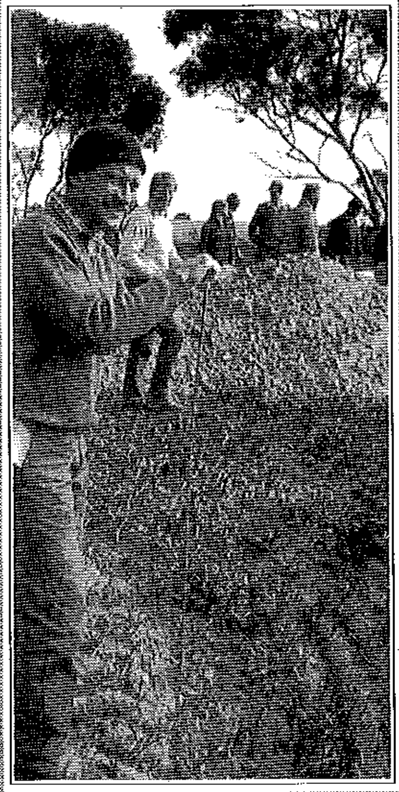

Chapter 3

Soil Structure and Drainage

3

Source: Hunt, N. and Gilkes, B. (1992) Farm Monitoring Handbook.
Published by University of Western Australia, Land Management Society, and National Dryland Salinity Program.

Source: Hunt, N. and Gilkes, B. (1992) Farm Monitoring Handbook.
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3.1 Introduction

Soil structure could be called the "architecture of the soil" (#14). It is simply a consequence of how soil particles and the spaces or pores between them are arranged or "aggregated" together. The sand, clay and silt particles with the help of organic matter as a binding agent, form clumps or aggregates. Soils with a good structure, ie: with a lot of these aggregates, allow air, water and nutrients to move freely through the spaces within and between the aggregates (Figure 3.1). A good soil structure also promotes microbial growth and easy penetration by plant roots (Figure 3.2).

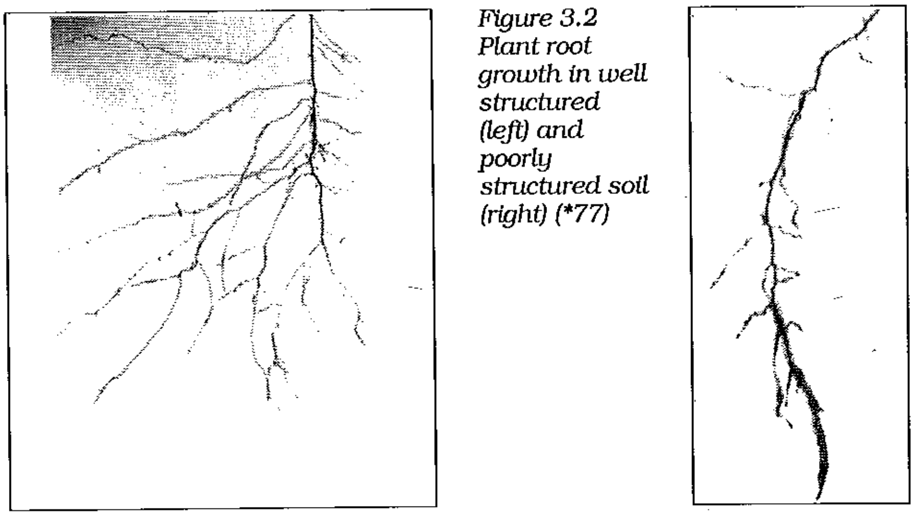


*Figure 3.2 Plant root growth in well structured (left) and poorly structured soil (right) (*77)*

3.1.1 Types of soil structure

A variety of different soil structure patterns can be formed, just as there are unlimited variations in the construction of houses and buildings. This variation reflects the different proportions and arrangements of sand, silt, clay and organic matter in the soil and the effects of management on the soil. Soil structure, unlike soil texture, can easily be altered by cultivation and management. The natural building blocks of sand, silt and clay (texture) can be rearranged into configurations that provide adequate or inadequate conditions for plant growth.

Some soils are not aggregated, either because they have very little clay or organic matter to provide bonds between particles, or because farm practices have destroyed aggregates. These soils are termed structureless, and either take the form of a single grain (eg: sands, especially after cultivation), or a massive structure, (eg: puddled or compacted clays) (Figure 3.3). The lack of structure has inherent problems associated with it. Soils comprised of single grains tend to be rapidly draining and have poor water holding capacity, whereas clay-rich soils that are massive are impermeable and poorly drained.

There are four major forms of soil structure that are described in terms of the shape of the main types of aggregates; crumb, prismatic, blocky and platey (Figure 3.3). A **crumb** structure consists of small, rounded aggregates that do not fit tightly to the adjoining aggregates. This soil is relatively porous and permeable and

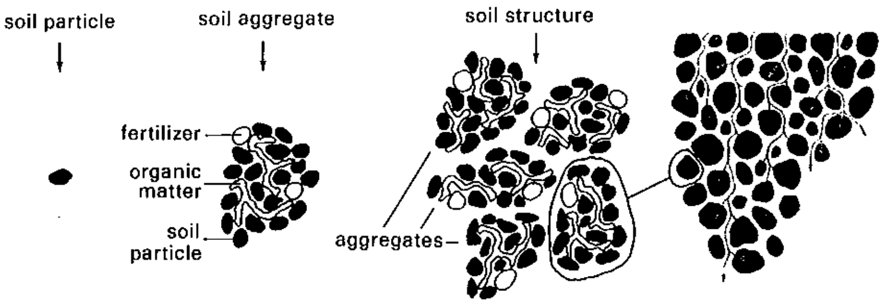


Figure 3.1
Particles of sand, silt, clay and organic matter join to form aggregates and a structured soil (#18). A good soil structure allows circulation of air, water and plant roots (#11).

