PART TWO

Processes Underlying Plant and Soil Responses to Tillage

Chapter 6

THE EFFECT OF TILLAGE ON SOIL PHYSICAL CONDITIONS

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Land management can only be sensibly evaluated in the context of specific climates and soils. Management practices have probably failed as frequently from disregard of this simple precept as through ignorance of physical or biological processes. The transference of agricultural techniques from temperate Europe to sub-tropical and tropical regions exemplifies this, nowhere better than in Australia. The distinctiveness of Australian flora and soils, resulting from long isolation and geological stability, has been altered in the past 200 years by land clearance for agriculture on a scale not known in Europe since the Anglo-Saxon migrations. Unfortunately, the soils of the agricultural regions of Australia have not always been so accommodating to these rapid changes as those of pedologically younger regions.

In this chapter a brief outline of the soil properties and processes that control soil physical conditions, and the effects of tillage on these, is given first. Then the current experimental work on tillage is reviewed and placed in the context of the more fundamental research carried out on structural stability of Australian soils. Finally a guide to the field assessment of soil physical conditions is provided. It is intended particularly for field workers, advisers, farmers and agronomists who have the onerous responsibility of managing the land not only for present profit but for future security and benefit.

SOIL PROPERTIES AND PROCESSES

SOIL STRUCTURE AND STRUCTURAL STABILITY

Soil structure

Because soil is a three-phase system of solids, liquids and gases it may be viewed as a special case of all porous media. However, it is chemically dominated by the reactive colloidal surfaces of the clays and organic materials it contains. It is this complex physico-chemical behaviour that provides the soil with its capacity to form aggregates composed of primary mineral particles, which are integral to a consideration of soil structure and structural stability. The 'structure' of the soil is frequently defined as the arrangement of the solid particles and their adjacent voids.

Historically, the solid particles and their colloidal behaviour were investigated first. Because it is the pore-structure which is crucial to the flow and storage of water, nutrients and gases to the plant, in recent decades there has been an increasing emphasis on the study of the effects of the properties of pores to explain the effects of soil structure on crop growth. Tillage alters the pore structures, not only of the topsoil, but of the upper part of the subsoil as well, in ways that have direct effects on plant growth. This fact recurs so frequently in the work reviewed in this chapter it may be considered its central theme.

There are three main aspects of the pore system that adequately characterise it: total porosity, pore-size distribution, and pore continuity.

Total porosity

Total porosity is defined as:

$$1 - (\rho_d / \rho_p)$$

where ρ_p is the mean particle density of solids in the soil and ρ_d is the bulk density. Bulk density equals the dry weight of the soil divided by the total volume. Porosity increases as aggregates are broken up into smaller sizes by tillage, by frost shattering, or when clay soils swell on wetting. It decreases when the soil is compressed by traffic or weight of overburden pressure, or by shrinkage. Porosity is usually calculated from the bulk density, assuming a particle density (ρ_p) of 2.65 t m^{-3}, which is the ρ_p of quartz. In soils with a high content of organic matter, ρ_p should be reduced proportionally.

Measurement of total porosity gives an estimate of the storage capacity of the soil. This pore space is either filled with liquids or gases. If the volumetric water content (Θ_v) is subtracted from the total porosity, the gas-filled pore space is derived. While the amount of oxygen required by plant roots depends more on the rate of oxygen supply than the total concentration, it is nevertheless a useful rule of thumb to remember that soils with less than about 10% air-filled pore-space may contain too little oxygen for adequate aerobic respiration.

Bulk density is often regarded by field scientists as the most useful parameter of soil structure, being used as an indicator of soil compaction, or loosening. However, it is also a rather insensitive measure of pore structure, and there are some traps for the unwary in its measurement and interpretation. In swelling soils, which may show 30% volume change between air-dry and fully-hydrated states, a constant value for bulk volume cannot be obtained, and bulk density must be expressed with respect to a state beyond which no further volume change occurs. In practice, it is often most sensible to make that volume the most fully swollen state and refer other states to it. Good values of bulk density also depend on obtaining representative, undisturbed soil volumes at the scale of structural units occurring in the field, with samples free of alteration by shattering or compression. This is not always easy in stoney or cemented soils, or in cloddy and cracked soils. Finally, the relationships between bulk density and other measures of soil compaction are not constant, but are generally empirically derived. Thus a limiting mechanical resistance to root growth may occur at a bulk density of 1.7 t m^{-3} in a loam, but at only 1.3 t m^{-3} in a clay (Barley and Greacen, 1967).

Pore-size distribution

Pore-size distribution describes the sizes of pores in particular size categories. The class intervals used are somewhat arbitrary but as pore sizes range from about 3×10^{-9} m to about 0.1 m in diameter, classes are chosen to represent each order of magnitude. Pore-size distribution is normally computed from the water-retention curve (the 'moisture characteristic' of Childs (1940)) by means of the equation:

$$\rho gh = 2\gamma \cos \alpha / r$$

where ρgh is the suction exerted on the water held in the soil (ρ = density of water, g =

Table 6.1 Pore dimensions, their origins and significance

Average pore diameter (μm)	Origin	Significance
0.003	Separation distance between clay platelets	Smallest pores; contain structural or bound water
0.1	Spaces between clay 'domains' or packages	Equivalent to permanent wilting point (−1.5 MPa)
1–2	Pores within stable micro-aggregates	'Storage' pores capable of penetration by hyphae and bacteria
5–10	Pores within stable micro-aggregates	Size of root hairs and higher order lateral roots
30	Pores between single-grain, close-packed sand or between micro-aggregates	'Field capacity' (−10 kPa), i.e. retaining water against gravity for 24 hours
100–1000	Created by roots and macro-fauna, pressure and tension cracks	Transmission pores for rapid transport of water
10 000–100 000	Primary shrinkage cracks in clay soils, fracture planes from tillage, fissures	Transmission pores for very rapid draining of water from clay soil surfaces

gravitational force and h = the hydrostatic suction or head), γ is the surface tension and α is the contact angle of the water held in the soil. Pores with radii small enough to sustain the water meniscus against ρgh have an upper limiting value of r. A full explanation of this concept is given in text books on soil physics. Pores of different sizes and their origin and significance are described in Table 6.1.

The significance of pores of different diameters rests on the fact that increasing suction (a negative potential energy) is required to withdraw or move water in smaller pores, because of the surface attraction of the water to the solid particles. For adequate plant growth, soils need a balanced distribution of large transmitting pores and small storage pores. Texture (or more correctly mechanical analysis) is the most important soil property governing the pore size distribution. Coarse sandy soils with a large proportion of pores > 30 μm diameter cannot hold water for more than about a day against a suction gradient. Sandy soils have pore water-retention capacities of < 100 mm m^{-1}. Clay soils on the other hand may have three times the water content, but hold half this water at suctions close to or beyond the limit of plant-available water (*c.* 1.5 MPa; note, 1.0 MPa = 10 bar). Massive clays with very few large pores also drain exceptionally slowly and may shed water as runoff simply because of their very low infiltration rate, even when their surfaces are not puddled or crusted.

Greenland (1977) and Luxmoore (1981) have attempted to classify these pore classes in terms of function rather than by size alone. Greenland's terminology is particularly helpful in emphasising the different requirements of the biological system for both small and large pores. His scheme is described in Table 6.2.

A well structured arable soil will contain nearly equal proportions of storage and transmission pores, with smaller proportions of residual, bonding, and very large pores.

While texture, or more precisely mechanical composition, dominates the general response of soils to water storage, the flow of water depends very largely on the soil structure, and on the number and continuity of the transmission pores and fissures. At low suctions (matric potentials of > 100 kPa) the water-retention curve of a surface soil, for example, is markedly altered by tillage or stock trampling. Figure 6.1 shows water-retention curves for undisturbed samples of zero-tilled and disturbed surface of a ploughed red-brown earth at Merredin, Western

Table 6.2 Classification of soil pores according to their functional significance (Greenland, 1977)

Size (μm diameter)	Equivalent capillary potential (kPa)	Name
<0.005	$<-6 \times 10^7$	Bonding pore
<0.05	$<-6 \times 10^3$	Residual pore
0.05 to 50	-6×10^3	Storage pore
50 to 100	−60 to −0.6	Transmission pore
>500	>−0.6	Fissure

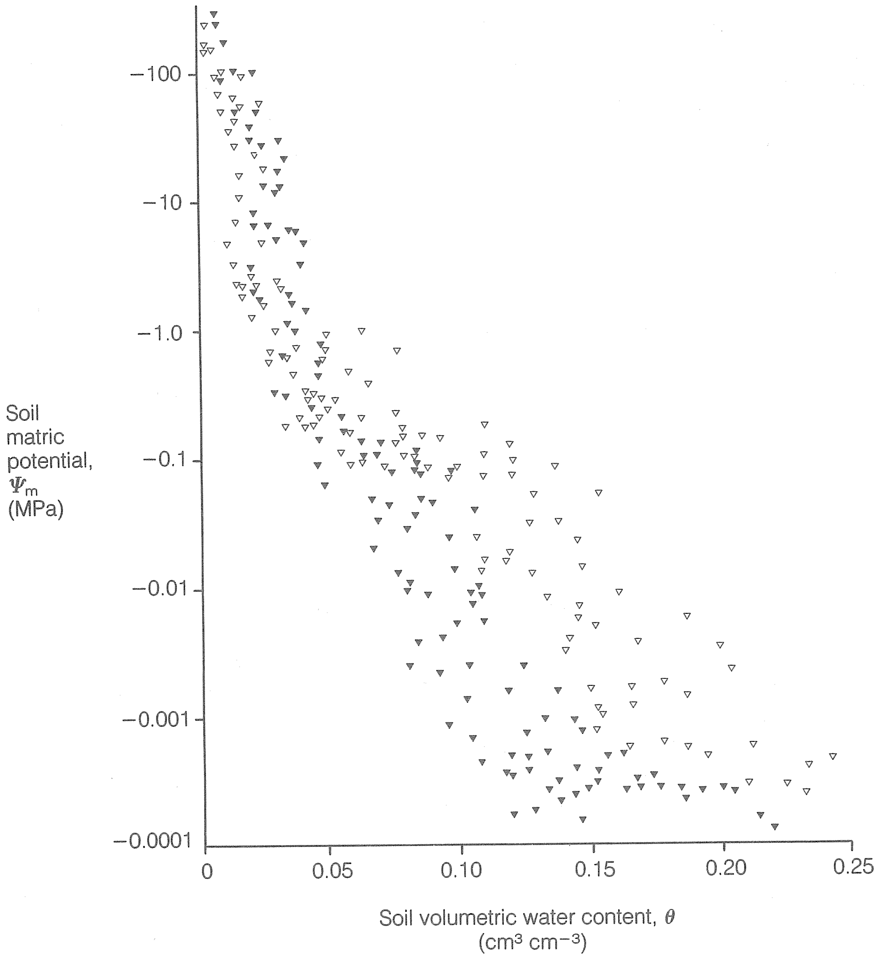


Figure 6.1 Water retention curves for the surface 4 cm of a red-brown earth (calcic Haploxeralf) at Merredin, Western Australia, zero-tilled (▽) and ploughed (▼) (Hamblin, unpublished)

Australia, after 3 years treatment (Hamblin, unpublished). The soil that was direct drilled with a triple disc (i.e. zero tilled) retained more water at higher matric potentials than the ploughed soil, equivalent to pore diameters of 3-300 μm.

Pore continuity

Water flow depends on the existence of a hydraulic gradient, and in a one-dimensional analysis the flux (volume of flow per unit time) depends on the hydraulic gradient and the 'conductivity'

(K (Θ)), which has units of length/time. K (Θ) is basically an expression of the pore geometry, but it is assumed to be a constant property, varying only with respect to the water status (content or potential) of the soil. This is clearly a simplification, as K is notoriously variable when measured at different points in a field (Nielsen *et al.*, 1973), with coefficients of variation exceeding 200% (Warrick and Nielsen, 1980). This variation tends to increase as the soil approaches saturation because the larger fissures are unevenly distributed within the soil matrix, their shapes seldom approach a uniform cylindrical geometry, and they are frequently discontinuous. Because hydraulic conductivity is both more variable and time consuming to measure than many other soil properties, indirect or derived properties are often measured instead. This point is discussed in more detail in the last part of the chapter.

Interest in pore continuity has been stimulated in recent years by an increased awareness that preferred-pathway flow of water, through vertically continuous pores, redistributes water into deeper parts of the soil profile faster than is predicted by conventional theory, and operates in nature more frequently than previously expected (Bouma *et al.*, 1978; Beven and Germann, 1981). Most problems of structural degradation of arable soils relate to the disruption of transmission-pore continuity.

Large diameter pores (of more than about 500 μm diameter, sometimes termed 'macropores') develop naturally from weathering processes such as shrink-swell in vertisols, cryoturbation in boral environments, and macro-faunal activity, as well as the more ubiquitous effects of roots. These processes are, however, relatively slow, with a time span of years, whereas many tillage and traffic operations alter soil structures instantaneously. There are many ways this disruption manifests itself in the field, as for example in the occurrence of perched water tables in the upper half metre of tilled soils, or in mottled and anaerobic zones at the base of tilled layers. The diagnostic criteria are described more fully in the final part of the chapter.

Soil structural stability

The sequence of aggregate development in topsoils should be viewed as being a dynamic one, which is intimately linked with a seasonal pattern of plant growth and decay, and of microbial and faunal activity. Into this naturally varying rhythm, cultivation practices introduce accelerated rates of microbial respiration, loss of organic matter, and a drastic reduction in macro-faunal activity. In addition, exposure of bare soil surface to rain and traffic causes slaking and dispersion of a much larger proportion of the surface than occurs under continuous plant cover. It is against this background that current tillage practices in Australia should be viewed.

