NSW DEPARTMENT OF
PRIMARY INDUSTRIES

SOILpak – cotton growers - Readers' Note

PART E. BACKGROUND INFORMATION

Chapter E1. Australian cotton soil
Chapter E2. Compaction and hardsetting
Chapter E3. Effects of sodicity and salinity on soil structure
Chapter E4. Clay minerals
Chapter E5. Organic matter and soil biota
Chapter E6. How soil structure and temperature affect plant growth
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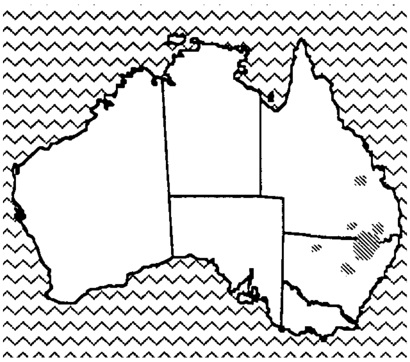
E1. Australian cotton soil



PURPOSE OF THIS CHAPTER

This chapter describes soil types found in the main cotton growing regions of Australia.

CHAPTER OVERVIEW

Major soil types and landscapes of the main cotton growing localities are outlined, and processes associated with their formation are discussed briefly.

Two main soil classification schemes are referred to: the 'Great Soil Groups' classification, and the new 'Australian Soil Classification' scheme devised by Ray Isbell.

Other chapters to refer to are:

- Chapter A2: 'The ideal soil for cotton'
- Chapter A3: 'District soil management problems'.

COTTON GROWING AREAS

The cotton growing areas of New South Wales and Queensland (Figure E1-1) are scattered between the southern latitudes of 23° 30' and 32° 30'.

Most of the cotton is irrigated, with major areas in the Gwydir, Namoi and Macquarie Valleys; near Bourke and Walgett on the Darling River of NSW; and in the St George, Darling Downs, Theodore–Biloela and Emerald districts of Queensland.

Rain-fed cotton in Queensland is grown primarily in the Dawson and Callide Valleys, on the Darling Downs and in the Emerald area. In northern NSW it is grown mainly east of Moree and west of Warialda. Some sowings exist as far south as the Breeza Plains near Gunnedah. In both States there are substantial areas of suitable soil for the expansion of rain-fed cotton sowings, should the economics prove worthwhile.

Figure E1-1. Cotton-growing localities of Queensland and New South Wales.

MAIN SOIL TYPES

Most cotton growing areas in Australia are dominated by cracking clay soil (black earths and grey and brown clays). These are sometimes referred to as Vertosols (Australian Soil Classification terminology) or Vertisols (US terminology).

In the Macquarie Valley, and to a lesser extent in the Namoi and Gwydir Valleys, red–brown earths are a minor component. In many of the Queensland districts, solodic and solodised–solonetz duplex soil types are minor components. These soil types are referred to as either Chromosols or Sodosols or Kurosols, depending on their characteristics and properties (Australian Soil Classification terminology).

Relatively young alluvial soil occurs on levees in the Dawson and Callide Valleys. There are also small areas of alluvial soil in the Macquarie, Upper Namoi, and Gwydir Valleys.

The soil types, and their positions in the landscape, for each of the major districts in Queensland and New South Wales, are described in Table E1-1. Even in their natural condition, most are less than ideal for cotton.

The main features of each soil type are summarised in Figure E1-2.

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See Chapter A2 for more information on the features of an ideal soil for cotton.

Table E1-1. Major soil types and soil landscapes of the Australian cotton industry.

(a) Queensland

Locality	**Soil series**	**Great Soil Group**	**Soil Landscape**
Emerald	B Ug-2	Black earth	Crest, upper and mid slopes of gently undulating basalt rises.
	Tb Ug-2	Black earth	Mid and lower slopes of gently undulating basalt rises.
	A Ug	Black earth and grey clay	Alluvial floodplains and terraces of mixed origins.
Dawson and Callide Valleys	Vermont	Grey clay	Alluvial flood plains of mixed origin.
	Retro	Solodised solonetz and solodic soil	Levees and flood plains of mixed origin.
	Warrinilla	Alluvial soil	Levees of mixed alluvial origin.
	Clemantis	Alluvial soil	Levees of mixed alluvial origin.
Darling Downs	Anchorfield	Black earth	Crests and slopes of very low ridges in alluvial plains of mixed but largely basaltic origin.
	Mywybilla	Black earth	Alluvial plains of mixed origin, some basaltic.
	Condamine	Black earth	Flood plains of mixed alluvium, largely basaltic.
	Waco	Black earth	Fans of basaltic alluvium from nearby hills.
St George irrigation area	Unnamed	Grey clays	Alluvial plains of mixed origin
	Unnamed	Solodised solonetz and solodic soil	Slightly elevated areas in the grey clay alluvial plains.
Waggamba Shire (Macintyre Valley)	Unnamed	Grey clays	Alluvial flood plains of mixed origin.

(b) New South Wales

Macintyre Valley	Unnamed	Grey clays	Alluvial plains of mixed origin.
Gwydir Valley	Unnamed	Black earth	Mid and lower slopes of gently undulating basalt rises.
		Grey and brown clays	Alluvial plains of mixed origin.
		Red–brown earths	Slightly elevated ridges in clay plains.
		Solodised solonetz	Slightly elevated ridges in clay plains.
Namoi Valley	Unnamed	Black earth	Mid and lower slopes of gently undulating basalt rises.
		Grey and brown clays	Alluvial plains of mixed origin.
		Red–brown earths	Slightly elevated ridges in clay plains.
Breeza/Spring Ridge	Unnamed	Black earth	Alluvial plains of basaltic origin.
Macquarie Valley	Mullah/ Buddah/ Snake	Grey and brown clays clays	Alluvial soil of mixed origin, but less basaltic influence than for the Namoi and Gwydir Valleys.
	Mitchell/ Wilga/ Byron	Red–brown earths	
	Macquarie	Alluvial soil	
Bourke	Unnamed	Grey clays	Flood plain of the Darling River.
Walgett	Unnamed	Grey clays	Flood plain of the Barwon/ Darling Rivers.

Cracking clays

Grey and brown clays

Typically, grey and brown clays are moderately deep to very deep clay soil types with a relatively uniform colour and uniform clay content to beyond a depth of one metre. They crack deeply on drying.

The surface structure is often self-mulching—that is, the cracking clay surface develops a soft and crumbly condition composed of fine units after wetting and drying. Sometimes they have a fragile surface crust a few millimetres thick. Less often the surface is hard and poorly structured with widely spaced cracks, such forms usually being associated with lower clay contents. Below about 5 cm there is a rapid change from fine (2-5 mm diameter) to coarse (>50 mm diameter) units, with many large diagonal shear planes (slickensides) below 40 cm.

Often grey and brown clays are alkaline (pH $CaCl_2$> 7) and calcareous (lime nodules present) from the surface down the whole profile. Sometimes they are slightly acid (pH, $CaCl_2$< 7) at the surface and become alkaline and calcareous at shallow depths. Occasionally, especially where brigalow once grew, they may be strongly acid in the deep subsoil, below either an alkaline or slightly acid topsoil.

Naturally occurring gypsum may or may not be present in the deep subsoil. Surface soil salinity is low, but below 0.5 to l.0 m, low to high amounts of soluble salts occur. Surface soil is generally non-sodic, but subsoil is often sodic to strongly sodic.

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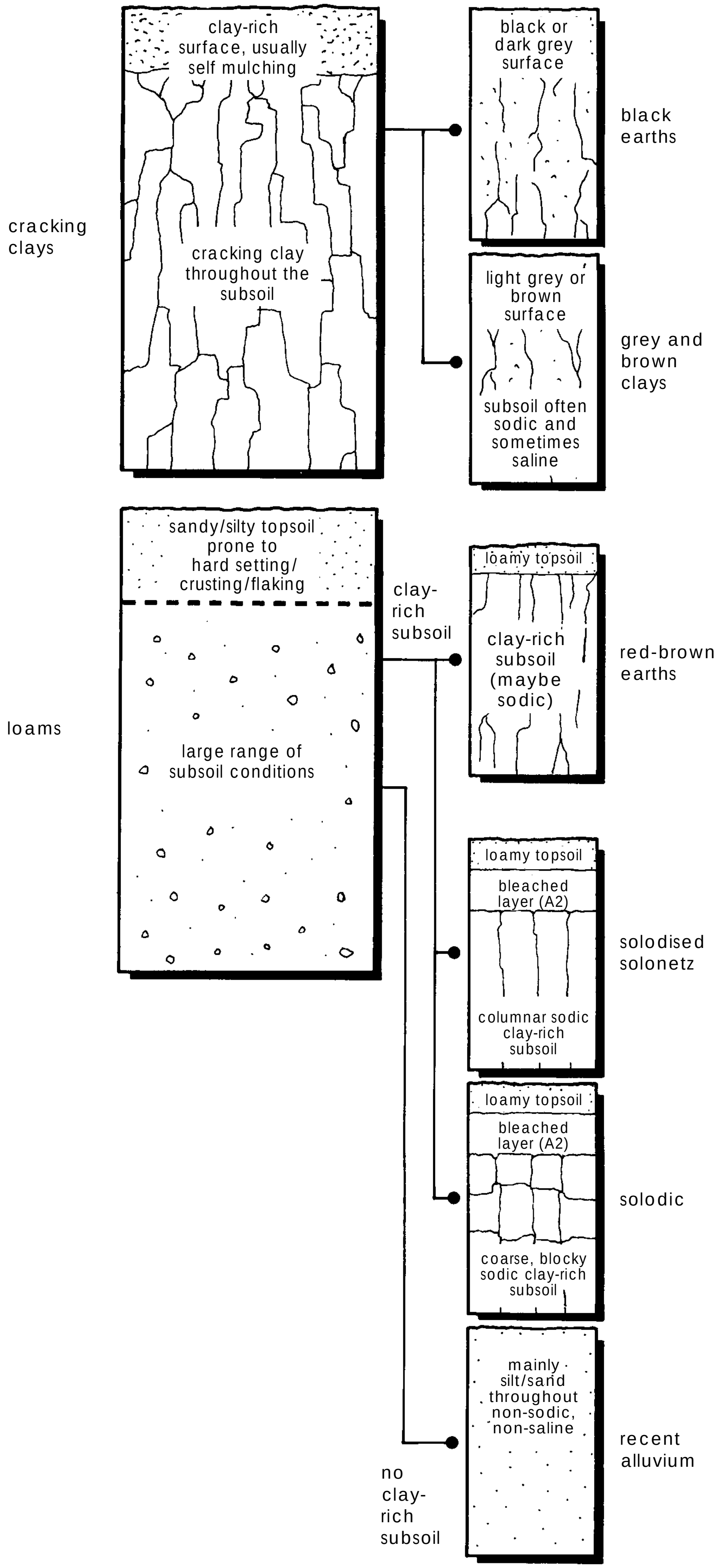
See Chapter E3 for a definition of sodicity and salinity.

Figure E1-2. Main features of contrasting soil types used for cotton production in Australia.



Black earths (black self-mulching clays)

These very dark grey brown or almost black clay soil types are typically alkaline, although the upper 25 to 30 cm are sometimes near neutral (pH $CaCl_2$ = 7). They develop closely spaced, wide, deep cracks on drying. The surface is usually strongly self-mulching, with aggregates grading through fine to coarse in the subsoil, with diagonal shear planes below about 40 cm.

Lime is usually present in the subsoil and soluble salts are present in low or moderate amounts. Anchorfield (Darling Downs) and the BUg-2 (Emerald) black earths have non-sodic subsoil; other black earths may have sodic or strongly sodic subsoil.

Some of the black earths are formed directly on basalt (a dark, fine-grained volcanic rock), as at Emerald. Others, for example those listed for the Darling Downs, are generally deeper and overly clayey materials deposited after movement by water.

Classifying cracking clays using the Australian Soil Classification system

The terms ‘grey clay’, ‘brown clay’ and ‘black earth’ come from the ‘Great Soil Groups’ soil classification system (see Stace et al. 1968—reference in Appendix 1). Australian soil is now being classified using the ‘Australian Soil Classification’ (ASC) soil classification system (see Isbell, 1996—reference in Appendix 1). Definitions of soil types based on the ASC have been obtained from Isbell (1996) and Isbell et al. (1997) (see Appendix 1).

Using the ASC system, grey and brown clays and black earths will be classified as Vertosols at the first hierarchical level (Orders). There are five hierarchical levels in the ASC: Order, Suborder, Great Groups, Subgroups and Family Criteria.

For a soil to be classified as a Vertosol it must have all of the following features:

- a clay field texture, or 35% or more clay throughout the soil profile, except for thin, crusty horizons 30 mm or less thick
- when dry, open cracks occur at least some time in most years. These are at least 5 mm wide and extend upward to the surface or to the base of any plough layer, self-mulching horizon, or thin, crusty horizon.
- slickensides and/or lenticular peds at some depth in the soil profile.

Many Vertosols are self-mulching. Gilgai micro-relief is sometimes associated with Vertosols, but it is not restricted to this soil type.

At the second hierarchical level (Suborders) Vertosols are primarily distinguished by colour. Therefore grey clays will be ‘Grey Vertosols’; brown clays, ‘Brown Vertosols’; and black earths, ‘Black Vertosols’. Further subdivision reflects other soil characteristics such as self-mulching behaviour, presence of a thin surface crust, acidity, salinity and sodicity.

Written in full, an example of a cracking clay classified using the ASC is:

Endohypersodic, Self-mulching, Grey Vertosol; non-gravelly, medium fine, very fine, very deep.

This name can be shortened, depending on how many levels of the hierarchy can be determined, for example, *Self-mulching, Grey Vertosol.*

The above Vertosol would be dominantly grey in the major part of the upper 0.5 m of the profile, self-mulching and have a sub-horizon below 0.5 m that has an ESP of 15 or greater. The surface of the soil and A1 (topsoil) horizon would contain less than 2% gravel, the clay content of the upper 0.1 m (excluding any surface crusty horizon) would be between 45 and 60%, the B horizon maximum clay content would be greater than 60% clay, and the depth of the soil would be 1.5–5.0 m.

Soil with a loamy topsoil

Red-brown earths

A reddish sandy, fine sandy, silt loam or clay loam surface layer (often weakly structured with few shrinkage cracks, and 10 to 45 cm thick) overlies a red–brown clay subsoil, usually with well defined clods separated by cracks.

