Principles and Practice of Soil Science

The Soil as a Natural Resource

Fourth Edition

ROBERT E. WHITE

Blackwell
Publishing

Principles and Practice of Soil Science

Dedication

This book is dedicated to my wife Esme Annette White without whose support and encouragement it would not have been completed.

Principles and Practice of Soil Science

The Soil as a Natural Resource

Fourth Edition

ROBERT E. WHITE

Blackwell
Publishing

BLACKWELL PUBLISHING
350 Main Street, Malden, MA 02148-5020, USA
9600 Garsington Road, Oxford OX4 2DQ, UK
550 Swanston Street, Carlton, Victoria 3053, Australia

First edition published 1979
Second edition published 1987
Third edition published 1997
Fourth edition published 2006

1 2006

Library of Congress Cataloging-in-Publication Data

White, R. E. (Robert Edwin), 1937–
Principles and practice of soil science : the soil as a natural resource / Robert E. White. – 4th ed.
p. cm.
Includes bibliographical references.
ISBN-13: 978-0-632-06455-7 (pbk. : alk. paper)
ISBN-10: 0-632-06455-2 (pbk. : alk. paper)
1. Soil science. I. Title.
S591.W49 2006
631.4–dc22

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

Set in 9.5/11.5pt Sabon
by Graphicraft Limited, Hong Kong
Printed and bound in Great Britain
by TJ International Ltd, Padstow, Cornwall

The publisher's policy is to use permanent paper from mills that operate a sustainable forestry policy, and which has been manufactured from pulp processed using acid-free and elementary chlorine-free practices. Furthermore, the publisher ensures that the text paper and cover board used have met acceptable environmental accreditation standards.

For further information on
Blackwell Publishing, visit our website:
www.blackwellpublishing.com

Contents

Part 1 The Soil Habitat

Part 2 Processes in the Soil Environment

Part 3 Soil Management

Preface to the Fourth Edition

Dr Samuel Johnson is reputed to have said 'what is written without effort is in general read without pleasure'. This edition of *Principles and Practice of Soil Science* has certainly taken much effort to complete, so I hope it will be enjoyed and provide valuable information to as wide an audience of interested readers as possible. The people I would expect to be interested in learning more about soils are not only soil scientists and others concerned with production systems, but also the various scientists and natural historians who are concerned about Earth's ecology in its broadest sense.

At the time of the third edition (1997) I wrote about the 'new generic concept' of ecologically sustainable development (ESD) that was being promoted by international agencies and appearing with increasing frequency in government policy documents. However, through the 1990s and into the early years of the 21st century, more has been *written* about ESD than has been achieved on the ground in implementation of the policy. I have expanded on the topic of 'sustainability' in Chapter 15, drawing particularly on examples in Australia where a relatively fragile landscape continues to be put under pressure from 'development'. The largest areas affected are rural areas, especially in the better watered coastal zone and the expanding irrigation regions, and areas of urban concentration (mainly along the coasts also). In this context, the quality and quantity of water have become key issues attracting much public and political attention. In recent years in Australia, these twin issues have become enmeshed with the question of climate change – by how much is it changing and where, and what are the possible positive and negative effects – which is directly linked to the emission of greenhouse gases from natural and human-influenced systems. Underlying these issues is soil behaviour because virtually all the precipitation that falls on land interacts with soil in some way. Hence, knowledge of the spatial distribution of different soil types and the pathways of water, with their associated physical, chemical and biological processes, in these various soil types becomes a very important component of land and water management. We need to be aware that everyone lives in a catchment and that the quality of life in that catchment depends on individual and collective human activities in that catchment. I have expounded on this subject in my 2003 G. W. Leeper Memorial Lecture 'What has soil got to do with water?', which is available on the Australian Society of Soil Science Inc. website (<wwwc>http://www.asssi.asn.au/asssi/flash/). Important tools for use in unravelling the complexity of water, energy and nutrient fluxes in catchments are models of the biophysical processes, incorporating a digital elevation model (DEM) and digital soil map, dynamically coupled with a Geographic Information System (GIS). I refer to these tools in Chapters 14 and 15.

Apart from updating and revising each chapter and adding colour photographs, I have provided sets of illustrative problems and questions at the end of each chapter, based on my experience in teaching undergraduate classes on soil resources and their management at The University of Melbourne. I have benefited from feedback from students and also from advice given by friends and colleagues, notably Dr Nick Uren and Dr Robert Edis. To all those who contributed I am most grateful, but the ultimate responsibility for any errors and omissions rests with me. I am also grateful to Debbie Seymour, Rosie Hayden and Hannah Berry at Blackwell Publishing who have been very tolerant and supportive while I was preparing this edition.

Robert E. White
Melbourne
13 December 2004

Units of Measurement and Abbreviations used in this Book

SI units

Basic unit	*Abbreviation*
metre	m
hectare	ha
gram	g
mole	mol
second	s
temperature	K
ampere	A
becquerel	Bq

Derived units

Unit	*Abbreviation*	*Value*
Celsius	°C	K-273
newton	N	kg.m/s
joule	J	N.m
pascal	P	N/m^2
volt	V	J/A/s
siemen	S	A/V
coulomb	C	A.s
litre	L	m^3/1000
tonne	t	kg.1000
bar	bar	Pa.10^5
Faraday's constant	F	96500 J/mol/V
Universal gas constant	R	8.3143 J/K/mol

Non-SI units used in soil science

Physical term	*Unit*	*Abbreviation*	*Value*
length	Angstrom	Å	10^{-10} m
concentration	moles/litre	M	mol/L
cation exchange capacity	meq/100 g	CEC	cmol charge (+)/kg
electrical conductivity	millimho/cm	EC	dS/m

Prefixes and suffixes to units

Prefix/suffix	*Abbreviation*	*Value*
tera-	T	10^{12}
giga-	G	10^{9}
mega-	M	10^{6}
kilo-	k	10^{3}
deca-	da	10^{1}
deci-	d	10^{-1}
centi-	c	10^{-2}
milli-	m	10^{-3}
micro-	µ	10^{-6}
nano-	n	10^{-9}
pico-	p	10^{-12}

Miscellaneous symbols

( )	denotes 'activity'
[ ]	denotes 'concentration'
≅	approximately equal to
~	of the order of
<	less than
>	greater than
≤	less than or equal to
≥	greater than or equal to
log	$\log_{10}$
ln	$\log_e$
exp	exponential of