Structural degradation implies an alteration of an initial structural state. There is a substantial body of evidence to show that aggregate stability is reduced when soils are repeatedly worked or agitated when wet, as when they are cleared for agriculture, cultivated, land-formed or harvested for root-crops. Much of our knowledge on the mechanisms of soil aggregation, aggregate stability and the physico-chemical processes that affect aggregation comes from work carried out on the South Australian red-brown earths (Haploxeralfs, according to the 'Soil Taxonomy'* classification (Soil Survey Staff, 1975)). Historically, it was found that there was a rapid decline in structural stability and nutritional fertility when these red-brown earths were cropped for cereals in a fallow-wheat rotation (Greacen, 1958). The

*'Soil Taxonomy' provides a table equating the terminologies of the various international taxonomic systems at the Great Soil Group (Order) level.

decline was more rapid than could be accounted for simply by correlation with reduction in total organic matter. Rain falling on the bare soil produced crusts of very much lower permeability than the underlying soil. Millington (1959) demonstrated that fallow-wheat rotations led to higher bulk density and poorer emergence of wheat than in pasture-wheat rotations, especially when heavy rain fell in the month after sowing. Quirk and Panabokke (1962) suggested that organic matter level *per se* was of less significance to structural stability than its distribution, in particular in stabilising the larger pores between micro-aggregates, which are destroyed on remoulding. Subsequent work by Greenland *et al.* (1962) and Clarke *et al.* (1967) endeavoured to identify specific organic binding agents and their distribution.

Circumstantial evidence suggested polysaccharides of plant and microbial origin were responsible for the 'short-term' aggregation that developed after a few years of non-cultivation (pasture), whereas the persistent, stable micro-aggregation appeared to be linked more closely to long-lasting metallo-organic bonding agents (Greenland, 1965). Iron oxides, which are present in abundance in these and many other Australian soils, do not appear to be acting as interparticle cements, but are present as small, discrete granules, randomly distributed through the soil (Deshpande *et al.*, 1964).

A model of the soil aggregate and its organic polymer bonds, developed by Emerson (1959), has formed a useful starting point for understanding soil aggregation. More recently, the work of identifying specific bonding substances and their disposition in different sized aggregates (Turchenek and Oades, 1978) has demonstrated that, whereas the amount of macro-aggregation is related to total organic matter the extra stability found in pasture soils is related to aromatic bonding materials, microbial polysaccharides and decomposing fine-root and hyphal material (Tisdall and Oades, 1980a). Much of the fine-root network that creates very stable micro-aggregates (20-50 μm) of pasture soils is physically ruptured and subsequently oxidised by cultivation. Cultivation also affects the wetting and drying cycles in the surface soil, leading to more rapid 'age-hardening' akin to thixotropic behaviour of clays (Utomo and Dexter, 1981a). This increases ped strength and reduces water availability.

In terms of soil management, therefore, it has been clearly demonstrated that persistent cultivation (over several years, or several times in one year) is structurally very damaging to such soils. This damage manifests itself as surface crusts, large clods in the seedbed, and poor germination and emergence. It is accelerated when soils are tilled while near their plastic limit (Utomo and Dexter, 1981b), or are mechanically disrupted by raindrop action. Restoration of soil structure can be achieved by all practices that return more organic materials to the soil: residue incorporation, dense pasture regrowth (promoted by reseeding, adequate fertilisation and grazing management), and by allowing biological processes the greatest scope through non-disturbance and high levels of plant nutrition, which encourage near-surface root growth and promote larger soil-animal populations. Direct drilling techniques that leave proportionately more of the organic matter at the soil surface have an obvious role here.

The findings from the Urrbrae loam (Waite Institute, Adelaide) cannot be extrapolated to all other red-brown earths, however, let alone all soils of different 'Great Soil Groups', as it is in some respects an atypical soil in its group (Northcote, 1981). It is a non-calcic form, which has developed in a wetter climate than many other wheatbelt xeric alfisols. Most red-brown earths are either sodic or saline, and are calcic at depth. Such soils slake and disperse, even more readily than the Urrbrae loam, under mechanical stress. These soils require gypsum to improve their cation balance and maintain a sufficient electrolyte concentration to suppress any further dispersion.

Slaking and dispersion

Soils that have very stable aggregation are those that do not slake or disperse when subjected to wetting, or wetting combined with imposed stress. Slaking describes the disaggregation of soil crumbs into constituent mineral fragments and clay 'micro-aggregates', a term coined by Edwards and Bremner (1967). Dispersion describes the process in which individual clay crystals migrate away from each other as the result of a net excess of repulsive over attractive electrical forces. Repulsion occurs as the result of expansion of the diffuse double layer of counterions, which balance the charge on the clay surfaces. This takes place when the concentration of the bulk-electrolyte solution is lowered so that exchangeable ions diffuse away from a tightly packed configuration, or when cations with hydration shells that fit into a close-packing arrangement exchange for those with larger hydration shells which fit more loosely around the clay. The most structurally damaging of these substitutions occurs when Na^{+} replaces Ca^{2+}. True, stable dispersion only occurs when the water-to-soil ratio is very much greater than one, that is when the soil is in a suspension, as it may be when flooded. However, temporary dispersion, with the clay reflocculating and settling out of solution in a short period, is widespread in surface depressions of wet and puddled soils. Clay skins then collect at the surface of the soil to dry as crusts, which can block the passage of air, water or underground shoots. If such clay is washed into the soil (a process referred to as illuviation) through larger cracks it may accumulate as a layer of hydraulic and mechanical impedance within the profile (Greenland, 1979). Soils in which exchangeable sodium and magnesium occupy some of the exchange sites on the edges and surfaces of the clay particles are therefore prone to dispersion.

Exchangeable-sodium percentage (ESP) has frequently been used as a measure of a soil's susceptibility to dispersion, but it is not in itself a totally reliable guide. The soil solution concentration, which controls the thickness of the double layer, together with the clay mineral composition, and the total clay content, must also be considered. In America, where exchangeable magnesium is seldom a problem, the 'critical' value of ESP is set at 15% whereas many Australian soils disperse with ESP values of as little as 6%, because they contain substantial amounts of exchangeable magnesium (Emerson, 1977). Smectitic clay minerals, of which montmorillonite is the best known example, swell very markedly when sodium saturated, whereas kandites (such as kaolinite) have very limited expansion.

In conclusion, it is important to reiterate the unique role of organic materials in stabilising aggregates in topsoils, despite their small total concentration. Other bonding agents such as metal polycations and hydrous oxides have a significant role in tropical and arid soils of very low organic-matter status, and in subsoils.

EROSION PROCESSES AND SOIL MOVEMENT

Water erosion

Water erosion occurs when the soil's capacity to absorb rain is less that the rate at which rain arrives at the soil surface. The surface therefore ponds. The infiltration capacity of the soil depends on the rate at which water is transmitted through the soil (some measure of the hydraulic conductivity, K) and the time of the total infiltration event. When water arrives at the soil surface at a rate equal to, or exceeding, the saturated conductivity (K_s) over short time periods of the order of minutes, the infiltration rate (I = the volume flux per unit area) equals the 'sorptivity' (S = the slope of the cumulative infiltration volume against time (Philip, 1957)):

$$I = S\,t^{1/2}$$

The power function denotes that this is a diffusion process. Water diffuses away from the zone of higher concentration to lower concentration. This equation predicts infiltration when water is ponded at the surface, as in flood irrigation, but to predict time-to-ponding under rainfall, where $I > K_s$, the rate of redistribution into the body of the soil depends on the hydraulic conductivity ($K(\Theta)$) and the soil water diffusivity ($D(\Theta)$).

$D(\Theta)$ and $K(\Theta)$ are difficult and time-consuming to measure, as discussed before, and recent developments in the theory of non-ponding infiltration have used scaled parameters of Θ and K_s to describe $K(\Theta)$ and $D(\Theta)$. Measurement of time-to-ponding and overland flow can then be made from changes in Θ with time, using sprinkling infiltrometers or other devices capable of delivering low-volume rates of water to the soil surface.These developments are described in more detail by White *et al.* (1982). Such developments have extended infiltration studies far beyond the empirical approaches of Green and Ampt (1911) and Horton (1933), which are still used in many catchment studies on erosion.

Prediction of time-to-ponding is, however, still hampered by imperfect characterisation of the soil surface and particularly its stability to rainfall. Where instability is known to occur one solution has been to assume that crusting occurs instantaneously, and to treat the crust as a separate layer that imposes a 'throttle', or negative head, on the redistribution of water into the bulk soil. Measured values of crust conductance show that crusts may have very much lower conductivities than the rest of the soil, as the data in Table 6.3 demonstrate. In other words the dry uncrusted soil could absorb rain at more than four orders of magnitude faster than the crusted soil.

Table 6.3 Saturated hydraulic conductivities (K_s) of a crusting red–brown earth (Haploxeralf), with equivalent rainfall rates (McIntyre, 1958)

Soil	K_s (m s^{-1})	Equivalent rainfall rate (mm hr^{-1})	Descriptive term
Clay skin	5×10^{-9}	0.02	Fine mist
Disaggregated surface layer	5×10^{-8}	0.2	Drizzle
Bulk soil below	1×10^{-5}	36	Downpour

Overland flow develops once the surface has ponded. This process is described in detail in Chapter 8. It is not readily seen because surface irregularities rapidly set up instabilities in the flow. Lateral concentration occurs, channelling the water into rills. Nevertheless it is effective in entraining sediment, despite the difficulties observers have had in obtaining experimental data of this elusive but ubiquitous process. Emmett (1978) quotes an example in a semi-arid environment (New Mexico) where 4.5 kg m^{-2} of sediment per year were collected from an apparently unrilled catchment slope. Surface erosion was operating by general entrainment or sheet-flow, not by rill erosion, which is the most noticeable form of accelerated erosion from degraded agricultural environments. The appearance of rills is influenced by many factors, but steepness of slope, high runoff rates and surface roughness are the most important. Overland flow (sometimes called Hortonian flow) appears to be more common in arid and semi-arid regions, or where the original vegetation and soil structure have been much degraded (Dunne, 1978). It is responsible for much of the sediment load that occurs in Australian creeks and dams. Sub-surface flow is most prominent in environments that have highly permeable surface soils, dense vegetation and deep litter layers.

Models for soil erosion by water usually express sediment transport as a function of distance from a watershed, multiplied by some power of the slope gradient. 'Distance' is in this way being equated with overland flow. The 'critical distance' over which overland flow occurs before appreciable erosion takes place depends on the annual rainfall, soil storage capacity and mean rainfall per rain-day (Kirkby, 1978). Kirkby demonstrated that the 'critical distance' decreased not only with increasing rainfall, but with increasing ratio of total rainfall to rain-per-rain day (R/N). Thus the critical distance for two British sites were 2×10^{10} m and 2×10^{3} m, but at a site in Arizona with half the rainfall but a low soil storage capacity the critical distance was only 3 m. This implies that sediment transport occurs over a larger proportion of each drainage basin in semi-arid areas than in well vegetated regions of low rainfall intensity.

On the scale of the drainage basin, soil-erosion models commonly express sediment transport rates as a function of the distance from the watershed to defined channels, multiplied by some power of the slope gradient. Carson and Kirkby (1972) found that the annual loss of sediment could be satisfactorily predicted by the annual cumulative overland flow and the slope of the hydraulic gradient down the catchment to its outflow. The fit remained good even when different vegetation covers were compared and when a fifty-fold variation was imposed on overland flow.

In summary, water erosion of soil operates whenever the rainfall rate exceeds the infiltration rate for more than a few minutes. As semi-arid and tropical regions experience many more rain events of high intensity (say over 20 mm hr^{-1}) than do temperate regions, the number of potential erosion events is greater in the sub-tropics and tropics irrespective of soil type. In addition, crusting from raindrop impact can reduce infiltration by three or four orders of magnitude, if the surface soil is unstable. Finally, overland flow that entrains sediment for transport in rills and streams is a more widespread phenomenon in areas of low, erratic rainfall than in areas of high rainfall. The critical distance over which water moves before entraining sediment is much less in semi-arid environments. All these aspects emphasise the high risk of erosion in Australia.

Wind erosion

Similar considerations of the interaction between low, erratic rainfall, sparse vegetation cover and large unbroken ground surfaces illustrate how these features predispose many of the sandier Australian soils to considerable risk of wind erosion. This is particularly significant in the western and southern coastal agricultural belt, where the largest areas of coarser textured soils occur and the prevailing westerlies and southerlies blow over long distances. The time of year in which high wind speeds, with localised gusts, occur varies from one part of Australia to another. June to September is the most probable period for southern Western Australia to experience these, whereas the south-eastern half of the continent encounters them more between September and December (Whittingham, 1964). The risk of wind erosion during periods of bare soils and during early crop establishment is therefore greater in the west, but wind erosion resulting from overgrazing and stock treading is likely to be greater in the east.

In all potentially vulnerable situations, wind erosion is most likely wherever there is loose, fine, dry soil with no protective cover. The risk increases where the surface is smooth and the fetch is unimpeded over long distances. Small topographic undulations, shelterbelts and windbreaks all help to reduce the fetch, but the greatest protection available to farmers in terms of cost-effectiveness on cropped land is to maintain a roughened, preferably vegetated, surface (Chapter 7). Thus, residue retention and direct drilling systems have gained more rapid acceptance in such regions as the Esperance and Geraldton sandplains of Western Australia, where the risk of sandblasting of young seedling crops is very great.

Soil particle movement occurs by suspension, saltation and surface creep, as defined by Bagnold (1941). Particles in suspension range from $< 2\ \mu m$ to $> 100\ \mu m$ in diameter, with a median diameter of about 50 μm. In long-distance transport only the finer particles ($< 20\ \mu m$) remain in suspension (Gillette, 1977). This, in effect, is a winnowing out of the most nutrient-rich fraction of the topsoil, and the decline in subsequent fertility has been measured in simulated wind-events, where the soil surface has been 'vacuumed' of millimetres of soil at a time (Marsh, 1971). Saltated particles, which are lifted a metre or so and then fall back initiating movement of other particles, may be up to 500 μm in diameter, but particles greater than this move only by surface creep. Saltated particles constitute 50 to 80% of soil movement by wind. These and the creep-moved particles accumulate at fence lines, against shrubs and in hollows. They are characteristic indicators of wind erosion.