Red–brown earths may have an A2 horizon in the lower topsoil. An A2 horizon is identified by the fact that it is paler than the A1 horizon above and the B horizon below. It is pale because it has less organic matter than the A1 horizon and because iron has leached from it (a sign of periodic waterlogging).

The deeper subsoil is usually yellowish or olive-brown, contains some lime, and is more friable and sandier than the upper subsoil.

The surface is usually slightly acid to acid, while the subsoil is normally alkaline and sodic or strongly sodic, sometimes containing appreciable soluble salts in the lower part.

After cultivation and subsequent loss of organic matter, red–brown earths may develop a hardsetting layer in the surface soil. Surface crusting is common.

Using the ASC system, red-brown earths (Great Soil Groups terminology) will be classified as either Chromosols, Sodosols or Kurosols at the Order level. Because they are dominantly red in the B2 horizon (subsoil) they will be known as Red Chromosols, Red Sodosols or Red Kurosols at the Suborder level.

Chromosols have a strong texture contrast between A and B horizons. Their B2 horizons are not strongly acid and are not sodic (ESP < 6) in their upper 0.2 m (or the major part of the B2 horizon if it is less than 0.2 m thick). Strongly acid soil is considered to have a pH of less than 5.5 (1:5 soil:water) or less than 4.6 (1:5 soil:0.01 M $CaCl_2$). Hardsetting in Chromosols can be exacerbated after years of cultivation.

Sodosols, which cover 13% of Australia, have the same features as Chromosols, except that the upper 0.2 m of the B2 horizon is sodic (ESP > 6). The sodic clay B horizons of Sodosols generally have a restricted hydraulic conductivity. This poor internal drainage can result in a seasonal perched watertable. Many Sodosols are hardsetting. Because the B horizons are sodic and highly dispersive they are particularly prone to tunnel and gully erosion if they are exposed to wind and water.

It is not likely that cotton is grown on naturally occurring Kurosols, as they are not widespread in Australia. Like the Chromosols and Sodosols they have a strong texture contrast between the A and B horizons, but the upper part of the B2 horizon is strongly acidic and may or may not be sodic. Agricultural practices may lead to Chromosols and Sodosols becoming Kurosols.

Solodised solonetz and solodic soil (red pine soil)

The surface layer of grey-brown sandy loam to clay loam is usually conspicuously bleached in the lower part. The surface layer abruptly overlies a sodic clay or sandy clay subsoil.

A solodised solonetz subsoil has a strong coarse columnar structure. A solodic subsoil is coarsely cloddy. The surface and upper subsoil are acid, grading to strongly alkaline horizons with lime and gypsum at depths below 60–90 cm. Limited data suggest that, in general, their subsoil is sodic, rather than strongly sodic.

Solodised solonetz and solodic soils can be classified as either Chromosols, Sodosols or Kurosols using the ASC system. Unlike the red-brown earths, they are not red in the subsoil, and so will not be defined as 'Red' at the Suborder level. They will likely be classified as 'Yellow' at the Suborder level.

Alluvial soil (river soil)

Soil types with a broad range of clay contents occur on young alluvium. They show variable organic matter accumulation in the darker surface horizons, overlying layers of gravel, sand, loam, and clay. They tend to be non-saline and non-sodic.

HOW AUSTRALIAN COTTON SOIL WAS FORMED

An understanding of how the different types of cotton soil were formed provides a framework for the transfer of soil management knowledge between different parts of a valley, as well as between neighbouring cotton growing districts. A knowledge of the location and features of old stream channels associated with the soil types helps us to predict, for example, which cotton soil is most prone to deep drainage losses.

In previous centuries, when the climate was much wetter, western rivers were a lot larger than they are today. Large amounts of gravel and sand were deposited during floods and underlie many Australian cotton fields.

The wet periods were interspersed with extremely arid periods when large amounts of dust and salt were deposited over the Murray–Darling Basin.

These events, and their effect on modern-day soil condition in the lower Macquarie Valley, have been described by CSIRO staff (see the 'Further Reading' section, Appendix 2). District geological maps provide similar, but less detailed, information.

KEY SOIL PROPERTIES– STATUS IN 1998

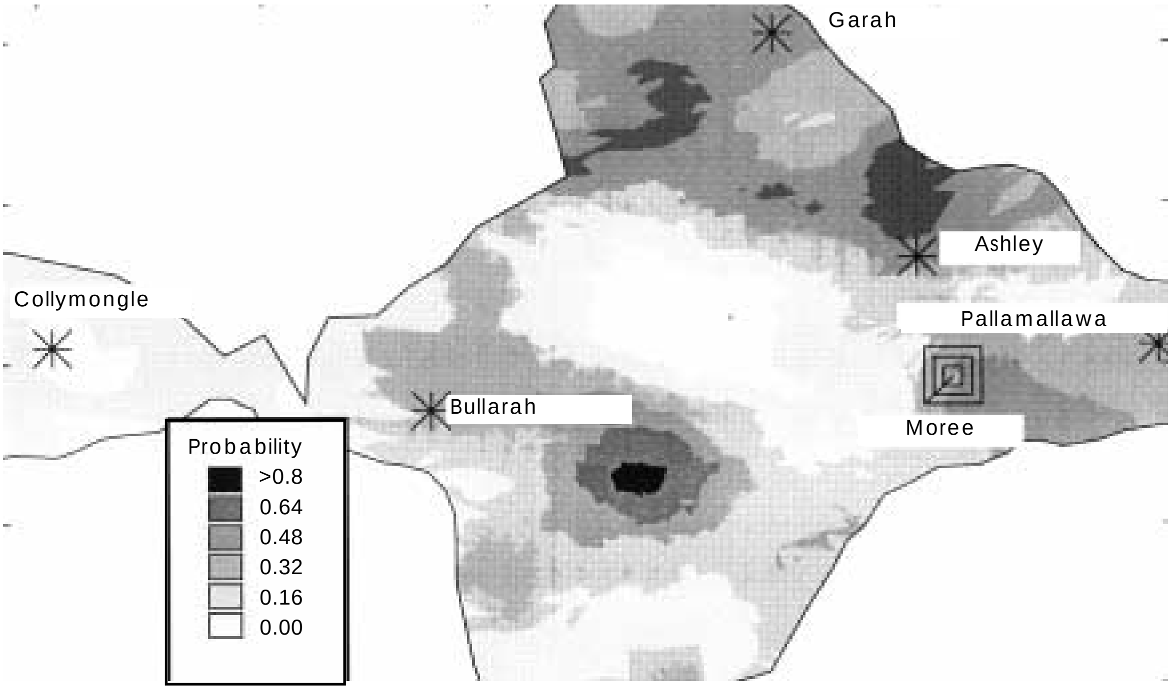
Sodicity and salinity

Sodicity and salinity trends in the Macintyre, Gwydir and Namoi Valleys are being mapped by staff at the Cotton CRC, University of Sydney. A sample of their information is shown in Figure E1-3.

Preliminary analysis of the lower Macintyre soil data set has found that:

- salinity increases from east to west across the valley, with subsoil EC_e values ranging from 0.2 to 27.0 dS/m.
- the pH of soil on irrigated cotton farms ranges from 4.7 to 9.7.

Figure E1-3. Map of the lower Gwydir Valley, showing the probabilities of needing gypsum for soil structural improvement



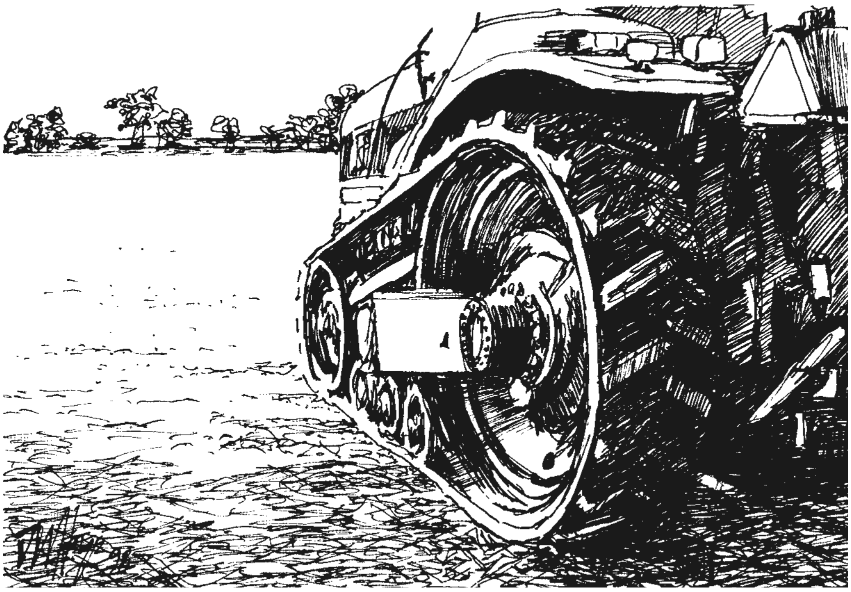
Other soil factors

Ideally, as well as having maps of sodicity and salinity, we need to develop maps (preferably at a scale of 1:25,000 or less) of the following soil factors for all cotton growing districts:

- shrink/swell potential
- organic matter
- pH
- nutrients
- compaction severity/risk.

Such maps should be accompanied by watertable and crop productivity maps. Geographic Information System packages are available to organise this information in an orderly fashion on desktop computers.

E2. Compaction and hardsetting



PURPOSE OF THIS CHAPTER

This chapter provides an overview of compaction and hardsetting processes in cotton soil.

CHAPTER OVERVIEW

The following points are covered:

- soil pores influenced by compaction
- the importance of soil water content
- processes associated with soil compaction:
  - —vehicle contact pressure (near-surface)
  - —vehicle pressure (subsoil)
  - —deep clay movement
  - —deep subsoil swelling
- smearing (compaction in narrow bands)
- remoulding
- hardsetting and crusting.

Other chapters to refer to are:

- Chapter E6: ‘How soil structure and temperature affect plant growth’.

INTRODUCTION

Compaction refers to the compression of a soil or a layer to give increased bulk density (that is, decreased porosity). Compression usually results from a vertical force, such as that produced by wheeled or tracked vehicles, on soil that is too moist and soft (wetter than the plastic limit) to resist deformation. Compaction may be accompanied by remoulding, which is the rearrangement of soil pores without an increase in bulk density.

Soil bulk density can also increase when an inherently unstable soil slumps in water and then suffers hardsetting or crusting when dried.

SOIL PORES INFLUENCED BY COMPACTION

The larger (and generally most useful) pores are the most easily compressed under wheels, because they are more likely to be full of air; the air is forced out of the soil when compacted. Smaller pores are less easily compressed. They are more likely to be full of water, which cannot be compressed and is not easily squeezed out of the soil. Completely saturated soil does not compress, because water is incompressible and there is no air to be lost. However, these pores may be rearranged (remoulded) if the vertical force is accompanied by a horizontal force (such as the wheel slip of a tractor).

Soil pores form the living space for plant roots and soil-dwelling organisms. The space is dynamic, changing with soil moisture content and outside forces. A good soil structure consists of relatively stable, interconnected pores with a range of sizes. The range in size of different soil components is shown in Figure E2-1.

Macropores are large enough to drain at field capacity. They are sometimes called ‘transmission pores’ because of their role in transmitting air and water through the soil. They include shrinkage cracks, burrows made by soil animals and old root channels. Not only must there be sufficient macropores, but they must also be stable and vertically continuous from the surface to near the bottom of the root zone. As well as permitting rapid water entry, they allow the root zone to quickly re-aerate after rain.

Mesopores are small enough to retain water at field capacity, but large enough for the water to be available to plants. They are sometimes called ‘storage pores’ because of their role in storing water for plant roots.

THE IMPORTANCE OF SOIL WATER CONTENT

The ability of a soil to resist compaction decreases as the soil water content becomes greater (Figure E2-2). There is approximately a 100-fold difference in soil strength between field capacity and wilting point. In contrast, the range in pressures under vehicles used for cotton production is about 7-fold. This means that soil water content has a much greater influence on soil compactibility than vehicle factors.

PROCESSES ASSOCIATED WITH SOIL COMPACTION

Vehicle pressure (near-surface)

The severity of surface and sub-surface compaction is related mainly to the ground contact pressure of tyres/tracks.

Tracked vehicles generally have a ‘softer footprint’ than wheeled tractors, particularly at depth, but there can be high-pressure peaks

Figure E2-1. The range in size of different soil components (source: Kay, 1990).

