds J. Blunden and N. Curry, Blackwells, 1988) Author of Alternative Farm Enterprises (2nd edn, Farming Press, 1989). Current research interests include agrienvironmental policy questions and the economic impact of rural tourism.

Richard J. Soffe, MPhil, MCIM, M Inst M, ARAgS.

Present appointment: Senior Lecturer, Farm Business Management, Faculty of Land, Food and Leisure, Seale-Hayne, University of Plymouth.

Previous appointments have included a lectureship at Sparsholt College, Winchester, and assistant farm manager of a large estate in Hampshire. Research interests include rural leadership management and marketing. Course Director of the innovative and well respected Challenge of Rural Leadership at the University of Plymouth. He was co-editor of the eighteenth edition, editor of the nineteenth edition of The Agricultural Notebook and is editor of the current edition.

Mark A.H. Stone BA (Hons), MSc (Econ), MCIPD.

Present appointment: University of Plymouth Teaching Fellow and Principal Lecturer in People Management and Electronically Supported Open and Distance Learning.

After reading economics and politics at the University of Central Lancashire he went on to a masters degree in Employment Studies at University College Cardiff. He spent five years working in industry, during which time he achieved membership status within the Chartered Institute of Personnel and Development. He is involved in People Management and Information Technology teaching. He along with Dr Neil Witt formed the Communication and Learning Technology Group in 1997 to facilitate cross-faculty research and development in this area. He is currently leading an HEFCE TDTL Project into Student Progression and Transfer.

M.A. Varley, BSc, PhD, MIBiol, CBiol.

Present appointment: Lecturer, Department of Animal Physiology and Nutrition, University of Leeds.

Before his present position, spent 4 years as a lecturer in animal science at Seale-Hayne Faculty, University of Plymouth, and then moved to the Rowett Research Institute where he was a Senior Scientific officer for 6 years. Research interests include reproductive physiology of the sow, neonatal immunology and animal behaviour and welfare.

Martyn Warren, BSc, MSc, FIAgM, FRSA MILT.

Present appointment: Head of Land Use and Rural Management Department, Faculty of Land, Food and Leisure, Seale-Hayne, University of Plymouth.

Martyn Warren was educated at Newcastle and Reading Universities, and since 1994 has been Head of Land Use and Rural Management at the University of Plymouth, at its Seale-Hayne campus. He is author of Financial Management for Farmers and Rural Managers, in its 4th edition after nearly 20 years in print, and is Editor of Farm Management, the journal of the Institute of Agricultural Management. His main research interest is in the role of information and communication technologies in rural businesses and communities.

R.J. Wilkins, BSc, PhD, DSc, FIBiol, CBiol, FRAgrS.

Present appointment: Visiting Professor, Faculty of Land, Food and Leisure, Seale-Hayne, University of Plymouth; Visiting Professor, Department of Agriculture, University of Reading; Research Associate, Institute of Grassland and Environmental Research; Academician, Russian Academy of Agricultural Science.

After completing a PhD at University of New England, Australia, he was appointed to the Grassland Research Institute, Hurley, in 1966. Held a series of posts in that Institute and its successor, the Institute of Grassland and Environmental Research, until retirement in 2000 from positions including Institute Deputy Director, Head of the North Wyke Research Station, Devon, and Head of the Soils and Agroecology Department. Research interests include the production and utilisation of grassland and the environmental implications of grassland farming. Recipient of the RASE Research Medal and the British Grassland Society Award; President of British Grassland Society, 1986–7 and 1995–6.
Part 1

Crops
Introduction

Fertile soil is essential for sustained agricultural production, and has been exploited as a growing medium since animals and plants were domesticated. Cultivation of soils in order to create improved conditions for the sowing of crops can be dated back to at least 6000 BC (Goudie, 2000). Primitive farmers exploited the natural buildup of soil fertility by growing crops on land that was allowed to remain uncultivated for several years after the previous crop was harvested. The intensification that followed the enclosure of land and the adoption of sequential cropping patterns in rotation has ultimately lead to greater demands being placed on the soil to supply the needs of the growing crop and to allow machinery access over much of the cropping year.

Today, it is possible to grow some crops continuously on many soils, with the addition of fertilizers for plant nutrition and agrochemicals to control weeds, pests and diseases. Over the centuries, crop yields have increased dramatically, but our understanding of basic soil properties has not always increased proportionately. During the 1970s and 1980s evidence began to accumulate which indicated that soil fertility could decline under intensive agricultural use, mainly due to modifications of physical properties that had not previously been considered important. These changes were highlighted by the Houghton Report on The Sustainable Use of Soil (Cm 3165, 1996). Soil erosion and enhanced leaching losses of nutrients became more common on arable land, particularly under continuous winter cereal cropping. The challenge for farmers in the twenty-first century is to manage the soil to optimize yields while reducing unnecessary applications of fertilizers and other agrochemicals. Managing soil in a sustainable manner can only be done with a full appreciation of soil physical, chemical and biological properties. In this chapter the principles of soil management and crop nutrition are discussed.