Thus protection from wind erosion depends on establishing and maintaining vegetation or vegetation residues, providing a rough surface to cultivated areas, and reducing the width of paddocks to a few hundred metres by the provision of shelterbelts. On some very sandy soils it is difficult to maintain vegetation during long dry periods, especially in combination with livestock enterprises. The only feasible option under these conditions is to reduce the stocking intensity and the number of crops in a rotation (Lyles, 1980).

SOIL STRENGTH AND COMPACTION

Soil strength depends on the cohesive and frictional properties of the material. The shear strength of soil is often measured by loading a sample in one direction (normal to the force) until it fails. The failure envelope, which develops from applying increasing loads, is described by the Mohr-Coulomb equation:

$$\tau = c + \delta \tan \phi$$

where τ is the shear stress, c is the cohesive force, that is the attractive force of particles for each other, δ is the stress normal to the shear plane and ϕ is the angle of internal friction. Cohesion increases with clay content because it depends strongly on the available surface area. It also increases with the number of absorbed water layers up to the point where water forms a continuous film, after which it declines rapidly. Friction increases with the number of interlocking particles, and is therefore influenced by the packing and angularity of primary grains. Sands that contain $< 5\%$ clay have little cohesive strength but may have considerable frictional strength, especially in cases where coatings of hydrous metal oxides create secondary cementation as the soil dries. Conversely, materials that increase intra-aggregate bonding, and develop electro-chemical repulsion between aggregates (as with lime and organic matter) reduce the angle of internal friction so that the soil shears at a lower value of imposed force.

When the soil is compressed there is a reduction in pore volume. At quite low pressures the particles reorient towards each other. Maximum pressures exerted by different types of agricultural machinery and farm animals have been summarised by Dexter and Tanner (1973). Tractor tyres produce pressures of 0.2 MPa (1 MPa = 1 MN m^{-2}, or 10 bar), horses and cows 0.3 MPa, sheep and humans 0.1 MPa. Interestingly, although roots can generate pressures of up to 1.0

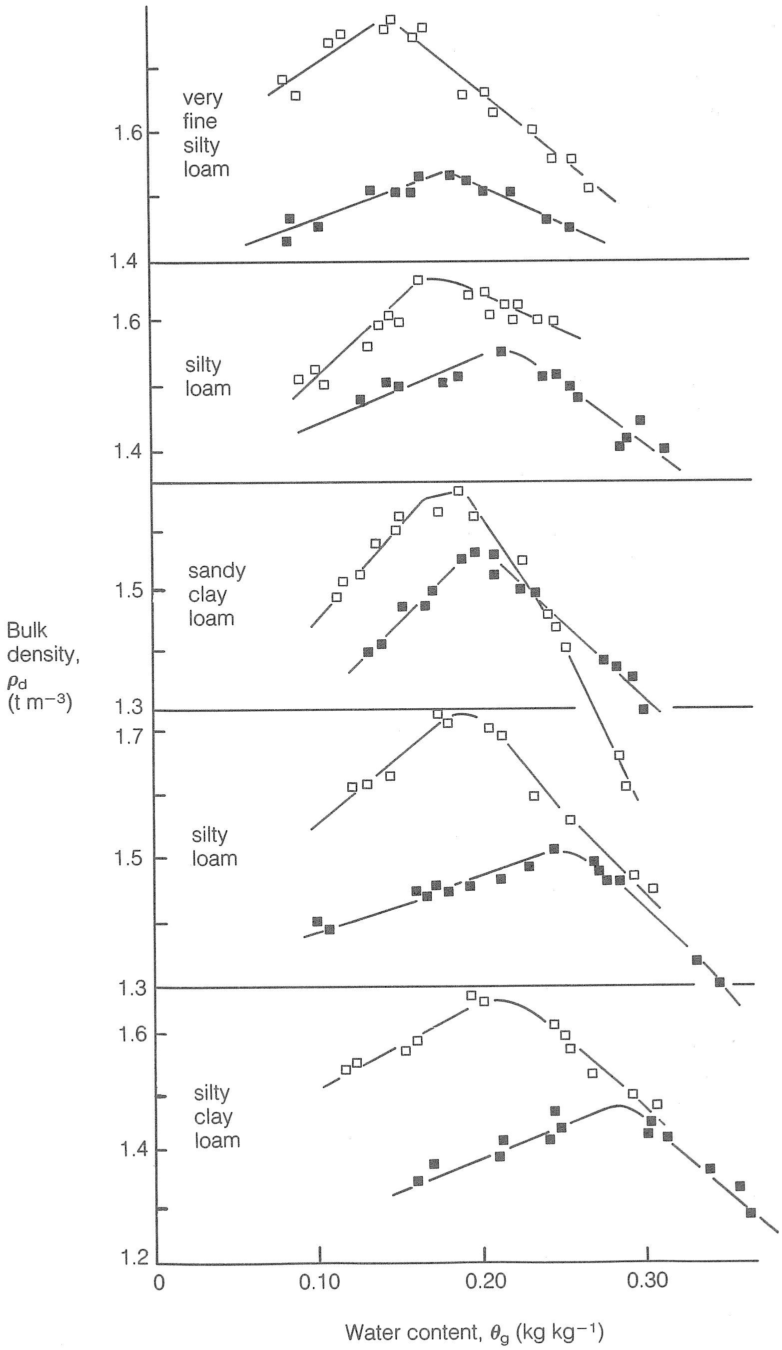


Figure 6.2 Bulk density at maximum confined compaction (Proctor test) over a range of water contents on a range of East Anglian silt-textured soils with high (■) and low (□) levels of organic matter (Hamblin, 1975)

MPa they can be deformed and impeded by external pressures of as little as 0.05 MPa. The compression that results from tractor tyres and other traffic expresses itself as compacted and sheared zones distributed over a pear-shaped vector resulting from arch-action, with decreasing loss of porosity outward across the vector. Distributing the load over a larger surface area, by using wider tyres or continuous track, can compensate for increased tractor weight to some extent, but some damage by tillage is inevitable in most circumstances. This is because any drawbar pull requires a certain load per unit area of ground contact to avoid wheelslip, which is just as damaging to the structure of the surface soil.

Compaction is best reduced by operating when the soil is at water contents in the lower end of the friable range, but this is seldom practicable, and conflicts with other management requirements. Compaction increases with soil water content up to the point where it is water rather than air that is compressed between particles, after which the incompressibility of water reduces the effect of the compactive load. Figure 6.2 shows the effect of increasing clay content on the bulk density at which confined compaction peaks with paired soil samples of high and low organic matter. This was tested over a range of water contents. The soils used were in the silt range of textures. The maximum compaction occurred at a water content below the plastic limit (that is, the water content at which the soil will deform plastically), while still in the friable range. Note that the sandier-textured soils compacted to higher bulk densities than the clay soils and that increasing organic matter substantially reduced the maximum density, even though the organic carbon levels were not particularly high. They were within the range of carbon contents found in many Australian soils, and this suggests that increasing organic matter may have an important role in improving mechanical properties.

Compaction can be reduced by restricting wheelings to certain defined pathways (tramways, in European terminology), reducing the number of operations, and by maintaining organic matter at levels in which soils remain friable over a wider range of water contents, thus requiring less draught during tillage.

THE AUSTRALIAN ENVIRONMENT AND ITS INTERACTION WITH TILLAGE AND SOIL STRUCTURE

THE ENVIRONMENT

The salient features of Australian rainfall dominate agricultural land management. The mean isohyets (Figure 6.3a) immediately draw attention to the small proportion of the continent that receives sufficient rain for rainfed agriculture. About 83% of South Australia, 58% of Western Australia, 20% of New South Wales and 13% of Queensland receive less than 250 mm per year. This low total quantity is characterised by substantial annual variation characteristic of semi-arid environments. Figure 6.3b shows the coefficient of variation (standard deviation of the mean expressed as a percentage) for the simplest rainfall parameters - mean annual rainfall. The arable zone is delineated by a dotted line, and within that the variation is for the most part at least 30%, with the variability increasing inland to drier districts. When this aspect is considered in the context of seasonal distribution (Figure 6.3c) it can be seen that there is only a small area for rainfed crop production, where growing-season rainfall is both reliable and sufficient. The consequences are that, firstly, fallow practices for soil water storage are ubiquitous through much of the cropping belt, secondly, that prolonged dry periods each year cause a net upward movement of salt and water through many soils, and thirdly, that drought is generally the most severe limitation to yield.

The number of rain-days per year (Figure 6.3d) is a conservative indicator of the proportion of the year in which the topsoil is biologically active. It is conservative because the topsoil will remain wet enough for continued microbial respiration for a week to a month after rain

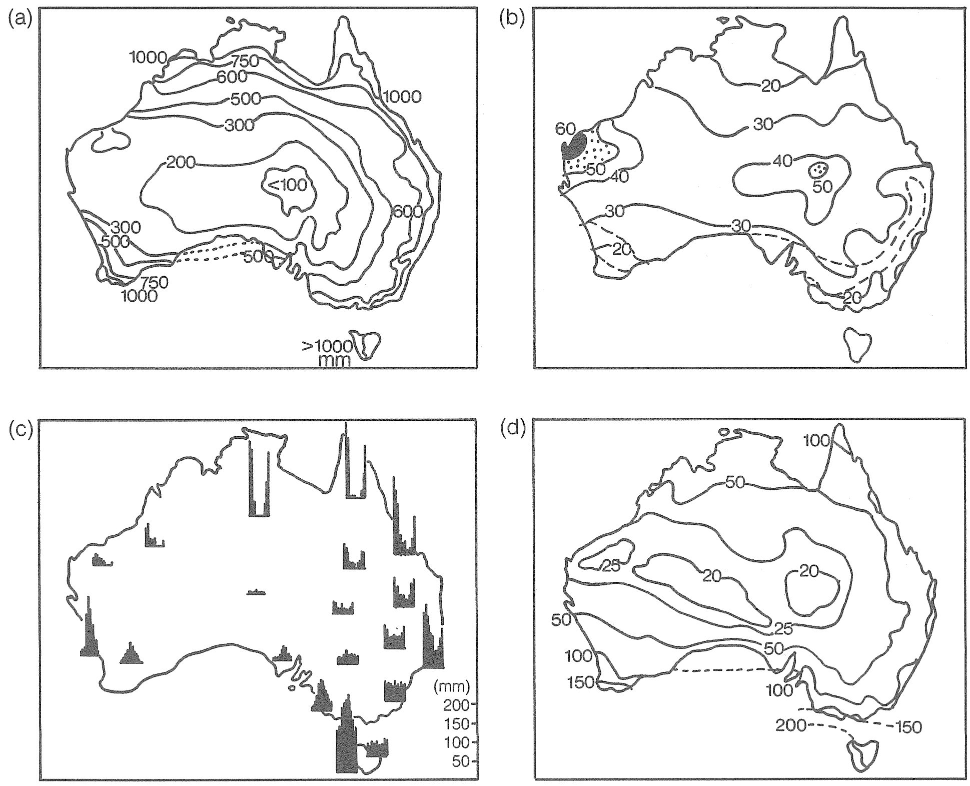


Figure 6.3 (a) Mean annual isohyets for Australia. (b) Rainfall variability (the coefficient of variation, expressed as a percentage, of the mean annual rainfall). (c) Monthly distribution of rainfall (the amount of rain shown in mm on the right-hand scale). (d) Mean annual number of rain days.

events of > 20 mm, and because alternating wet and dry cycles frequently cause 'flushes' of microbial activity with higher biomass turnover than continuously wet conditions. However, some damping down of microbial activity in the south and east will also occur in areas receiving up to 60 or more frosts a year. On balance, however, it is only for one-third to one-half of the year that biological activity takes place in Australian soils. Rainfall characteristics thus strongly influence the biological activity in the soil and the rates of change in soil organic and physical properties that may occur with changes in land-management practice.

Because Australia has undergone no major orogenies or glaciations in the recent geological past, most of the soils are very old, greatly weathered, and nutritionally of moderate to low status. Of the major soil taxa the mollisols (prairie soils, chernozems) and spodosols (podsols, gleyed soils) are sparsely represented, while much of the arable land is composed of alfisols (red earths, solonetz soils, sierozems), vertisols (black earths) and ultisols (latisols, red-yellow podsolics). The latter are frequently developed as catenary sequences in the landscape, often containing buried horizons, and truncated profiles. A large proportion of Australian arable soils have a vertical heterogeneity in which texturally coarser materials overlie finer ones, so that subsoils often have much lower hydraulic conductivities than topsoils (Stace *et al.*, 1968). As a result, deep parts of the profile may not wet up adequately for exploration by plant roots, and water may be lost through interflow, surface ponding and runoff. Many such soils do not wet to depths greater than 1 m in most seasons, which is thus the depth of the root zone of annual crops. In addition, most topsoils are low in organic matter and exchangeable bases, and have poor aggregate stability. Subsoils can be either very acid (pH < 4.5) or very alkaline (pH > 9.5). Alkaline fine textured soils in lower rainfall areas are sodic to some degree. Thus the soils are often of low inherent productivity, but their cropping potential is often further reduced by the physical constraints of surface crusting, transient waterlogging and high subsoil strength.

Over 66% of seasonal variation in Australian wheat yields is attributable to variation in rainfall (Nix and Fitzpatrick, 1969). It is thus imperative for land-management practices to maximise infiltration and redistribution of water in the profile, while minimising runoff and soil evaporation. Encouraging results from land-management-system experiments show that combinations of practices such as minimum tillage, residue mulching, deep ripping (subsoiling) and gypsum application can offer some scope in halting further land degradation, improving soil physical conditions sufficiently to show yield increases. The average cereal yields of Australia, in common with other semi-arid grain producers, have shown almost no increase in the period 1960 to 1980, and remain around 2 t ha^{-1} (Turner and Begg, 1981).