Abbreviations

ACIAR	Australian Centre for International Agricultural Research
ACLEP	Australian Collaborative Land Evaluation Program
ADAS	Agricultural Development and Advisory Service
AEC	anion exchange capacity
AM	arbuscular mycorrhizas
AMO	ammonia mono-oxygenase
ANZECC	Australian and New Zealand Environment and Conservation Council
AR	activity ratio
ASC	Australian Soil Classification
ASRIS	Australian Soil Resources Information System
ASSSI	Australian Society of Soil Science Inc.
ATC	4-amino-1,2,4-triazole
ATP	adenosine triphosphate
AWC	available water capacity
BET	Brunauer, Emmet and Teller
BIO	microbial biomass
BMP	best management practice
BP	before present
CEC	cation exchange capacity
CFCs	chlorofluorocarbons
CPMAS	cross-polarization, magic angle spinning
CREAMS	Chemicals, Runoff and Erosion from Agricultural Management Systems
CRF	controlled-release fertilizer
CSIRO	Commonwealth Scientific and Industrial Research Organization
DAP	diammonium phosphate
DCD	dicyandiamide
DCP	dicalcium phosphate
DCPD	dicalcium phosphate dihydrate
DDL	diffuse double layer
DDT	dichlorodiphenyltrichloroethane
DEM	digital elevation model
DL	diffuse layer
DM	dry matter
DNA	desoxyribose nucleic acid
DOC	dissolved organic carbon
DPM	decomposable plant material
DTPA	diethylene triamine pentaacetic acid
E	evaporation
EC	electrical conductivity
ECEC	effective cation exchange capacity
EDDHA	ethylenediamine di (O-hydroxyphenylacetic acid)
EDTA	ethylenediamine tetraacetic acid
EMR	electromagnetic radiation
ENV	effective neutralizing value
EOC	extracted organic C
ESD	ecologically sustainable development
ESP	exchangeable sodium percentage
E_t	evapotranspiration
EU	European Union
FA	fulvic acid
FAO	Food and Agriculture Organization
FC	field capacity
FESLM	Framework for Sustainable Land Management
FTIR	Fourier Transform Infrared
FYM	farmyard manure
GIS	Geographic Information System
GLC	gas-liquid chromatography
GPS	Global Positioning System
GR	gypsum required
HA	humic acid
HAp	hydroxyapatite
HARM	hull acid rain model
HUM	humified organic matter
HYV	high-yielding variety
IBDU	isobutylidene urea
IOM	inert organic matter
IPCC	Intergovernmental Panel on Climate Change
IPM	integrated pest management
IR	infiltration rate

IS	inner sphere
IUSS	International Union of Soil Sciences
KE	kinetic energy
LAI	leaf area index
LF	leaching fraction
LR	leaching requirement
LRA	land resource assessment
LSI	Langelier saturation index
MAFF	Ministry of Agriculture, Fisheries and Food
MAH	monocyclic aromatic hydrocarbons
MAP	monoammonium phosphate
MCP	monocalcium phosphate
MDB	Murray-Darling Basin
meq	milli-equivalent
MPN	most probable number
MWD	maximum potential soil water deficit
NASIS	National Soil Information System
NCPISA	National Collaborative Project on Indicators for Sustainable Agriculture
NDS	non-linear dynamic systems
NHMRC	National Health and Medical Research Council
NMR	nuclear magnetic resonance
NRCS	Natural Resources Conservation Service
NSESD	National Strategy for Ecologically Sustainable Development
NV	neutralizing value
OCP	octacalcium phosphate
o.d.	oven-dry
OS	outer sphere
p, pp.	page, singular and plural
P	precipitation
PAH	polycyclic aromatic hydrocarbons
PAM	polyacrylamide
PAPR	partially acidulated phosphate rock
PAW	plant available water
PBC	phosphate buffering capacity
PEG	polyethyleneglycol
POM	particulate organic matter
PR	phosphate rock
PSCU	polymer-coated sulphur-coated urea
PVA	polyvinyl alcohol
PVAc	polyvinylacetate
PVC	polyvinyl chloride
PWP	permanent wilting point
PZC	point of zero charge
Q/I	quantity/intensity
RAW	readily available water
RH	relative humidity
RNA	ribose nucleic acid
RPM	resistant plant material
RPR	reactive phosphate rock
RUSLE	Revised Universal Soil Loss Equation
RWEQ	Revised Wind Erosion Equation
SAR	sodium adsorption ratio
SCU	sulphur-coated urea
SGS	Sustainable Grazing Systems
SI	Système International
SIR	substrate-induced respiration
SLM	sustainable land management
SOM	soil organic matter
SOTER	World Soils and Terrain Database
sp, spp.	species, singular and plural
SRF	slow-release fertilizer
SSP	single superphosphate
ST	Soil Taxonomy
SUNDIAL	Simulation of Nitrogen Dynamics in Arable Land
SWD	soil water deficit
TCP	tricalcium phosphate
TDR	time domain reflectometer/reflectometry
TDS	total dissolved salts
TEC	threshold electrolyte concentration
TSP	triple superphosphate
UF	urea formaldehyde
UN	United Nations
UNEP	United Nations Environment Program
USDA	United States Department of Agriculture
USLE	Universal Soil Loss Equation
VD	vapour density
VP	vapour pressure
WCED	World Commission on Environment and Development
WEPP	Water Erosion Prediction Project
WEPS	Wind Erosion Prediction System
WEQ	Wind Erosion Equation
WHO	World Health Organization
WRB	World Reference Base for Soil Resources
VFA	volatile fatty acid
XRD	X-ray diffraction

Part 1

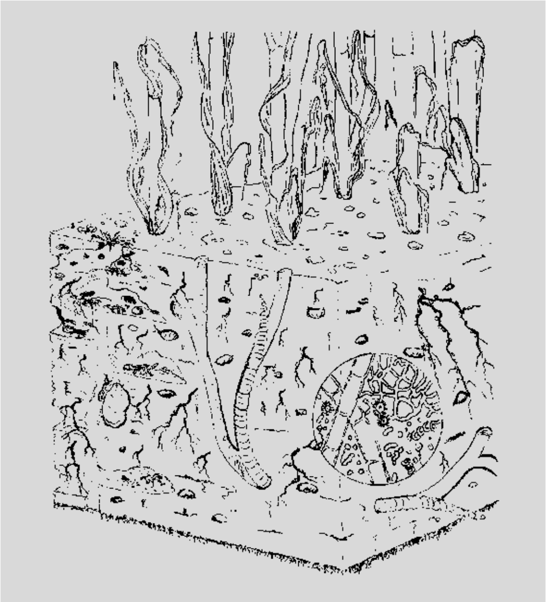
The Soil Habitat

'Soils are the surface mineral and organic formations, always more or less coloured by humus, which constantly manifest themselves as a result of the combined activity of the following agencies; living and dead organisms (plants and animals) parent material, climate and relief.'

V. V. Dokuchaev (1879), quoted by J. S. Joffe in *Pedology*

'The soil is teeming with life. It is a world of darkness, of caverns, tunnels and crevices, inhabited by a bizarre assortment of living creatures . . .'

J. A. Wallwork (1975) in *The Distribution and Diversity of Soil Fauna*



Redrawn from Reganold J. P., Papendick R. I. & Parr J. F. (1990) Sustainable agriculture. *Scientific American* **262**(6), 112–20.

Chapter 1

Introduction to the Soil

1.1 Soil in the making

With the exposure of rock to a new environment – following an outflow of lava, an uplift of sediments, recession of a water body, or the retreat of a glacier – a soil begins to form. Decomposition proceeds inexorably towards decreased free energy and increased entropy. The free energy of a closed system, such as a rock fragment, is that portion of its total energy that is available for work, other than work done in expanding its volume. Part of the energy released in a spontaneous reaction, such as rock weathering, appears as entropic energy, and the degree of disorder created in the system is measured by its entropy. For example, as the rock weathers, minerals of all kinds are converted into simpler molecules and ions, some of which are leached out by water or escape as gases.

Weathering is hastened by the appearance of primitive plants on rock surfaces. These plants – lichens, mosses and liverworts – can store radiant energy from the sun as chemical energy in the products of photosynthesis. Lichens, which are symbiotic associations of an alga and fungus, are able to 'fix' atmospheric nitrogen (N_2) and incorporate it into plant protein, and to extract elements from the weathering rock surface. On the death of each generation of these primitive plants, some of the rock elements and a variety of complex organic molecules are returned to the weathering surface where they nourish the succession of organisms gradually colonizing the embryonic soil.