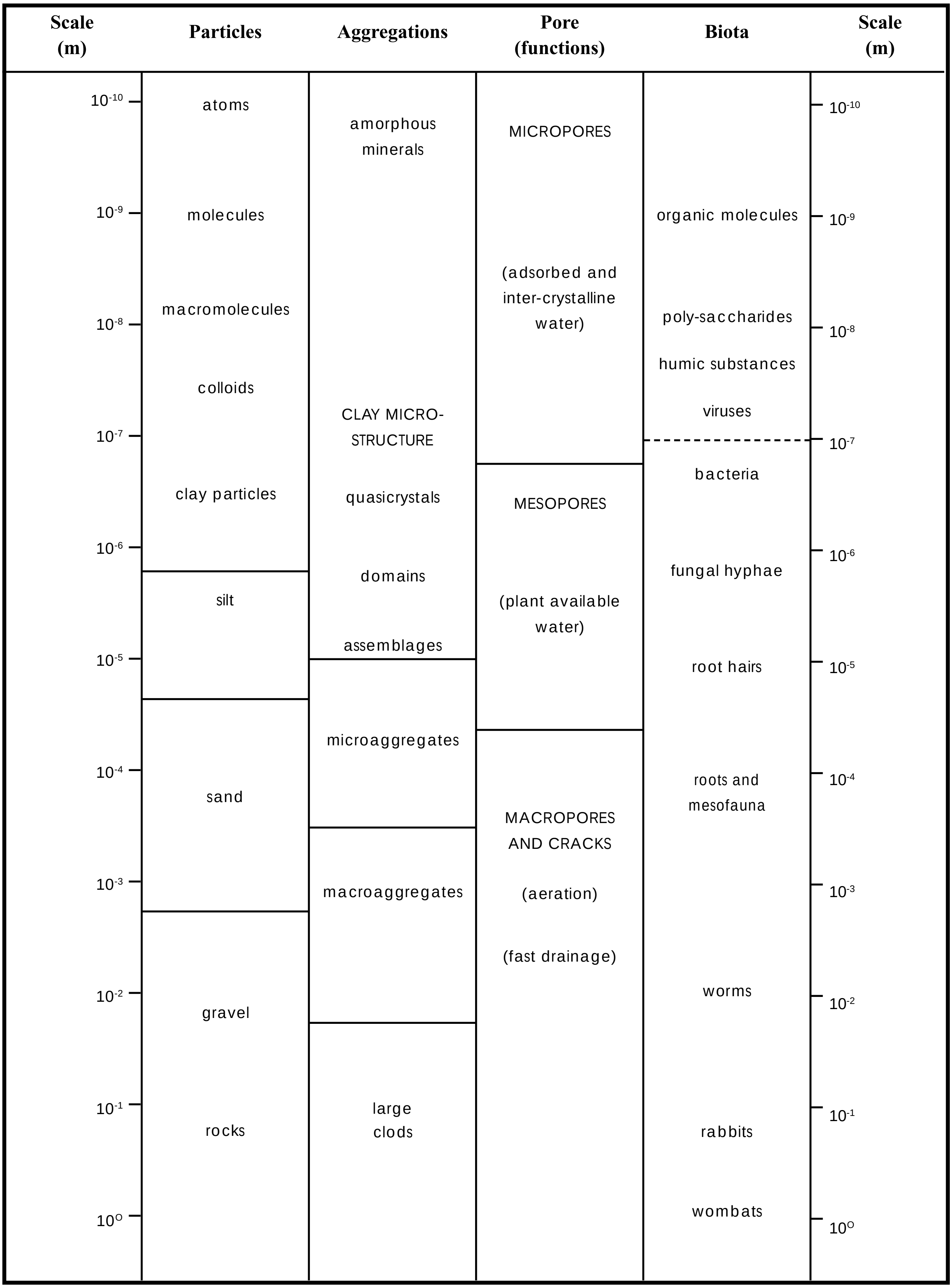
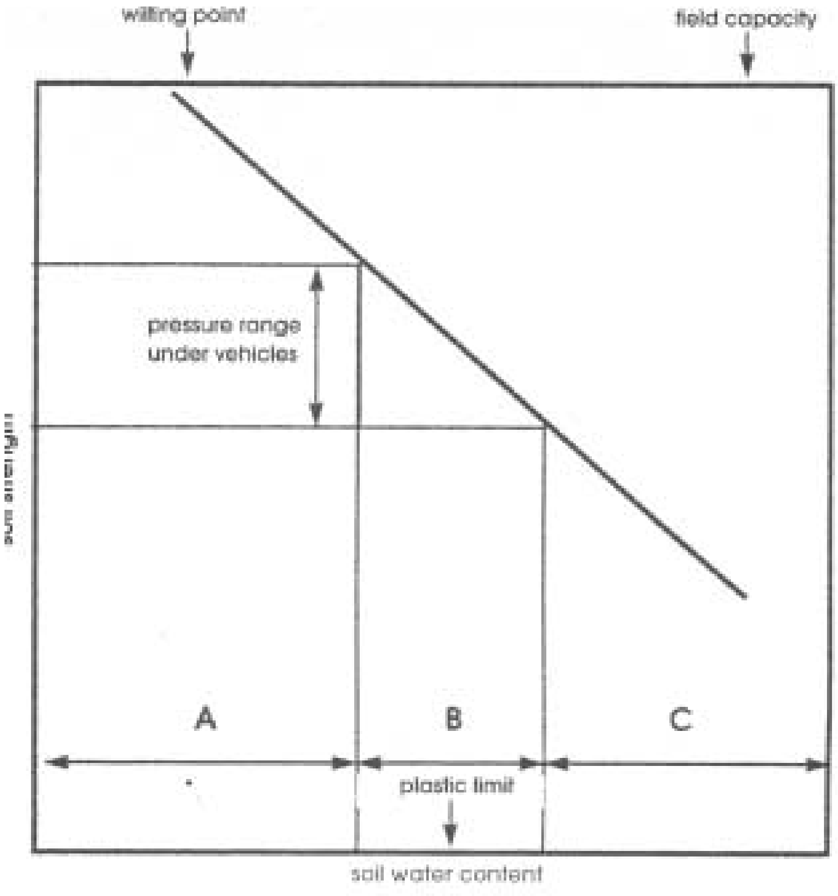


Figure E2-2. Soil strength in relation to soil water content (schematic). When cotton vehicles are driven on wet soil (zone C), compaction and/or remoulding will occur. The same vehicles on zone A soil, which is drier than about the plastic limit, will be supported without damage to the soil.



below each idler on the bogey, and there tends to be a large peak at one end of the track. The largest peak for a tracked machine tends to be lower than for an average tyred vehicle, but can be as much as two to three times the calculated average pressure under a track. The main benefit of tracks appears to be better traction, and more efficient use of engine power.

Once compaction has occurred at a given moisture content, subsequent passes of the compacting force will only marginally increase the amount of compaction; 80–90% of the damage occurs during the first pass of equipment on moist soil. However, this figure will be much lower if the first pass occurs on drier soil than the second pass. The amount of compaction tends to decrease as vehicle speed increases.

It is important that tyres or tracks be narrow enough to avoid bridging across the furrow and compression of the bed edges. Having a flat bottom in the furrow, rather than a V-shape, also reduces bed shoulder compaction.

Compaction of the topsoil and sub-surface is unavoidable—the main priority is to restrict it to narrow laneways as part of a controlled traffic farming system.

Vehicle pressure (subsoil)

Deep subsoil compaction (that is, below a depth of about 30 cm) is more a function of total axle load rather than tyre pressure and width, particularly when the axle load is greater than about 10 t. Axle loads as great as 14 t occur under cotton pickers.

Research in Sweden has shown that machinery pressures can penetrate to as deep as 80 cm. The forces may penetrate even deeper in situations where the wheels of heavy machinery rest on ‘pillars’ of dry soil (in between large vertical shrinkage cracks) that act like pistons and push into moist soil deep in the profile. Recent studies by workers from Southern Cross University found that cotton farming near Warren had increased oven-dry bulk density (from 1.77 to 1.84 t/m^3) at a depth of 190–205 cm.

The use of dual wheels to spread the weight of heavy machinery will reduce deep subsoil compaction only when the wheels are spaced by more than about 1.5 m. A tandem arrangement of wheels is likely to be a better option for load spreading because it compacts a smaller proportion of a field than a dual arrangement.

Subsoil compaction is unavoidable—the main priority is to restrict it to ‘narrow pillars’ of soil underneath the wheeled furrows.

Deep clay movement

Clay dispersion, whereby individual clay particles separate from soil microaggregates, can occur spontaneously or be aggravated by remoulding. An example of remoulding is the rearrangement of wet soil by the wheel slip of a tractor. The dispersed clay particles block pores; on drying, the dispersed soil sets hard, with fewer large pore spaces. It has been observed that run-off water from wheel tracks contains more dispersed clay than run-off from unwheeled furrows.

Recent studies near Warren and Narrabri have shown that translocated clay does not have a major effect on soil bulk density, but coatings on clods may retard the growth of root hairs seeking water and nutrients.

Deep subsoil swelling

Deep subsoil will become more prone to swelling if sodicity increases (due, for example, to translocation of sodium from gypsum-treated topsoil), and/or if salinity decreases (due to an increase in the amount of deep drainage). An increase in the amount of swelling in a confined space is likely to decrease soil porosity under moist conditions.

Smearing (compaction in thin layers)

Smearing is the realignment of clay particles from a random to a parallel orientation, producing a hard, shiny surface overlying a thin layer with high bulk density. It results from horizontal shear forces, produced by, for example, a blunt tine moving through moist soil. Smearing may impede water and air movement and root growth, but these problems do not persist for long in a cracking clay soil, providing the soil undergoes restructuring by shrinking and swelling.

Remoulding

Remoulding refers to the rearrangement of soil pores (usually with a reduction in pore continuity) without an increase in soil bulk density. It is associated with tractor wheel slip in very wet soil.

Slumping and hardsetting

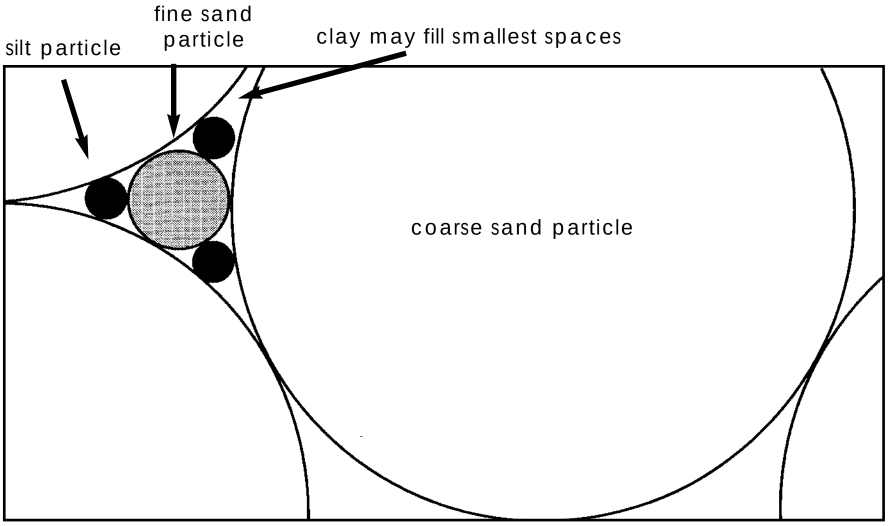
A hardsetting soil is one that becomes massive (poorly structured) or cemented throughout a significant proportion of the soil profile, due to wetting and slumping followed by drying. In hardset layers, pores may be observed, but they tend to be disconnected. Hardsetting can occur in soil that has never been cultivated. Hardset layers, although very hard when dry, are quite soft when wet.

Factors that influence the hardsetting potential of a soil include:

- particle-size distribution
- dominant clay minerals in the clay fraction
- dispersibility (sodicity and electrolyte concentration)
- the organic matter content
- the presence of cementing or stabilising materials.

The particle size distribution (amount of clay, silt and sand) in a soil has a major role in determining whether a soil will be hardsetting or not. Hardsetting is most common in soil with a high content of silt and fine sand (Figure E2-3). In a hardsetting soil, the particle size distribution is such that the individual soil particles will pack down to a high density upon wetting; it is a 'concrete-like' mixture.

Figure E2-3. Theoretical packing of spherical particles.



The clay minerals that dominate the clay fraction also determine whether a soil will have the potential to be hardsetting. If the main clay minerals are kaolinite and/or illite, hardsetting will be more likely. If the main clay mineral is smectite, and the clay content is high enough, the soil will swell and shrink and the soil will be able to regenerate itself if any hardsetting does occur. Kaolinite and illite do not swell much when they absorb water. This prevents a hardset soil from repairing itself quickly.

Hardsetting becomes worse as the amount of exchangeable sodium increases (and as the salt concentration in soil solution decreases), because there will be a greater proportion of dispersible clay. When the clay disperses it blocks pores, resulting in close packing of soil particles and very small pore sizes. The soil becomes very hard upon drying, because of the tightly packed structure.

Other factors that play a role in hardsetting are low amounts of organic matter (less than 2%) and the presence of cementing or stabilising materials (for example, aluminosilicate cements).

The structure collapses upon wetting and the soil hardens—without regeneration of structure—during drying. It involves:

- **slumping.** Hardset soil has not developed water-stable aggregates and so slumps when wet; the aggregates disintegrate by softening and swelling, often by slaking, and sometimes by dispersion of the clay fraction. When the soil slumps, small particles pack between larger particles.
- **uniaxial shrinkage.** The closer the particles are to one another, the greater the strength of the soil after drying.
- **hardsetting and the development of soil strength.**

Consequences of having a hardsetting layer are:

- timing of cultivation is restricted
- seedling emergence will be restricted
- root penetration will be restricted
- aeration will be limited, particularly when the soil is wet
- drainage of water through the soil profile will be reduced
- waterlogging or a perched watertable may occur
- run-off and erosion will increase.

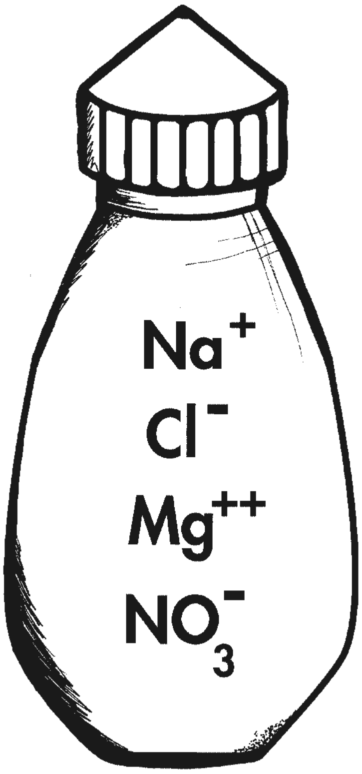
Crusting

A crust is a transient soil surface layer that is denser or more cemented (with less pore space) than the soil beneath it. Because it is denser, it will be more waterlogged when wet and stronger when dry than the more porous soil beneath it.

Crusts usually range in thickness from a few millimetres to a few centimetres. They may be separated and lifted off the soil below, which is usually loose.

Crusting of soil is a widespread problem; it usually results after rainfall on bare, cultivated soil. Crusting is more common on soil that is prone to slaking in water due to a lack of organic matter, and that has a high percentage of silt or fine sand. Instability in water is aggravated by the presence of excessive exchangeable sodium and inadequate salt concentration.

E3. Effects of sodicity and salinity on soil structure



PURPOSE OF THIS CHAPTER

This chapter explains the difference between sodicity and salinity, and describes how they interact to affect soil stability in water.

CHAPTER OVERVIEW

The following points are covered:

- sodicity
- salinity
- gypsum and lime.

Other chapters to refer to are:

- Chapter C4: 'Structural condition'.
- Chapter C7: 'Salinity'.
- Chapter D4: 'Avoiding salinity problems'.
- Chapter E4: 'Clay minerals'.

For further information, see the NSW Agriculture Agfact *Improving soil structure with gypsum and lime.*

INTRODUCTION

Sodicity refers to the proportion of exchangeable sodium cations held on the surface of clay particles. The greater the proportion of sodium in the total exchangeable cations, the more sodic the soil is. Excessive exchangeable sodium promotes clay dispersion—an undesirable condition. Excessive clay swelling and pore blockage are more of a problem when sodicity problems are confined to the subsoil.