TILLAGE-INDUCED STRUCTURES

SUMMER-DOMINANT RAINFALL ZONE

The 400-700 mm rainfall zone, in which annual cropping is carried out both with and without irrigation, extends in a broad arc between latitudes 23° and 29°, west of the Great Dividing Range. The climate and cropping practices of this zone are described in Chapter 3. The majority of soils are fine textured, with high clay contents. The properties of the clay dominate soil physical behaviour, particularly the degree of swelling and shrinkage, and the pore structure that develops. In the far north, the major environmental constraints to successful crop production are high soil temperatures and high rainfall intensities. In these environments the efficacy of surface mulches and non-disturbance of the surface level is clearly demonstrated (Lal, 1974).

Tillage practices to reduce erosion

Soil and water losses from accelerated erosion are the greatest management problem in this region. Berndt and White (1976) evaluated the significance of surface runoff from black, cracking clays of the Darling Downs to the water balance, crop yields and the economic viability of three cropping systems with different amounts of bare fallow. Their simulation demonstrated that strategies that increased cropping frequency and decreased duration of each cultivated fallow phase resulted in the greatest water-use efficiency and crop yield because there was less soil and water loss. This was particularly marked in the case of wheat, where yields were significantly correlated with antecedent water storage on all the sites that were used for experimental verification. Soil conservation research in Queensland and northern New South Wales has been active in assessing the relative protection offered by residue retention and direct sowing systems on black, cracking clays and on the grey clays, which have less pronounced structural shrinkage. Agronomic aspects of this work are reviewed in Chapter 3 while effects on the soil are considered here.

Black cracking clays (vertisols)

Experiments at Warwick (Queensland) were started in 1968 by J.W. Littler and J.M.T. Marley, and are among the oldest long-term cropping experiments on clay soils. The main treatments were ploughing or the use of herbicides for weed control, and burning or retention of crop residues, in combination. Ploughed soils were cultivated several times in each fallow phase. Residues were incorporated in the plough plus residue-retained treatment. The combination of residue retention with chemical weed control is known as 'no-till'. These experiments are reported in considerable detail here because they form an excellent example of the complexity of interactions that occur between tillage, stubble management, soil water regime and soil structure. It is the uncertainty of predicting the outcome of such interactions from established physical and chemical principles that has made it imperative to undertake many new long-term tillage trials on various soils across Australia following the adoption of direct sowing techniques into existing fallowing and rotational practices.

Several studies have been made on the soil structures that have developed in the Warwick experiment. Hewitt and Dexter (1980) measured the macro-porosity after 9 years of continuous cropping. Cultivated soil had 30% greater macro-porosity and 17% larger mean void size than uncultivated soil. However, residue management had an equally large effect. Soil in the no-till treatment had 45% larger mean void size than in the uncultivated treatment where residues were burnt. The authors also compared these structures with those developed on freshly tilled ground of the Waco and Mywybilla series, used in a study by Yule *et al.* (1976) (see later in this section). They found that the Mywybilla structures corresponded closely with those developed in uncultivated soil at Warwick, but that both of these differed from the Waco macro-porosity (which had a smaller mean aggregate and void size). They concluded that the increased void and aggregate size in the residue-retained treatments arose from the slower drying of the mulched soil surface, which caused slower shrinkage and fewer stress fractures.

Loch and Coughlan (1984) sampled the Warwick trial in the 6th year and found the percentage of large aggregates to be significantly less in the uncultivated, residue-burnt treatment (6.5 mm diameter as against an average of 10.6 mm in the cultivated treatments, and 9.1 mm for residue-retained treatment). Differences in organic matter were small and not correlated with aggregate stability, as measured by the ratio of clay dispersed by shaking in water to total clay content. Uncultivated treatments had more stable surface aggregates, and exchangeable sodium percentage (ESP) values were lower although they fluctuated from year to year, and in later years were not significantly different between treatments. When stability-related tests of the no-till and cultivated residue-retained treatments were compared by Hamblin (1980) in their 8th year, they showed significant differences in the results of those tests that dispersed the clay, but not in those tests that only slaked the aggregates. Selective extraction of bonding agents suggested that trivalent chelating metals were responsible for the greater stability of the no-till soil.

The Warwick experiments may be seen as a model for the processes working on all similar black cracking clay soils. They show that structural degradation occurs through slaking and dispersion of clay with raindrop impact on bare ground, or by working the soil when very wet. A surface layer of small clay aggregates then develops with only small-scale crack systems leading into the subsoil. Little excess surface water can then move rapidly down into the soil profile by preferred-pathway flow before the cracks are filled and runoff occurs. Slower surface soil drainage leads to a build-up of salts in the topsoil, which in time gives rise to higher ESPs and reduced stability of newly formed aggregates. The sequence can be halted and even reversed when residues are left to cover the surface, allowing soil cracks to form at wider spacings and to greater depths. These must then be left relatively undisturbed by direct sowing in order to persist and stabilise.

At Gunnedah a similar black cracking clay occurs on a 5° slope, where two residue-management treatments have been maintained since 1972 on large (1 ha) plots for runoff and soil-loss measurements. Residue levels on the incorporated plots averaged > 3 t ha^{-1} in the first 5 years (Marston and Hird, 1978) but the organic carbon levels did not apparently vary significantly between treatments, nor did any index of structural stability. Marston and Hird suggested that the effects of the high clay content (40% at Gunnedah, but still 20% less than at Warwick) had obliterated any measurable effect of organic matter as a bonding agent. However, in a later study, Donaldson and Marston (1984) split the treatment plots and imposed a new set of management treatments, as shown in Table 6.4. They reported that burning the residues reduced the level of organic matter on the Gunnedah site and that this was associated both with a reduction in percentage of water-stable aggregates and increased runoff. Soil losses when residues were burnt were 5 to 40 times greater than when retained (Marston, 1979; Marston and Donaldson, 1984). The differences in response to residue treatment reported by Marston and Hird (1978) and then by Marston and Donaldson (1984) may possibly be accounted for by the fact that changes in management occurred during the life of the trial. These changes have resulted in profound residual effects of past treatments on the soil surface behaviour under the present tillage treatments. They are exemplified by differences in organic carbon, water stored in the profile at sowing, and yields (see Table 6.4). D.F. Thompson (personal communication) indicated that the differences in levels of stored water resulting from burning versus incorporating stubble for 9 years are most striking and are significantly correlated with the yield differences, although the correlations between organic carbon and yield, and between carbon and stored water are not significant. Differences that had developed in surface crack development and aggregate stability may have been responsible for the differences in infiltration. The lower storage values of the previously burnt replicates could reflect a smaller minimum structural unit with less well developed deep cracks. This type of difference in the quantity of stored water has been reported from other fallowing trials on black and grey cracking clays, at Warialda and Croppa Creek in the Moree district and from Greenwood (grey clay) and Greenmount (black clay) sites near Toowoomba. At these latter two sites Freebairn and Wockner (1983) and Freebairn and

Table 6.4 Differences between duplicate plots sampled 2 years after new treatments had been imposed on 9-year-old burnt and stubble-incorporated plots at Gunnedah, New South Wales (Thompson, 1983a)

Treatment	Former straw management	Straw at sowing 1982 season (%)	Grain yield (t ha^{-1})	Organic carbon (g 100 g^{-1})	Water stored in top 90 cm at sowing (mm)
Burnt	B	1	1.05	1.03	290
	I	1	1.28	1.54	313
Incorporated	B	6	0.79	1.30	279
	I	6	1.15	1.79	350
Mulched	B	38	0.85	1.41	275
	I	38	1.09	1.45	335
No-till	B	85	0.75	1.71	275
	I	85	1.23	1.52	378

B = burnt 1971–1980.
I = stubble incorporated 1971–1980.

Boughton (1981) have reported consistent increases in infiltration and soil water storage for all residue-retention treatments, compared with a residue-burnt treatment, during 40 runoff events. It is not possible to differentiate between the effects of tillage, cover, and antecedent water content in their results. The residue-mulched treatment infiltrated more water than the no-till treatment at both sites, although soil loss was less without tillage. Other findings were in keeping with the observation in Chapter 8 that crop residues have a greater influence on soil evaporation than does tillage.

As a final note on the properties of the black self-mulching clays it is worth commenting on those studies that have been made on the reasons for different aggregate sizes that develop in different soil series, irrespective of season or cultural practice. Yule *et al.* (1976) found two size distributions of dryland seedbed aggregates. Group A soils from the Waco, Norille and Condamine series had a high proportion of small (< 2 mm) aggregates, and always gave good seedling emergence. Group B soils from the Anchorfield, Mywybilla and Cecilvale series had a higher percentage of larger aggregates (> 5 mm) and poor seedling emergence, although both groups had a modal aggregate size of 2-5 mm. These authors could find no significant difference in clay content, exchangeable sodium percentage (ESP), cation exchange capacity or organic-matter content to account for this, but soils in Group A did have a higher electrical conductivity of the saturated extract.

This work has been further extended by Coughlan and Loch (1984) to a wider range of cultivated soils from the same area, and examination of a larger number of soil properties. They concluded that large aggregates were formed from dispersed clay, which was derived from combined wetting and mechanical action, such as traffic on wet soil, or raindrop impact. They found that soils with lower cation exchange capacity were more likely to form large aggregates when dispersed in this manner, but no quantitative mineralogical study was undertaken that might have confirmed whether the proportions of clay of high surface charge or area varied between the groups. As cohesive strength increases with surface area, the largest aggregate sizes should be associated with highest proportions of smectitic clays. Aggregate size in self-mulching soils strongly influences infiltration and soil erodibility as well as crop performance (Loch and Donnallan, 1983; Bryan, 1968). If physico-chemical properties of the clay alone influenced the soil surface structure, the possibility of reducing erosion hazard by changing the tillage system would be remote. The efficacy of residue retention and zero tillage in reducing soil and water loss from these soils demonstrates that this is not the case.

Grey (brigalow) clays

The grey 'brigalow' clays (classified as Ug 5.24 by Northcote (1979) or chromic vertisols) of this region vary between self-mulching, structurally stable, soils, to hard-setting, dispersive and sodic soils. Structural instability occurs across a range of soil textures, but is associated with ESPs of > 4% and exchangeable magnesium percentages (EMgPs) of > 30%. Organic-matter levels are low in these soils (0.5%) but responses to organic ameliorants have been less long-lasting than to gypsum (Doyle *et al.*, 1979). However, no long-term surface-management experiments were established until 1981 (at Gurley and Croppa Creek, New South Wales) to test the types of soil structural response that might develop as a result of intact root systems and non-disturbance, as distinct from experiments using soil conditioners such as PVA and chopped hay. Table 6.5 compares these effects from two experimental sites on sodic grey clays at Gurley.

In many dryland cropping situations the weight of surface residue after harvest may be equalled by that below ground and the rate of disappearance of that material is much slower in

Table 6.5 Comparative effects of soil ameliorants and tillage treatments on the physical properties of two sodic grey clays at Gurley, New South Wales

Site A—clay 43%, organic carbon 0.51%, exchangeable Na 11%, exchangeable Mg 42% (So *et al.*, 1976)

Treatment	Surface-crust strength* (kPa)	Surface-soil hydraulic conductivity (cm hr^{-1})	Wet sieved aggregates > 100 μm (%)
None	525[a]	0.46	37.7
Deep ploughing	340[bc]	0.50	–
12.5 t ha^{-1} gypsum	100[e]	2.05	47.8
12.5 t ha^{-1} gypsum + deep plough	108[e]	0.66	43.6
5 t ha^{-1} chopped hay	205[de]	0.30	38.7
0.2% PVA in top 7 cm	418[ab]	0.91	43.1
LSD (0.05)		0.23	1.9

Site B—clay 49%, organic carbon 0.56%, exchangeable Na 4%, exchangeable Mg 34% (data from Marschke and Harte, 1983; Thompson, 1983b)

Treatment	Organic C 1982*	Presowing residues		Wet seived aggregates >250 μm* (%)
		Above ground	Below ground	
No till, stubble retained	0.73[a]	0.97	1.46	32.1[a]
Ploughed, stubble burnt	0.74[a]	0.16	1.31	27.7[b]
Ploughed, stubble incorporated	0.79[a]	0.12	1.11	26.4[b]

* Values having the same letter are not significantly different.

uncultivated systems. At Gurley, the first 2 years data from site B show greater aggregate stability under no-till despite no change in organic carbon. This suggests that macro-organic bonding (by roots) may have an important role to play in aggregate stabilisation. There is no doubt, however, that gypsum is the most significant ameliorant capable of providing rapid improvement in the physical properties of such soils by maintaining the coagulation of clay, which is a necessary prerequisite to the macro-aggregation developed either by organic materials or wetting and drying cycles.

On site A a dense plough layer at 30 cm was broken up by deep ploughing treatments. This layer had acted as an additional throttle to water penetration. So *et al.* (1976) reasoned that initial recharge of the subsoil depended on the extent and depth of normal or induced cracking at the onset of heavy summer rain, whereas subsequent water intake during the growing season and fallow period depended on the hydraulic conductivity of the surface soil. These experimental results bear out the contention that stabilisation of a desired structural condition depends on the use of conservation farming practices after chemical and mechanical amelioration.

EQUISEASONAL RAINFALL ZONE

Central and northern New South Wales, north-eastern South Australia and northern Victoria have an evenly distributed rainfall throughout the year. In many districts, however, less than 35 mm falls each month, there are few rain days exceeding 20 mm, and monthly averages are highly variable. Many of the soils have loam or clay-loam textures, but the surface layer is frequently more sandy than the B horizon, and is structurally unstable. The red-brown earths (alfisols of the Haploxeralf, Haplustalf and Rhodoxeralf groups) are widely distributed through this region, and are characterised by a clay ratio between the B and A horizon of 2 or more, a redder colour in the subsoil, accumulations of calcium carbonate, and ESPs > 6 in the subsoil, thus having an alkaline reaction. They have developed through weathering and illuviation of clay from parent materials rich in quartz and felspar (Chittleborough and Oades, 1980) and have lower hydraulic conductivities in the B horizon than in the A horizon. Long cultivated red-brown earths develop 'throttles' to infiltration in the upper part of the B horizon, as data from Olsson and Rose (1978) show in Table 6.6.