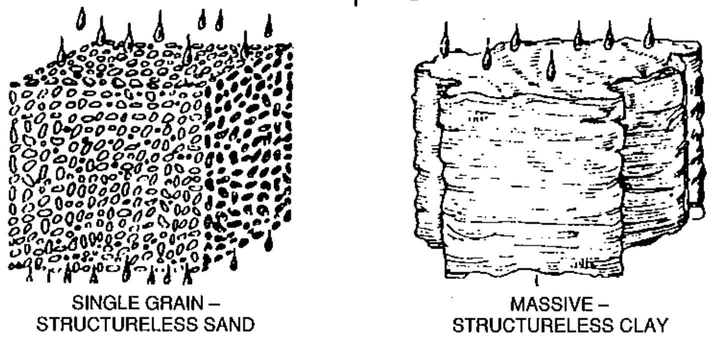
Source: Hunt, N. and Gilkes, B. (1992) Farm Monitoring Handbook.
Published by University of Western Australia, Land Management Society, and National Dryland Salinity Program.

as such is a desirable structure. It is the typical structure of some cultivated topsoils. A **prismatic** structure is formed by column-like aggregates with sharp edges and flat tops and which are separated by a network of deep cracks. This type of structure is common in the clay rich subsoils of many W.A. duplex or texture contrast soils. This structure is different from a crumb structure because aggregates fit together to form a clod. These may break into smaller blocky clods, in which case the soil is fairly well drained, and this structure is found mainly in the subsoils. A **blocky** structure, as its name suggests, is made up of block-like aggregates that often break down into smaller aggregates. It is moderately permeable, and often found in the clayey subsoils. A **platey** structure has horizontally oriented plate-like aggregates that usually overlap so permeability is reduced and drainage is poor. This structure is often found in soil on recent alluvium (river deposited sediment) and also forms in plough-pans. An ideal soil consists solely of crumb aggregates in a loosely packed arrangement that is not easily destroyed by water or cultivation.

3.1.2 How does soil structure influence management?

These different soil structures or arrangements of aggregates influence many soil properties and characteristics. They determine how the soil will affect water movement through the soil (infiltration and water holding), plant root growth, aeration, and the environment for soil animals. A good soil structure, with abundant pores and stable aggregates reduces water erosion risk as it promotes water entry by keeping the soil open and friable. Good soil structure also encourages root growth and thus water use by crops and pastures improves.

Soil structure can be degraded by forces, both external and internal, or a combination of both. External pressures involve machinery such as tractors, livestock trampling and raindrop impact. In heavy rainstorms raindrops can have a velocity of 9 m/sec and impact pressure can equal 60 bar (#14) (atmospheric pressure is 1 bar). It is important that you help protect your soil with plant cover and maintain a high organic matter content, to help keep the soil particles bound together. In addition to the initial impact of raindrops, the presence of water can disrupt a soil aggregate simply by forcing its way between the soil particles and explosively pushing out trapped air. This is an example of internal forces contributing to soil structure degradation.



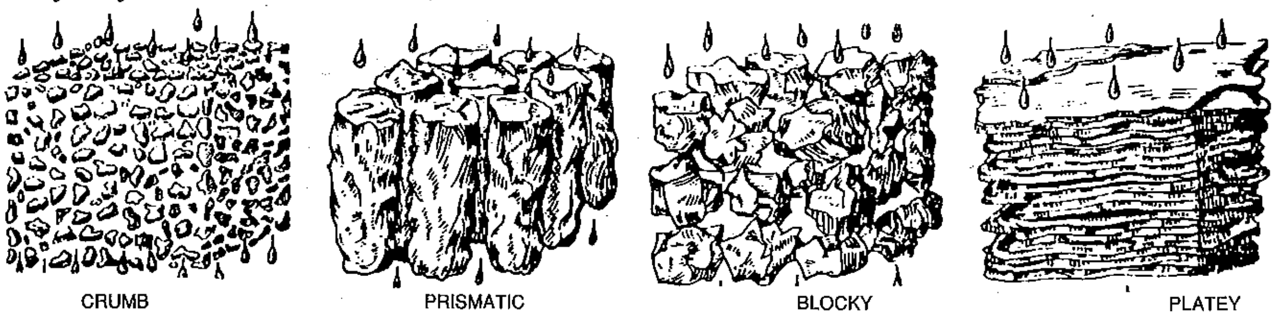


Figure 3.3 Two common forms of a structureless soil and four common forms of aggregates in a structured soil (#69).

Source: Hunt, N. and Gilkes, B. (1992) Farm Monitoring Handbook.
Published by University of Western Australia, Land Management Society, and National Dryland Salinity Program.

3.1.3 Forms of soil structure decline

If soil structure is degraded many factors essential for plant growth are adversely affected. Smaller pores are created, and some pores are removed totally, which reduces the air content and rates of oxygen and water movement through the soil. If the soil is on a slope and a surface crust is present, water will run off, often causing erosion problems.