Salinity refers to the amount of dissolved salt in the soil solution between soil particles and between soil clods. It includes both anions and cations of all salts. A large concentration of any salt gives high salinity. Increasing salinity improves soil structural stability, but it becomes more difficult for plant roots to absorb water.

SODICITY

How is sodicity measured?

A sodic soil has a strong tendency to disperse in water. The field signs are shown in Figure E3-1; note the separation of pale, fine sand from the dispersed clay.

Sodicity is determined by the exchangeable sodium percentage (ESP):

ESP = (exchangeable sodium ÷ sum of exchangeable cations) x 100

The major exchangeable cations are calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), potassium (K^{+}) and aluminium (Al^{3+}). Under alkaline conditions, the sum of exchangeable cations is approximately equal to the actual ‘cation exchange capacity’ (CEC). A sample calculation of ESP is shown below, using the values given in Table E3-1. Quantities of cations are commonly given in centimoles of positive charge per kg of soil (cmol(+)/kg).

Figure E3-1. Appearance of clods of sodic soil after wetting and drying.

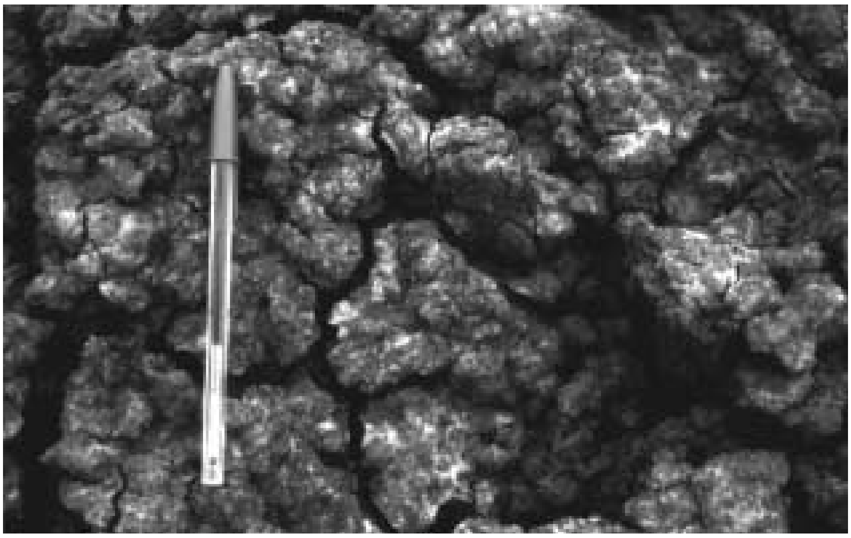


Table E3-1. Quantities of exchangeable cations found in a grey cracking clay soil near Warren at a depth of 0–10 cm.

Cation	Quantity of cation (cmol(+)/kg)
Ca^{2+}	22.6
Mg^{2+}	9.5
Na^+	0.4
K^+	2.1

Example

To find the ESP of the soil described in the above table:

Sum of exchangeable cations (cmol(+)/kg) = 22.6 + 9.5 + 0.4 + 2.1
= 34.6

ESP (%) = (exchangeable Na^+/sum of exchangeable cations) x 100
= (0.4 ÷ 34.6) x 100
= 1.1.

Critical ESP values range from 2 to 15, due mainly to differences in soil salinity. The relationship between dispersion, sodicity and salinity will be discussed later in this chapter.

Why does sodic soil disperse?

An excess of exchangeable sodium relative to other exchangeable cations causes soil to disperse because of its effect on the thickness of the diffuse double layer.

☞

See Chapter E4 for more information on the properties of clay minerals.

A large amount of exchangeable sodium relative to other exchangeable cations results in a fat double layer, while a large amount of exchangeable calcium relative to other exchangeable cations results in a thin double layer (Figure E3-2). A fat double layer results in dispersion, while flocculation occurs when there is a thin double layer.

A fat double layer promotes dispersion, because the negatively-charged clay surfaces are held together inadequately by the positively-charged cations that lie between them. The addition of water to the soil forces these individual clay surfaces even further apart, particularly when the cations are weakly charged.

What determines the thickness of the double layer?

The valency of exchangeable cations determines the thickness of the double layers. The higher the valency of the dominant exchangeable cation, the thinner the double layers. Sodium has a valency of 1 (Na^+) while calcium has a valency of 2 (Ca^{2+}). A soil with a high level of exchangeable aluminium will have very thin double layers because it has a valency of 3 (Al^{3+}). Al^{3+} can be pictured as a ‘magnet’ having 3 times the strength of a Na^+ ‘magnet’.

Differences in the thickness of the double layer occur even with cations with the same valency, for example, calcium and magnesium. The hydrated magnesium cation is larger than the hydrated calcium cation, which forces clay platelets apart.

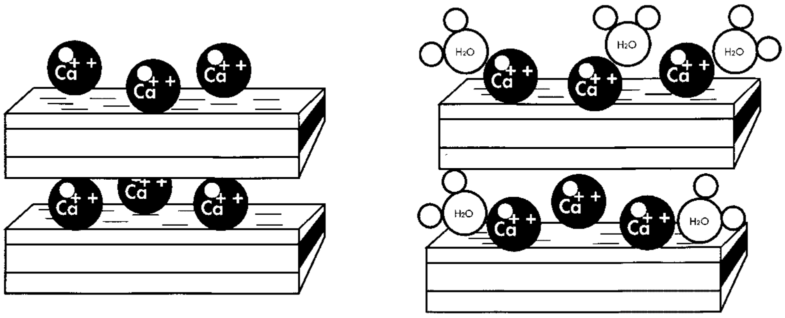
Relationship between the exchangeable sodium percentage (ESP) and the sodium adsorption ratio (SAR)

The concentration of sodium in the double layer (ESP) is in equilibrium with sodium in the soil solution (SAR). This means that

Figure E3-2. The reaction of sodic and non-sodic clay to the addition of water.

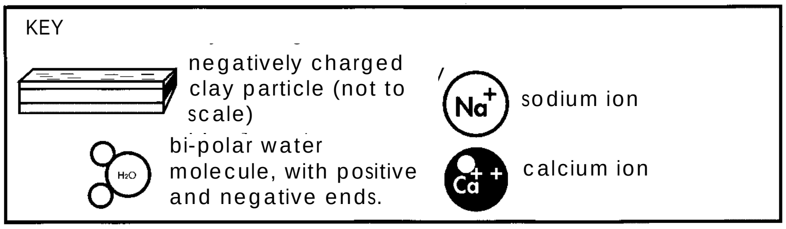
non-sodic clay

non-sodic clay and water



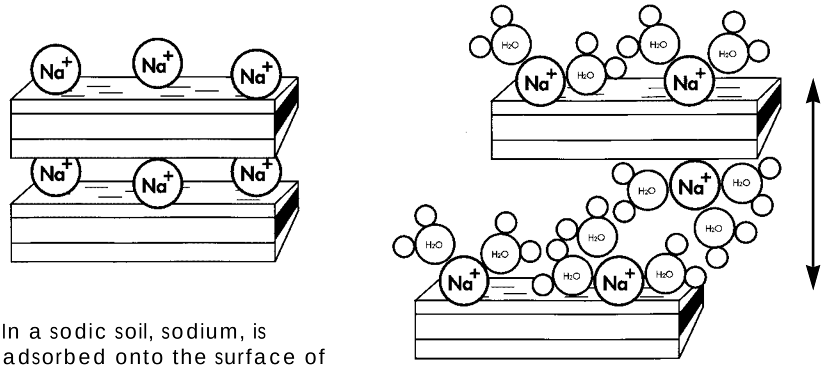
In a non-sodic soil calcium is adsorbed onto the surface of the negatively charged clay particles. This is a small ion with a strong charge.

Water can enter between the platelets in a non-sodic soil, which leads to swelling. However, the binding forces between the particles by calcium ions are never completely overcome. The soil does not disperse.



sodic clay (high ESP)

sodic clay + water



In a sodic soil, sodium, is adsorbed onto the surface of the clay. It is a large ion with a weak charge. The positive ions bind the negatively charged clay particles together.

As water is added to a sodic soil the water is attracted to the sodium. The ions hydrate, forcing the plates apart. The ions' role in binding the clay platelets is overcome, and the clay swells then disperses with water.

ESP can be estimated by measuring sodium concentration in the soil solution, in relation to calcium and magnesium, although the relationship varies from one site to another:

$$\mathrm{SAR} = \mathrm{Na} \div [-(\mathrm{Ca} + \mathrm{Mg}) \div 2]$$

$$\mathrm{ESP} = \frac{100\,(-0.0126 + 0.01475\ \mathrm{SAR})}{1 + (-0.0126 + 0.01475\ \mathrm{SAR})}$$ (this relationship is specific to Californian soil)

SALINITY

A saline soil is one that contains sufficient water-soluble salts (electrolytes) to adversely affect the growth of most plants. The water-soluble salts are mainly of sodium, calcium and magnesium, and may be chlorides, sulfates or carbonates.

Some plant species are extremely sensitive to salt, while others are extremely tolerant.

A benefit of salinity, however, is that it improves soil structure. The process is described below.

See Chapter C7 for details on the salt sensitivity of different plants.

RELATIONSHIP BETWEEN SODICITY AND SALINITY

When the soil is sodic, clay dispersion declines as the salt concentration of the soil solution becomes greater.

If the soil is sodic and the salt concentration is negligible, the soil will disperse severely. This occurs when rainwater (with a low electrical conductivity—EC) falls on to a saline sodic soil. Some salt is necessary to prevent the soil dispersing. Even if a soil has an ESP as low as 2, it may disperse if the EC of the soil is negligible. It must be remembered, however, that even though high salt levels will prevent the soil dispersing, they will adversely affect crop growth.

A convenient way of expressing the relationship between sodicity and salinity is to calculate the 'electrochemical stability index' (ESI):

$$\text{ESI} = \frac{\text{EC}_{1:5}\ (\text{dS/m})}{\text{ESP}}$$

ESI values less than 0.05 indicate soil dispersion problems.

GYPSUM AND LIME

Gypsum and lime may be used to help to overcome soil structure problems associated with sodicity.

How does gypsum improve soil structure?

There are two reasons why gypsum (calcium sulfate—$CaSO_4.2H_2O$) improves soil structure. Both require the gypsum to be dissolved so that it can enter the soil solution.

- The dispersion of sodic soil decreases as the salinity of the soil solution increases. By adding gypsum, which is a mildly soluble salt, the salinity of the soil solution increases. The effect is only short-term, because it ceases when the applied gypsum has been leached from the soil.
- The second reason why gypsum improves soil structure is that calcium entering the soil solution exchanges with sodium and magnesium on the clay.

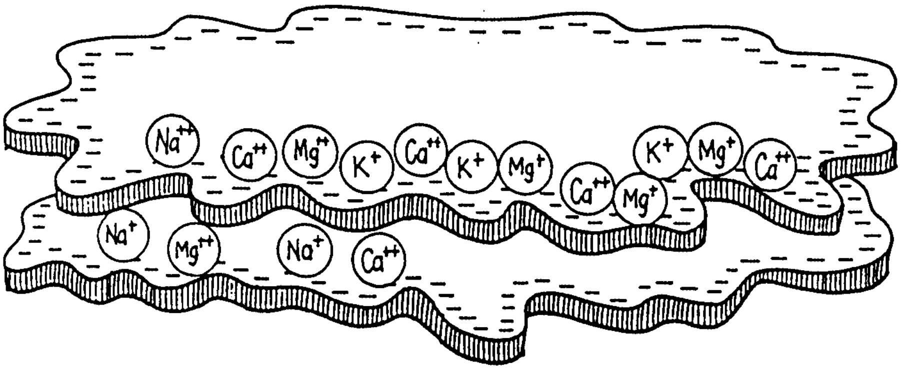
As a result of the clay becoming dominated by exchangeable calcium, clay dispersion and swelling are reduced. The sodium cations that are released into the soil solution are leached below the root zone, where their presence is less crucial than nearer the surface.

When is lime useful?

Lime (calcium carbonate—$CaCO_3$), another calcium compound, can also be used to improve soil structure, either by itself or in a mixture of lime and gypsum. Lime can be used to improve soil structural stability when the pH (in $CaCl_2$) is below about 6.5.

Lime is much less soluble in water than gypsum, but both compounds improve structure via the electrolyte and exchangeable cation effects. In some situations, lime may also act as a cementing agent.

E4. Clay minerals



PURPOSE OF THIS CHAPTER

This chapter provides an overview of the properties of some common clay minerals found in Australian cotton soil.

CHAPTER OVERVIEW

The following topics are considered:

- the structure of clay minerals
- the effect of clay minerals on swell–shrink behaviour
- the influence of positive ions (cations) on swell–shrink behaviour
- clay as a colloid—dispersion and flocculation
- the effects of total salt concentration, pH and clay type on dispersion and flocculation.

STRUCTURE OF CLAY MINERALS

The clay fraction of the soil consists of mineral particles with a diameter less than 0.002 mm. Many chemical and physical properties of the soil depend not only on the amount of clay the soil contains, but also on the type of clay.

There are many types of clay minerals: kaolinite, smectite (montmorillonite), illite (mica), vermiculite and chlorite for example. They result from the weathering of various minerals in rock.

Clay minerals are made up of a number of crystalline sheets. There are two types of sheet: tetrahedral (silicate) and octahedral.

Tetrahedral sheets are made up of silicon (Si^{4+}) and oxygen (O^{2-}). Octahedral sheets are made up of hydroxide (OH^{-}) and either aluminium (Al^{3+}) or magnesium (Mg^{2+}). An octahedral sheet is referred to as dioctahedral if it contains aluminium, and trioctahedral if it contains magnesium.

The different clay minerals are made up of various combinations of tetrahedral and octahedral sheets. For example, kaolinite is made up of one tetrahedral sheet plus one octahedral sheet (1:1 layer), while smectite and illite are made up of two tetrahedral sheets and one octahedral sheet (2:1 layer) (Figure E4-1).

The space between layers (for example, two tetrahedral sheets plus one octahedral sheet) is known as the interlayer space. The interlayer space may contain positive ions known as cations (for example, potassium—K^{+}). Different clay minerals contain different cations in the interlayer space. The interlayer spacing of kaolin does not contain cations, because the layers are held together by hydrogen bonding.

The basal spacing of a clay mineral is the distance from the top of one layer to the top of the next layer. The basal spacing varies among clay minerals.