Table 6.6 Hydraulic conductivities (m s^{-1}) of a structurally degraded red–brown earth at Tatura, Victoria (adapted from Olsson and Rose, 1978)

Horizon (cm)	Soil water potential (ψ)		
	−10 cm	−100 cm	−1000 cm
A (12 cm)	1×10^{-5}	2×10^{-7}	5×10^{-9}
B_1 (40 cm)	1×10^{1}	1×10^{1}	–
B_2 (90 cm)	5×10^{-6}	1×10^{-7}	–

The surfaces, which are unstable, can be quite rapidly degraded by tillage operations and rainfall. In other words, they are soils that disperse when mechanically deformed while wet. This corresponds to category 3 of Emerson's (1967) classification of structural stability. Their structural stability has been closely correlated with their organic-matter content and composition. Many of the other soil types in this zone are also characterised by unstable structures and by particle sorting at the surface. There is thus as much, if not more, need as in the northern agricultural districts to reduce runoff, maintain and improve infiltration, and prevent crusting.

In this environment, soil water storage is necessary for adequate crop growth in most seasons (see Chapter 8). The value of stubble mulching may rest more on protecting the surface from crusting during infiltration than from reducing evaporative losses, because yields of grain need to exceed about 2 t ha^{-1} to give enough straw to significantly reduce evaporation (McCalla and Army, 1961).

Traditionally, farmers burn residues and then cultivate to kill weeds during fallow periods, but increasing use of blade ploughs now allows some residue retention with fallowing. Residues are often incorporated, or left standing for much of the summer, being burnt just prior to sowing. Burning has been a regular part of direct drilling operations, in contrast to the practice of the summer-rainfall belt. Experiments that seek to compare tillage methods in this region are therefore open to a wider variety of management options (length of fallow, sowing dates, degree of residue retention) than in other parts of Australia. In addition there is a grazing component (by sheep) of the residues which is common to the rest of southern Australia, but missing from the summer-rainfall cropping region.

Yield responses to tillage treatment

Yield responses at most tillage experimental sites have varied between treatments from year to year, with no clear indication of one treatment being more favourable under variations of seasonal distribution of rainfall. A very commonly observed phenomenon, however, in these soils is for slower earlier growth and reduced vigour of direct drilled crops (Gates *et al.*, 1981; Cornish, 1985; Mason and Fischer, 1985). Many reasons for this have been sought but the problem has not often been investigated in terms of the soil physical conditions in the topsoil. Osborne *et al.* (1978) measured the bulk density, infiltration rate and aggregate stability of seedbeds from the 6th and 7th years of a long-term tillage trial at Wagga Wagga. They found that there were significant differences between treatments, with most structural deterioration on the conventionally cultivated treatment. However, they did not assess plant growth other than yield. Grain yield was correlated with seedbed structural parameters only in those sub-treatments that received no nitrogen. When nitrogen had been added, less than 1% of the yield variation was due to structural factors. Hamblin (1980) found a reduction in the saturated hydraulic conductivity of the conventionally cultivated treatment from the same trial after 7 years of continuous cropping, together with a marked increase in the organic carbon percentage of micro-aggregates (75-200 μm) of the direct-drilled soil. It is possible that the lower yields on conventionally cultivated soil were related to poorer germination and emergence through crusted surfaces, although Rowell *et al.* (1977) reported that lowest numbers and low early vigour occurred on the direct drilled treatments in early years on the same experiment.

Infiltration, soil structure and tillage treatment

Detailed infiltration studies have been used to identify differences in structures resulting from tillage at some sites. This approach has much to recommend it over the conventional assessment of structural stability, in which aggregate behaviour, organic-matter content and crop yield are (hopefully) correlated, provided that the infiltration process simulates the unsaturated rainfall conditions of the real world, in terms of intensity, duration and droplet energy. Packer *et al.* (1984) measured hydraulic properties and associated soil properties on two sites that had had 7 and 8 years continuous cropping respectively at Ginninderra (G) and Wagga Wagga (WW). The plots at Wagga Wagga were measured in mid-summer when transient effects of recent tillage were minimised, and at Ginninderra after 18 months pasture regrowth, when cropping sequence had terminated. Table 6.7 shows the results.

Table 6.7 Soil properties and hydraulic properties on a calcic red–brown earth (Rhodoxeralf) and a brown podzolic (Haplustalf) soil after 7 and 8 years continuous cropping (0–10 cm depth) (Packer *et al.*, 1984)

Property measured	Tillage treatment					
	Conventional		Reduced		Direct drill	
	G[a]	WW[b]	G	WW	G	WW
Organic C (%)	0.99	1.10	1.16	1.22	1.45	1.28
Bulk density (kg m^3)	1.41	1.36	1.36	1.34	1.22	1.42
% infiltration	50	57	65	84	94	86
% runoff	50	43	35	16	6	14
Soil loss (kg ha^{-1})	330	410	215	290	20	180
Sorptivity (10^{-4}m s$^{-1/2}$)	0.8	3.9	1.1	4.8	1.3	3.7
Saturated hydraulic conductivity (10^6m s^{-1})	4.5	2.0	3.5	1.7	15.1	4.1
Total infiltration (mm)	5.3	17.3	6.0	14.5	8.9	11.5
Time to ponding (min)	5.0	16.5	7.0	23.9	6.0	25.2

[a]28 mm hr^{-1} for 20 minutes (Ginninderra).
[b]45 mm hr^{-1} for 40 minutes (Wagga Wagga).

Unsaturated sorptivity was measured at a negative pressure of 4 cm. This is equivalent to pores of diameter > 750 μm. Thus the increased rate of water redistribution into direct drilled soils would not have been due to redistribution through large shrinkage cracks and wormholes, but through pores of root-sized dimensions. In the Ginninderra soil, however, larger pores were also present (compare the saturated conductivities and unsaturated sorptivities) in the direct-drilled soil, which may have been the result of earthworm activity although this was not measured at the same time.

In most water-balance studies (see Chapter 8) there have been no marked differences between the amount of water stored, as a result of summer fallowing, between tilled and untilled treatments. This conflicts with previous, specific infiltration studies. However, the reason for this lack of tillage effect on stored water may lie with weed and stubble control in many instances. Cornish (1985, unpublished data) found that residue retention and fallow weed control increased water storage 2 months after a 78 mm rain event by 28-50 mm depending on tillage history. However, there was almost no net storage in either tillage treatment in the presence of weeds and/or the absence of crop residues. Residues increased infiltration, and weed control was necessary to retain water for the subsequent crop.

Earthworm activity is known to be strongly affected by tillage disturbance, and increased earthworm activity has been well documented on direct drilled soils in temperate (Ehlers, 1975; Edwards and Lofty, 1978) and tropical (Lal, 1974) environments. Australian studies on earthworms are reviewed in Chapter 12, but Australian literature on the effect of tillage on earthworm populations is very sparse. Given the important role that preferred-pathway flow has in increasing infiltration into hard-setting and massively structured soils (Tisdall, 1978; Bouma and Dekker, 1978; Beven and Germann, 1981) it seems curious that earthworm activity has received so little attention in Australian tillage experiments. It is possible that their presence has not been anticipated and has thus been overlooked. Alternatively, burning of residues, which is ubiquitous in much of this climatic zone and in the winter-dominant rainfall region, may reduce levels of coarse organic matter below that necessary to maintain viable populations. M.J. Goss and R.A. Fischer (unpublished data 1984) in a tillage trial at Murrumbateman, New South Wales, have found high densities of earthworm holes (> 200 m^{-2}) but there were no significant differences in the total number or size distribution with depth between treatments. The present sequence of long-term tillage experiments forms a most valuable field laboratory of biologically developed transmission pores and biologically stabilised soil aggregates. This is an area that requires much more research within the context of dryland agriculture.

WINTER DOMINANT RAINFALL ZONE

This broad belt, which straddles both western and eastern parts of the southern cereal-growing region of Australia, includes a number of major soil groups less well represented further north. In addition to the red-brown earths there are extensive areas of coarser textured sands, gravels and textural-contrast soils (sands over clays, ironstone gravels, or calcareous nodules) in Western and South Australia. Many of these soils are being actively podsolised and have transient water tables during the wet winter period. The combination of winter waterlogging and spring drought make for a particularly harsh cropping environment. In addition some of the lower-lying soils that are poorly drained have also been victims of secondary salinity encroachment as a result of extensive land clearance over the past century and a half. Areas of arable land affected by secondary salinity encroachment are particularly widespread in Western Australia (4% of total agricultural land) and Victoria (2%). While this chapter is not concerned with rehabilitation of such badly degraded land, it considers the advantages of whole-systems approaches to land management, which can be readily incorporated into cropping enterprises to improve and restore degraded structure.

Deep tillage

Deep tillage is one such practice, which is too costly to be considered as a routine method of cultivation, but can be used as an ameliorative treatment, sometimes in combination with gypsum application. Deep tillage (subsoiling or deep ripping) has long been advocated to break up traffic pans, plough soles, and other compacted layers (e.g. naturally occurring cemented layers in podsols), where these occur relatively shallowly in the profile (Barnes *et al.* 1971; Cannell, 1977; Cassel, 1980). The draft requirements and size of equipment normally restrict the operation to depths of less than about 0.5 m. While the practice of deep tillage is not confined to the winter-rainfall belt, current research is active in parts of southern Australia, and on a wider range of soil types than further north, so it is appropriate to treat deep tillage in this section.

Deep tillage combined with gypsum incorporated at depth has been most researched on the irrigated, duplex soils of the Riverina (Rengasamy *et al.*, 1984; Muirhead and Humphreys, 1984; Jayawardane and Blackwell, 1985). Studies carried out both at Tatura, Victoria (and described in detail by Tisdall and Huett in Chapter 4) and at Griffith, New South Wales, have demonstrated the necessity for improving the very poor hydraulic conductivity of the clay subsoils of these alluvial duplex soils, by both creating large fissures in them and by stabilising the resultant fissures with gypsum. In these instances the soil amelioration treatment has been part of a total land-management system designed to improve crop productivity substantially. The success of the Victorian experiment, which was carried out on stone-fruit orchard crops, was demonstrated by the four-fold improvements in yield achieved solely by soil management techniques (Cockcroft and Tisdall, 1978). In the more northerly irrigated annual cropping region the necessity of cultivating and harvesting frequently has introduced greater problems for successful maintenance of soil structural improvement than occur in the winter rainfed districts. However, these problems demonstrate the principle that it is first necessary to identify and rectify existing structural damage, by specialised techniques, then to maintain this improvement with a reduced or zero tillage system thereafter. Direct drilling alone cannot ameliorate cultivation damage that exists below the soil surface. This has been demonstrated in deep-tillage and direct-drilling experiments both at Rutherglen (Victoria) and at Wongan Hills (Western Australia).

At Rutherglen, a direct-drilling system based on ley-cereal rotations was developed in the early 1970s (Reeves and Ellington, 1974). The soils were brown podsolics (Cryandepts and Haplorthods) with impeded subsoil drainage, much of which had been induced by the development of dense traffic pans. In this wetter part of northern Victoria (mean annual rainfall 590 mm) denitrification losses and diseases associated with continuous wheat cultivation caused larger differences in yield between tillage treatments than did any surface structural differences. Later, lupin-cereal rotations were substituted, with marked improvement in cereal yields attributable to reduced disease and improved nitrogen use (Ellington and Reeves, 1978). More recently, deep tillage followed by direct drilling has been found to give yet another yield increase (Ellington, 1982). Nevertheless there are still significant soil physical and chemical problems, as many of these soils have dispersive subsoils, and some are very acid at depth. Further yield improvements, which are potentially possible in climatic terms, will depend on the use of gypsum, and on chemical or biological solutions to the soil-acidity problem.

In Western Australia, on the other hand, traffic pans have been found to be extensive in deep, loamy sands, which cover much of the north and central wheatbelt. Such traffic pans are distinguishable by variation in penetrometer resistance at certain water contents and by reduced root growth in the compacted zone, but are not otherwise visible (Hamblin and Tennant, 1981).

At Wongan Hills in Western Australia such a soil (typic Psamment) soon develops a traffic pan at 20-30 cm after clearing for cultivation. Conventional cultivation re-loosens only the surface soil, which is then reconsolidated each year by raindrop action, and by sheep treading when crop residues or pastures are grazed. A marked inflection in root growth within the pan coincides with increased penetrometer resistance and reduced water uptake (see Figure 6.4). Evidence from Ginninderra suggests that several years of cereal cropping by direct drilling can lead to increased numbers of 'bio pores' responsible for more rapid water redistribution in the profile. However, in the sandy soils in Western Australia there was no evidence of this development after 4 and 5 years of continuous cropping. Infiltration and rate of wetting-front migration were consistently faster on the most disturbed (conventionally cultivated) treatment. Higher soil strengths in the surface soil also led to reduced rates of root extension, shoot growth and lowest yields every year in the direct drilled treatment, especially at nil or low levels of fertiliser nitrogen (Jarvis *et al.*, 1985).