Soil structure degradation can take many forms. It is important to separate surface degradation from subsoil degradation. Some of the finer textured or clay soils, are susceptible to breakdown, or are what we term "unstable". Your soil may appear to have a good structure, one with pores and aggregates, but these aggregates may easily break down in an unstable soil. This breakdown of aggregates is sometimes described as melting of the surface. If these soils are present on the surface, and are exposed to either rain and/or cultivation, their structure can break down, and when they dry they develop a hard crust which can prevent seedlings from emerging (this is known as the silly seedling problem/syndrome). Water entry or infiltration into the soil is retarded and can contribute to potential water erosion problems if the soil is on a slope, or surface waterlogging occurs on flat land. Some of the particles when dry are also susceptible to wind erosion because they are not attached to form aggregates.

Clay soils are also susceptible to a form of subsoil compaction called a "plough-pan", where a combination of wet conditions and cultivation by heavy machinery smears the clay particles just below the implement. This increases the density of the soil and blocks off the openings to soil pores, which has a detrimental effect on water movement (see Section 3.4). Thus soils with this form of subsoil compaction often become water-logged. Another form of subsoil compaction, called "traffic hard pan" is more common on the sandier soils of Western Australia, and is due to heavy machinery compacting the soil at a depth between 10 - 40 cm below the soil surface. This form of subsoil compaction may allow water and nutrients to infiltrate through the pan but limits plant root growth so that the plant has restricted access to the water and nutrients below the pan.

It is important to point out that in some cases, especially on more clayey soils, the soil can become quite dense as structure declines but will not quite form a compacted layer. This increase in density can still have adverse effects on drainage and root growth.

The following sections look at the major problems associated with soil structure decline, and how they can be monitored. There is a simple test to determine the stability of your soil, to predict if it will form a surface crust. Procedures are given on how to detect subsoil compaction problems - due to both traffic hard pans and plough pans; and how to measure the ability of your soil to allow water to enter the surface (infiltration), and to drain through the soil (hydraulic conductivity).

SUMMARY

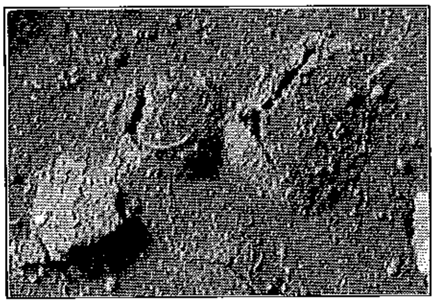
- arrangement of sand, silt and clay particles and organic matter into aggregates
- a good soil structure provides abundant stable pore spaces between and within aggregates
- different arrangements of aggregates affect plant growth, water and air movement
- soil structure can be degraded by water (instability), including raindrop impact and by management (compaction and smearing by machinery and stock).

3.2 Soil structural instability

3.2.1 Introduction

Some finer textured (ie: clayey) soils may appear to have a stable structure, with many aggregates and pores for air, water and plant root movement, but is the structure stable? How a soil behaves when it is wet and especially after cultivation is a very important management consideration. If the soil structure is unstable, that is, the aggregates bound by clay and organic matter are easily broken down into their individual soil particles, plant growth can be seriously inhibited. The combination of water and mechanical working can break down

*Figure 3.4 A hard setting crust inhibiting seedling emergence (*73).*



Source: Hunt, N. and Gilkes, B. (1992) Farm Monitoring Handbook.
Published by University of Western Australia, Land Management Society, and National Dryland Salinity Program.

the aggregates, and once the soil dries out, surface sealing or a "hard-setting" crust can form on the surface preventing subsequent rain from infiltrating and seedlings from emerging (Figure 3.4).

Soil structural instability affects about 3.5 million hectares of Western Australia's southern agricultural regions (#10). This form of soil structural degradation is most noticeable in the top 1-2 cm of soil. It can also occur in the subsoil, in some cases leading to tunnel erosion as the aggregates in the subsoil disperse and clay washes away. The surface crust remains but is undercut until it too is eventually eroded. Subsoil dispersion can also be responsible for waterlogging in heavy soils, reducing oxygen levels in the soil and restricting water movement. Soil strength is increased to excessive levels by crusting, preventing adequate plant emergence.

Reduced soil stability can also increase the proportion of fine particles within the soil leading to a lack of pore space as the finer particles fill in the spaces. As a consequence of this, poor drainage, a loss of friability when the soil is cultivated and increased wind and water erosion (finer particles are readily removed by wind or water), with an associated loss of soil nutrients, may occur.

SUMMARY:

- structural instability is a property of finer textured soils
- unstable due to effects of water, cultivation or both.
- surface crust can form, preventing seedling emergence
- reduced water drainage, aeration, friability and increased risk of wind and water erosion.

3.2.2 Susceptible soils and sites

Soil structural instability and surface crusting occur due to external forces such as raindrop impact, trampling by stock and cultivation, and to internal forces created as soil is wetted and dried.

Soil type, water content and soil chemistry are the main factors that determine the tendency of a soil to become unstable, and consequently form a surface seal.

(a) Soil type

Generally the importance of soil structural instability increases as the clay content of the soil increases. Sands have little if any structure, and the structure they do have is due mostly to plant roots and organic matter binding the particles together rather than to the action of clay.

Exposed subsoils and scalds, where the sandy topsoil of a duplex soil has been eroded away exposing the inhospitable clay subsoil, may also be prone to structural instability. These soils are low in productivity, often requiring gypsum and higher than normal fertilizer application rates to achieve reasonable returns.