Soil physical properties

Soil components

Soils are a complex mixture of mineral materials and organic matter that evolved over long periods of time, in some cases thousands of years, as a result of interactions between parent materials, soil organisms and climate. Analysis and understanding of the physical properties of soils and the way they respond when cultivated demands a detailed knowledge of the basic soil components, and how these components are arranged. A fertile soil will contain a mixture of mineral particles, organic matter and void spaces. These voids may be occupied by air or water. In Fig. 1.1 the proportion of these components is given for a well-managed topsoil. The properties of most agricultural soils are dominated by weathered mineral material. The primary components comprise the *texture* of a soil. Some soils, such as peats, are composed mostly of organic matter, in which case a texture description, based on the mineral fraction, is not appropriate. The combination of primary components with organic matter forms the *structure* of soils. In this section the agricultural significance of texture and structure will be described, followed by other important soil physical properties, most of which are controlled by texture or structure, and may be modified by agricultural practices.
Texture

Mineral particles in soil range widely in size from large stones to minute clay fragments. The proportion of various sized particles has a major impact on soil physical, chemical and biological properties. Hence the description and characterization of soil texture is of primary importance to farmers and growers. Texture determination can be carried out approximately, but rapidly, by hand texturing in the field, or quantitatively by laboratory analysis.

Field determination

Hand texturing is a rapid but relatively crude method of determining soil texture. A soil sample is moistened in the fingers and rubbed in order to break down any natural structures that exist. Coarse sand grains can be seen with the naked eye, and will make the sample feel ‘gritty’. Fine sand and silt feel smooth, and can make the sample ‘slippery’. Clay binds soils together, and imparts a sticky feel. A description of these different size components is given in Table 1.1. More detailed description of the determination of soil texture in the field can be found in Rowell (1994). Accurate hand texturing requires technical skill and years of practice. Care must be taken when hand texturing, as some organic matter fractions feel slippery or soapy, similar to silt-sized particles. Mineral soils with high organic matter levels can feel finer in texture than is actually the case.

Laboratory determination

Laboratory determination of texture or particle size distribution by a process known as mechanical analysis is time consuming and is only carried out when detailed information is required. The procedure is based upon sieving and sedimentation in water after thorough disaggregation. MAFF (1986) describes a three-phase process. Firstly, the soil sample is passed through a 2-mm sieve to remove stones. The analysis continues on the fine earth fraction that passes through the sieve. Secondly, the soil is dispersed using hydrogen peroxide (which destroys organic matter) and sodium hydroxide (which separates individual particles). Finally, the suspension of soil and water is passed through a series of sieves or a process of controlled sedimentation is carried out, so that the precise proportion of different sized mineral particles can be determined following dry weighing. The equivalent diameters of sand, silt and clay particles are shown in Table 1.1. This is the system employed in the UK (see Rowell, 1994); in other countries different size classes are used. The results of a particle size analysis can be plotted on a graph that has been subdivided into named texture classes (Fig. 1.2). A plot of percentage clay versus sand includes the silt component by difference, as the total must add up to 100%. For example, a soil containing 40% sand and 30% clay (and hence 30% silt) would be described as a clay loam. Having defined texture in a quantitative manner, it is possible to predict more accurately the behaviour of the soil in specific management situations.

Mineral materials

The mineral components of soils derive primarily from the underlying parent material. Hence the character of a soil will depend intimately on the type of rock from which the soil has been formed. In simple terms, soils composed of coarse particles derived from rocks such as

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Table 1.1 Range of particle size and properties for mineral components of soil

<table>
<thead>
<tr>
<th>Particle</th>
<th>Diameter (mm)</th>
<th>Characteristic properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravel or stones</td>
<td>&gt;2.0</td>
<td>—</td>
</tr>
<tr>
<td>Coarse sand</td>
<td>0.2–2.0</td>
<td>Coarse builder’s sand or beach sand, particles clearly visible</td>
</tr>
<tr>
<td>Fine sand</td>
<td>0.06–0.2</td>
<td>Egg timer sand, just visible with naked eye</td>
</tr>
<tr>
<td>Silt</td>
<td>0.002–0.06</td>
<td>Flour, visible with hand lens</td>
</tr>
<tr>
<td>Clay</td>
<td>&lt;0.002</td>
<td>Plasticine or putty, visible using electron microscope</td>
</tr>
</tbody>
</table>

---
sandstone and granite will produce coarse-textured, sandy soils. Mudstones and slates will produce fine-textured soils. The chemical character of a soil is also related to the size and origin of the mineral components. Sand and silt-sized particles tend to be dominated by only a few primary, rock-forming minerals, of which quartz (silicon dioxide) is the most common. Quartz is chemically unreactive, and therefore plays no part in nutrient retention by soils. In contrast, the clay fraction is dominated by clay minerals that have a varied chemical composition and can be chemically and physically very reactive. The potential for soil mineral particles to be physically and chemically reactive is partially explained by the increasing surface area with decreasing particle size. Table 1.2 shows the theoretical relationship between particle diameter and surface area. Clay minerals that have an expanding lattice structure, such as montmorillonite, exhibit large surface areas that allow water and nutrients to be retained, while sandy soils possess a small surface area and tend to be chemically inert. Silt is intermediate in behaviour, and does not have the large surface area possessed by clay, nor does it have the often beneficial properties attributed to sand (see next section for more details). In practice, soils are a mixture of all three mineral components, although one may dominate and hence control soil behaviour in the field.