A simple example is that of soil formation under the extensive deciduous forests of the cool humid areas of Europe, Asia and North America, on calcareous deposits exposed by the retreat of the Pleistocene ice cap (Table 1.1). The profile development is summarized in Fig. 1.1. The initial state is little more than a thin layer of weathered material stabilized by primitive plants. Within a century or so, as the organo-mineral material accumulates, more advanced species of sedge and grass appear, which are adapted to the harsh habitat. The developing soil is described as a Lithosol (Entisol or Rudosol*). Pioneering micro-organisms and animals feed on the dead plant remains and gradually increase in abundance and variety. The litter deposited on the surface is mixed into the soil by burrowing animals and insects, where its decomposition is hastened. The eventual appearance of larger plants – shrubs and trees – with their deeper roots, pushes the zone of rock weathering farther below the soil surface. After a few hundred more years, a Brown Forest Soil (Inceptisol or Tenosol) emerges. We shall return to the topic of soil formation, and the wide range of soils that occur in the landscape, in Chapters 5 and 9.

1.2 Concepts of soil

The soil is at the interface between the atmosphere and lithosphere (the mantle of rocks making up the Earth's crust). It also has an interface with bodies of fresh and salt water (collectively called the hydrosphere). The soil sustains the growth of many plants and animals, and so forms part of the biosphere.

---

* See Box 1.1 for a discussion of soil names.

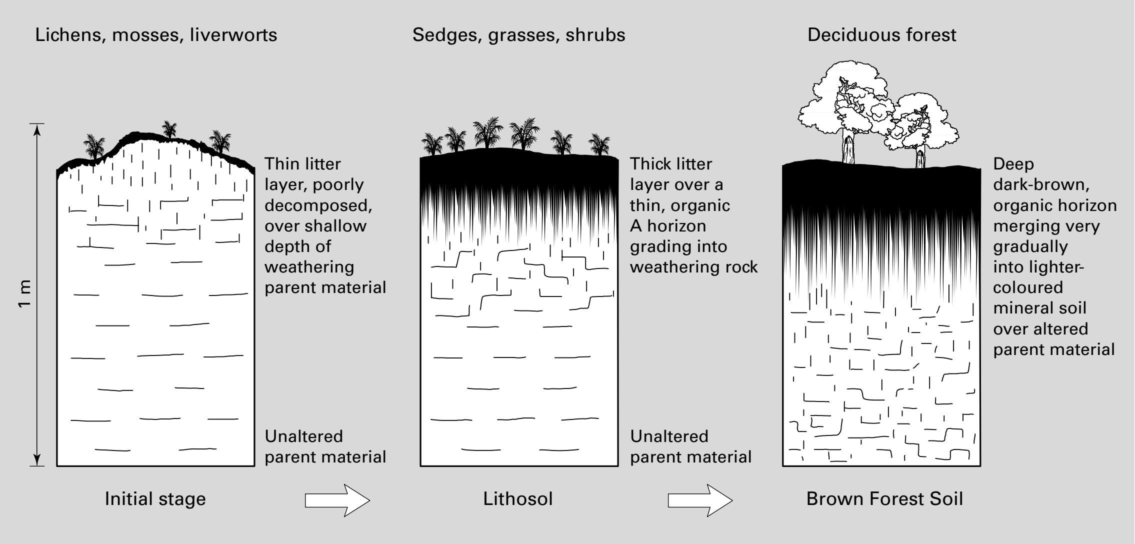


Fig. 1.1 Stages in soil formation on a calcareous parent material in a humid temperate climate.

Box 1.1 Soil variability, description and classification.

The landscape displays a remarkable range of soil types, resulting from an almost infinite variation in geology, climate, vegetation and other organisms, topography, and the time for which these factors have combined to influence soil formation (human activity is included among the effects of organisms). To bring order to such variety and to disseminate knowledge about soils, soil scientists have developed ways of classifying soils. Individual soils are described in terms of their properties, and possibly their mode of formation, and similar soils are grouped into classes that are given distinctive names. However, unlike the plant and animal kingdoms, there are no soil 'individuals' – the boundaries between different soils in the landscape are not sharp. Partly because of the difficulty in setting class limits, and because of the evolving nature of soil science, no universally accepted system of classifying (and naming) soils exists. For many years, Great Soil Group names based on the United States Department of Agriculture (USDA) Classification of Baldwin *et al.* (1938) (Section 5.3) held sway. But in the last 30 years, new classifications and a plethora of new soil names have evolved (Chapter 14). Some of these classifications (e.g. *Soil Taxonomy*, Soil Survey Staff, 1999) and the *World Reference Base for Soil Resources* (FAO, 1998) purport to be international. Others such as *The Australian Soil Classification* (Isbell, 2002) and the *Soil Classification for England and Wales* (Avery, 1980) are national in focus. This diversity of classifications creates problems for non-specialists in naming soils and understanding the meaning conveyed by a particular soil name. In this book, the more descriptive and (to many) more familiar Great Soil Group names will be used. Where possible, the approximate equivalent at the Order or Suborder level in Soil Taxonomy (ST) and the Australian Soil Classification (ASC) will be given in parentheses.

There is little merit in attempting to give a rigorous definition of soil because of the complexity of its make-up, and of the physical, chemical and biological forces that act on it. Nor is it necessary to do so, for soil means different things to different users. For example, to the geologist and engineer, the soil is little more than finely divided rock material. The hydrologist may see the soil as

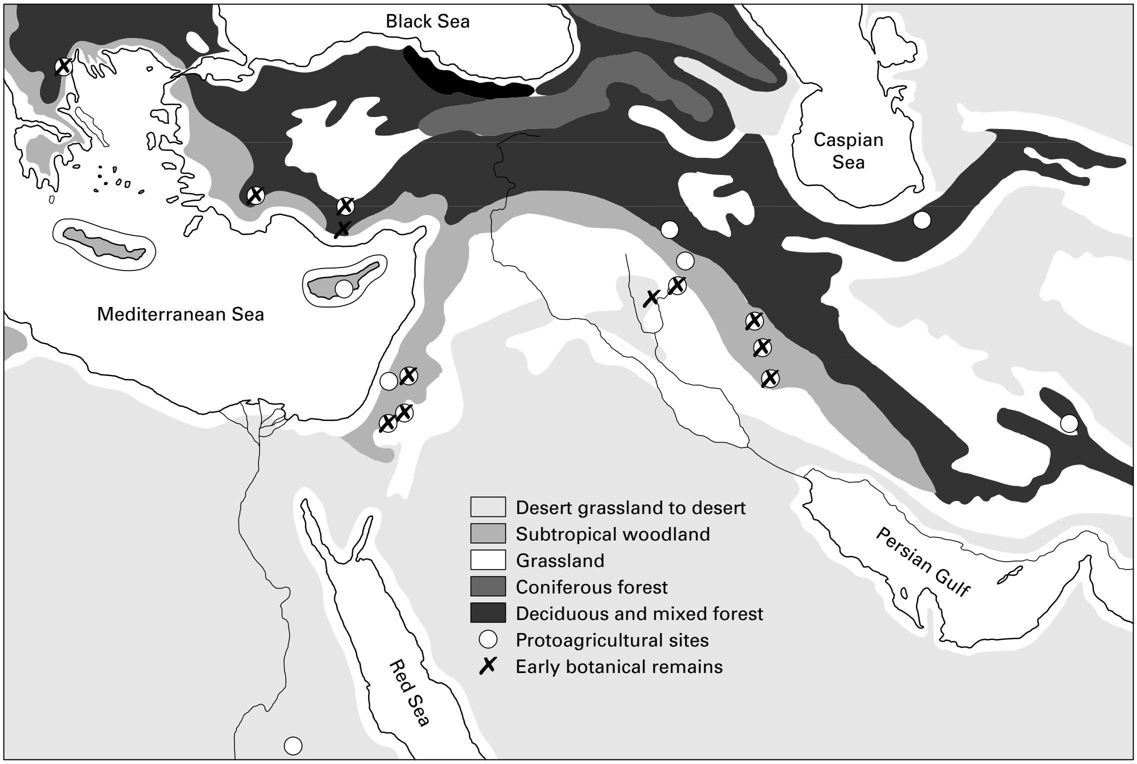


Fig. 1.2 Sites of primitive settlements in the Middle East (after Gates, 1976).

a storage reservoir affecting the water balance of a catchment, while the ecologist may be interested only in those soil properties that influence the growth and distribution of plants and animals. The farmer is naturally concerned about the many ways in which soil influences crop growth and the health of his livestock, although frequently his interest does not extend below the depth of soil disturbed by a plough (15–20 cm).