(b) Water content

The water content is a very important consideration when assessing soil stability. Water weakens the bonds between the particles in aggregates and forces air out of the aggregate, almost like an explosion. The particles that have broken away fill in the pores and cracks in the soil structure which then inhibits root and water penetration. Once dry, crusts formed in this way can restrict seedling emergence. Working of the soil can cause aggregates to break down. The extent to which the soil is degraded due to mechanical cultivation depends on the tillage implement and its speed through the soil, in addition to the nature of the soil structure.

(c) Soil chemistry

Many Australian soils are described as sodic. Sodic soils contain many sodium (Na^+) ions adsorbed onto the surfaces of the clay particles. Compared to soils that are rich in magnesium (Mg^{2+}) and calcium (Ca^{2+}), sodic soils easily lose their structure when wet. This is due to water adsorbing onto the sodium which is itself adsorbed on clay particles. This water forces the soil particles apart. The swelling forces due to water being adsorbed onto sodium ions are enormous and in some clay soils these forces can push up the soil to form large mounds and depressions (crab holes, melon holes, gilgai) (Figure 3.5), damaging roads, buildings and fences. The presence of abundant sodium ions in a soil is not the only reason why soils may have a poor stability, however, soils that do have many sodium ions generally tend to be unstable.

One way of increasing the stability of sodic soils is to apply gypsum (calcium sulphate - $CaSO_4.2H_2O$). As the gypsum dissolves it releases calcium ions (Ca^{2+}) which replace some of the sodium ions. The sodium is then leached away by rain or irrigation. Indeed those farmers who irrigate with water containing high ratios of Na^+ to Ca^{2+} have to be particularly careful not to damage the structure of their soils. The Ca^{2+} from gypsum that is dissolved in soil

Source: Hunt, N. and Gilkes, B. (1992) Farm Monitoring Handbook.
Published by University of Western Australia, Land Management Society, and National Dryland Salinity Program.

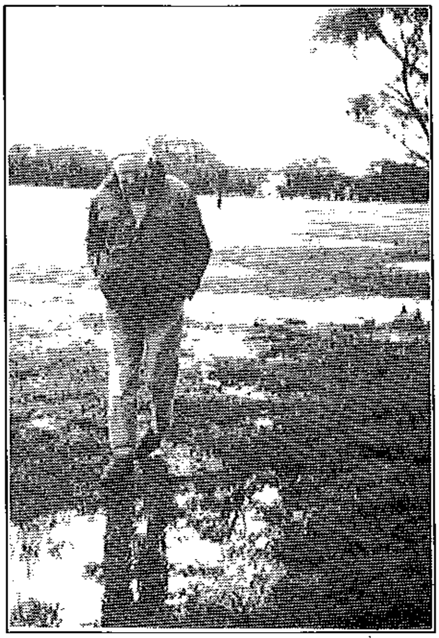
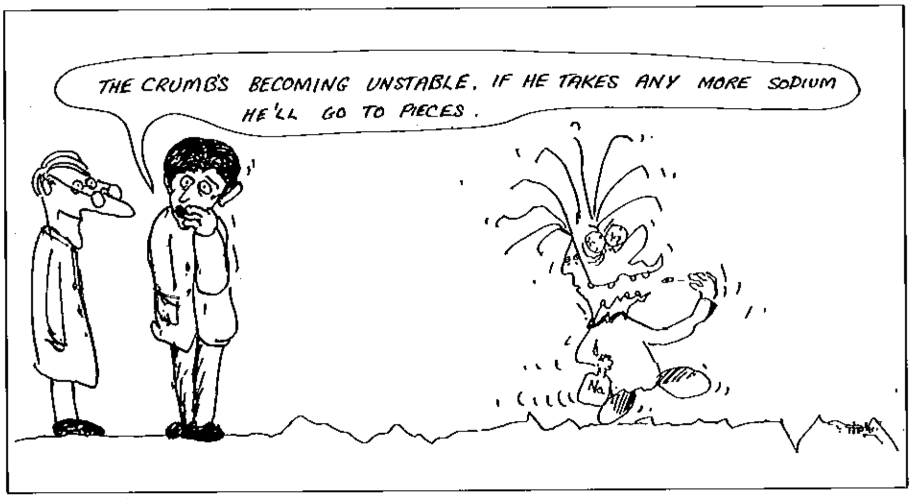


Figure 3.5 Sodic soils forming gilgai as they shrink and swell.

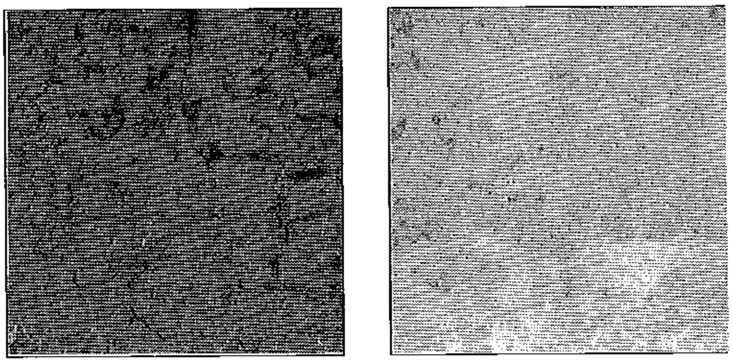


solution and sorbed by clay particles helps stabilize the aggregates, preventing the soil pores from collapsing and keeping the soil structure intact (Figure 3.6). Gypsum is not a cement, it only works if it is first dissolved in rain-water.