SWELL-SHRINK BEHAVIOUR OF CLAYS

The physical characteristics of clays change with their chemical composition. Some clay minerals swell when wet. Soil types with their clay fraction dominated by a clay mineral that swells when wet show strong swell–shrink behaviour.

Kaolinite shows little expansion on absorption of water and is therefore used for ceramics. Illite also shows little expansion on absorption of water.

Smectite, on the other hand, shows large expansion on absorption of water. Therefore clay soil types with the clay fraction dominated by smectite swell markedly when they become wet. Cracking clay soil types contain a large proportion of smectite in their clay fraction. Smectite is used in agriculture as ‘bentonite’ for sealing dams.

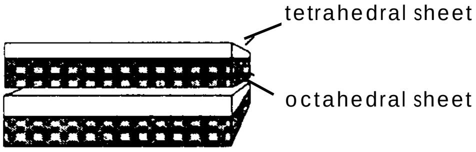
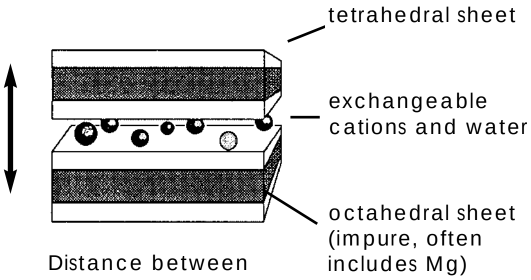
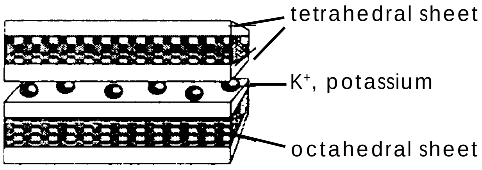
CLAY SIZE AND SURFACE AREA

Clay particles are small. Their small size means that a small volume of clay particles has a large surface area (Figure E4-2). This large surface area makes available many reactive sites of exchange of ions in a small volume of soil.

WHY IS CLAY NEGATIVELY CHARGED?

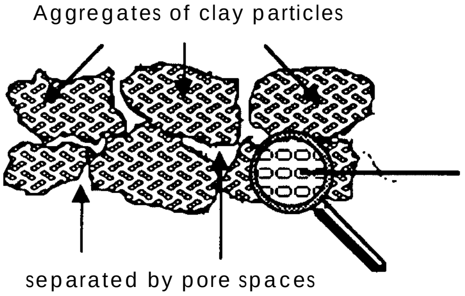
The basic building blocks of clay minerals are silicon atoms surrounded by four oxygen atoms (tetrahedra), and aluminium atoms

Figure E4-1. Structure of the three main clay minerals found in cotton soil.

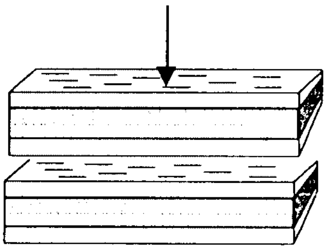
Clay structure	Characteristics	Cation Exchange Capacity (CEC)*
kaolinite  	Little expansion on addition. of water. Used for ceramics.	3-20 cmol (+)/kg
Smectite (montmorillonite)  Distance between the layers varies as exchangeable ions and water enter or leave.	Swelling on absorption of water between the layers of mineral. Agricultural uses, eg. bentonite in dam sealing. This clay mineral has a major effect on the behaviour of cracking clays.	80-120 cmol(+)/kg
Illite  The potassium ions bond closely between the mineral sheets, balancing charge.	Little expansion on addition of water.	10-40 cmol(+)/kg.

*Although the charge on the surface is negative, it is measured by the number of moles of cation charge (+) adsorbed.

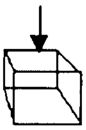
Figure E4-2. Clay particle size and surface area



Clay particles are smaller than 0.002 mm.
The platelets are negatively charged.



A 1cm cube could contain up to 10^{15} particles the size of fine clay with a surface area of 60 square metres.



surrounded by six hydroxide groups (dioctahedra), or magnesium atoms surrounded by six hydroxide groups (trioctahedra). These groups of atoms are arranged in sheets. The atoms in these sheets are tightly bound and are not exchangeable with other ions in the soil solution.

When the single tetrahedra and octahedra join to form sheets, the positive (Si^{4+}, Al^{3+}, Mg^{2+}) and negative charges (O^{2}-, OH^{-}) are balanced. However, oxygen atoms that are exposed on the surface of the clay are not wholly balanced by positively charged atoms. A net negative charge results. The negative surfaces of clays can attract and hold cations.

A negative layer charge can also be the result of isomorphous substitution. Isomorphous substitution is the substitution of Al^{3+} for some of the Si^{4+} in the tetrahedral sheet. This results in a negative charge. Mica has 25% of its Si^{4+} substituted by Al^{3+} in the tetrahedral sheet; the potassium cation (K^{+}) is necessary in the interlayer spacing to neutralise the negative layer charge.

THE IMPORTANCE OF NEGATIVE CHARGE

The negative charge on the surface of clay particles attracts positive ions (cations). This is important for the storage of cations that can be used by plants as nutrients. It also allows us to alter soil structural characteristics chemically by changing the cations that are adsorbed on the clay surface.

The ability of clay minerals to hold cations is called the ‘cation exchange capacity’ (CEC). Smectite has a much greater ability than kaolinite to hold cations. The CECs of kaolinite, smectite and illite are approximately 9, 100 and 25 cmol(+)/kg respectively.

Organic matter also contributes to CEC and has a CEC of approximately 250 cmol(+)/kg (at pH 8.5).

DISPERSION AND FLOCCULATION OF CLAY

Colloidal clay

Clay is a colloid. Colloidal particles have special properties due to their very small size. First, their large surface area in relation to their mass makes them very reactive—in clays, this reactivity is shown as an electrostatic attraction of cations. Secondly, colloids can exist in water as either suspensions (dispersed) or as gels (flocculated).

The tendency of a colloid to flocculate or disperse depends on three things:

- the nature of the colloidal particles
- the total salt concentration
- the nature of the adsorbed ions.

Nature of colloidal particles

Colloidal particles are either hydrophilic (water-loving) or hydrophobic (water-repelling). Hydrophilic colloids (for example, starch) form stable suspensions and do not readily flocculate. Hydrophobic colloids (for example, clay) form unstable suspensions and flocculate easily. The term ‘unstable’ here refers to the suspension, not the soil aggregates.

The nature of the colloidal clay particle (hydrophobic) means that clay will flocculate if allowed to. This is good for soil structure!

Total salt concentration

The more concentrated the salts (electrolytes) in the soil solution, the more likely it is that clay will flocculate. This is the ‘electrolyte effect’. All soluble salts have this effect, including common salt (sodium chloride), and gypsum (calcium sulfate).

When the salt concentration of the soil solution is greater than between the clay platelets, water will move from between the platelets into the soil solution (by the process of osmosis); the clay will flocculate and be very stable. In contrast, if the soil solution has a low salt concentration, water will tend to move from the soil solution into the zone between clay platelets; this will cause swelling and dispersion unless the cations there are strongly charged.

Salts such as gypsum, lime (calcium carbonate which, when dissolved, forms calcium salts with whatever anions are present), ammonium or nitrate salts in fertiliser or manure, various forms of phosphate, potassium salts, and trace elements such as zinc sulfate are all salts that are added to the soil in agriculture. Each adds to the total salt (electrolyte) concentration of the soil solution.

Nature of adsorbed ions

The type of cations adsorbed on to the negative surface of clay influences flocculation (clustering of clay particles into microaggregates). Calcium adsorbed on to the clay surface allows the clay to flocculate even when the total salt concentration is low. When sodium is adsorbed on to the clay surface the salt concentration has to be much higher for the clay to flocculate.

The effects of pH and clay type on dispersion

pH

Increasing pH results in the charge on the edges of clay layers becoming more negative. This aggravates dispersion in kaolinite, because negative edge to positive face bonding is the main factor in flocculation. In contrast, pH has only a slight effect on the dispersibility of soil dominated by smectite and illite; these clay minerals have a charge that is mainly permanent (independent of pH).

Clay type

Illite has a greater sensitivity to exchangeable sodium than smectite. This is caused by the smaller edge-to-face attractive forces in illite than in smectite, due apparently to the irregular shape of illite particles. Illite requires four times as much electrolyte to stabilise it compared with smectite, when their exchange sites are dominated by sodium.

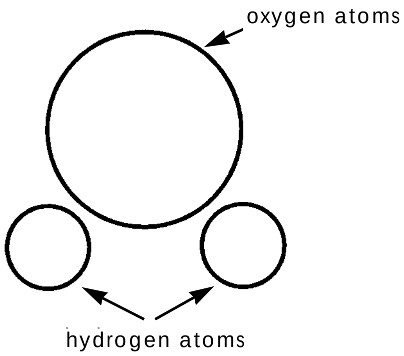
Water: its structure and importance in swelling clays

The structure of the water molecule (Figure E4-3) is important in how it reacts with charged particles. Water is a dipolar molecule—it has a slightly positive and a slightly negative end. This allows a water molecule to be attracted to both negative and positive ions and particles, and to other water particles (‘head’ to ‘tail’).

Water surrounds cations in a shell of oriented water molecules—a hydration shell (Figure E4-4).

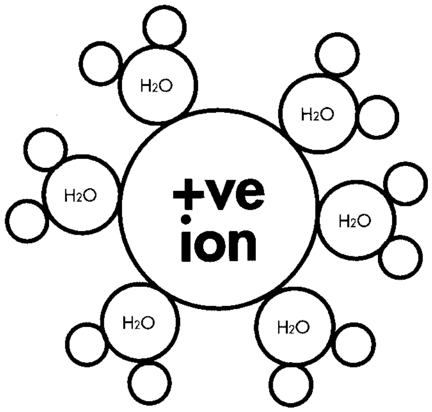
Figure E4-3. The dipolar water molecule.

Negative end of water molecule. This side of the molecule is attracted to positive charges e.g. cations in solution.



Positive end of water molecule. This side of the molecule is attracted to negative charges e.g. a clay surface or the negative end of other water molecules, or anions in solution.

Figure E4-4. Hydration shell of water molecules clustered around a positively charged ion (cation).



The thickness of the hydration shell depends on the cation. The shell around Na$^+$ is bigger than that around Mg^{2+}, which is bigger than the shell around Ca^{2+}.

The diffuse double layer

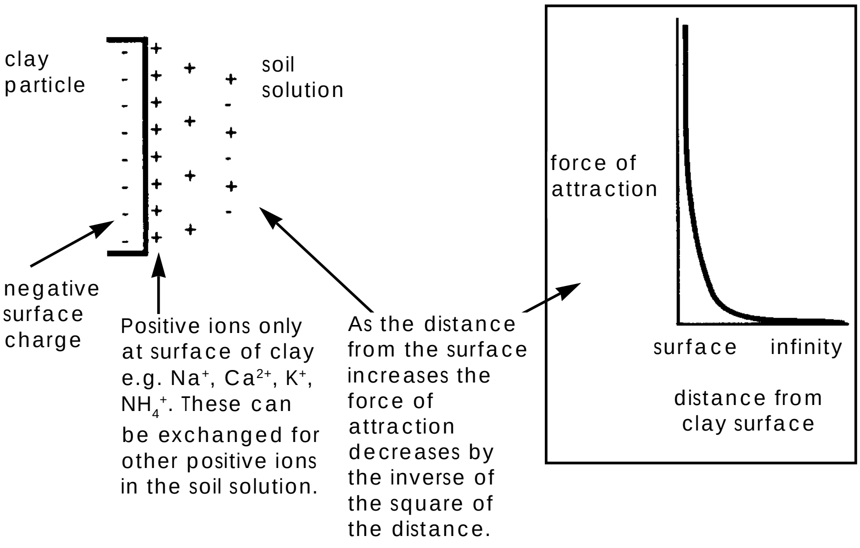
The surface of a clay particle, being negatively charged, attracts positive ions. When the clay is wet, the exchangeable positive ions on the surface of the clay move into the soil solution surrounding the clay particle. They are, however, still attracted to the clay surface, and consequently swarm close to it.

This region of attracted positive ions in solution and the negatively charged surface of the clay is termed the ‘diffuse (or Stern–Gouy) double layer’. It is called ‘diffuse’, because a net positive charge of ions extends away from the surface (Figure E4-5). The further from the surface, the less is the net positive charge of the solution.

The force of attraction on the cations by the clay reduces quickly as the distance from the clay surface increases (Figure E4-5).

For one cation to leave the double layer it must be replaced by another from the soil solution. Plant roots, in order to take up cations as nutrients, give up hydrogen ions (H$^+$) in exchange.

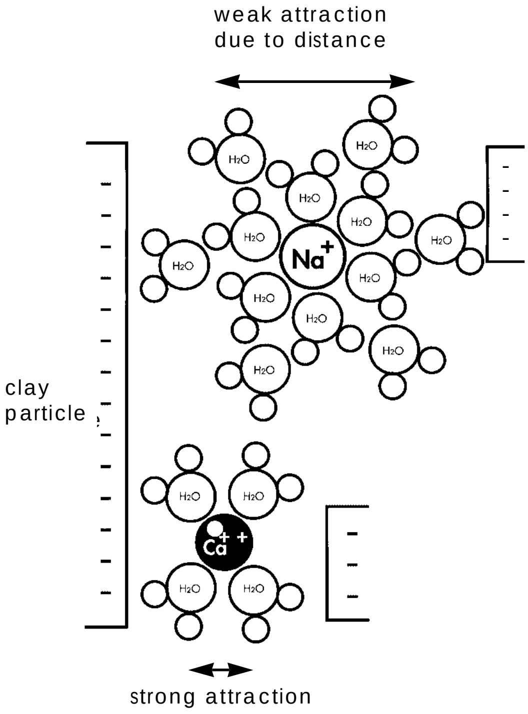
Figure E4-5. The double layer at the face of a clay particle.



Positive ions only at surface of clay e.g. Na$^+$, Ca^{2+}, K$^+$, NH_4^+. These can be exchanged for other positive ions in the soil solution.

As the distance from the surface increases the force of attraction decreases by the inverse of the square of the distance.

Figure E4-6. Strength of attraction of common soil cations



Na$^+$: Strongly hydrated ions such as sodium are surrounded by a shell of water which effectively increases their distance from the surface of the particle and decreases the attactive electrical force acting on the ion.

Mg^{2+}: Magnesium is also a highly hydrated ion like sodium, so despite its double positive charge it is held more weakly than calcium due to its distance from the surface.