In view of this wide spectrum of potential user-interest, it is appropriate when introducing the topic of soil to readers, perhaps for the first time, to review briefly the evolution of our relationship with the soil and identify some of the past and present concepts of soil.

Soil as a medium for plant growth

Human's use of soil for food production began two or three thousand years after the close of the last Pleistocene ice age, which occurred about 11,000 years BP (before present). Neolithic people and their primitive agriculture spread outwards from settlements in the fertile crescent embracing the ancient lands of Mesopotamia, Canaan and southern Turkey (Fig. 1.2) and reached as far as China and the Americas within a few thousand years. In China, for example, the earliest records of soil survey (4000 years BP) show how soil fertility was used as a basis for levying taxes on landholders. To study the soil was a practical exercise of everyday life, and the knowledge of soil husbandry that had been acquired by Roman times was passed on by peasants and landlords, with little innovation, until the early 18th century.

From that time onwards, however, the rise in demand for agricultural products in Europe was dramatic. Conditions of comparative peace, and rising living standards as a result of the Industrial Revolution, further stimulated this demand throughout the 19th century. The period was also one of great discoveries in physics and chemistry,

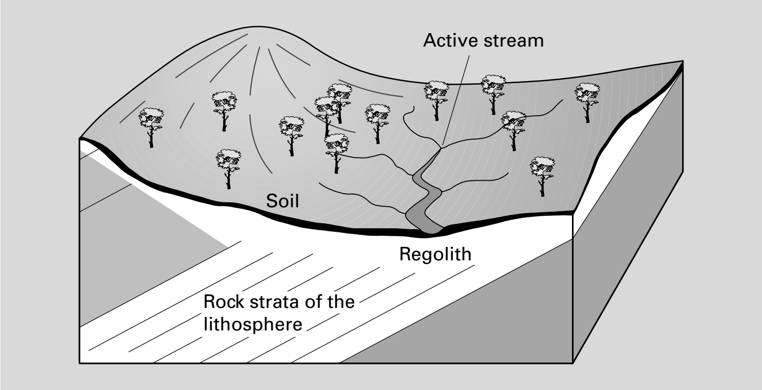


Fig. 1.3 Soil development in relation to the landscape and underlying regolith.

the implications of which sometimes burst with shattering effect on the conservative world of agriculture. In 1840, von Liebig established that plants absorbed nutrients as inorganic compounds from the soil, although he insisted that plants obtained their nitrogen (N) from the atmosphere: Lawes and Gilbert at Rothamsted subsequently demonstrated that plants (except legumes) absorbed inorganic N from the soil. In the 1850s, Way discovered the process of cation exchange in soil. During the years from 1860 to 1890, eminent bacteriologists including Pasteur, Warington and Winogradsky elucidated the role of micro-organisms in the decomposition of plant residues and the conversion of ammonia to nitrate.

Over the same period, botanists such as von Sachs and Knop, by careful experiments in water culture and analysis of plant ash, identified the major elements that were essential for healthy plant growth. Agricultural chemists drew up balance sheets of the quantities of these elements taken up by crops and, by inference, the quantities that should be returned to the soil in fertilizers or animal manure to sustain growth. This approach, whereby the soil was regarded as a relatively inert medium providing water, mineral* ions and physical support for plants, has been called the ‘nutrient bin’ concept.

Soil and the influence of geology

The pioneering chemists who investigated a soil’s ability to supply nutrients to plants tended to see the soil as a chemical and biochemical reaction medium. They little appreciated soil as part of the landscape, moulded by natural forces acting on the land surface. In the late 19th century, great contributions were made to our knowledge of soil by geologists who defined the mantle of loose, weathered material on the Earth’s surface as the regolith, of which only the upper 50–150 cm, superficially enriched with organic matter, could be called soil (Fig. 1.3). Below the soil was the subsoil that was largely devoid of organic matter. However, the mineral matter of both soil and subsoil was recognized as being derived from the weathering of underlying rocks, which led to an interest in the influence of rock type on the soils formed. As the science of geology developed, the history of the Earth’s rocks was subdivided into a time scale consisting of eras, periods and epochs, going back some 550 million years BP. Periods within the eras are usually associated with prominent sequences of sedimentary rocks that were deposited in the region now known as Europe. But examples of these rocks are found elsewhere, so the European time divisions have gradually been accepted worldwide (although the European divisions are not necessarily as clear-cut in all cases outside Europe). Studies of the relationship between soil and the underlying geology led to the practice of classifying soils loosely in geological terms, such as granitic (from granite), marly (derived from a mixture of limestone and clay),

---

* The term ‘mineral’ is used in two contexts: first, as an adjective referring to the inorganic constituents of the soil (ions, salts and particulate matter); second, as a noun referring to specific inorganic compounds found in rocks and soil, such as quartz and feldspars (Chapter 2).

Table 1.1 The geological time scale.

Era	*Period*	*Epoch*	*Start time (million years BP)*
Cainozoic	Quaternary	Recent	0.011
		Pleistocene	2
	Tertiary	Pliocene	5
		Miocene	23
		Oligocene	36
		Eocene	53
		Palaeocene	65
Mesozoic		Cretaceous	145
		Jurassic	205
		Triassic	250
Palaeozoic		Permian	290
		Carboniferous	360
		Devonian	405
		Silurian	436
		Ordovician	510
		Cambrian	550
Pre-Cambrian			4600

loessial (derived from wind-blown silt-size particles), glacial (from glacial deposits) and alluvial (from river deposits).

A simplified version of the geological time scale from the pre-Cambrian period to the present is shown in Table 1.1.

The influence of Russian soil science

Russia is a vast country covering many climatic zones in which, at the end of the 19th century, crop production was limited not so much by soil fertility, but by primitive methods of agriculture. Early Russian soil science was therefore concerned not with soil fertility, but with observing soils in the field and studying relationships between soil properties and the environment in which the soil had formed. From 1870 onwards, Dokuchaev and his school emphasized the distinctive features of a soil that developed gradually and distinguished it from the undifferentiated weathering rock or parent material below. This was the beginning of the science of pedology*.

Following the Russian lead, scientists in other countries began to appreciate that factors such as climate, parent material, vegetation, topography and time interacted in many ways to produce an almost infinite variety of soil types. For any particular combination of these soil-forming factors (Chapter 5), a unique physicochemical and biological environment was established that led to the development of a distinctive soil body – the process of pedogenesis. A set of new terms was developed to describe soil features, such as:

- Soil profile – constituting a vertical face exposed by excavating the soil from the surface to the parent material;
- soil horizons – layers in the profile distinguished by their colour, hardness, texture, the occurrence of included structures, and other visible or tangible properties. The upper layer, from which materials are generally washed downwards, is described as eluvial; lower layers in which these materials accumulate are called illuvial.