The application of gypsum may only give a short term soil structure improvement lasting perhaps 3 or 4 years. Gypsum alters the soil salt content but the Ca^{2+} ion and dissolved calcium sulphate will eventually leach away as did the sodium. More Na^{+} will move into the soil and the soil structure will then begin to deteriorate. To increase the benefit derived from the application of gypsum, it should be combined with minimum tillage practices so that structure damaging forces are minimal. Avoid all unnecessary tillage and traffic.

It is important to realise that salinity and sodicity are two very different soil chemical properties. Firstly when we talk of salt in the soil we mean a large range of compounds (salts) and not just common salt (sodium chloride or NaCl). Salinity is a measure of the free salts in soil solution, whereas sodicity is a measure of the exchangeable sodium bound to the clay particles. Soils high in sodicity may be low in salt, therefore to keep them stable a higher salt concentration may be needed and the Ca salt gypsum is applied. DO NOT take this to mean that you can apply any salt, (for example, sodium chloride, NaCl) to help improve the structure of your soil. It must be a salt containing calcium as it is the superior effect of Ca over Na that promotes a stable soil structure.

*Figure 3.6 Severe puddling of water on poorly structured sodic surface soil (right) compared with gypsum treated soil (left) showing the increased amount of water penetration into the treated soil (*77).*



Source: Hunt, N. and Gilkes, B. (1992) Farm Monitoring Handbook.
Published by University of Western Australia, Land Management Society, and National Dryland Salinity Program.

SUMMARY:

- caused by water, raindrop impact, cultivation and trampling by stock
- soil texture - instability very dependent on clay content
- water content - the wetter the soil, the greater the risk of breakdown during cultivation
- soil chemistry - sodic (sodium containing) soils may be very unstable (dispersive). Gypsum can improve structural stability.

3.2.3 Monitoring

Do you have a well structured, heavy textured soil that is stable during cultivation? Is it stable when wet? How can you test the stability of your soil? We give you some visual indications of soil instability, and means of monitoring the soil so that you can determine if the stability of the structure of your soils is improving over time.

(a) Visual indications

(see also Section 3.3).

• Is the soil surface hard when dry? A quick indication of surface crusting problems is to push a screwdriver into the soil (#35) a couple of days after the soil has received a soaking rain. You could also use a sharpened length of metal rod, (about 5 cm long) or a sharpened pencil in the palm of your hand (Figure 3.7). The greater the strength of the soil, the more you will have to push. If surface crusting is a problem, you will find it difficult to penetrate the first few centimetres of soil. If hard layers are any deeper than this they are no longer a surface crust, and the high soil strength of the subsoil may be limiting plant root growth.

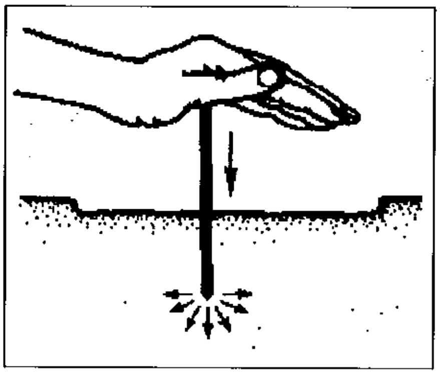


Figure 3.7 Detecting surface crusting and subsoil compaction by pushing a pencil into the soil with the palm of your hand (#35).

If the penetration of your probe into the soil is less under stunted plants than under nearby more vigorous plants, high soil strength may be restricting root growth and contributing to the poor growth. Do further testing using a penetrometer, make bulk density measurements, (see Section 3.5) or dig a pit and observe water movement and root growth (see Section 3.3).

• Wind-blown soil is easily seen and is familiar to farmers in many drier areas. It is indicative of a poorly structured surface soil (see Chapter 7). Soil particles are sorted by the wind when they are eroded and transported, with the clay and fine organic matter being removed. The accumulation of fine sand and coarse silt particles around fence lines and perennial vegetation indicates that wind erosion has occurred.

• Does water pond easily on the soil surface, and remain for days or even weeks? Is the ponded water cloudy (due to dispersed clay)? You may see grains of sand concentrated in surface depressions, indicating aggregate disruption and slaking.

• Is the soil boggy after only a little rain and you can't produce a good seed bed? Does the seed bed break down quickly when wet, leading to poor seedling emergence?

• Is crop growth patchy?

• Are there wide and deep cracks in the soil surface when it is dry?

• Do you find it more difficult to work one paddock or one part of it than another?

If you answered "yes" to two or more of the above questions, you could have a soil surface instability problem. Do the following tests to give you a better indication of the stability of your soil, but be careful. Before you change your management practices by applying large amounts of gypsum or adopting minimum cultivation techniques, check with your consultant or adviser, etc.

(b) Measurements

(i) Dispersion test

Below is a test designed to assess the stability of soil aggregates. It is for soils containing at least 15% clay (see Chapter 2) - do not use it for sandy soils. It measures how aggregates behave in water both before and after being mechanically worked (representing cultivation).

Materials

- plastic bags (2 for each area sampled)
- marker pen
- clear containers of about 50 - 100 ml capacity, clear plastic cups are ideal (2 for each area sampled)

Source: Hunt, N. and Gilkes, B. (1992) Farm Monitoring Handbook.
Published by University of Western Australia, Land Management Society, and National Dryland Salinity Program.