**Texture and soil management**

Texture exerts a profound influence on soil management. Ultimately the choice and flexibility of cropping,
as well as potential yields, all depend on soil texture. Detailed knowledge of texture variations within and between fields can help farmers to manage soils and inputs such as fertilizers and manures effectively. The most important impacts of texture are given below. Many of these relationships are discussed further in other sections of this chapter, and in more detail by Davies et al. (1993).

Drainage status
Clay-rich soils retain water against gravity and therefore have high water contents during the winter months. At such a time a clay loam might hold 50–60% water, in comparison with a sandy loam which may hold only 25–30%. High water contents lead to reduced oxygen levels and poor plant growth as well as risk of soil damage by vehicles and livestock (see ‘Agricultural land drainage’ for more discussion of the consequences of poor drainage).

Water availability to plants
While finer textured soils retain more water than coarser soils, much of it is held so strongly (by capillary forces) that crop plants cannot extract the water. Consequently, silt soils tend to have the highest reserves of plant-available water, and are the most drought tolerant. Sandy soils tend to be very droughty due to the small volume of stored water.

Workability and trafficability
Access to land in the critical autumn and spring months can be controlled by soil texture. Sandy, well-drained soils have few access restrictions, making them suitable for the growth of a wide range of arable crops. Clay-textured soils are often difficult to cultivate, being too hard when dry and too soft when wet, and frequently cannot support the weight of agricultural machinery during the winter. Cultivation operations must be timed very carefully in order to minimize the risk of soil damage due to cultivation when too wet.

Nutrient retention
Clay-sized particles retain nutrients very effectively, while sandy soils are often described as ‘hungry’, that is nutrients need to be added frequently but in small doses in order to supply the requirements of crop plants (see ‘Nutrient retention – cation and anion exchange’ for further discussion).

Soil texture describes the fine earth fraction (particles <2 mm). Stones and gravel are therefore excluded from this discussion, but quite clearly the presence of significant proportions of stone-sized material can have a major influence on the growth of root crops and cultivation operations. Many of the glacially derived soils of northern Britain and the flinty chalk-derived soils of southern Britain contain significant quantities of stones that limit the choice of crops. No hard and fast rule can be given as to the amount of stones that will restrict crop choice or influence cultivations, as stone type and distribution are equally important. Soil organic matter can influence many of the properties listed above. High levels of organic matter can increase nutrient retention, increase water retention and make soils more workable (see ‘Soil organic matter and the carbon cycle’ for further discussion).

Structure
Formation of soil structure
As soils develop, mineral particles of sand, silt and clay are mixed with organic matter by soil organisms. This mixing process creates stable aggregates and hence the soil structures. Immature soils, such as might be found on a river flood plain or sand dune, tend to show little evidence of structure development, but most soils in agricultural use are well structured. Stable soil structure develops over long periods of time, as soils shrink and swell throughout the year, and as organic residues are combined with mineral particles, often through the action of soil organisms. A simplistic representation of soil structural components is given in Fig. 1.3, which helps to explain the important process of structure

Figure 1.3 Detailed representation of soil structure formation.
formation by the intermixing of soil mineral and organic components. Certain soil characteristics aid structure development, namely organic matter (most important), clay, calcium carbonate and iron oxide (least important). A well-structured soil will display fine, even-sized structures in the topsoil, with progressively larger aggregates in the lower horizons of the soil. Figure 1.4 shows several example soil profiles broken down into structure types.

**Importance of soil structure**

Well-structure soils display high porosity, low density, adequate water storage, free drainage and movement of air within the soil profile. Plant roots are able to exploit the whole soil volume, and will display a fine fibrous root system. The fine stable aggregates near the soil surface will be resistant to collapse and therefore will allow free passage of water and air through the surface layers. Roots will extract water and nutrients from within the aggregates, while excess water will drain away through gaps between the aggregates, resulting in no prolonged periods of waterlogging. The importance of structure cannot be underestimated in agricultural production systems, although assessment of soil structure is a difficult task. Experience can be gained by frequent field soil examination, particularly of soil profile pit faces that have been allowed to weather naturally for a few days, after which time natural structure patterns become more visible.

**Modification of soil structure**

Many agricultural practices modify soil structure and the stability of soil aggregates; the creation of a seedbed by ploughing and secondary cultivation, for example, is direct modification of soil structure designed to suit the needs of the seed to be sown. Unlike texture, structure is not permanent. Soil aggregate stability can be changed by the cultivation and intensive use of soils. Serious structure breakdown can lead to soil compaction and soil erosion. Many soils in the UK have suffered from problems relating to modification of structure by farming practices. The intensification of agricultural activity in the latter part of the twentieth century has lead to some deterioration of soil structure. Most notably, arable cropping has caused organic matter levels in some soils to decline, due to the removal of crop products, such as grain and straw. This reduction has become critical for many sandy soils that tend to have naturally low organic matter contents. Rates of organic matter decline are variable, but soils with organic matter levels of less than 5% are susceptible to compaction and soil erosion.