In 1932, an international meeting of soil scientists adopted the notation of A and B for the eluvial and illuvial horizons, respectively, and C horizon for the parent material. The A and B horizons comprise the solum. Unweathered rock below the parent material is called bedrock R. Organic litter on the surface, not incorporated in the soil, is designated as an L layer. A typical Alfisol (ST) or Chromosol (ASC) soil profile showing a well-developed A, B and C horizon is shown in Fig. 1.4.

Soil genesis is now known to be much more complex than this early work suggested. For example, many soils are polygenetic in origin; that is, they have undergone successive phases of development due to changes in climate and other environmental factors over time. In other cases, two or more layers of different parent material are found in one soil profile. Nevertheless, the Russian approach was a considerable advance on traditional thinking, and recognition of the relationship between a soil and its environment encouraged soil scientists to survey and map the distribution of soils. The wide range of soil morphology that was revealed in turn stimulated studies of pedogenesis, an understanding of which, it was believed, would enable the copious field data on soils to be collated more systematically. Thus, Russian soil science provided the inspiration for many of the early soil classifications.

---

* From the Greek word for ground or earth.

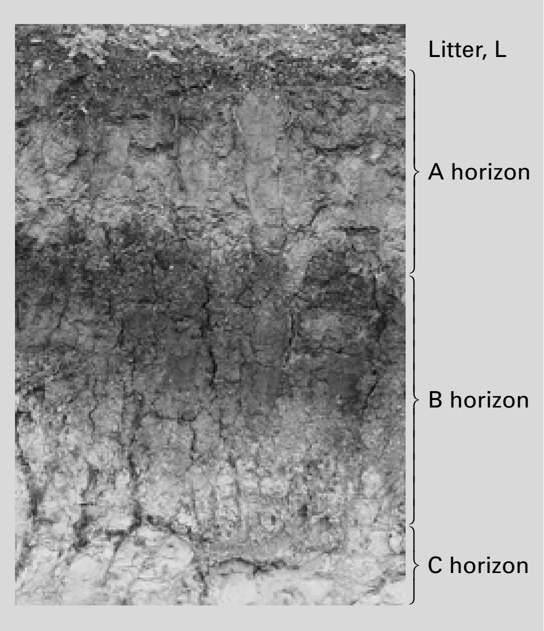


Fig. 1.4 Profile of an Alfisol (ST) or Chromosol (ASC) showing well-developed A, B and C horizons (see Plate 1.4).

Box 1.2 Soil as a natural body.

A soil is clearly distinguished from inert rock material by:

- The presence of plant and animal life;
- a structural organization that reflects the action of pedogenic processes;
- a capacity to respond to environmental change that might alter the balance between gains and losses in the profile, and predetermine the formation of a different soil in equilibrium with a new set of environmental conditions.

The last point indicates that soil has no fixed inheritance, because it depends on the conditions prevailing during its formation. Nor is it possible to unambiguously define the boundaries of the soil body. The soil atmosphere is continuous with air above the ground, many soil organisms live as well on the surface as within the soil, the litter layer usually merges gradually with decomposed organic matter in the soil, and likewise the boundary between soil and parent material is difficult to demarcate. We therefore speak of the soil as *a three-dimensional body that is continuously variable in time and space.*

A contemporary view of soil

Between the two World Wars of the 20th century, the philosophy of the soil as a 'nutrient bin' was prevalent, particularly in the western world. More and more land was brought into cultivation, much of which was marginal for crop production because of limitations of climate, soil and topography. With the balance between crop success and failure made even more precarious than in favourable areas, the age-old problems of wind and water erosion, encroachment by weeds, and the accumulation of salts in irrigated lands became more serious. Since 1945, demand for food, fibre and forest products from an escalating world population (now > 6 billion) has led to increased use of fertilizers to improve yields, and pesticides to control pests and diseases (Chapter 12). Such practices have resulted in some accumulation of undesirable pesticide residues in soil, and in increased losses of soluble constituents such as nitrate and phosphates to surface waters and groundwater. There has also been widespread dispersal of the very stable pesticides (e.g. organo-chlorines) in the biosphere, and their accumulation to concentrations potentially toxic to some species of birds and fish.

More recently, however, scientists, producers and planners have acknowledged the need to compromise between maximizing crop production and conserving a valuable natural resource. Emphasis is now placed on maintaining the soil's natural condition by minimizing the disturbance when crops are grown, matching fertilizer additions more closely to crop demand in order to reduce losses, using legumes to fix N_2 from the air, and returning plant residues and waste materials to the soil to supply some of a crop's nutrient requirements. In short, more emphasis is being placed on the soil as a natural body (Box 1.2) and on the concept of sustainable land management (Chapter 15).

1.3 Components of the soil

We have seen that a combination of physical, chemical and biotic forces acts on organic materials and weathered rock to produce a soil with a porous fabric that retains water and gases. The mineral matter derived from weathered rock

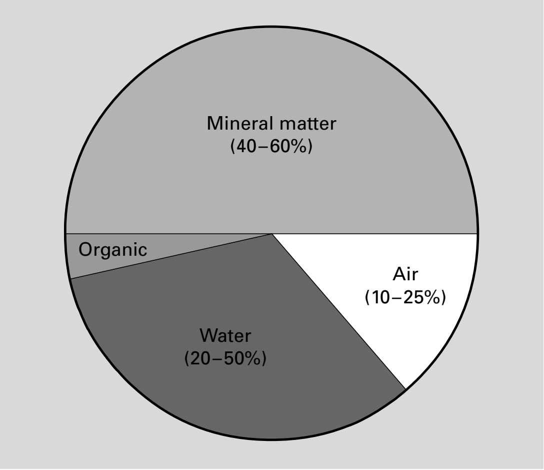


Fig. 1.5 Proportions of the main soil components by volume.

consists of particles of different size, ranging from clay (the smallest), to silt, sand, gravel, stones, and in some cases boulders (Section 2.1). The particle density ρ_p (rho p) varies according to the mineralogy (Section 2.3), but the average ρ_p is 2.65 Mg/m^3. Organic matter has a lower density of 1–1.3 Mg/m^3, depending on the extent of its decomposition. Water has a density of 1.0 Mg/m^3 at normal temperatures (*c*. 20°C)*.

Soil water contains dissolved organic and inorganic solutes and is called the soil solution. While the soil air consists primarily of N_2 and oxygen (O_2), it usually contains higher concentrations of carbon dioxide (CO_2) than the atmosphere, and traces of other gases that are by-products of microbial metabolism. The relative proportions of the four major components – *mineral matter, organic matter, water and air* – may vary widely, but generally lie within the ranges indicated in Fig. 1.5. These components are discussed in more detail in the subsequent chapters of Part 1.

1.4 Summary

Soil forms at the interface between the atmosphere and the weathering products of the regolith. Physical and chemical weathering, erosion and redeposition, combined with the activities of a succession of colonizing plants and animals, moulds a distinctive soil body from the milieu of rock minerals in the parent material. The process of soil formation, called pedogenesis, culminates in a remarkably variable differentiation of soil material into a series of horizons that constitute a soil profile. Soil horizons are distinguished by their visible and tangible properties such as colour, hardness, texture and structural organization. The intimate mixing of mineral and organic matter to form a porous fabric, permeated by water and air, creates a favourable habitat for a variety of plant and animal life. Soil is a fragile component of the environment. Its use for food and fibre production, and waste disposal, must be managed in a way that minimizes the off-site effects of these activities and preserves the soil for future generations. This is the basis of sustainable soil management.

References

Avery B. W. (1980) *Soil Classification for England and Wales*. Soil Survey Technical Monograph No. 14. Rothamsted Experimental Station, Harpenden.