Ca^{2+}: Calcium is not as strongly hydrated as sodium or magnesium; therefore, the calcium ions are held closer to the surface with consequently greater attraction. The double positive charge also leads to greater attraction.

Strength of attraction of exchangeable cations

The cations adsorbed on to the surface of the clay particles can greatly affect how the clay behaves. The cations act as a link between the clay particles. Similarly, dispersive organic matter (with negatively charged edges) can be linked strongly by positively charged cations.

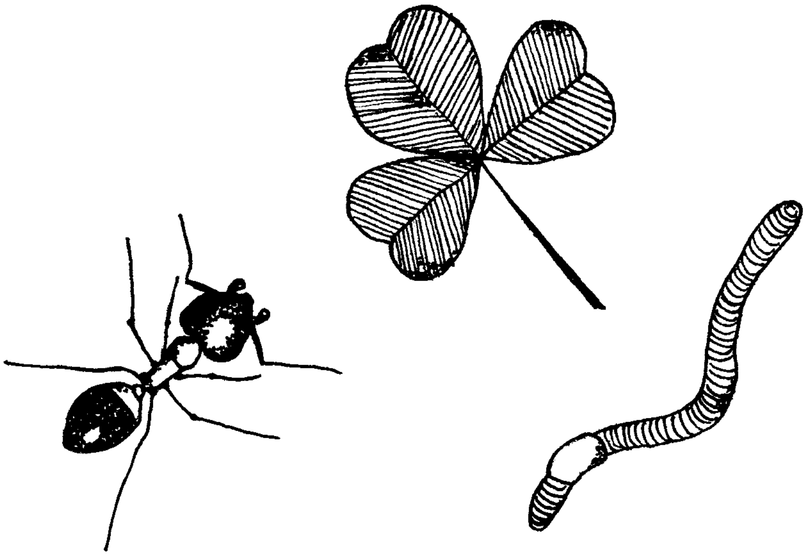
The binding force on to and between the clay plates depends on a number of factors including:

- the charge of the cations
- the size of the cations, including their hydration shell
- the thickness of the double layer outside the surface of the clay particles.

The strength of the bond depends on the cations present. Sodium ions have a single positive charge, so their clay-binding ability is poor. Calcium ions have a double positive charge, so their clay-binding ability is good. Magnesium is intermediate because, although it has a double positive charge like calcium, when hydrated it is larger than a hydrated calcium ion. This is explained in Figure E4-6.

In a dispersive soil with a large exchangeable sodium percentage and small concentrations of water-soluble salts, the weak bonding of the clay particles by sodium ions can be broken. As water enters between the clay particles it hydrates the sodium ions. This in turn forces the plates away from the ions and lowers the attractive force between the particles and the ions. The plates may move far enough apart for attraction forces to be overcome. The result is dispersion.

E5. Organic matter and soil biota



PURPOSE OF THIS CHAPTER

This chapter aims to give an understanding of the role of organic matter in the soil, and of factors that can cause an increase or decrease in organic matter levels.

CHAPTER OVERVIEW

This chapter covers the following points:

- types of organic matter
- benefits of organic matter
- problems associated with organic matter
- accumulation and destruction of organic matter
- cotton farming and organic matter.

Other chapters to refer to are:

- Chapter E4: ‘Clay minerals’.

INTRODUCTION

In most soil types, organic matter is considered to be essential for maintaining soil structure, although the actual composition and amount that is required has not been clearly defined. However, the structure of cracking clay soil apparently depends less on organic matter than on other soil types; the shrink–swell nature of the clay minerals creates and maintains a desirable soil structure.

Clay particles also retain and release cations as nutrients for plants, a task that is handled by organic matter in light textured (sandy) soil. Consequently, cracking clays can have good soil structure and good nutrient status at organic matter levels that would be low enough to cause problems on non-clay soils. Loam soil used for cotton production is more reliant on organic matter for the creation and stabilisation of a desirable soil structure.

Despite these differences between soil types, organic matter in general has numerous benefits, plus several undesirable effects.

TYPES OF ORGANIC MATTER

Soil organic matter consists of living roots and organisms (including earthworms, bacteria and fungi), decomposing plant, animal and microbial residues, exudates from plant roots and microbes, and humus. Most soil organisms are understood very poorly— only a fraction have been identified. It is estimated that 80–90% of soil biological activity is carried out by bacteria and fungi.

Humus is the dark, relatively stable end-product of organic matter breakdown. It may be thousands of years old. Some carbon (as much as 50%) may be in the relatively inert form of charcoal. Figure E5-1 shows how carbon cycles through soil organic matter.

Readily oxidised (labile) organic carbon is of particular value in soil management. Unless the soil is being regularly supplied with fresh organic matter, the amount of useful (labile) material in the soil will decline. For information about the development of a ‘carbon management index’ test, based on the measurement of total and labile carbon, refer to the paper by Blair, Lefroy and Lisle in Appendix 1.

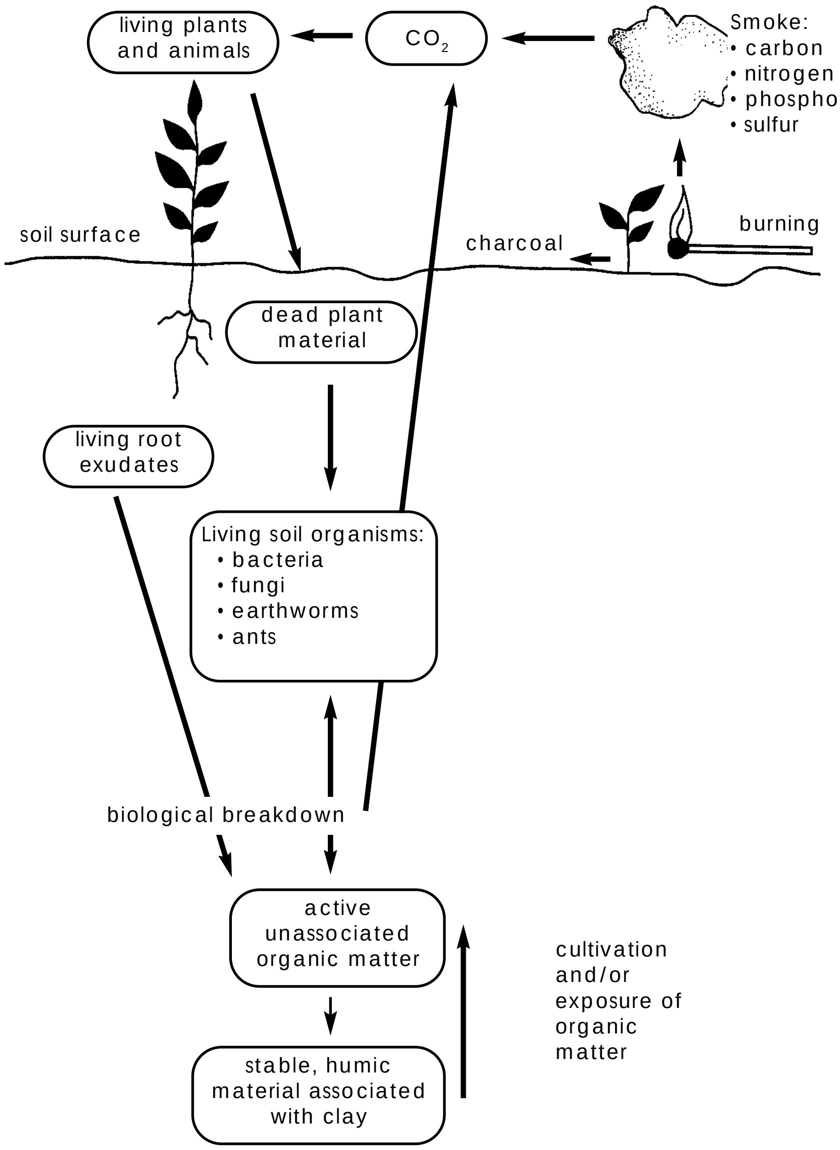
LIVING ORGANIC MATTER

Active roots. Roots force apart mineral components of the soil and leave channels for water flow and oxygen diffusion when they eventually die and decompose.

Burrowing animals such as earthworms, ants and termites create larger pores in their burrowing. Soil passed through earthworm guts ensures intimate mixing of organic and mineral matter, which can improve soil aggregation. Some of the ants in cotton fields are predacious, and may decrease pest populations. Other creatures that may be found in cotton soil include beetles, earwigs, spiders, springtails and mites. A burrowing organism that is not welcome in cotton fields is the larva/pupa of *Heliothis armigera*.

Fungi and mycorrhizae. Fungi help in the breakdown of dead plant material to its component parts. Live fungal hyphae also bind the soil into aggregates, by tangling with individual soil particles, thus improving structure, especially on lighter textured soil types. The mycorrhizal group of fungi (‘vesicular-arbuscular mycorrhizae’—VAM) live in a symbiotic relationship with plant roots. They provide, in effect, an extended root system, and help the plants to extract a

Figure E5-1. Carbon cycling in cotton soil.



number of nutrients (especially phosphorus and zinc) from the soil. In return they receive carbohydrates, amino acids and a protected habitat. In many cases the growth of plants is retarded if mycorrhizae are removed. Mycorrhizal growth is retarded by poor soil structure and waterlogging. The creation of heavily cut areas after landforming leaves bare subsoil that is depleted of mycorrhizae.

Bacteria assist in the breakdown of dead macro-organic matter and contribute to the polysaccharides found in the soil. Macro-organic matter is composed of the complex dead cells of plants and animals. The polysaccharide sugars form a part of the glue that holds aggregates together. Some bacteria damage cotton (for example, ‘bacterial stunt’, also known as ‘Galathera syndrome’ or ‘early season growth disorder’); other types are beneficial.

Actinomycetes. This group of organisms has a complexity that is mid-way between the fungi and bacteria. Like the bacteria, they assist in the breakdown of organic matter. They are also more tolerant of dry hot conditions than either fungi or bacteria.

Non-living organic matter

Root exudates. Roots exude a variety of organic materials as they penetrate the soil. With the pressure from root penetration, organic matter is forced into close association with soil particles.

Decaying material. This includes material in the process of decomposition by soil microbes that was once part of living organisms, e.g. surface mulch.

Humus. This is the stable part of organic matter, made up of large organic molecules that are the result of decomposition of plant and animal cells. Humus is composed of a complex of different molecules from a number of chemical groups. It consists mainly of carbon, hydrogen and oxygen; however, large amounts of nitrogen and sulfur are also involved.

Charcoal, a relatively inert form of soil carbon, sometimes accounts for a large proportional of the carbon in a soil.

As dead plant and animal material is broken down to humus, carbon is lost in the form of carbon dioxide (CO_2) due to respiration by the soil micro-organisms.

Clay particles have a role in stabilising organic matter. Organic matter is adsorbed on to the surfaces of, and between, clay particles; this in turn makes it inaccessible to soil micro-organisms that would normally decompose the organic matter.

BENEFITS OF ORGANIC MATTER

Ion adsorption

Most humus particles have very large surface areas. They are negatively charged and act in much the same way as clay particles in the exchange of positive ions such as ammonium, calcium, sodium, magnesium, zinc, copper and iron. They make a very significant contribution to the cation exchange capacity (CEC) of a soil. For example, an organic matter content of just 2.5% in soil with a clay content of 25% accounts for approximately one-third of the CEC of the soil.

Some humus particles or parts of particles are positively charged and can adsorb and store on their surface the negative ions found in the soil solution—for example, nitrate, sulfate, phosphate and chloride.

Metal chelation

Some organic matter forms complexes with metal ions. The metal ions in these complexes are in a form that is available to plants. If these elements were not protected in these molecules, they would be readily precipitated into a form that would be unavailable to plants.

Metals that are chelated in the soil by this means include copper, iron, manganese and zinc.

Acting as a source of plant nutrients

The breakdown of organic matter by soil microbes (mineralisation) provides plant nutrients and is one of the major sources of nitrogen for plants. The ammonium form of nitrogen is the form first produced when organic matter is broken down. Plants can use this form of nitrogen as well as nitrate (a secondary microbial breakdown product of ammonium).

The breakdown of organic matter to form available nitrogen is slow, however, and may not meet the peak demand of a growing crop.

Aggregate stabilisation

Organic matter binds the aggregates of cotton soil and helps to reduce clay dispersion. The benefits for cotton growers tend to become greater as the clay content decreases. Organic matter improves soil friability.

In loam soil, it has been shown that microaggregates are stabilised by mucilages/polysaccharides. These units are held together by the action of fungal hyphae (mainly mycorrhizae) growing through the soil. Casts produced by earthworms also improve soil structural stability in water.

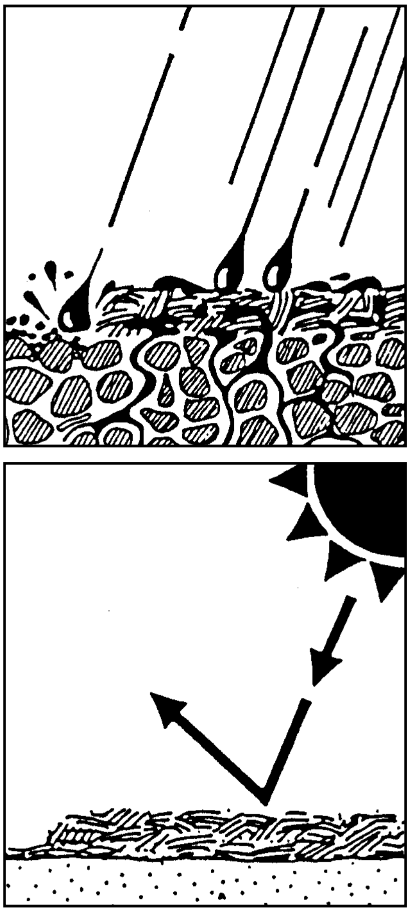
Creation of macropores

Earthworms and ants can improve soil structure by their burrowing activities. For example, *Heteroprodrilus mediterreus* ('Myall worm'), a large (50 cm long) native earthworm found in grey cracking clay soil under Mitchell grass, builds channels that can improve water entry into the soil and maintain subsoil aeration after closure of shrinkage cracks in wet weather. Under dry conditions, they apparently reside at a depth of about 2 m.

Ants provide similar benefits. In hardsetting soil, they can improve surface structure by bringing up well-structured subsoil.

Cotton crops with very high yields (>12.5 bales per hectare) have been associated with soil containing plenty of earthworms.