•a litre of rainwater (not scheme or dam water as it contains salts that will affect the results) or distilled/ deionised water sold for use in steam irons.

•dark surface (bench, cloth or paper)

Method (#24, #26, #42).

Choose the area you want to test. Scrape off the litter and collect about a cupful of soil from the depth of cultivation (usually 5-8 cm or 2-4 inches). Due to natural variations in soil, you should take samples from at least six different sites in the area you are sampling and gently mix them in the plastic bag. Collect a total of about 1/2 kg of soil. It may also be interesting to take some samples from a depth of about 15 cm. If you do, take care to not mix the subsoil and topsoil in the same plastic bag. If the soil is wet when you collected it, dry it by leaving it open to the air before proceeding. Break the samples into aggregates of about 3-5 mm diameter.

At this stage you should note how easily the soil breaks into aggregates and also estimate what proportion of the soil consists of aggregates and what proportion consists of single sand, silt and clay particles. These observations will tell you how well structured the soil is. Aggregates are naturally occurring fragments of soil and if the soil does not break readily into these natural aggregates it is not well structured. The following tests assess the stability of the structure.

1st step

Fill the containers to about 1/4 full with rainwater or distilled water. Pick out about five 3-5 mm size aggregates from each of your soils. (Be careful not to choose small pieces of gravel!). Gently drop these aggregates into the water in the glass. Do not shake the glass. Leave undisturbed for 20 minutes and observe what happens. If you have trouble deciding where your soils fit in the classification scheme, see Figures 3.8 and 3.9.

If the aggregates have broken down or disintegrated into individual soil particles of sand, silt and clay and the water is cloudy, you soil has 'dispersed' (Class 1) (Figure 3.8). The repulsive forces between the clay particles due to water binding with them and forcing them apart are enormous and produce this spontaneous dispersion.

If your soil has not dispersed, observe again in 24 hours. It is necessary to leave them for a day because some soils will not break down in a matter of minutes, but are still unstable. If your soil disperses only after several hours in water, it is still a Class 1 soil.

If the aggregates are intact, this soil structure is very stable (Class 4).

If the aggregates have broken down into smaller aggregates but have still retained the basic "clump" form of the aggregate, your soil has "slaked" (Figures 3.8 and 3.9). This breakdown is due to air rushing out as water rushes in. The faster the aggregate is wetted, the greater the disruption caused by entrapped air inside pores. This soil is slightly

(a)
(b)
(c)
(d)

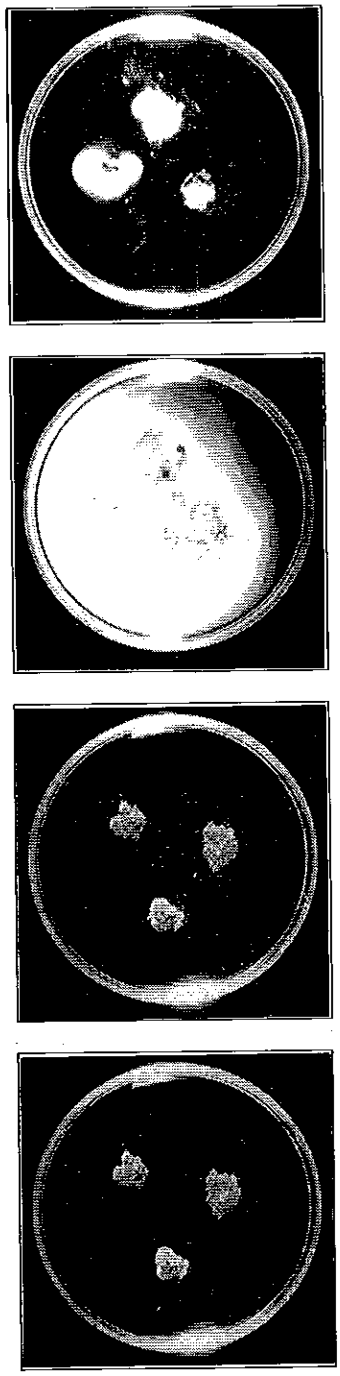
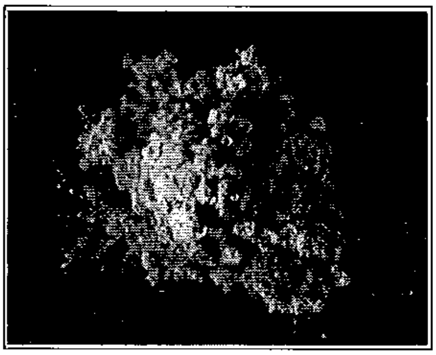


*Figure 3.8 A dispersive medium clay soil (Class 1) 5 minutes (a) and 24 hours (b) after the aggregates were immersed in water, and a slaking fine sandy loam 5 minutes (c) and 24 hours (d) after immersion (*71)*

Source: Hunt, N. and Gilkes, B. (1992) Farm Monitoring Handbook.
Published by University of Western Australia, Land Management Society, and National Dryland Salinity Program.

*Figure 3.9 A slaking soil (*76)*



unstable but not very dispersive. Go on to the next step.

2nd step

This step is done if your soil does not fit into either the Class 1 or Class 4 categories.

Again, fill the drinking glasses to about 1/4 full with rainwater or distilled/deionised water. Select 7-10 more aggregates from the soil to be tested, and place these in the palm of your hand. Remove any loose coarse organic matter. Add enough distilled water or rainwater to make the aggregates moist. Roll the soil into a loose ball and keep working it for about 1 minute. This remoulding of the soil simulates the forces that are applied to the soil when it is cultivated. Add only enough distilled water to ensure the soil does not stick to your fingers.