Tilth is the term applied to the finely structured surface soil that has been worked down by cultivation implements to create ideal conditions for the germination and growth of crops. Unfortunately the repeated cultivation of soils destroys natural, stable aggregates, resulting in weaker, finer structures that ultimately may

![Figure 1.4](Figure 1.4) Some examples of soil structure types under good and poor management (after Davies et al., 1993).
collapse, hence leading to deterioration in the soil physical environment. It is therefore important that soil is not overcultivated, particularly for autumn-sown crops where soils are exposed to the full force of the winter weather with minimal protection from a growing crop.

Soil structure can be improved by a number of agricultural practices: use of (long) grass leys in rotations, adding manures and other organic materials, adding lime, and the use of deep-rooting green manure crops. All these will help to stabilize the soil and maintain fertility.

**Soil density**

Figure 1.1 gave a typical breakdown of soil components for a well-structured topsoil, which is made up of 50% solids and 50% pore space. As the structural properties of a soil change under agricultural management, so will the density and pore space. As roots need to access water and air held in these pore spaces, an understanding of such changes is important.

**Bulk density**

Bulk density is defined as the mass of oven-dry soil per unit volume, and depends on the densities of the constituent soil particles and, most importantly, how these constituents are packed together. Bulk density is usually determined by extracting a soil core of known volume, oven drying at 105°C for 24 hours to remove the soil water and then weighing the core. Values of bulk density range widely, as shown in Table 1.3. In general, root access to soil pore spaces becomes difficult above a bulk density of 1.5–1.6 t m\(^{-3}\). Soil compaction results in an increase in bulk density. In Fig. 1.5 some example bulk density profiles are given for a soil that has suffered surface compaction due to excessive animal grazing (Profile B) and a soil that has been compacted at plough depth due to repeated cultivation when soil conditions were too wet, resulting in smearing and structure destruction (Profile C).

Under good management, bulk density will tend to reduce until an equilibrium value is reached for a given soil and cropping situation. Bulk density is simply an indication of the general status of the soil in physical terms – to understand the effect on crop plants, it is necessary to describe pore space changes associated with increases in bulk density.

Given bulk density, it is possible to calculate the mass of soil in a given area. For example, assuming a bulk density of 1.0 t m\(^{-3}\), 1 ha of soil down to plough depth (200 mm) will have a mass of 2000 t. This represents a considerable mass of material that is moved every time the soil is ploughed.

**Particle density**

It is necessary to know the density of mineral particles (or when unweathered, solid rock) in order to calculate the pore space in a soil. Particle density is defined as the mass per unit volume of mineral particles in soil, and does not include air spaces or water. Typical values for particle density range from 2.50–2.70 t m\(^{-3}\). For example, a 1 m\(^3\) solid granite block weighs approximately 2.65 t. A value of 2.65 t m\(^{-3}\) can be assumed for quartz-dominated mineral material in British soils. Organic matter weighs considerably less than mineral material; values of 1.20–1.50 t m\(^{-3}\) are common for organic material. Given this difference, it is important to state the

<table>
<thead>
<tr>
<th>Bulk density (t m(^{-3}))</th>
<th>Pore space (%)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5–0.8</td>
<td>&gt;70</td>
<td>Loose, uncompacted topsoils. Peats and organic soils</td>
</tr>
<tr>
<td>~1.0</td>
<td>60–65</td>
<td>Permanent pasture, woodland soils, well structured</td>
</tr>
<tr>
<td>~1.5</td>
<td>45</td>
<td>Compacted, root penetration difficult</td>
</tr>
<tr>
<td>~2.0</td>
<td>25</td>
<td>Dense, no root growth</td>
</tr>
</tbody>
</table>

Figure 1.5 Example bulk density profiles. A Uncompacted soil; B heavily grazed soil showing surface compaction; C cultivated soil showing compaction at plough depth.
organic matter content of a mineral soil when describing pore space of soils.

**Pore space**

The size, shape and arrangement of soil aggregates control not only the density but also the total porosity of a soil. When density changes as a result of soil management practices, porosity also changes. Total pore space is defined as the volume of pores expressed as a fraction of the total soil volume, and is usually determined by measuring the bulk density and assuming a particle density of 2.65 t m$^{-3}$. 

\[
% \text{Pore space} = \frac{1 - (\text{bulk density}/\text{particle density})}{1} \times 100
\]

For the example given in Fig. 1.1, the total pore space is 50%. By substitution into the equation above, this equates to a bulk density of 1.32 t m$^{-3}$. A well-structured topsoil under permanent grass with a bulk density of 1.0 t m$^{-3}$ would have a total pore space of 62%; i.e. greater than half the soil is pore space. Increases in bulk density, which are associated with compaction, lead to reductions in pore space. Further examples of increasing bulk density and decreasing pore space are given in Table 1.3.

Total porosity does not provide any direct information about the size of the individual pores, or their function. It is simply an expression of the total volume of a soil that may act as a store of air or water.

**Water retention**

Water occupies pore space in soil. The mechanisms by which water is held in soils, and then released to plants or allowed to drain out of the profile, depend upon the size of the pores. Pores can be classed as having various functions according to their approximate diameter. The larger pores (termed macropores, >60 μm in diameter), for example drying cracks and earthworm burrows, allow excess water to drain out of the soil, as gravitational forces exceed the low capillary forces in such large pores. These voids are very important during the winter months when heavy textured soils are prone to waterlogging. Macropores tend to be the first to be lost when soils are compacted, hence leading to drainage problems. In addition, these pores allow air to enter the soil profile.