Baldwin H., Kellogg C. W. & Thorpe J. (1938) Soil classification, in *Soils and Man*. United States Government Printing Office. Washington DC.

FAO (1998) *World Reference Base for Soil Resources*. World Resources Report No. 84. FAO, Rome.

Gates C. T. (1976) China in a world setting: agricultural response to climatic change. *Journal of the Australian Institute of Agricultural Science* **42**, 75–93.

Isbell R. F. (2002) *The Australian Soil Classification*, revised edn. Australian Soil and Land Survey Handbooks Series Volume 4. CSIRO Publishing, Melbourne.

Soil Survey Staff (1999) *Soil Taxonomy. A Basic Classification for Making and Interpreting Soil Surveys*, 2nd edn. United States Department of Agriculture Handbook No. 436. Natural Resources Conservation Service, Washington DC.

Further reading

Hillel D. (1991) *Out of the Earth: Civilization and the Life of the Soil*. The Free Press, New York.

Jenny H. (1980) *The Soil Resource – Origin and Behaviour*. Springer-Verlag, New York.

Marschner H. (1995) *Mineral Nutrition of Higher Plants*, 2nd edn. Academic Press, London.

McKenzie N. & Brown K. (2004) *Australian Soils and Landscapes: an Illustrated Compendium*. CSIRO Publishing, Melbourne.

---

* The density of water is 1.000 Mg/m^3 at 4°C and 0.998 Mg/m^3 at 20°C, which is rounded to 1.0.

Example questions and problems

1 The upper-most horizon of a soil is generally enriched with organic matter, in varying states of decomposition. Where does most of this organic matter come from?

2 (a) Give the notation for the main horizons recognized in a soil profile.
  (b) What do the terms 'eluvial' and 'illuvial' mean in the context of soil profile description?

3 What are the main external factors that cause soil variation in the landscape?

4 Soil samples were taken from the 0–10 cm depth along two transects at right angles in a pasture grazed by cattle. The samples were spaced at 5 m intervals and analysed for organic carbon (C) content. The results, in percent organic C, were as follows.

Transect 1	2.5	1.6	1.1	1.7	1.5	2.1	2.7	2.2	3.0	1.3
Transect 2	1.6	1.9	1.5	2.9	2.5	2.2	1.5	1.0	1.4	2.7

  (a) Calculate the mean organic C content for each transect, and the coefficient of variation (CV) for each set of values

$$\left(\text{CV} = \frac{\text{standard deviation}}{\text{mean}} \times 100\right).$$

  (b) Can you suggest a reason for the spatial variation in organic C content?

5 Suppose that the volume fraction of mineral matter in a field soil is 0.5, and the organic matter fraction is 0.025.
  (a) Calculate the remaining volume fraction and say what this volume fraction is called.
  (b) (i) Calculate the weight in tonnes (t) of 1 cubic metre (1 m^3) of completely dry soil, given that the particle densities (ρ_p) of the mineral and organic fractions are 2.65 and 1.2 Mg/m^3, respectively, and (ii) calculate the weight of 5 cm^3 of dry soil (roughly 1 teaspoon).
  (c) If the depth of ploughing in this soil is 15 cm, what is the weight of dry soil (Mg) per hectare to 15 cm depth?
  (d) Suppose the 50% mineral matter (by volume) of a field soil included 10% iron oxide ($\rho_p = 5.55$ Mg/m^3) and organic matter was negligible. (i) What would be the weight of 1 m^3 of soil, and (ii) the weight of 1 ha of dry soil to 15 cm depth?

Chapter 2

The Mineral Component of the Soil

2.1 The size range

Rock fragments and mineral particles in soil vary enormously in size from boulders and stones down to sand grains and very small particles that are beyond the resolving power of an optical microscope (< 0.2 μm in diameter). Particles smaller than *c.* 1 μm are classed as colloidal. Particles that do not settle quickly when mixed with water are said to form a colloidal solution or sol; if they settle within a few hours they form a suspension. Colloidal solutions are distinguished from true solutions (dispersions of ions and molecules) by the Tyndall effect. This occurs when the path of a beam of light passing through the solution can be seen from either side at right angles to the beam, indicating a scattering of the light rays.

An arbitrary division is made by size-grading soil into material:

- That passes through a sieve with 2 mm diameter holes – the *fine earth*, and
- that retained on the sieve (> 2 mm) – *the stones or gravel*, but smaller than
- fragments > 600 mm, which are called *boulders.*

The separation by sieving is carried out on air-dry soil that has been gently ground by mortar and pestle, or crushed between wooden rollers, to break up the aggregates. Air-dry soil is soil allowed to dry in air at ambient temperatures (between 20 and 40°C).

Particle-size distribution of the fine earth

The distribution of particle sizes determines the soil texture, which may be assessed subjectively in the field or more rigorously by particle-size analysis in the laboratory.

Size classes

All soils show a continuous range of particle sizes, called a frequency distribution, which is obtained by plotting the number (or mass) of particles of a given size against their actual size. When the number or mass in each size class is summed sequentially we obtain a cumulative distribution of soil particle sizes, some examples of which are given in Fig. 2.1. In practice, it is convenient to

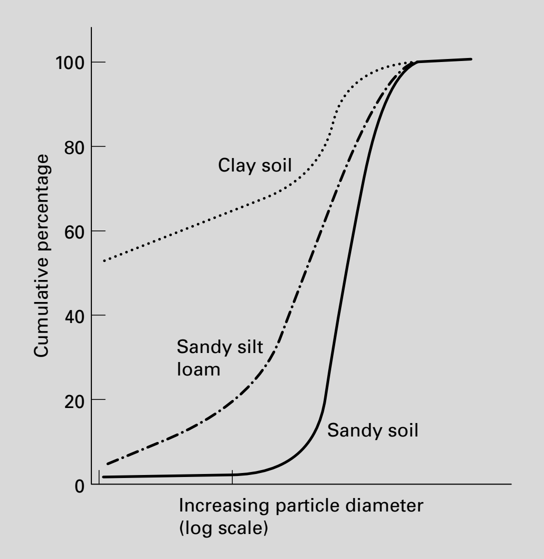


Fig. 2.1 Cumulative frequency distributions of soil particle sizes in a typical clay, sandy silt loam and sandy soil.

subdivide the continuous distribution into several class intervals that define the size limits of the *sand*, *silt* and *clay* fractions. The extent of this subdivision, and the class limits chosen, vary from country to country and even between institutions within countries. The major systems in use are those adopted by the Soil Survey Staff of the USDA, the British Standards Institution and the International Union of Soil Sciences (IUSS). These are illustrated in Fig. 2.2. All three systems set the upper limit for clay at 2 μm diameter, but differ in the upper limit chosen for silt and the way in which the sand fraction is subdivided.

Field texture

A soil surveyor assesses soil texture by moistening a sample with water until it glistens. It is then kneaded between fingers and thumb until the aggregates are broken down and the soil grains thoroughly wetted. The proportions of sand, silt and clay are estimated according to the following qualitative criteria:

- *Coarse sand* grains are large enough to grate against each other and can be detected individually by sight and feel;
- *fine sand* grains are much less obvious, but when they comprise more than about 10% of the sample they can be detected by biting the sample between the teeth;
- *silt* grains cannot be detected by feel, but their presence makes the soil feel smooth and silky and only slightly sticky;
- *clay* is characteristically sticky, although some dry clays, especially of the expanding type (Section 2.3), require much moistening and kneading before they develop their maximum stickiness.

High organic matter contents tend to reduce the stickiness of clay soils and to make sandy soils feel more silty. Finely divided calcium carbonate also gives a silt-like feeling to the soil.