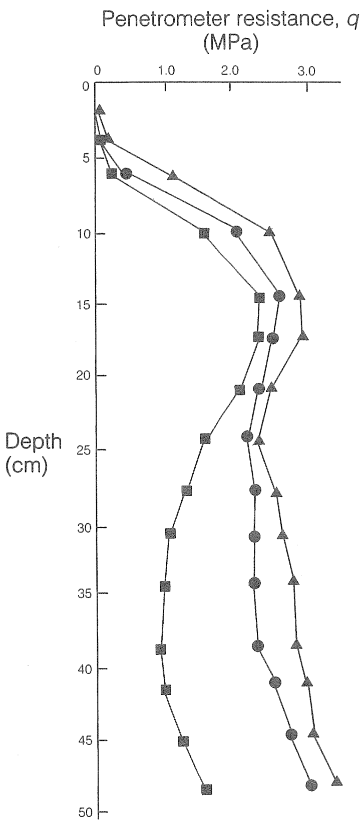


Figure 6.4 Penetrometer resistance (q) for a uniform-textured yellow earth (typic Xeropsamment) at Wongan Hills, which developed a traffic pan prior to three cultivation treatments being imposed: direct-drilled (triple-disc) (▲), combine direct-drilled (●) and cultivated (■) (Hamblin *et al.*, 1982)

Effects from deep tillage do not persist indefinitely, even when direct drilled thereafter. Table 6.8 shows the residual response in the second year (1982) after subsoiling at 20-40 cm in 1981 on a long-term tillage experiment at Wongan Hills (Jarvis *et al.*, 1985). The response was far greater initially on the zero-tilled treatment, which had the lowest growth rate and yield

Table 6.8 Grain-yield response (kg ha^{-1}) in the year of deep tillage (1981) and one year later on loamy sand at Wongan Hills, Western Australia (Jarvis *et al.*, 1985)

	Zero till (triple-disc drill)			Direct drill with combine			Conventional cultivation		
	No deep till	Deep till	Percent-age increase	No deep till	Deep till	Percent-age increase	No deep till	Deep till	Percent-age increase
1981	1516	2171	43.0	1881	2543	35.2	2041	2648	22.9
1982	1766	1974	11.8	1998	2154	7.8	2075	2089	6.7

in the unripped state, because of the higher mechanical strength in the topsoil of that treatment.

These two examples of deep tillage demonstrate that soil loosening may improve crop growth for different reasons. In the Victorian experiments transient waterlogging above the compacted zone restricted root growth into the subsoil. This exacerbated the effect of spring drought stress as well as causing nitrogen losses and anoxia. In Western Australia delayed root extension reduced the eventual rooting depth and total root length per unit area. This reduced the total water use and nitrogen uptake by the crop, because the sandy soils most prone to compaction have low waterholding capacities (less than 80 mm per metre), and the crop must mature during a period of rapidly increasing water stress, when deeper rooting confers additional water supply. In some compacted-soil situations, however, loosening may have deleterious effects if, for example, large clods are brought up because the soil is too dry at the time of operation, if very saline or acid subsoils are drawn up to the surface in the process, or if too much mixing dilutes surface phosphate reserves into the subsoil, where they are less available when the crop is very young. Deep tillage has still to be effectively introduced safely into whole-farm land-management programmes in dryland farming in Australia.

Tillage responses on red-brown earths

Early in the chapter a distinction was made between the Urrbrae series red-brown earths (Haploxerolfs) and the red-brown earths of drier inland areas, which are saline, calcic or sodic (Halplustralfs, Palexeralfs and Rhodoxeralfs) and which frequently respond to gypsum application. While conservation of organic materials by direct drilling, residue retention and good pasture growth have been identified as crucial to the good structural conditions of the non-calcic forms, the red-brown earths of drier areas often require gypsum treatment **prior** to any other management practice to prevent crust formation and improve drainage at the top of the B horizon. Stability tests for coherence in water do not distinguish between the effects of gypsum attributable to changing exchangeable sodium levels and those attributable to electrolyte concentration. Rengesamy *et al.* (1984) developed a general scheme for classifying dispersive behaviour of red-brown earths, which may be used as a guide to suitable management options. Soils are tested for spontaneous dispersion (where no mechanical agitation occurs) and for mechanical dispersion, these being the extremes of dispersive effect that may affect the soil; the spontaneous dispersion value represents the effect occurring when the soil is protected by plants and is undisturbed. The mechanical dispersion line represents the effect of either rain or tillage on bare soil. In the surface soils examined, the sodium adsorption ratio (SAR) was 1.3 times as important as the total cation concentration (TCC), whereas in the subsoils it was 3.6 times more important. Where SAR was > 3, soils dispersed spontaneously, whereas those with SAR < 3 dispersed only after mechanical agitation The authors suggest that the non-saline, sodic soils (SAR > 3) will have severe structural problems even when subject to minimum stress, such as direct drilling or pasture. Amelioration with calcium compounds such as gypsum, aimed at both reducing the sodium level on the exchange complex, and maintaining sufficient electrolyte in the soil solution for flocculation, is the only remedy for such soils. Soils that are potentially dispersive (SAR < 3, but > 0) still need their electrolyte level sufficently maintained to avoid dispersion, but it is impractical to apply such large amounts of calcium ameliorants to remove all the exchangeable Na^+ from the clay. In north-central Victoria, for example, Greene and Ford (1985) have found that gypsum is leached from such soil at a rate of 1 t ha^{-1} per 125-360 mm rainfall, depending on the frequency of gypsum application. These soils present few problems if they are managed with minimum tillage systems once their structure has been restored, but they may deteriorate badly if continually cultivated by conventional means.

Hamblin (1984) monitored the comparative effects of three tillage systems on a red-brown earth at Merredin, Western Australia, over a 6 year continuous cropping sequence. Structural deterioration was not detected until the 4th season, but thereafter both structural parameters and yields declined on the cultivated treatment, and in the 5th and 6th years the cultivated treatment yielded only half that of the zero-tilled treatment (direct drilled with a triple-disc drill). The degraded surface structure adversely affected the soil water balance and produced a cloddy, irregular seedbed. The result was a 40% reduction in plant density, a higher soil evaporation component, and a 3-week difference in maturation rate through delayed emergence. Table 6.9 summarises the structural changes over the 6 years.

Table 6.9 Soil structural changes (0–10 cm) in a red–brown earth (Rhodoxeralf) at Merredin, over a 6-year period of continuous wheat cultivation (Hamblin, 1984)

	K_s ($m\ s^{-1} \times 10^{-7}$)[a]				Soil resistance (MPa)				Slake-dispersion index			
	C	M	Z	LSD[b]	C	M	Z	LSD	C	M	Z	LSD
1977					2.07	3.21	4.41	0.8	10.3	10.2	10.4	0.5
1978	0.7	0.54	0.5	0.25								
1979	1.73	1.23	1.71	0.5	1.48	1.83	2.39	0.54				
1980									11.4	10.7	10.2	0.7
1981	0.09	0.84	1.27	0.18	2.08	1.55	–	0.32				
1982					2.81	1.98	3.83	1.04	13.7	11.9	9.9	1.4

C = conventional, M = minimum tilled, Z = zero-tilled.
[a] Geometric means.
[b] Least significant differences $P < 0.05$

An interesting aspect of the difference in surface structure was the greater depth of wetted profile found under the zero and minimum tilled treatments on each occasion that the profile rewetted. Typically, a difference of 4-6 cm occurred, which extended the wetting into the top of the B1 horizon. Thus the movement of applied solutes (such as dissolved calcium) would also penetrate this poorly-permeable layer more readily.

Hamblin attributed the decline in structural stability to a loss of organic matter from the top few centimetres of the surface in the cultivated treatment. A pronounced stratification of organic materials, with an accumulation at the surface, has frequently been noted in direct-drilled soils (Baeumer and Bakermans, 1973). Ploughing, or scarifying, inevitably dilutes surface-accumulated coarse organic materials through a greater depth, although with shallow cultivation in Western Australia this disturbed layer is only 8-10 cm deep.

The Merredin trial forms one of a sequence of long-term experiments in Western Australia (Jarvis *et al.*, 1985). At 3-yearly intervals soil chemical properties have been monitored at small depth increments on three of the tillage treatments and at two nitrogen levels. The results for the 3rd and 6th years are presented in Table 6.10 for the 0-2.5 cm layer, where differences are greatest.

Differences between treatments within years and within nitrogen levels were significant after 3 years at Avondale, Wongan Hills and Mt Barker, and at all sites after 6 years. In all instances after 6 years the greatest organic carbon content occurred in the zero-tilled treatment, and least in the conventionally cultivated (ploughed or scarified). Some of this relative difference may be attributed to the dilution through mixing of the organic matter through the top 10 cm but a real oxidative loss has also occurred in the top 10 cm, from all treatments since the inception of the trials. This loss is greatest in the cultivated soils. Levels of organic matter do not vary consistently with the most nitrogen-responsive sites (Wongan Hills, Esperance and Mt Barker), however. Cultivated soils are losing organic carbon at a rate of 0.02 to 0.05 g/100 g/year faster than uncultivated soils. Nevertheless a small amount of organic matter is also being lost from the least-disturbed treatments, except at Esperance and Merredin. At these two sites, particularly at Esperance, there may be a real trend to organic matter accumulation through non-disturbance.

Plant root factor and time interval for structural improvement

Greenland (1971) reviewed the interactions of soil fertility, soil structure, and crop yield in Australian wheat-soils. He concluded that the contribution of partially humified 'light fraction' material (with a half-life of 1-2 years, according to Jenkinson and Rayner, 1977), which builds up rapidly under pasture and is then mineralised by cultivation, is particularly important in reversing the decline in soil physical conditions, nitrogen status and yield found in all Australian long-term cultivation rotations. Clarke and Russell (1977) provided extensive details of these long-term experiments. Greenland was writing before the present development of conservation farming in Australia, but there is as yet little evidence to suggest that, under conditions of continuous cropping, minimal soil disturbance and residue-retention systems are capable of restoring and improving the soil structure and fertility to the status of the same soil under good pasture conditions.

Hamblin (1980) compared the structural stability of a range of Australian soils after 3 to 8 years of conventional cultivation and direct drilling. Relative structural improvement took place in all the direct drilled soils, but the rates of change were slower than those reported from wet temperate and tropical environments. An illuminating study by Tisdall and Oades (1980b) gives some indication as to the reasons for this slower rate of change. Tisdall and Oades postulated that, if stability of pasture soils was due, in part, to fine-root and hyphal development, changes in growth that resulted in different amounts of organic materials being released from decayed roots into the soil would give rise to different levels of aggregate stability. Frequent small stresses (grazing or wilting) were compared with a single large stress (death of plants). They found that the fastest rate of stabilisation was achieved by frequent watering and clipping of the grass. Wilting reduced aggregate stability, while early death of plants did not allow for sufficient root and hyphal growth to prevent subsequent disruption of aggregates. However, when older plants with vesicular arbuscular mycorrhizae (VAM) were killed and left in soil they persisted sufficiently intact to maintain a measured improvement in aggregate stability. Although cereals also form VAM associations they are often less heavily infected than ryegrass or clovers because arable soils are more frequently treated with

Table 6.10 Organic carbon levels from 0–2.5 cm after 3 and 6 years of continuous cropping on five Western Australian soils (Hamblin and Tennant, unpublished data)

Site	Nitrogen level (kg ha^{-1})	Annual rainfall (mm)	Carbon after 3 years (%)			Carbon after 6 years (%)			Grain yield 6 year average[a] (kg ha^{-1})		
			C	M	Z	C	M	Z	C	M	Z
Avondale	0	389	1.27	1.55	1.67	1.34	1.54	1.62	2223	2145	1958
(18.0% clay)	60		1.43	1.73	1.83	1.38	1.67	1.76	2366	2403	2448
Wongan Hills	0	345	0.81	0.81	0.89	0.70	0.80	0.85	1071	1047	716
(11.0% clay)	40		0.88	0.88	0.97	0.73	0.82	0.88	1552	1210	1112
Merredin	0	289	0.98	1.00	1.07	0.91	1.02	1.10	738	1020	876
(22.0% clay)	20		0.91	1.12	1.09	0.91	1.07	1.09	816	958	800
Esperance	0	494	0.90	0.96	0.91	0.95	0.99	1.04	1110	1170	1296
(4.0% clay)	80		1.12	1.16	1.05	1.02	1.07	1.16	1650	1735	1636
Mt Barker	0	645	2.83	2.99	3.07	–	–	–[b]	1811	1876	2044[c]
(15.0% clay)	80		2.62	2.86	2.92	2.50	2.60	2.64	1965	2169	2277

C = conventionally cultivated.
M = minimum tilled (combined sown).
Z = zero-tilled (triple disc sown).
[a] Average of four nitrogen levels.
[b] Experimental design changed; no zero N plots remained.
[c] 4 years only.

phosphate fertilisers. Moreover, some crop species (notably *Lupinus* species and members of the Brassicaceae) are not normally infected.

Wheat root lengths (in the top 10 cm soil) may be up to 8 km m^{-2} in fertile red earths (Walter and Barley, 1974), but they are frequently less than half this in soils of lower fertility. Clover-grass swards develop very much larger root densities in topsoils than crops. This factor, more than any other, is of special importance in the role of pastures in restoring soil structural stability. The possibility of achieving structural improvement in the topsoils of no-till soils by cereal 'root-effects' seems less likely than with a number of years of good pasture. When Hamblin and Tennant (1981) monitored soil physical conditions on an apedal, yellow, loamy sand in Western Australia over several years of continuous cropping no change was found in the hydraulic properties of the 0-10 cm layer of each tillage treatment. The zero-tilled soil continued to have the lowest hydraulic conductivity, highest soil strength and lowest air-permeabilities (K_a: see p.163) and the cultivated soil the highest. Values of K_a regressed against soil water content (Θ_v), taken from several years, fell on the same curve - demonstrable proof of the lack of change from year to year (Figure 6.5). This was unexpected. It had been argued that the undisturbed soil would develop continuous root channels, which would increase the air and water conductivity, but yields and root growth were persistently poorer on the zero-tilled treatment (Hamblin *et al.*, 1982) and thus a smaller crop root system developed, which could not compensate for the tillage-created transmission pores developed each year in the cultivated treatment.