The smaller pores (<60 μm in diameter) store water against gravity, due to capillary forces. These forces become stronger the smaller the pore diameter. Eventually a point is reached where the pore is so small that plants cannot overcome the capillary force, and so any water contained in that pore is considered to be unavailable. Figure 1.6 displays the relationship between soil texture and the quantity of water, expressed as a percentage of the soil volume, that is available (held in mesopores between 0.2 and 60 μm in diameter) or unavailable (held in micropores <0.2 μm in diameter). These differences are of vital importance in cropping systems; sandy soils may have only 5–10% available water, while at the other end of the range, silty soils may contain more than 20% available water. In a dry summer these differences may lead to crop failure or poor yields on sandy soils, while heavier textured soils may be able to maintain crop growth throughout a drought period.

As well as soil texture, the depth of a soil exerts a controlling influence over the total amount of water that is available to plants in the soil profile. The total available water that is stored in three example soils is given in Table 1.4. Soil A is coarse textured, but deep, while soils

---

**Figure 1.6** Soil texture and available water capacity.

**Table 1.4** Total plant-available water for three example soil types

<table>
<thead>
<tr>
<th>Soil depth (mm)</th>
<th>Available water (mm)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$A$</td>
<td>$B$</td>
</tr>
<tr>
<td>Sandy loam</td>
<td>40</td>
<td>80</td>
</tr>
<tr>
<td>Silt loam</td>
<td>21</td>
<td>45</td>
</tr>
<tr>
<td>Silt loam (0.5 m deep)</td>
<td>25</td>
<td>50</td>
</tr>
<tr>
<td>Total</td>
<td>86</td>
<td>175</td>
</tr>
</tbody>
</table>
B and C are fine textured, although soil C is only 0.5 m deep, below which weathered rock is encountered. The impact that texture and soil depth have on the amount of water available to a plant is clearly seen in this example. The need for irrigation is dependent upon soil texture and hence available water capacity, as well as the climate and weather patterns in a given area.

**Aeration**

Soil air differs from the free atmosphere above the soil surface in being enriched in carbon dioxide and sometimes depleted in oxygen. A steady supply of oxygen is needed in soils for root respiration and to support aerobic bacteria that carry out important functions in the soil (see ‘Micro-organisms’). If the volume of macropores that allow drainage and aeration falls below 10%, it is likely that there will be insufficient air for root respiration. Any practice that increases the volume of air-filled pore space, such as soil loosening, is to be encouraged.

The consequences of poor aeration are that soil conditions change to the detriment of most crop plants, although the susceptibility to poor drainage varies from crop to crop. Breakdown of organic matter in anaerobic conditions can lead to the production of organic acids and ethylene (C₂H₄), both of which inhibit root extension. Nitrate may be denitrified to gaseous nitrous oxide (N₂O) or dinitrogen (N₂), and lost from the soil system.

**Soil strength and cultivation**

Careful management of soils will lead to continued high productivity and few physical problems. However, it is not always possible to cultivate under optimum conditions, and it is sometimes necessary to keep animals out on the land when high soil water contents will lead to damage occurring. The ability of a soil to resist deformation and damage depends upon the relationship between water content and strength. This relationship is unique for each soil type. In general, high soil water contents lead to low strength, and hence greater susceptibility to potential damage under applied load, for example a tractor tyre or an animal hoof. Figure 1.7 displays this general relationship for a well-structured soil. Optimum conditions for cultivation occur when the soil will fail in a brittle, friable manner, as indicated by the asterisked arrow in Fig. 1.7.

Various problems can ensue if trafficking or animal trampling (‘poaching’) occurs when the soil is at a high water content such that deformation occurs in a plastic rather than a brittle manner. Some of these problems are described below, and are discussed in more detail in Davies *et al.* (2001).

**Cultivation pans**

A cultivation pan or plough layer will form following repeated cultivation under conditions that are too wet. Structural aggregates will be destroyed and a compacted smeared layer will be formed (see Fig. 1.5). Such pans can occur in soils of any texture, but they are most common in heavy textured soils that tend to have higher water contents. The presence of a pan will lead to temporary waterlogging, even in better drained soils, as well as higher bulk density, both of which will restrict root development. Alleviation of the problem is usually by soil loosening to below the depth of the pan under dry conditions, when brittle failure will occur.

**Surface compaction**

Surface compaction may be due to machinery access or livestock grazing of land that is too wet, resulting in plastic deformation, smearing and compaction of the surface layer (see Fig. 1.5). In consequence, aeration will be restricted and surface run-off may occur. Given the opportunity, soils will naturally ‘restructure’ at the surface, as a result of wetting and drying cycles that occur in all soils during the year. Removing the cause of the initial damage and allowing the soil to recover naturally is often all that is needed in such circumstances.

**‘Puffy’ seedbeds**

Overcultivation of soils with high sand and silt contents can lead to structure breakdown with very light, puffy
seedbeds. In such cases rolling may be necessary to ensure good soil:seed contact following drilling. Failure to roll may result in uneven germination and poor establishment.