Break 3-4 small (1/3 cm) pieces of soil off the ball and roll these into small balls. Drop these into the water in the glass. At the end of 5 minutes, observe what happens.

If the water becomes cloudy or a "halo" effect can be seen around the piece of soil, your soil has "dispersed" (Class 2) and is therefore quite unstable. If the water remains clear, or only slightly cloudy, and the soil has not dispersed although it may have broken down, your soil is quite stable (Class 3).

Record the class category you obtain for your soil on your data sheet.

Table 3.1 is an example of how to record your data. Section 3.2.4 will give you a brief outline of the management alternatives you can undertake given the class your soil fitted into.

Table 3.1 Example of structure class allocation and paddock record sheet

Paddock	Sample Number and Time of Sampling	Comments	Structure Class
Hillside, 200 m north from gate.	1. 30/11/89	In pasture last 12 months. No gypsum applied.	2
	2. 6/12/90	Gypsum applied at 2.5 t/ha 3 months previously.	3
	3.		
	4.		
	5.		
Valley floor, 100 m south from gate.	etc.		

Source: Hunt, N. and Gilkes, B. (1992) Farm Monitoring Handbook.
Published by University of Western Australia, Land Management Society, and National Dryland Salinity Program.

Gypsum responsive soil (#2)

If you want to check if your soil is gypsum responsive, (but only if it exhibited Class 1 or Class 2 behaviour), one quick on-farm test is to add about a teaspoon of gypsum to about 100 ml of distilled or rainwater in a bottle and shake vigorously to partially dissolve it. Repeat the above dispersion test (only the first step) with this water. If dispersion is prevented, gypsum should be successful in improving soil structure (Figure 3.10). However, before you undertake a major gypsum application program, first apply test strips of gypsum to your problem soils.

Another method of investigating the stability of your soil structure involves measuring the water movement through gypsum treated and untreated soil (#2). Take two tin cans, punch a few holes in the bottom of each and put a piece of porous material such as hessian or coarse cloth on the bottom. Sample the soil as for the dispersion test (keep the topsoil and subsoil samples separate and ensure they are air dry). Add the soil to the cans, filling each about three quarters full. Pack the soil as uniformly as possible by tapping each can against a hard surface. Add pure rainwater or distilled water to one can, and water containing gypsum to the other, and time the outflow of water from the cans. You can repeat the test using the subsoil. If the outflow rate is at least three times greater with water plus gypsum for either the topsoil or the subsoil, then a good field response to gypsum is likely. Once again, however, it would be best to instal some test strips before embarking on a major gypsum application program.

(ii) Soil strength test (*73)

The Dispersion test is one of the easiest ways of assessing soil structural stability. However this simple test has two limitations: it is not easy to be consistent in categorising soil because the criteria used are subjective, and secondly, the categories into which soils can be classified are fairly broad and each encompasses a wide range of soil structural properties. The test described below was developed to provide a more objective and quantitative method of measuring the structural stability of soils which tend to set hard - the soils that are most difficult to manage to their full potential.

The test involves making small cylindrical soil blocks approximately 20 mm in diameter and 10 mm high, by wetting and drying soil which has been loosely packed into a plastic mould, then measuring the strength of the dry soil blocks using a hand held gauge or penetrometer (Figure 3.11). The greater the strength of the dry soil blocks the less stable the soil.

(a)

(b)

(c)

(d)

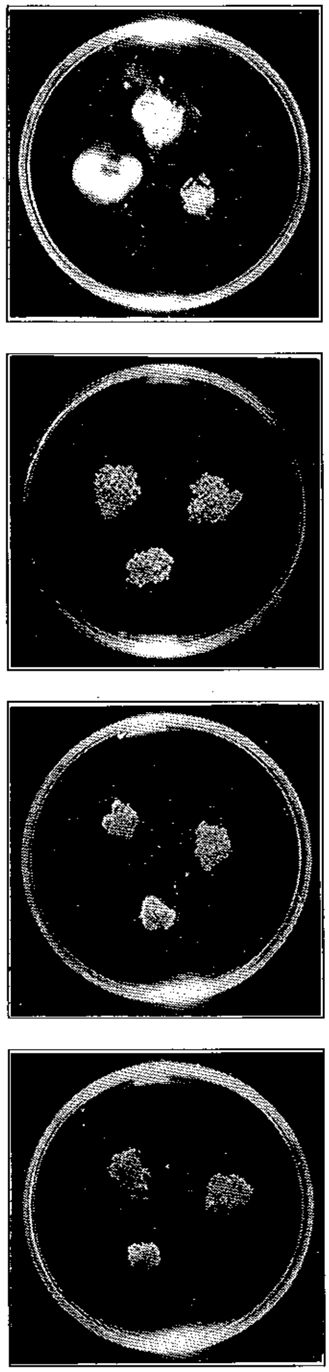


*Figure 3.10 Gypsum prevents the dispersion of the medium clay (a & b), but cannot prevent slaking of the fine sandy loam (c & d). Gypsum cannot correct slaking behaviour, only dispersion (*71).*

Source: Hunt, N. and Gilkes, B. (1992) Farm Monitoring Handbook.
Published by University of Western Australia, Land Management Society, and National Dryland Salinity Program.