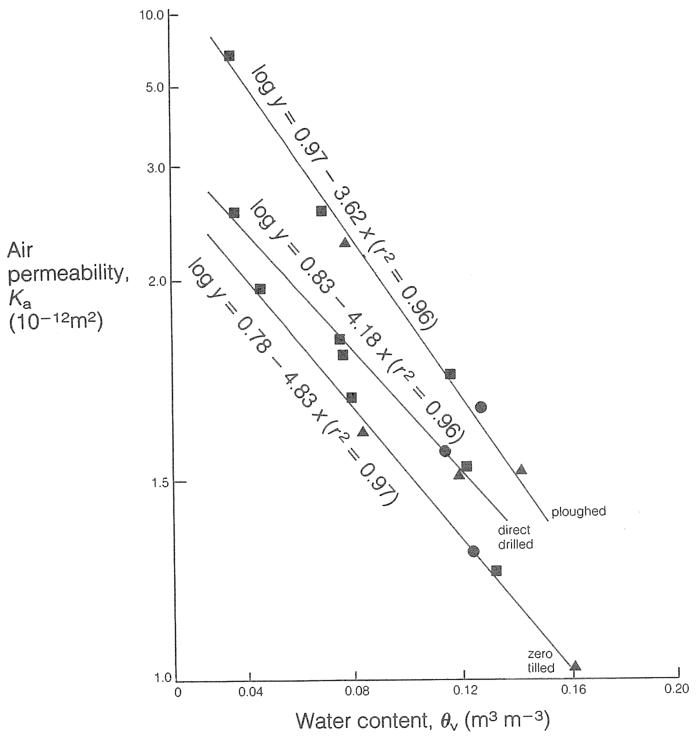


Figure 6.5 Mean values of air permeability (K_a) over a range of field water contents and seasons for a direct-drilled (triple-disc drill), combine direct-drilled and cultivated yellow earth in 1977 (■), 1979 (▲) and 1980 (●) (Hamblin and Tennant, 1981).

In summary, the experiments currently investigating tillage methods in the southern half of Australia include not just residue-retention and surface-tillage combinations, but gypsum incorporation, deep tillage, stock grazing and other management practices. Although a 'systems' approach to research has many logistic problems for the experimental scientist, the 'systems' approach to land management by the farmer will undoubtedly achieve greater and longer-lasting soil conservation than piecemeal adoption of particular tillage practices. Direct drilling is capable of producing similar or better yields in some seasons and on some soil types. It is now known that many of the earlier, and some of the present, trials that are trying to compare reduced tillage practices with ploughing have been laid down on soils that had already become structurally degraded. As described, direct drilling is not a complete restorative in itself. Chemical amendments, deep tillage, judicious rotation of species, and careful management of crop residues are all required to achieve improved soil structures in these soils. First, however, recognition and diagnosis of different aspects of structural degradation must be improved before the most appropriate soil management strategy is implemented.

RECOGNITION OF PHYSICAL PROBLEMS PRODUCED BY TILLAGE

While the principles of soil conservation are often well understood, recognition of soil physical problems is frequently confined to specialists. The reductions in yield that result from degraded soil structure are less easily demonstrated than those resulting from poor crop fertilisation or weed control. Moreover, the hidden costs of soil degradation are less easy to compute in the farm budget than the costs of delays to farm operations or a rise in interest rates. However, the costs can include increased fuel consumption and implement wear, reduced cropping potential, and increased capital installations (drainage, bank construction).

Cultivation remains the simplest way of killing weeds and producing a seedbed in many instances. It is also the only practicable way of breaking open compacted or hard-set soils. However, there is little doubt that many farmers still cultivate far more than is necessary. Here an attempt is made to provide a guide to visible or readily measurable characteristics of structural degradation resulting from such excessive cultivation.

The soil profile is used as the basis of soil classification and land capability assessment. This has a drawback with respect to hydraulic properties of soils, since the soil forms a spatially continuous material in which the hydrology is intimately linked with topography. Nevertheless the profile is the most practical starting point for soil examination. The Northcote scheme is the most frequently used field classification of soils in Australia. It uses readily discernible characteristics such as colour, texture and pH reaction, and places less reliance on laboratory-determined properties, which are less available to the farmer and adviser.

ASSESSMENT OF STRUCTURAL CONDITIONS IN ARABLE SOILS

Field assessment

Soils should be inspected a few weeks after sowing the crop. Variations in crop establishment may indicate structural problems and the soil is more easily dug while moist. The surface soil may be examined by digging out intact clods or spadefuls of soil with as little disturbance or compaction as possible. Usually these samples are taken at random, but where there are obvious differences in crop growth, samples from good and bad areas should be placed side by side for comparison. The soil in gateways and headlands will indicate the severity of maximum compaction. Conversely the soil in fence-lines and in uncleared areas adjacent to tilled land provide reference samples of least disturbance. A well illustrated publication of the British Ministry of Agriculture (HMSO, 1983) shows the correct procedure for cutting and examining soil samples; Figures 6.6a-6.6d are redrawn from this leaflet.

Soil surface

Appearance when uncultivated Structural instability may be recognised through the following:

* particle sorting by water - larger single grains of sand, which are concentrated in surface depressions indicate aggregate disruption and slaking. The rest of the surface is often hard, lacking visible pores.

* particle sorting by wind - accumulation of particles in the range of fine sand to coarse silt (50-180 μm diameter) around fence lines and perennial vegetation indicates wind erosion has occurred. Wind-blown soil is visible and familiar to farmers in many drier areas, and is often indicative of overstocking of arable land.

Appearance when cultivated There may be:

* Blocky, angular peds - these are produced in clay soils of low organic matter content when tilled at the drier end of the friable range. In addition, soils with more than 30% clay tend to smear along cleavage planes when cultivated at water contents near the plastic limit (Figure 6.6a).

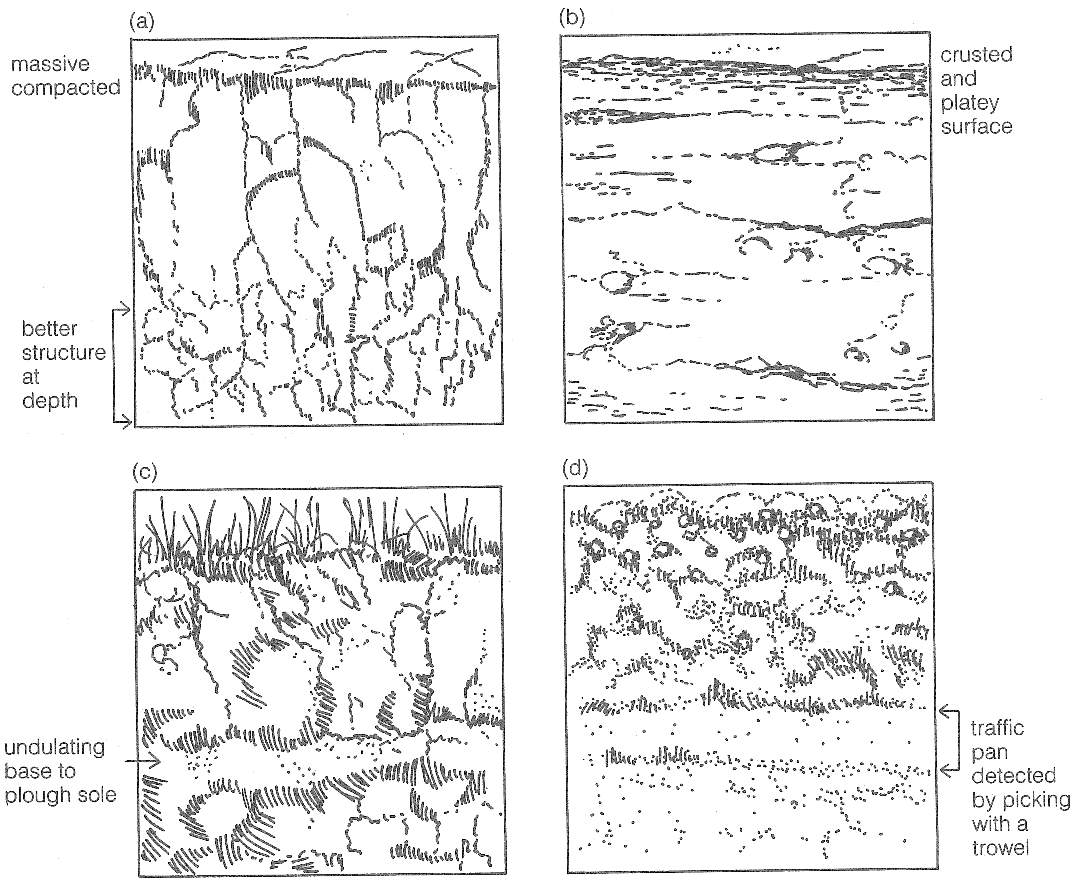


Figure 6.6 (a) Blocky ped structures of a compacted surface in a clay soil (adapted from HMSO, 1983). (b) Crusting developed on a fine, sandy soil with horizontal cracking of the bedding planes (adapted from HMSO, 1983). (c) Plough pan developed in a poorly drained clay, showing undulating base to the plough sole (adapted from HMSO, 1983). (d) Typical traffic pan developed beneath a loosened, cultivated topsoil in a loamy sand (adapted from HMSO, 1983).

- Disaggregation - rain falling on unstable cultivated peds causes them to slake to give a typically 'melted' appearance, in which individual aggregates coalesce. These soils frequently dry to a hard surface crust.

- Surface crusts - soils with very low clay contents do not form crusts normally, although secondary cementation can make the whole soil set hard. Typically, any cracks that develop are horizontal below the crust, not vertical (Figure 6.6b).

  Crust strength is often measured by the modulus of rupture test (Richards, 1953) on the cohesive strength of formed, dried brickettes. Aylmore and Sills (1982) found that the crust strength increased in soils known to be hard-setting and in soils with a high SAR (sodium adsorption ratio). As crust strength is also highly dependent on water content, care should be taken to compare soils or treatments at the same water content.

- Standing water - this is indicative of sheared and compressed surfaces when it occurs in wheel tracks, headlands and poached ground, but it can also indicate impedance below the surface, which has resulted in a transient perched water table. Low-lying areas of paddocks showing nitrogen deficiency and low plant densities from poor emergence are often symptomatic of impeded sub-surface drainage. Air-photo surveys taken after unusually heavy rain in autumn provide good evidence of this type of structural problem. Many alfisols (e.g. red-brown earths) develop surface crusts that are not sufficiently hard when dry to impede emergence, but are sufficiently impermeable to reduce infiltration substantially, as shown in Tables 6.3 and 6.9.

Soil profile

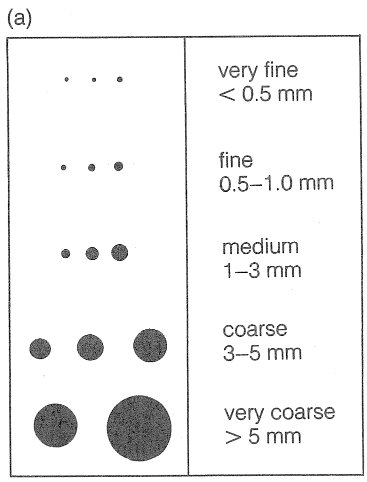
The soil profile can only be adequately investigated by digging a pit to expose at least 0.5 m of soil, and preferably the full depth of the crop root-zone or annual water recharge, if this can be separately distinguished more readily. The effect of traffic and implements may extend well into this layer. In the A horizon a distinctive darker, well mixed layer is diagnostic of ploughed soils, with no significant A_o litter layer. Soils that have been direct-sown with single or triple-disc drills develop more conspicuously stratified organic-rich surfaces over a number of years, but this depends greatly on the total biomass production and the number of biologically active days per year.

- The A horizon of a tilled soil contains a large proportion of transmission pores when first tilled, but these may collapse under natural rainfall conditions within a single season (Dexter, 1977; Hamblin, 1982). The depth of tillage disturbance marks a distinct discontinuity for transmission pores, whether this coincides with a change of colour or not (Figure 6.6c).

- Plough pans (that is, distinct sheared layers at the base of the tilled layer) can often best be seen by carefully excavating the tilled soil layer to expose platey peds, smeared and blocked transmission pores, and undulations in a denser subsoil zone, typical of the implement shape, as shown in Figure 6.6c.

- Traffic pans, which result from wheelings, often exist only as a subsoil 'pan' because subsequent tillage has loosened the surface layer, Figure 6.6d. They are readily identifiable with a steel probe or a penetrometer, as shown previously in Figure 6.4.