**Machinery work days**

Autumn and spring are the critical periods of the year when soil damage is possible due to high water contents at times when essential cultivations need to be carried out. The concept of machinery work days describes the potential cultivation opportunities that exist for given soil types. These opportunities are measured during the main autumn and spring periods, and describe those occasions when harvesting, tillage and drilling operations can be conducted without risk of structural damage to the soil. Soil Survey regional bulletins (see ‘Further reading’) contain a detailed description of the system employed in England and Wales. These descriptions form a basis for the discrimination of soils according to their flexibility of management at those critical times of the year when access to the land is necessary in order to be able to establish and then harvest arable crops. Table 1.5 lists the machinery work days for three soil types that occur in south-west England. Texture can be seen to exert a strong influence on the number of machinery work days.

**Soil erosion**

Erosion is a natural process, but changes in soil properties caused by intensive use of land can lead to accelerated rates of soil loss. On a global scale, there are many examples of severe erosion, often associated with the removal of protective vegetation cover in areas subjected to intense rainfall or high winds. The ‘Dust-Bowl’ of the mid-west United States and severe gullying in the footslopes of the Himalayas demonstrate the importance of protecting vulnerable soils. In the UK, accelerated rates of erosion are associated most frequently with winter cereals, and to a lesser extent potatoes, sugar beet and oilseed rape (MAFF, 1999a). The Houghton Report on *The Sustainable Use of Soil* (Cm 3165, 1996) noted that up to 15% of arable land was at risk of erosion in any one year. Erosion not only results in the loss of valuable topsoil, hence leading to potential yield reductions, but also causes significant pollution of water courses. Examples include sediment clogging gravel-bottomed rivers and nutrients (such as nitrogen and phosphorus) contributing to eutrophication. Erosion can also occur in grassland and moorland, mainly due to overgrazing which in upland areas has been found to contribute to accelerated erosion.

Water erosion is the most common process of soil loss in the UK. First, rainsplash detaches soil particles. Various factors, summarized in Table 1.6, increase the risk of splash detachment occurring, such as soil aggregate stability and the soil surface protection or cover. Declining organic matter content and the increased area of winter cereals are the main factors leading to water erosion in the UK. Losses in excess of 10 t ha\(^{-1}\) year\(^{-1}\) are becoming more common. Strategies to control water erosion must be based on awareness of the problem. MAFF (1999a) details steps that should be taken; the key elements are summarized in Table 1.6, with maintenance of a rough seedbed with some stubble or other surface cover being essential. The principles of Integrated Crop Management include many of these strategies. If these are unsuccessful, then it will be necessary to revert to more grass in the rotation to allow the soil to recover naturally.

Erosion by wind is a problem in some eastern counties of England, notably the Fenland and the Vale of York, where vulnerable soils (peats and fine sands/silts) are intensively cropped with sugar beet and potatoes. Fine seedbeds produced in the spring can be vulnerable to ‘windblow’ if dry weather follows drilling. The establishment of windbreaks at field boundaries and use of non-cultivated strips within the field can help to reduce the risk of soil and crop loss by wind erosion.

<table>
<thead>
<tr>
<th>Location</th>
<th>Soil association and texture</th>
<th>Autumn (1 Sept–31 Dec)</th>
<th>Spring (1 Mar–30 Apr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bridgnorth</td>
<td>Loamy sand</td>
<td>86</td>
<td>29</td>
</tr>
<tr>
<td>Frilsham</td>
<td>Sandy clay loam</td>
<td>73</td>
<td>18</td>
</tr>
<tr>
<td>Hodnet</td>
<td>Silty loam/clay loam</td>
<td>32</td>
<td>3</td>
</tr>
</tbody>
</table>
Agricultural land drainage

Drainage needs and benefits

Why drain?
The removal of excess water from soil by an artificial drainage system can reduce soil management problems and increase crop yields. The need for drainage in the UK arises either from heavy textured soils retaining excess winter water, or from a high water table, for example on a river floodplain. Heavy textured soils have an ability to retain nutrients and provide the water needed to satisfy the requirements of demanding crops, and hence are capable of producing high yields, particularly of cereals and grass. For example, the majority of 10th wheat crops have been obtained from clay loam or clay textured soils, but only with efficient drainage systems to remove excess winter water from the soil.
The move in recent years to lower-input farming systems puts more emphasis on the need to ensure that soil physical conditions are optimal; in addition, the increased variability in weather patterns associated with global warming is predicted to result in increased rainfall in north-west Europe. Both these factors demonstrate the need to ensure that drainage systems function effectively.

Annual patterns of water loss and gain are very variable across the UK. As a result of higher rainfall and less sunshine, the soils in western Britain tend to pose more drainage problems than do those in the east. This does not mean that the arable soils in eastern Britain do not need drainage. The greater demands placed on soils in arable cropping systems have lead to the need for increased flexibility of soil management in arable situations, and hence many soils in eastern Britain have been drained prior to being cropped intensively.