Depending on the estimated proportions of sand, silt and clay, the soil is assigned to a textural class according to a triangular diagram (Fig. 2.3). The triangle in Fig. 2.3a is used by the Soil Survey of England and Wales and is based on the British Standards system of particle-size grading (Fig. 2.2); the one in Fig. 2.3b is used in Australia and is based on the International system (Fig. 2.2). The USDA system is very similar to the British Standards system. Note that in these systems there are 11 textural classes, but the Australian system has

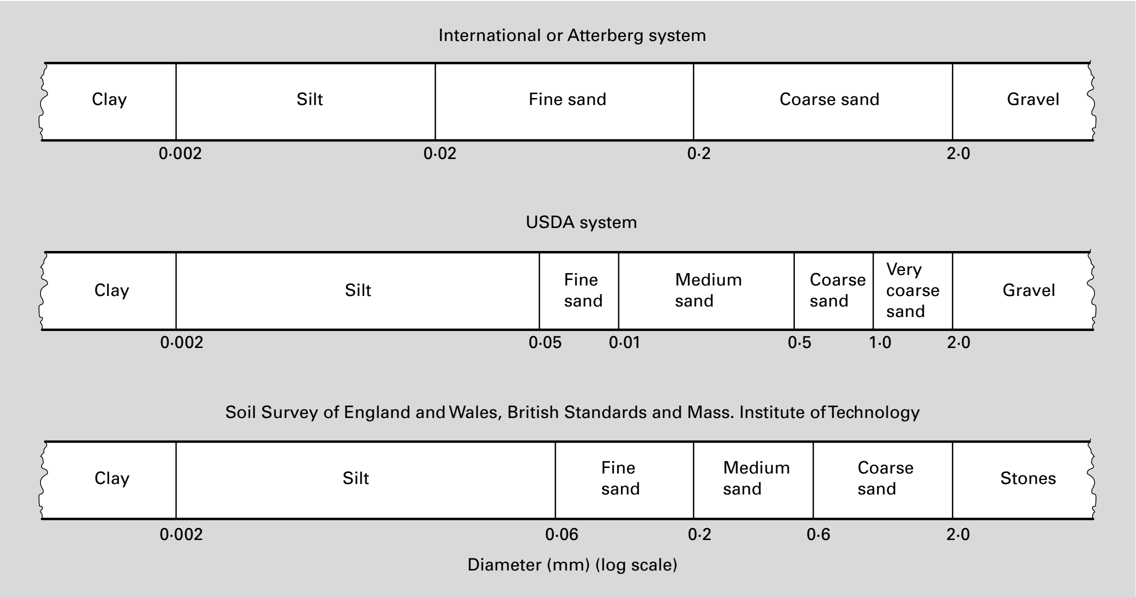


Fig. 2.2 Particle-size classes most widely adopted internationally.

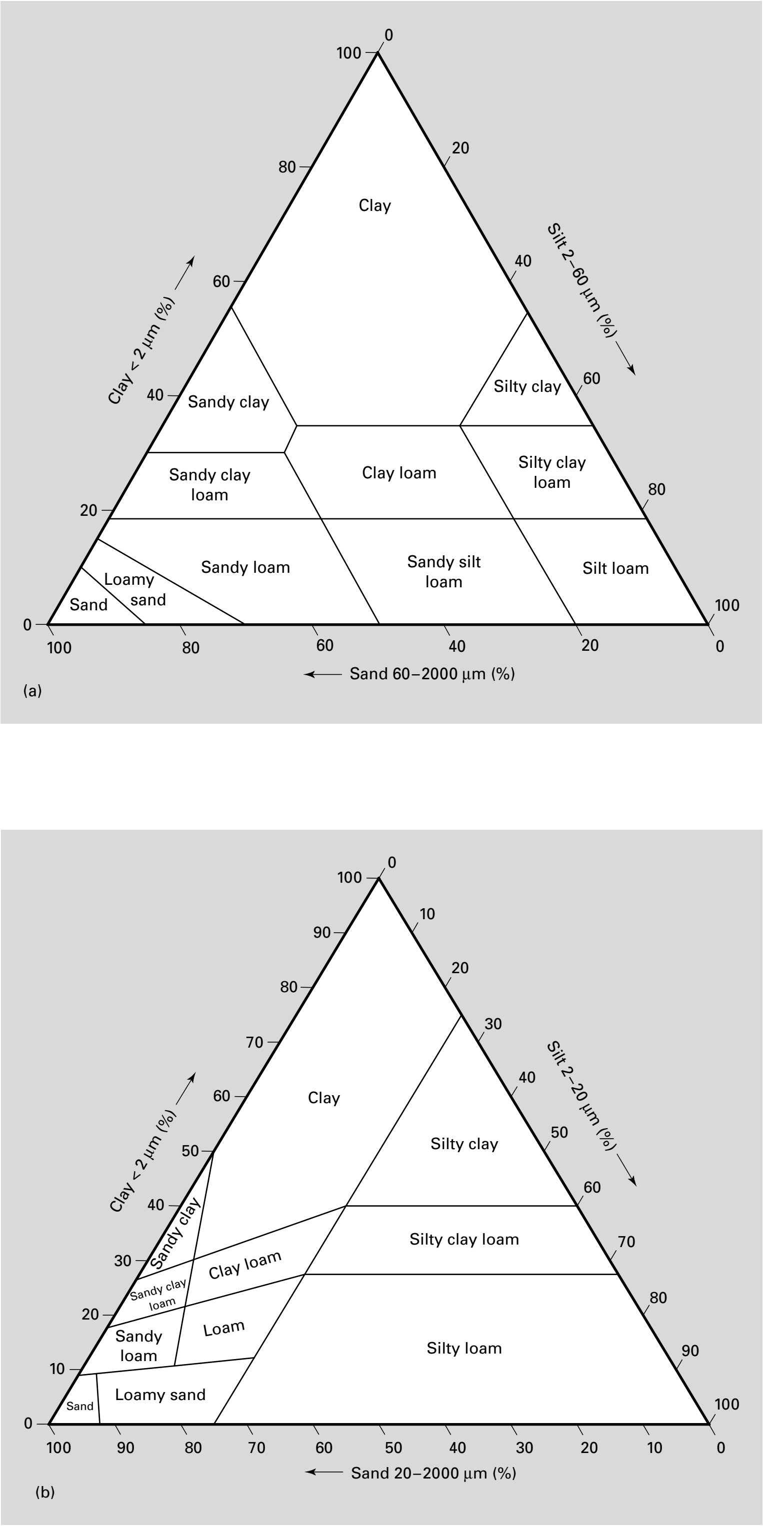


Fig. 2.3 (a) Triangular diagram of soil textural classes adopted in England and Wales (after Hodgson, 1974). (b) Triangular diagram of soil textural classes adopted in Australia (after McDonald *et al.*, 1998).

broader classes for the silty clays, silty clay loams and silty loams than the British or USDA systems.

Soil surveyors become expert at texturing after years of experience, which is gained by their checking field assessments of texture against a laboratory analysis of a soil's particle-size distribution.

Particle-size analysis in the laboratory

The success of the method relies on the complete disruption of soil aggregates and the addition of chemicals that ensure dispersion of the soil colloids in water. Full details of the methods employed are given in standard texts, for example Klute (1986) and Rayment and Higginson (1992). The sand particles are separated by sieving; silt and clay are separated using the differences in their settling velocities in suspension. The principle of the latter technique is outlined in Box 2.1.