Figure E5-2. The benefits of mulch.



Protection of the surface soil from raindrop impact and rapid drying

Mulch protects the soil from raindrop impact, and reduces evaporation of water from the soil (Figure E5-2). The extra moisture under mulches can promote root growth in the topsoil, where nutrients are concentrated. It allows cotton crops that otherwise would have been adversely affected by 'bacterial stunt' to grow strongly. If dense enough, mulches can also reduce weed emergence, although excessive coolness in the topsoil may be a problem in spring. Mulches also protect cotton seedlings from wind-blast damage during windy weather.

Acting as an anti-compaction agent

The effects of compaction are less pronounced in soil that is rich in organic matter. The theory behind organic matter being an anti-compaction agent is that the long-chain carbon bonds found in organic matter are more flexible than the bonds formed between clay particles. This gives the particles joined by organic matter more freedom to move, while still being attached in aggregates.

Soil reinforcement is also gained by the effect of living and dead plant fibres, such as fungal hyphae and plant roots, within macroaggregates and microaggregates.

Acting as a source of nutrients for beneficial soil organisms

Biological activity is likely to be helped by the nutrients contained within the more labile organic residues. The carbon in organic matter is a vital energy source for soil biota.

Water retention

As the soil organic matter content increases, the soil water holding capacity becomes greater. This effect is most marked in light-textured soil.

Acceleration of the biodegradation of pesticide residues

Organic matter helps with pesticide decomposition, although detailed information is not available.

Fixation of carbon dioxide, a ‘greenhouse gas’

Accumulation of soil organic matter (particularly as humus) reduces the amount of carbon dioxide (CO_2) gas in the atmosphere. This makes a small but important contribution to a slowing of global warming, which is caused by ‘greenhouse gas’ emission.

Reduction of soil alkalinity

Most of the material in organic matter is eventually converted to carbon dioxide gas (CO_2) and water, with heat as a by-product (this is why composting straw feels warm). Some of the CO_2 dissolves in the soil solution, which forms carbonic acid (H_2CO_3). This mild acid lowers soil pH—a desirable process in alkaline clay. Respiring roots also emit CO_2.

PROBLEMS ASSOCIATED WITH ORGANIC MATTER

Mechanical problems

Large amounts of plant residue can be difficult to handle mechanically—either when incorporating them into the soil or when planting through stubble.

Possible negative effects on weed control

Surface mulch can reduce weed growth by shading the soil, and by producing leachates which inhibit weed emergence. However, stubble tends to reduce herbicide–soil contact and limit the mechanical incorporation of herbicides.

Nitrogen tie-up

Organic matter with a high C:N ratio (high carbon content and a low nitrogen content, for example, straw) can tie up nitrogen in the short term. This is because the material acts as a food source for soil microbes, which increase in number. The microbes need nitrogen to form their body proteins, and they use up the available nitrate in the soil. Later, when the food source is used up and the majority of microbes die, their bodies decompose and the nitrogen returns to the available pool.

Phytotoxin production

The breakdown of plant material can produce phytotoxins that adversely affect crop growth in the short term (allelopathy).

Water repellence

In some sandy soil types, coatings on sand grains of organic materials produced by micro-organisms can cause water repellence.

Encouraging disease

Plant residues may be a repository for plant diseases. This is the main method of survival for cotton diseases, including bacterial blight, verticillium wilt, seedling diseases, fusarium wilt, phytophthora boll rot and alternaria leaf spot.

If cotton is to follow cotton in a crop sequence, dispose of suspect plant residues by incorporation. An exception is for fusarium, where cotton crop residues need to be left on the surface; burial aggravates the problem. Early incorporation followed by moist soil conditions will speed the complete breakdown of macro-organic matter and its associated disease organisms, as well as returning plant nutrients to the soil.

However, as the web of ‘predator–prey’ relationships in the soil becomes more stable, suppression of harmful organisms tends to become greater.

Aggravation of soil dispersion problems

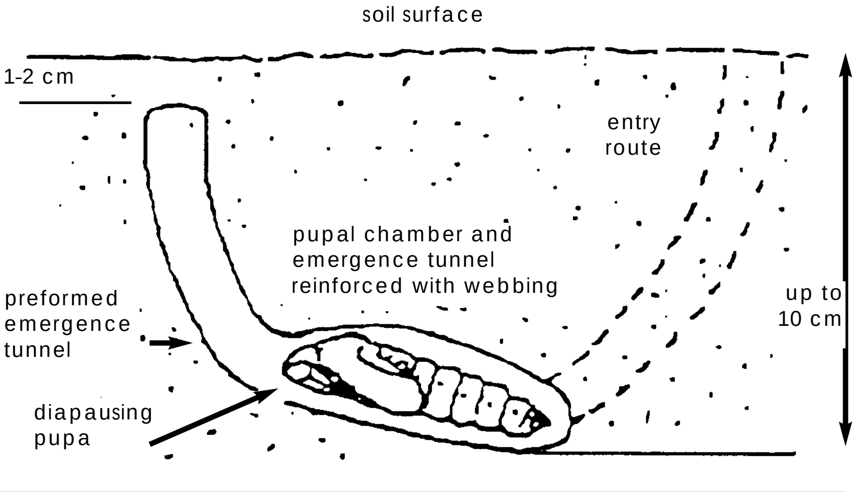
In soil aggregates where organic molecules have a negative charge, and the positively charged cations linking these molecules and negatively charged clay are only weakly attractive (for example, sodium ions), disruption of the bonds by tillage will make the soil become dispersive. As the amount of negatively charged organic matter becomes greater in such a situation, the dispersion problem will become worse. Adding calcium ions will help to address such problems.

Heliothis pupae

Over-wintering pupae of *Heliothis armigera* lie in the soil to a depth of about 10 cm. They are highly resistant to insecticides, and must be destroyed within a few months of cotton harvest—the end of the following August is the deadline.

An illustration of pupal position in the soil (burrow morphology) is shown in Figure E5-3. At present, the only feasible control measure is thorough cultivation of the topsoil (0–10 cm). Clod diameter after tillage needs to be less than 5 cm.

Figure E5-3. Position of Heliothis pupa in the soil.



FACTORS THAT CAN INCREASE SOIL ORGANIC MATTER CONTENT

Rainfall and irrigation

The growth of plants that eventually break down to soil organic matter depends on soil moisture. Increasing soil moisture through rainfall or irrigation stimulates plant growth, and consequently provides a greater input of organic matter to the soil. However, soil moisture also increases the rate of breakdown of organic matter. For organic matter levels to increase, other factors must be favourable.

Increased soil fertility

Fertile soil in general has higher levels of stable organic matter, reflecting the greater amount of plant growth.

Relatively high clay content

Clay particles form stable associations with organic matter and protect it from attack and consequent breakdown by soil organisms. Very sandy soil is unable to retain much organic matter, because it has only a small amount of clay available to protect the humus.

In general, smectite clays have more organic matter than kaolinite clays. This is due to the greater number of sites available for bonding.

High numbers of soil organisms

The greater the activity of soil organisms, the faster the conversion of organic residues to stable humus. Low temperatures, acidity and low aeration inhibit microbial activity; organic residues may break down only partly and form peat under such conditions. For example, various forms of peat occur in peat bogs (cool, waterlogged and acid), in swamps (waterlogged), in tundra (cold) and even as thatch under acid pasture or lawn turf.

Acidity also inhibits earthworm proliferation, and consequently reduces the natural incorporation of organic residues into the soil, where they can decompose more fully (although ants may take the place of earthworms).

Appropriate land use

Until now, the best form of agricultural land use for increasing organic matter levels is pasture. Organic matter is supplied constantly to the soil through dead leaves and roots, root exudates and the droppings of grazing animals. The lack of tillage helps to maintain the organic matter.

On cropland, reduced tillage will help to keep organic matter at higher levels. Permanent beds and minimum tillage retain more organic matter than ‘maximum tillage’ systems.

Manure application

Green manure crops (especially nitrogen-fixing legumes) and animal manure can be added to soil. However, tillage to incorporate the manure decreases soil organic matter (and may disrupt soil macropores), so very large quantities of either of these manures are required to have a significant beneficial effect. In the first year, three-quarters of the added carbon disappears as carbon dioxide from the respiration of soil organisms. After three years, as little as 10% of the original organic carbon remains.

Other materials to consider include composted gin trash and synthetic polymers.

FACTORS THAT CAN DECREASE SOIL ORGANIC MATTER CONTENT

Tillage

Organic matter, especially the smaller stable humus fraction, is protected from biological attack by being located within very small pores in the soil (even between clay particles). Tillage disturbs these small pores, exposing the organic matter to decomposition. More reactive parts of the organic matter that formerly may have been attached to clay particles may also be exposed.

Pesticides

Herbicides appear to have few (if any) adverse effects on soil biological processes. Fungicides are more damaging, but are rarely used by cotton growers. Insecticides may disrupt beneficial soil biota, such as predacious ants. The introduction of transgenic cotton varieties is likely to reduce pesticide use in the Australian cotton industry, so it should be possible to make better use of soil-borne fauna in the future.

Burning

Burning destroys above-ground organic matter. Smoke carries away elements such as nitrogen and sulfur. However, under permanent beds, the roots of the previous crop and the stable organic matter will remain in the soil despite the burning of the upper parts of the plant. Burning may, in fact, destroy less organic matter than tillage, especially when there is little stubble to incorporate.

If the elements lost in smoke are replaced by fertilisers, a stable and profitable farming system can result. The ash (rich in phosphorus, potassium, zinc and calcium) that remains after burning may provide a beneficial electrolyte effect when dissolved in water.

Nevertheless, burning should be considered only as a ‘last resort’ by cotton managers—for example, in very wet winters when soil disturbance by tillage needs to be minimised. It is a practice that wastes valuable nutrients and soil organic matter, and makes the distribution of P, K and Zn less uniform due to the raking of stalks into windrows.

COTTON FARMING AND ORGANIC MATTER

Cotton crops are poor returners of organic matter to the soil. The stems are hard and lignified and contain only small (albeit useful) amounts of nitrogen, and so decompose slowly. They take up to two years to decompose, although it may be possible to accelerate this process by spraying the stalks with sulfuric acid. The roots make up only 10–30% of the mass of the plant. In some agricultural crops, up to two-thirds of the mass is in the roots. Nevertheless, cotton residues contain enough nutrients and useful organic matter to justify retention rather than burning under most circumstances. Experiments at Narrabri have shown that N fertiliser recovery is improved by 10% where cotton stalks are retained rather than burnt.

If alternative crops such as wheat are grown in rotation with cotton to increase organic matter levels, it is important to reduce tillage to a minimum to preserve the organic matter that is produced. A permanent bed system is the best way of achieving this goal. On hardsetting soil types such as red-brown earths, retaining a mulch is very important for the protection of the fragile surface structure from raindrop impact. Mulches also encourage root growth in the nutrient-rich topsoil—this zone is usually too dry for root function where the soil is left bare.

Mulches make weed control more difficult, but practical solutions have been developed. Weed management under mulches is likely to become easier when herbicide-tolerant cotton varieties are released. They will allow ‘over the top’ applications of herbicides that previously could not safely be applied to cotton.

Incorporating stubble or ‘green manure’ may not necessarily increase organic matter levels. Unless the volumes of stubble are large, soil organic matter content may decrease through the process of cultivation to incorporate fresh unstable organic matter.

Most cotton growers place a lot of emphasis on the return of organic matter, but are not sure why. There is uncertainty about the value of organic matter in old roots versus surface residues, and from various rotation crops. We do not have ‘critical values’ of total and labile carbon for optimal cotton growth on the different soil types used to produce cotton in Australia.

Future research is likely to answer these questions.

E6. How soil structure and temperature affect plant growth

PURPOSE OF THIS CHAPTER

This chapter explains how cotton roots and seedlings respond to different soil structural conditions.

CHAPTER OVERVIEW

The following points are covered:

- the physiology of cotton roots
- root growth and the ‘non-limiting water range’
- root activity in relation to soil temperature.

INTRODUCTION

Cotton has considerable flexibility in its response to environmental conditions because of its bud and boll shedding ability and growth indeterminacy. If conditions are less favourable than usual, greater than average shedding occurs, but if conditions become more favourable a higher proportion of bolls is retained, and this at least partly compensates for previous losses. The cotton plant, therefore, adjusts to environmental fluctuations by altering its fruiting pattern. Nevertheless, cotton productivity usually is well short of potential, due to the limiting effects of soil physical conditions and the interacting effects of climate on cotton root growth and function.

Root systems are particularly important. They anchor plants, absorb water and nutrients, act as storage organs, and are the site of production of growth-controlling substances. To fulfil these functions, roots need to elongate and expand to explore the soil during and after seedling establishment. Poor subsoil aeration and excessive soil strength are the main problems; they are aggravated by soil compaction, remoulding and/or hardsetting.

Crusting and/or hardsetting of the soil can be a problem for emerging seedlings—particularly where the seedbed is sodic and/or is prone to hardsetting—but most Australian cotton soil does not have this problem. Excessively low or high temperatures and the presence of soil-borne diseases of cotton tend to be the main seedling establishment problems.

THE PHYSIOLOGY OF COTTON ROOTS

Cotton roots have the following features, which should be appreciated by soil managers:

- Cotton can tap soil moisture from as far as 3 m below the surface.
- Deep roots are as effective as shallow roots in water extraction, although cotton taproot dominance generally wanes with depth.
- Rates of cotton taproot elongation as great as 80 mm/day have been recorded in the laboratory, but elongation rates are generally slower in the field.
- Cotton taproot length reaches a maximum between first bloom and just before the appearance of mature bolls.
- Developing bolls out-compete roots for carbohydrates, so root system development must occur early in the season.
- The addition of N stimulates vegetative growth and increases auxin production, which depresses root growth further.
- Cotton has been shown in laboratory experiments to have the ability to move water via its roots from wet to dry soil during periods of low evaporative demand. This may be a survival mechanism under certain circumstances, allowing plants to lift water passively from deep, relatively moist soil layers during the night, thus allowing continued uptake of nutrients in the surface soil, which otherwise would be too dry .
- Cotton has a poor tolerance of waterlogging. It has been shown that the elongation of cotton taproots at 30^{O}C ceases completely within two to three minutes of oxygen removal from the soil, but returns to normal shortly after the return of 21% oxygen to the system, provided the period without oxygen does not exceed 30 minutes. Most of the roots die after three hours without oxygen.