The first drainage systems date from Roman times, but it was only after the large-scale enclosure of common lands in the eighteenth century that drainage became widespread. Techniques used varied widely, with most systems relying on stones, straw or other bulky material to form and stabilize a channel to remove excess water. The mechanical production of clay tiles in the mid-nineteenth century led to dramatic improvements in the quality of drainpipes, and 100-year-old systems can still be found that are working well today.

Estimates of areas drained in the nineteenth and early twentieth centuries suggest that up to 50% of the agricultural land in southern England was drained, all by hand. Mechanical drain installation became the norm by the middle part of the twentieth century, when 50 000–100 000 ha were drained annually. The current rate of drainage is very much less, in the region of 10 000 ha year⁻¹, due to the progressive reduction in grants for drainage schemes and changes in the economics of arable crop production in the 1980s and 1990s. In addition, the conservation value of wetland habitats is now more appreciated than formerly, such that decisions to drain areas of land are no longer based solely on considerations of likely yield increases after drainage. The conservation value of species-rich grasslands, for example, may depend on land remaining undrained. In some cases grants are now available to encourage farmers to choose this option (e.g. Countryside Stewardship Scheme). The following discussion refers only to land of little conservation value where drainage is needed to improve soil management and raise yields.

Table 1.6 Soil erosion: high-risk situations and control strategies

<table>
<thead>
<tr>
<th>Factors leading to high risk of erosion</th>
<th>Erosion control strategies</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Water</strong></td>
<td></td>
</tr>
<tr>
<td>Sandy or fine silty texture</td>
<td>Survey farm to identify vulnerable soils and sites where erosion has occurred in the past</td>
</tr>
<tr>
<td>Valley features which concentrate run-off</td>
<td>Use field margins as buffer zones to detain run-off</td>
</tr>
<tr>
<td>Steep slopes (10%)</td>
<td>Replace or add field boundaries, cultivate across slope</td>
</tr>
<tr>
<td>Long unbroken slopes</td>
<td>Reduce frequency of cultivation, add organic manures</td>
</tr>
<tr>
<td>Low organic matter content</td>
<td>Adjust timing and intensity of cultivation to avoid compaction and leave seedbed rough</td>
</tr>
<tr>
<td>Compacted soils</td>
<td>Leave stubble on surface; use non-inversion tillage</td>
</tr>
<tr>
<td>Fine seedbeds</td>
<td>Identify soils at risk</td>
</tr>
<tr>
<td>Lack of surface protection, e.g. stubble</td>
<td>Avoid overcultivation, leave seedbed rough</td>
</tr>
<tr>
<td><strong>Wind</strong></td>
<td>Plant windbreaks, subdivide field, plant different crops</td>
</tr>
<tr>
<td>Silty texture or peaty soils</td>
<td></td>
</tr>
<tr>
<td>Fine seedbeds, particularly in late spring</td>
<td></td>
</tr>
<tr>
<td>Large, flat fields, few hedges</td>
<td></td>
</tr>
</tbody>
</table>
Drainage benefits
Lowering soil water contents by drainage results in several changes in the crop rooting environment, all of which are beneficial to the crop and soil management (Parkinson, 1988). These benefits are summarized below.

Duration of waterlogging
Autumn-sown crops rely on efficient water table control to allow development of a root system. Failure to control waterlogging in the late autumn/winter/early spring period will result in a stunted root system unable to exploit deeper-seated water and nutrient reserves during the following summer.

Soil workability and trafficability
A reduction in water content will increase soil strength. Successful cultivation usually depends on the soil water content being below the lower plastic limit. Drainage lowers the water content of the topsoil, resulting in increased cultivation opportunities during the critical autumn and spring months. In grazing systems, the benefits from drainage will come from the increased number of days that livestock can graze a sward without risk of damage to the soil structure.

Soil temperature
Drainage reduces soil specific heat capacity and therefore can lead to higher temperatures. Castle et al. (1984) noted a 2°C elevation in spring soil temperatures on a clay soil in eastern England compared to when underdrained. Such an increase may lead to the more rapid germination and emergence of spring-sown crops, and may accelerate the development of winter-sown crops. It must be noted, however, that soil temperature does not always rise following drainage. In some field experiments no benefits have been found.

Efficiency of fertilizer use
More aerobic, warmer soil conditions will lead to more efficient use of applied fertilizers, particularly nitrogen top dressings. Growing roots will absorb nutrients more readily and less will be lost by leaching or denitrification.

Arable crop yield benefits
The benefit obtained as a result of installing a drainage system can be most easily measured in terms of crop yield, but the variability of the British climate often produces a wide range of yield benefits from year to year. The yield advantage for most crops when comparing drained and undrained soils is 10–25%. For example, average winter wheat yields can be increased by up to 1.0tha⁻¹. In wet years, however, efficient drainage can make the difference between crop failure and success.

Grassland/livestock benefits
In the wetter regions of the UK, drainage is essential in order to maximize grass utilization. The benefits can be expressed in terms of dry matter yield or liveweight gain. For example, Tyson et al. (1992) reported that drainage of a clay soil in Devon resulted in a 5-day longer growing season and an increase of 11% in beef cattle liveweight gain compared to the undrained soil. Drainage can alter the composition of the sward, increasing the proportion of productive grasses at the expense of weed species, as well as increasing the response to nitrogen. In addition to liveweight gain, other benefits in a livestock production system can include a reduction in the incidence of liver fluke and foot problems.