The result of particle-size analysis is expressed as the mass of the individual fractions per 100 g of oven-dry (o.d.) soil (fine earth only). Oven-dry soil is soil dried to a constant weight at 105°C. When the coarse and fine sand fractions are combined, the soil may be represented by one point on the triangular diagrams of Fig. 2.3 (a, b). Alternatively, by stepwise addition of particle-size percentages, graphs of cumulative percentage against particle diameter of the kind shown in Fig. 2.1 are obtained.

2.2 The importance of soil texture

Soil scientists are primarily interested in the texture of the fine earth fraction. Nevertheless, in some soils the size and abundance of stones cannot be ignored because they can have a marked influence on the soil's suitability for agriculture. As the stone content increases, a soil holds less water than a stoneless soil of the same fine-earth texture, so that crops become more susceptible to drought. Conversely, such soils may be better drained and therefore warm up more quickly in spring in cool temperate regions. Large stones on the soil surface act as sinks during daytime for heat energy that is slowly released at night – this is of benefit in cool climate vineyards, such as in the Rhône Valley, France, where frost in spring and early summer can damage flowering and fruit

Box 2.1 Measurement of silt and clay by sedimentation.

A rigid particle falling freely through a liquid of lower density will attain a constant velocity when the force opposing movement is equal and opposite to the force of gravity acting on the particle. The frictional force acting vertically upward on a spherical particle is calculated from Stoke's law. The net gravitational force acting downwards is equal to the weight of the submerged particle. At equilibrium, these expressions can be combined to give an equation for the terminal settling velocity *v*, as

$$v = \frac{2}{9}\frac{g}{\eta}\left(\rho_p - \rho_w\right)r^2, \tag{B2.1.1}$$

where *g* is the acceleration due to gravity, η (eta) is the coefficient of viscosity of the liquid (water), which varies with temperature, ρ_p is the particle density, ρ_w is the density of water, and *r* is the particle radius.

When all the constants in this equation are collected into one term *A*, we derive the simple relationship

$$v = Ar^2 = \frac{h}{t}, \tag{B2.1.2}$$

where *h* is the depth, measured from the liquid surface, below which all particles of radius *r* will have fallen in time *t*. To illustrate the use of Equation B2.1.2, we can calculate that all particles > 2 μm in diameter settling in a suspension at 20°C will fall below a depth of 10 cm in 7.73 hours. Thus,

Box 2.1 *continued*

by sampling the mass per unit volume of the suspension at this depth after 7.73 hours, the amount of clay can be calculated. The suspension density at a particular depth can be measured in one of several ways:

- By withdrawing a sample volume of the suspension, evaporating to dryness, and weighing the mass of sediment – the pipette method;
- by using a Bouyoucos hydrometer in the suspension; or
- by calculating the loss in weight of a bulb of known volume when immersed in the suspension – the plummet balance method, illustrated in Fig. B2.1.1.

Note that constant temperature should be maintained (because of the temperature effect on the viscosity of water), and also that simplifying assumptions are made in the calculation of settling velocity by Equation B2.1.2. In particular, note that:

- Clay and silt particles are not smooth spheres, but have irregular plate-like shapes;
- the particle density varies with the mineral type (Section 2.3).

In practice, we take an average value for ρ_p of 2.65 Mg/m^3, and speak of the 'equivalent spherical diameter' of the particles being measured.

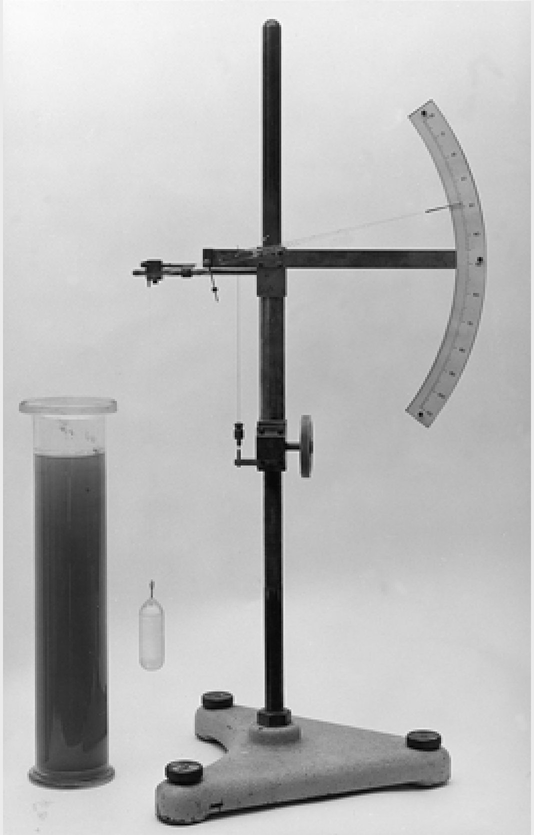


Fig. B2.1.1 A settling soil suspension and plummet balance (courtesy of J. Loveday).

set (Fig. 2.4). Stoniness also determines the ease, and to some extent the cost of cultivation, as well as the abrasive effect of the soil on tillage implements.

Texture is one of the most stable soil properties and is a useful index of several other properties that determine a soil's agricultural potential. Fine and medium-textured soils, such as clays, clay loams, silty clays and silty clay loams, are generally more desirable than coarse-textured soils because of their superior retention of nutrients and water. Conversely, where rapid infiltration and good drainage are required, as for irrigation or liquid waste disposal, sandy or coarse-textured soils are preferred. In farming terms, clay soils are described as 'heavy' and sandy soils as 'light', which does not refer to their mass per unit volume, but to the power required to draw a plough or other implements through the soil. Because it is easy to estimate, and is routinely measured in soil surveys, texture (and more specifically clay content) has been used as a 'surrogate' variable for other soil properties that are less easily measured, such as the cation exchange capacity (Section 2.5).

Texture has a pronounced effect on soil temperature. Clays hold more water than sandy soils, and the presence of water considerably modifies the heat required to change a soil's temperature because:

Fig. 2.4 Boulders and stones covering the soil surface in a vineyard in the central Rhône Valley, France (see also Plate 2.4).

- Its specific heat capacity is 3–4 times that of the soil solids;
- considerable latent heat is either absorbed or evolved during a change in the physical state of water, for example, from ice to liquid or *vice versa*. Thus, the temperature of wet clay soils responds more slowly than that of sandy soils to changes in air temperature in spring and autumn (Section 6.6).

Texture should not be confused with tilth, of which it is said that a good farmer can recognize it with his boot, but no soil scientist can describe it. Tilth refers to the condition of the surface of ploughed soil prepared for seed sowing: how sticky it is when wet and how hard it sets when dry. The action of frost in cold climates breaks down the massive clods left on the surface of a heavy clay soil after autumn ploughing, producing a mellow 'frost tilth' of numerous small granules (Section 4.2).

2.3 Mineralogy of the sand and silt fractions

Simple crystalline structures

Sand and silt consist almost entirely of the resistant residues of primary rock minerals, although small amounts of secondary minerals (salts, oxides and hydroxides) formed by weathering also occur. The primary rock minerals are predominantly silicates, which have a crystalline structure based upon a simple unit – the silicon tetrahedron, SiO_4^{4-} (Fig. 2.5). An electrically neutral crystal is formed when cations, such as Al^{3+}, Fe^{3+}, Fe^{2+}, Ca^{2+}, Mg^{2+}, K^+ and Na^+, become covalently bonded to the O atoms in the tetrahedron and the surplus valencies of the O^{2-} ions in the SiO_4^{4-} group are satisfied. An example of this kind of structure is the primary mineral olivine, which has the composition $(Mg, Fe)_2SiO_4$.