In the absence of a penetrometer, a steel survey peg can still give a good indication, always providing care is taken to ensure that differences in water content are not wholly responsible for any variation in apparent strength. Soils with uniform texture down the profile are most readily assessed in this way, that is, those with a Uc, Ug or Um classification in Northcote's scheme. However, in the G and D soils (gradational and duplex) there is a natural increase in clay content at the base of the A horizon and into the B horizon, which may coincidentally be at the same depth as soil compaction by traffic, after the surface has been re-loosened by tillage. Distinction of traffic pans in such situations is much more difficult but is aided by close inspection of the visible pore structure and the ped configuration. Figure 6.7a taken from Hodgson (1974) shows the sizes of pores that can be seen with the naked eye. Figure 6.7b should be used in conjunction with it to aid the estimation of percentage of transmission pores in otherwise massive soils. Theoretical and measured estimates of the proportion of pores approximately 3 mm in diameter necessary to maintain drainage in clays of low hydraulic



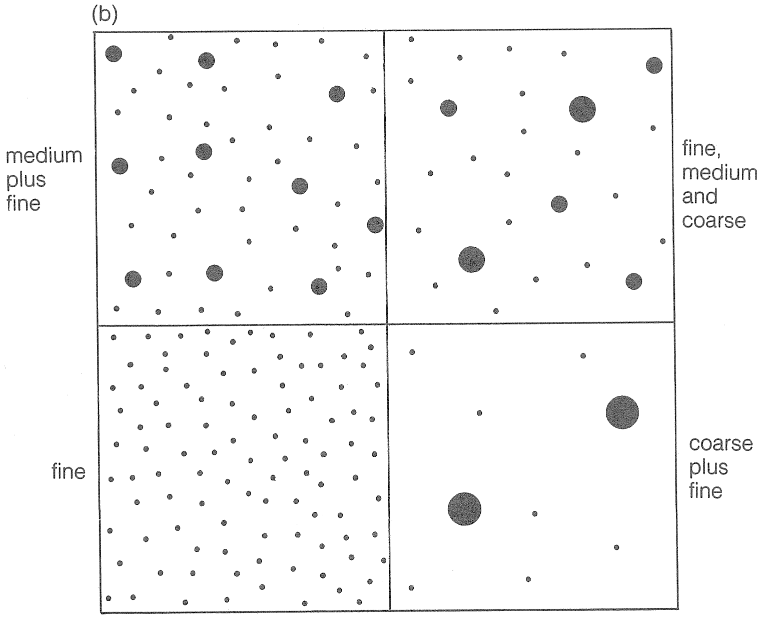


Figure 6.7a Size of macropores seen with the naked eye (Hodgson, 1974)

Figure 6.7b A 2% distribution of such pores in a plane (Hodgson, 1974) conductivity have been put at as little as 2-3% of total porosity by Bouma *et al.* (1978) and Beven and Germann (1981). Massive horizons that show no discernible pores will act as severe barriers to water movement, even if these layers are very narrow.

* Mottling - variation in chroma occurring in small patches and lenses within the soil, especially where reddish colours occur around pores, cracks and channels, and greyish colours in the denser matrix of the soil, are evidence of impeded drainage and low oxygen status for a part of the year. Total grey coloration indicates a long-term lack of oxidative conditions, with complete reduction of iron, manganese and other transition metals. While mottling may be viewed as evidence of compaction in some situations it is also a widespread feature of naturally varying drainage conditions in G and D soils. Moreover, many Australian yellow-duplex soils (Dy soils of Northcote's classification) have mottled layers, which may be indicative of former weathering processes. Present oxidative-reductive regimes may not be fully mirrored in the soil's appearance. Whatever the cause, however, mottling usually indicates an adverse root environment for crop growth. Where mottling only occurs very deep in a profile, however, (at the depth of 1 m or more) it may sometimes indicate a satisfactory reserve of subsoil water available to deep-rooted crops in some seasons.

* Ped structures - pedality is defined as the spatial arrangement of aggregated primary particles of soil. Peds are therefore more indicative of the soil-forming processes in the undisturbed subsoil than they are higher in the profile. Some soil types are distinguished by their very regular ped structures, as for example the vertisols or black cracking clays with gilgai phenomena, or the natric salorthids (solanchak and solanetz soils) which are dominated by upward movement of soluble salts. Ped structures are classified in terms of development as: apedal, with no observable aggregation; weakly pedal, showing faint cracks between peds; well-formed pedality, in which peds retain coherence when dug out of the soil face; and compound peds, which frequently occur in clay-textured soils, with large peds that break down with physical disruption or wetting to small-sized (< 10% original size) stable peds of equal coherence.

MEASUREMENTS OF STRUCTURALLY RELATED PROPERTIES

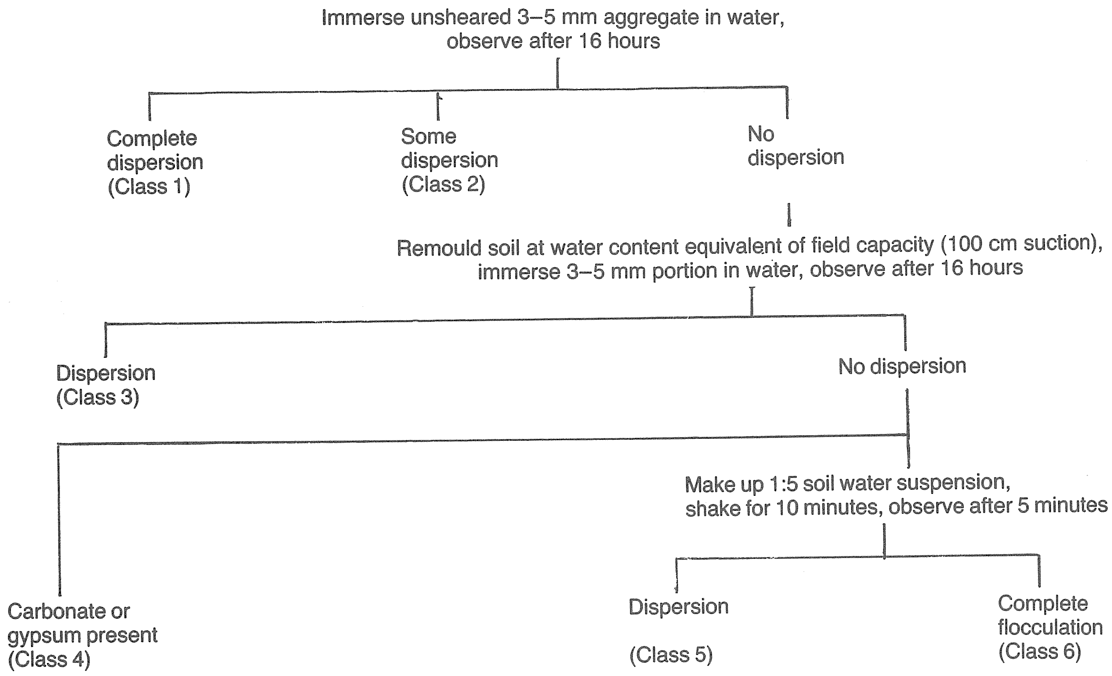
Methods for assessment of structural stability described below have been selected for their relative rapidity and repeatability. Many methods that have enjoyed fleeting popularity in the literature require elaborate facilities or are subject to a high degree of variation depending on the operating conditions.

Aggregate stability

This is the most important single measure of the behaviour of the soil surface to rain and to imposed force while wet. However, the most commonly used test relied on in much of the older literature was wet-sieving (Yoder, 1936) in which repeatability can be poor and correlation with other soil properties weak unless very large numbers of samples are taken and operating conditions are most carefully controlled (Kemper and Koch, 1966).

A much less arbitrary test was proposed by Emerson (1967) and is now widely used not only for agricultural soils but also in testing road foundations, dam construction and irrigation bays. Emerson's test correctly differentiated between the two processes of slaking (disaggregation) and dispersion (deflocculation of clay colloids). Eight categories of stability were recognised, depending on the soil's reaction to immersion, when dry, into rainwater (or the test-water in the case of irrigation or dams), and to its subsequent reaction, where necessary, after remoulding and rewetting from a standardised equilibrium water potential of -10 kPa. Remoulding wet soil by puddling disrupts the bonding forces responsible for much micro-aggregation. Dispersion will then take place when the soil is once more placed in a solution of very low electrolyte concentration unless the short-range (Van der Waal's) forces, which are related to the charge density, cation composition and capacity, are sufficient to maintain flocculation. Table 6.11 outlines the six categories in Emerson's 1967 paper. Elaborations of Emerson's original method have been described by Loveday and Pyle (1973) and Emerson (1977). The scoring proposed by Loveday and Pyle recognises both an immediate and a slower reaction so that two scores for each process are added to make a final score.

Table 6.11 A classification of soil aggregates according to their dispersion in water (Emerson, 1967)



Both methods have the advantage of being rapid, requiring little equipment and being based on sound physico-chemical principles. They will not always discriminate between small differences in stability, which develop as the result of short-term differences in soil management, but are invaluable in a survey approach, such as land-use evaluation. Inevitably, as with tests for sodicity (electrical conductivity, for example) variations occur seasonally in some soils depending on the soil-solution electrolyte concentration and composition. Standardisation is achieved in all structural stability tests by taking samples either after sowing when soils are moist and fully tilled or during a long dry period in summer.

Measurement of pore conduction

Although hydraulic conductivity is the material property most affected by collapse and loss of transmission porosity it is the most variable (as was discussed earlier in the chapter) and presents substantial problems for field measurements. If laboratory determinations of K_s are used to provide comparative measures of structural change they should be done on undisturbed cores taken in accordance with standard precautions regarding the wall thickness of the cutting cylinder and the ratio of the cylinder diameter to the wall thickness (Loveday, 1974). An alternative approach is to use the derived function, sorptivity, (discussed previously). Sorptivity, infiltration rate and the proportion of flow attributable to transmission pores of various sizes can be determined at different depths in the soil profile, either on cores or in the field by use of a sorptivity apparatus (Clothier and White, 1981). The apparatus consists of a base plate of porous material having an air-entry value greater than the capacity of an adjustable constant-head device set in the head of the base plate (see Figure 6.8), and a graduated reservoir. The constant-head device is set to a value of negative head equivalent to the size of visible transmission pores, placed in intimate contact with the soil surface, and the rate of flow measured on the reservoir. By then repeating the measurement at a smaller negative head (say < 1 cm) the contribution of the transmission pores can be found.

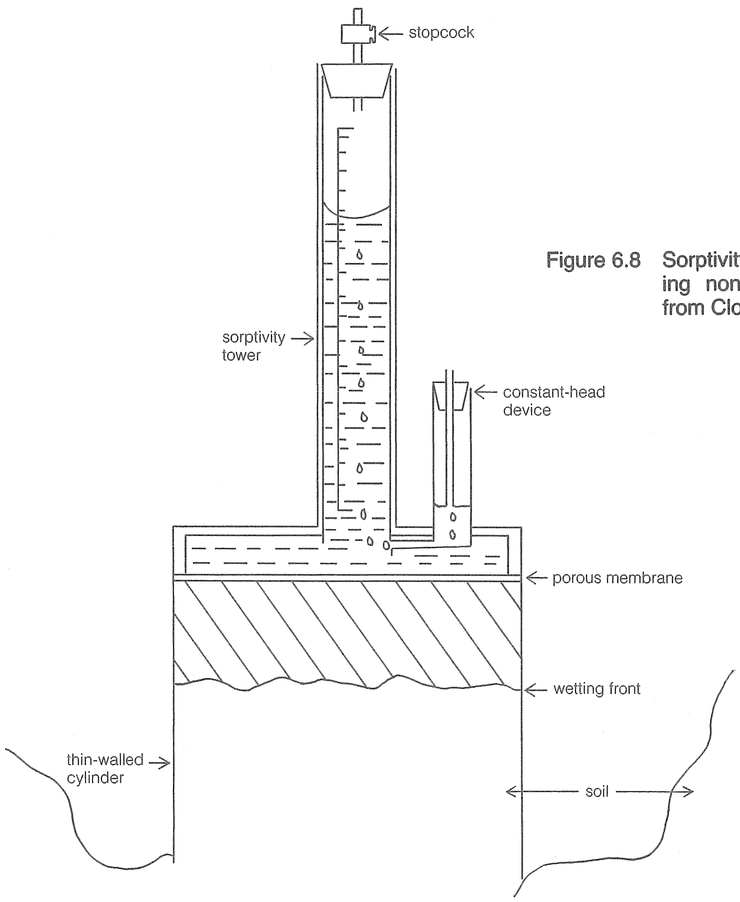


Figure 6.8 Sorptivity tower apparatus for measuring non-ponded infiltration (adapted from Clothier and White, 1981)

An interesting test of the stability of transmission pores can be made on undisturbed soil cores by comparing their flow rate in air (Green and Fordham, 1975) and in water (Hamblin, 1980). Because of the difference in viscosity of the two fluids (approximately 10^5 difference) the air permeability (K_a) rather than conductivity is being measured:

$$K_a = \frac{Q/\eta}{AP}$$

Where η is the viscosity of air or water (Pa.s), A is the cross-sectional area of the core, P is the pressure difference at the head and base of the cylinder and Q is the flow rate ($m^3 s^{-1}$).

Cores of soil are wetted up to a known potential and the air permeability (K_a) measured at a known head. The saturated water permeability (K_s) is then measured immediately afterwards. If K_a / K_s is < 1.0 some collapse of pores will have occurred during the water flow.

Chemical reaction

Soils with poor structural properties (as was mentioned earlier) and high exchangeable Na^+ and Mg^{++}, may also be saline with electrical conductivities of over 40 mS m^{-1}. Soils of very high pH (> pH 8.4, i.e. containing free $CaCO_3$ - ions) or very low pH (< pH 3.8 containing exchangeable Al^{3+} with monomeric Al^{4+} in the soil solution) have low microbiological activity, reduced root growth and are at greater risk from imposed mechanical stress when wet than soils of more neutral reaction. Diagnostic chemical tests for soil reaction and toxic-metal levels are fully described in Page *et al.* (1982) and Loveday (1974). Unfavourable pH and sodicity should always be considered as possible causes of poor crop growth and restricted root development in conjunction with any structural assessment, and in many instances these may be synergistically related factors, as was seen in the example of black cracking clays on the Darling Downs.

CONCLUSIONS

Many Australian agricultural soils are of low inherent fertility, and low subsoil permeability. Cropping practices have frequently exacerbated this low-productivity potential by degradation of the soil structure. The symptoms most frequently found are surface crusting, surface and subsoil compaction and accelerated erosion. The effect is to reduce water-use efficiency by restricting infiltration, increasing surface waterlogging or runoff. This has a pronounced effect on crop yields in such a dry environment. Amelioration can be achieved by the adoption of minimum disturbance and residue conservation cropping practices in conjunction with physical or chemical treatments needed to remedy specific structural problems. The most common of these are gypsum application to stabilise dispersive clays, and subsoiling or drainage to improve water movement and root growth through compacted subsoils. These treatments are costly to broadacre farming and still require developmental research before they can be introduced effectively across the range of soil types on which such structural problems exist. Wider recognition of soil structural conditions in the field by farmers, advisers and agronomists would speed the adoption of more suitable cropping practices.

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