Drainage systems
Land can be drained by a system of ditches or pipes laid in the soil, or a combination of both. In the case of pipe drainage, additional short-lived measures, such as mole draining, can be carried out to increase the effectiveness of the drainage system. Both permanent and temporary systems serve specific purposes and must be installed following recommended guidelines (see Castle et al., 1984). The principles and some of the practical points are outlined here.

Open ditch drainage
Most drainage systems find outlets into an open ditch that usually leads to a larger watercourse. These ditches are a vital component of a drainage system, and in some cases may be the sole method of water removal. Careful design, construction and maintenance are therefore very important. Ditches allow direct access for water, have a large capacity to carry storm flows and are easily maintained. However, they can hinder cultivations, they need fencing to exclude livestock and are susceptible to wall collapse and blockage by vegetation.

Ditch specifications
Design standards require that ditches must be of sufficient capacity for the catchment area drained. Theoretical capacity can be calculated given catchment size and design rainfall rate (see, for example, Farr and Henderson, 1986, p. 131). Ditch width and depth will depend upon soil and geology. The more stable the soil, the steeper the permissible slope. Some examples are given in Table 1.7. Ditches dug in sandy materials must have
lower slopes than those in more stable finer-textured soil. Ditch floor gradient will in practice depend upon local topography. The gradient should be uniform and not too steep (leading to channel erosion) or too shallow (leading to silting). A gradient of 0.5–1.0% is generally considered to be adequate. Ditch sidewall collapse can be minimized by guarding against water erosion and livestock damage. Pipe drain outfalls should be fitted with splash plates, ditches should be fenced and, in areas with highly erodible soils, the sidewalls should be grassed down. Ditches must be piped under roads and farm tracks. The pipes used, normally concrete, must be large enough to carry anticipated peak flows. The design flow can be calculated (see MAFF, 1982), but the minimum recommended pipe diameter is 225 mm. This size of pipe will serve a catchment area of up to approximately 12 ha.

**Pipe drainage**

Pipe drains remove excess water without reducing the area of land cropped or interfering with field operations. Installing a permanent system of clay tiles or plastic pipes to carry water below plough depth can solve drainage problems efficiently and can be a worthwhile investment. It is particularly important that the principles of operation, design, installation and maintenance are all understood and followed, as a buried drainage scheme is difficult to inspect and maintain once installed. The successful operation of a drainage pipe system depends upon the flow of water from the soil surface into the pipe itself.

Water flow in soil depends upon the hydraulic conductivity. In a uniformly permeable material, such as a sandy textured soil that is underdrained because of a high regional water table, as, for example, would be found on a river floodplain near sea level, water movement takes place through the whole soil (see Fig. 1.8a). In heavy textured soils with low rates of water movement, particularly in the subsoil, water tends to move in the topsoil and into the trench created by the drain-laying operation (see Fig. 1.8b). The bulk of the subsoil plays little part in the disposal of excess water. Rates of water movement depend on soil texture. Table 1.8 gives examples of water flow rates, class descriptions and soil types that are used in drainage design (MAFF, 1982). Water flow rates in coarse textured soils can be 100 or 1000 times more rapid than in clay soils, hence reinforcing the need for drainage of many heavy soils.

**Drain materials**

Several choices need to be made when installing a drainage system. Drains may be clay or plastic. Clay tiles are normally cylindrical and 250 mm in length. Tiles are supplied in a palletized form, which allows for easy mechanical handling. The most common sizes are 75, 100 or 150 mm internal diameter. Good-quality tiles are essential, as the failure of one tile can cause the failure of a complete lateral. The tiles are laid in the trench to butt up to one another, but with a gap of 0.5–2.0 mm resulting from the uneven ends of successive pipes. Plastic pipes have largely superseded clay tiles. The former have several advantages, being easier and lighter to handle, and more suited for mechanical laying. In addition, disjointed drain runs are unlikely. However, the rough interior surface of a plastic pipe results in a lower hydraulic carrying capacity, and the material is inherently weaker. Slots run the length of plastic pipes so water entry is relatively unrestricted. Standard joints and junctions are available for both plastic and clay pipes, so that laterals can be led into main drains. Plastic pipes are available prewrapped with a filter, which may be necessary in silty soils to prevent blockage of the slots by sediment.

Some form of gravel is placed over pipes in about half of field drainage systems installed in England and Wales. As permeable fill may account for 50% of total installation costs, it is important to justify its use. Permeable fill acts as a connector to allow water movement from the topsoil to the drainpipe. In addition, backfill forms a permeable surround, to improve water entry to the pipe, and acts as a filter to prevent soil particles entering the drain. Washed gravel with a mean particle diameter of 20–50 mm is the most suitable permeable fill material. The use of permeable fill is not recommended for medium and coarse textured soils.

Where a pipe discharges directly into a ditch, the first 1.5 m of the pipe should be sealed, rigid and frost resistant. The pipe should be able to discharge freely – therefore the invert of the pipe should be at least 150 mm above the normal ditch water level. Where the ditch sides are unstable the pipe should be supported by a con-