- Cotton roots can, themselves, modify the aeration status of a soil. It has been shown that cotton lateral roots at a depth of 0.8 m shrink in the middle of the day to about 60% of their maximum diameter; shrinkage occurs when roots lose water faster (due to transpiration) than they absorb it. The resultant gaps apparently allow movement of gases in the soil.

There is evidence to suggest that the degree of Bt expression in transgenic cotton varieties is reduced by waterlogging stress. This makes Heliothis control particularly difficult.

ROOT GROWTH AND THE 'NON-LIMITING WATER RANGE'

As a soil becomes more compact, there is an increase in the range of water contents over which root growth is restricted by poor aeration and excessive soil strength.

Good soil structure prevents the 'non-limiting water range' (NLWR) for cotton growth becoming less than the available water range. If the soil is compacted (low NLWR), cotton growth can be restricted by a lack of oxygen when the soil is wet and by high soil strength when the soil is dry. The water content at which hardness of the soil starts to become limiting corresponds to the 'refill point'. The 'partially-limiting water range' (PLWR) indicates the zone where between 10% and 90% of the soil has adequate aeration and freedom from strength limitations.

These effects are illustrated in Figure E6-1. It shows the water content range that needs to be maintained in the soil to avoid aeration problems at high water contents, and to avoid strength limitations when the soil is dry, for various degrees of compaction as measured by the SOILpak score.

Note:
1. Compaction severity becomes worse as one moves towards the top of the diagram.
2. Cotton farmers should aim to maintain their soil water contents within a range that coincides with the Non-Limiting Water Range (NLWR).

The cotton root symptoms associated with contrasting degrees of compaction are shown in Figure E6-2. Restriction of root growth limits the volume of soil that can be utilised by plants.

COMPACTION, ROOT GROWTH AND CROP YIELD

Impeded root systems will exploit a smaller soil volume for plant nutrients and water than root systems that are unrestricted. Retarding the growth of new roots means that existing roots have to maintain a greater than normal uptake rate of water and nutrients per unit root length in order to keep pace with demand. Plants confined to a restricted soil volume, therefore, are more susceptible to water or nutrient stress.

Good crop yields are difficult to achieve on compacted soil. However, soil compaction does not always reduce crop yield. University of Queensland researchers, working on a cracking clay with and without irrigation, found that pigeonpea growth restrictions resulting from compaction were related mainly to reduced water uptake resulting from decreased infiltration and storage of water, and restricted root growth. Seasonal conditions—in particular, the distribution of rainfall—exerted a strong influence on plant response. Yield reductions resulting from compaction varied from 100% in a dry

Figure E6-1. The range of soil water contents (schematic) over which soil strength (S) and soil aeration (A) effects are not limiting to root growth (non-limiting water range; NLWR) or partly limiting to root growth (partially-limiting water range; PLWR) as the severity of soil compaction becomes worse. The PLWR indicates the zone where between 10% and 90% of the soil has adequate aeration and freedom from strength limitations.

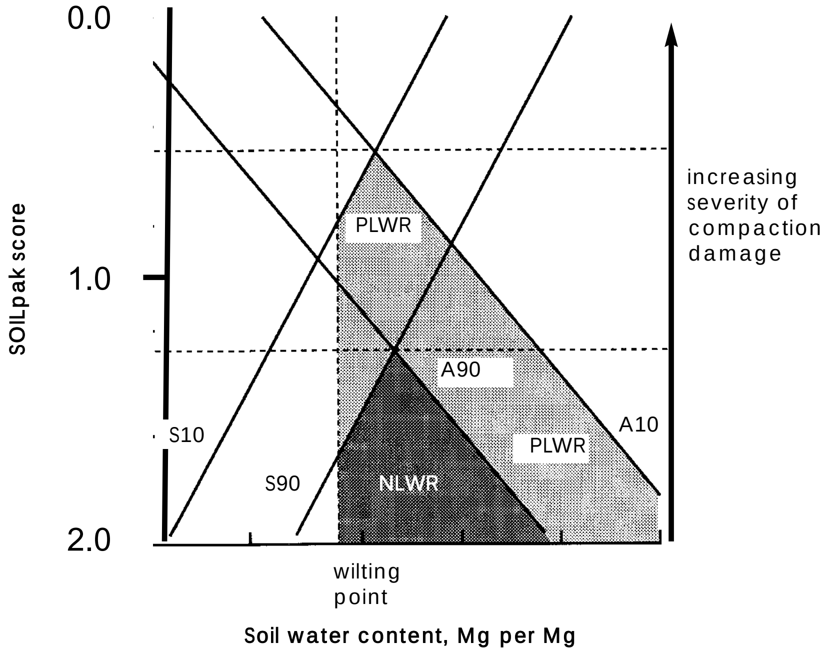
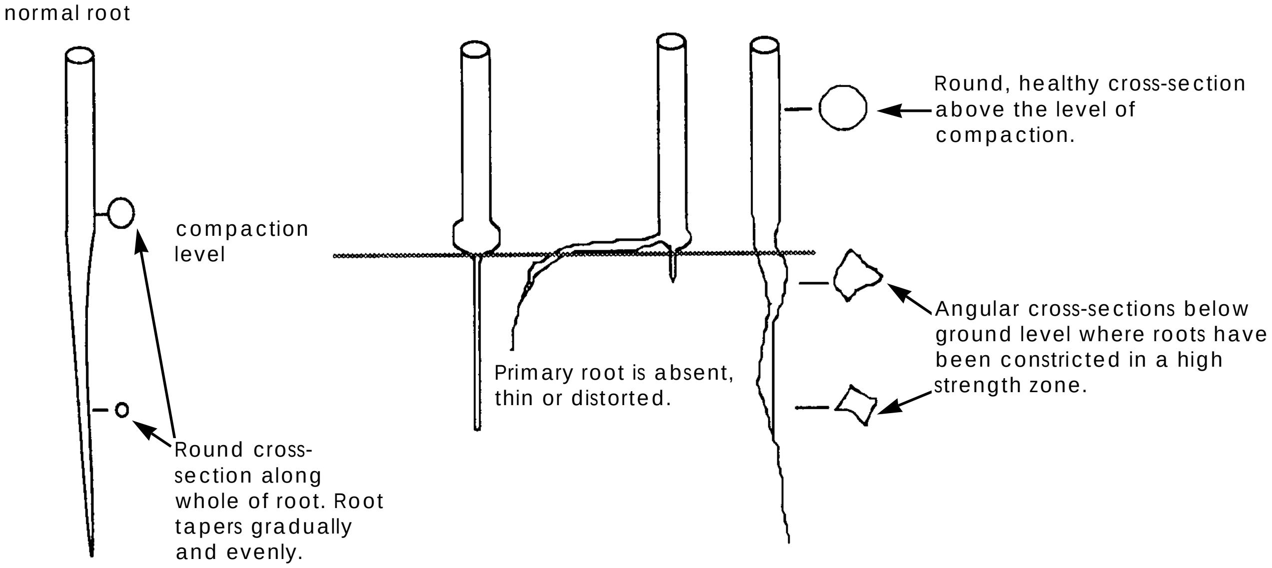


Figure E6-2. Cotton root symptoms following compaction, The left-hand damaged root is referred to as a 'nub' root.



season to 0% in a wet season, so it is difficult to nominate a critical level of compaction when ameliorative measures might be required.

Researchers at Narrabri and Trangie have shown that the adverse effects of soil compaction on cotton root growth can be offset by irrigating more frequently, and by adding extra nitrogen to replace that lost by denitrification.

ROOT ACTIVITY IN RELATION TO SOIL TEMPERATURE

Cotton originated in the tropics, and becomes inactive at low temperatures. Maximum temperatures between 27ºC and 35ºC and minimum temperatures between 15ºC and 20ºC constitute the optimum range for productivity, although the temperature optimum for both the primary roots and hypocotyls of cotton shifts with time and stage of growth. Experiments at Narrabri have shown that cotton development ceases below 11.4ºC.

Wet soil warms much more slowly than dry soil, so effective field drainage is important for seedling survival under cool conditions. Mulches can insulate the surface soil from extremes of temperature in winter and summer.

An associated limitation is that caused by a reduction in light intensity. On dark, foggy days, lateral roots became more dominant than the taproots, even when the temperature is suitable for root growth.

High soil temperature can be a problem in some cotton growing districts. The surface of dark soil can reach a temperature as great as 75ºC, which is not conducive to root growth. Irrigation water and/or rain cools the soil surface, particularly in summer.

Temperature interacts strongly with the effects of mechanical impedance on root growth. The soil strength at which roots are restricted becomes greater as temperature increases.

Seed size also is important. The rate of root elongation for a broad range of plants is positively correlated with seed size; the relationship becomes stronger as temperature decreases.

E7. Water movement

PURPOSE OF THIS CHAPTER

This chapter describes the key parts of the hydrologic cycle that need to be understood clearly by cotton soil managers.

CHAPTER OVERVIEW

This chapter covers the following points:

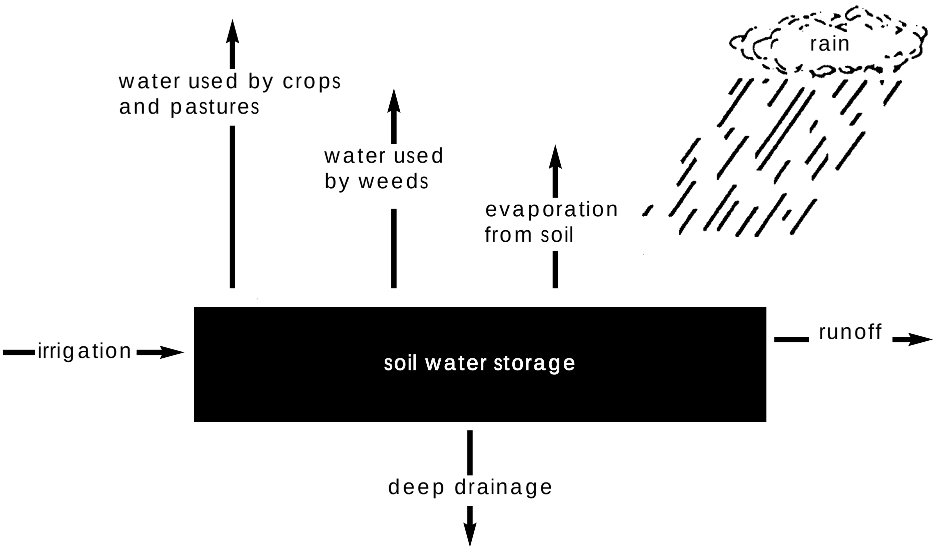
- movement of surface water in cotton fields
  - —water entry
  - —waterlogging
  - —soil movement
- movement of water within the root zone of cotton
- deep drainage below cotton fields.

INTRODUCTION

The most important process to be understood by the managers of cotton soil is the hydrologic cycle. It drives aeration and strength (the main soil structural factors influencing root growth), provides water for nutrient transport and plant growth, erodes soil, transports salt, and determines the trafficability of farm machinery.

The cycle is shown schematically in Figure E7-1. Computer models are available to simulate hydrological processes; contact a soil scientist or your local advisory officer for further information.

Figure E7-1. The hydrologic cycle



MOVEMENT OF SURFACE WATER IN COTTON FIELDS

Water entry

Water entry into cracking clays is rapid and deep when the soil profile has been dried and shrinkage cracks are present. However, if the surface soil has been slowly wet by, for example, light showers of rain, the cracks will close up and water entry will be much slower than where deep cracks extend to the soil surface.

Where irrigation water is applied via furrows (as is done for most of the Australian cotton crop), its penetration into the root zone may be restricted by bed shoulder compaction (that is, poor ‘subbing’). This damage is caused by poor matching of furrow shape and tyre width.

Loam soil, particularly if prone to hardsetting, needs to be maintained in excellent structural condition because of its very slow self-repair potential. The macropores in the water entry zone should be protected.

With the introduction of very accurate tractor guidance systems, it may become possible to separate the traffic laneways and water application zones by driving along the middle of 2 m wide beds.

Waterlogging

In flat cotton fields with heavy clay soil, waterlogging (lack of oxygen in the root zone) is a potential hazard. It does not necessarily mean that the entire root zone of the soil is poorly structured. For example, if a well structured topsoil overlies a poorly-drained subsoil, too much water may be allowed into the profile if water application is not carefully controlled.

Compacted soil will have waterlogging problems due to temporary perching of water near the soil surface.

One approach to waterlogging management is to steepen the irrigation fields. This will not be feasible, though, if large areas of poorly structured subsoil are to be exposed.

The other way of dealing with poor surface drainage is to build raised beds. Their architecture needs to be matched with soil resilience (shrink–swell potential), slope, type of farm machinery, and water application method. Unfortunately, very little ‘hard data’ are available to provide such designs for growers; until further research is carried out, ‘trial and error’ is necessary.

Soil movement

The problem of soil loss from cotton fields becomes worse as:

- rainfall intensity and amount become greater
- surface cover becomes lower
- slope becomes steeper
- the distance between contour banks becomes greater
- run-off water becomes concentrated rather than spread out
- soil wetness becomes greater.

MOVEMENT AND STORAGE OF WATER WITHIN THE ROOT ZONE OF COTTON

As discussed in Chapter A2, soil within the root zone needs to be able to store as much water as possible. However, even more important (particularly for irrigators) is to redistribute water quickly within the root zone so that adequate aeration is re-established.

It is inevitable that some of the interiors of clods in the soil profile will be anaerobic just after irrigation; the challenge is to keep aggregate diameter in the range 2 to 4 mm, so that roots still have access to a large area of well-aerated clod surfaces.

Water losses via evaporation can be minimised by encouraging storage of water in the sub-surface and subsoil, rather than in the topsoil.

DEEP DRAINAGE BELOW COTTON FIELDS

It is crucial that excessive deep drainage be avoided when growing cotton. It can be justified only if salt that has entered fields via the irrigation water has to be leached to below the root zone. Loss of water as deep drainage leads to problems such as rising water tables, and inefficient use of a scarce resource.

In horticultural areas, permanent drains are installed to reduce waterlogging and to intercept deep drainage. Generally, the cost is too great for cotton producers. Another (much cheaper) option is to install mole drains. However, the need to have a non-sodic subsoil that does not cause collapse of the cavity means that much of the cotton soil in Australia appears to be unsuitable for this technology.

Deep subsoil compaction caused by heavy machinery apparently is a desirable process in terms of restricting the deep movement of water.