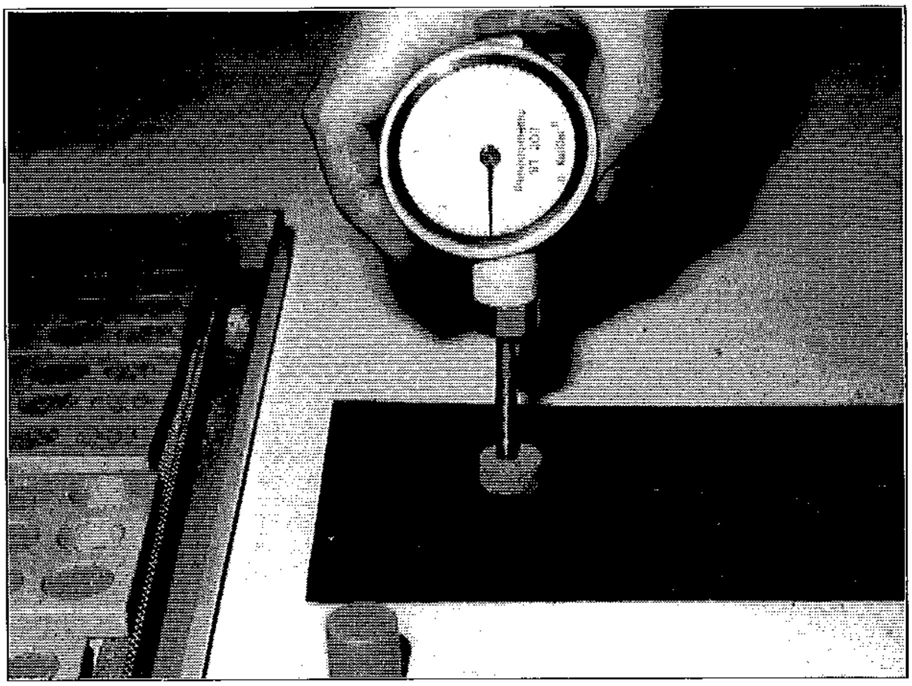


*Figure 3.11 Penetrometer used to measure soil strength and other equipment from the monitoring kit (*73).*

The equipment required to perform this test is currently available as a kit, for loan from the Soil Science Dept., U.W.A., and may eventually become available commercially. Test kits contain all the necessary equipment and an illustrated instruction sheet which provides more detail on the procedure than is presented here. However many farmers would find it fairly easy to make up a simple test kit of their own at home.

Materials
- shovel
- plastic bags or containers (one for each area selected)
- clean, dry buckets
- 2 mm sieve
- microwave or conventional oven
- toilet paper
- wire tray (part of kit) or make one
- plastic soaking tray (part of kit) or make one
- mould (part of kit) or make one
- short powder funnel (part of kit) or make one
- distilled or rainwater
- pocket penetrometer (see Section 3.2.5) or kitchen scales
- flat tipped rod of steel, plastic or wood (in place of penetrometer).

Sampling

Choose at least six different sampling sites within the selected area avoiding firebreaks, heavily trafficked areas and areas that may have had a fertiliser spillage as these will not be representative of the area. Remove loose organic material and gravel from the surface. Collect soil samples from a straight sided hole with a spade or trowel (pogo sticks used for collecting soils for chemical analysis are not recommended as they can damage soil structure). Take topsoil samples only, from a consistent depth (for example, 75 mm or 3 inches), and be careful not to contaminate the samples with subsoil, especially if the subsoil is clay. Collect about a shovelful per site and place them all into one bag or container. Collect samples when the soil is reasonably dry as wet heavy soils are very susceptible to structural damage.

Method

Crush any clods using the minimum force necessary. Mix the soil from the six different sites in the area thoroughly, on a clean surface or in a clean, dry bucket. Select a cupful of soil and sieve this subsample with a 2 mm sieve. Use a rubber bung or block of wood to gently push the soil through the mesh until all but the gravel has passed through. Mix the sieved soil and take about 100 ml of this soil by spooning from different parts of the sieved sample into a small container. Remember that excessive force in crushing the soil will damage its structure. If you are hoping to detect differences in structural stability associated with tillage, harsh treatment of the soil at this stage could obscure any real differences in the soil's stability caused by the differences in tillage.

The soil is now ready to be made into blocks using the following procedure.

1. Place a layer of toilet paper in the base of the wire mesh tray.
2. Place the wire tray in the plastic soaking tray.

Source: Hunt, N. and Gilkes, B. (1992) Farm Monitoring Handbook.
Published by University of Western Australia, Land Management Society, and National Dryland Salinity Program.

3. Place a mould on top of the toilet paper (up to four different soils can be tested in one tray using the kit).
4. Rest the base of a short powder funnel in a hole in the plastic mould and dump the vial full of soil into the funnel.
5. Distribute the soil amongst all the holes in the mould; soil should not be allowed to fall into the holes and should not be compressed.
6. Level the soil at the surface of the mould using a short straight edge.

Wetting the soil:

Place the plastic tray on a level surface and pour a cup of either rainwater or distilled water slowly into the soaking tray, taking care not to wet the soil from the top.

Allow the soil to soak for 30 minutes.

Drying the soil:

Gently remove the wire tray from the soaking tray, tilt it slightly and allow water to drain from the soil for about 30 seconds, then leave it to dry. Soil is most susceptible to damage when wet so gentle handling is important at this stage. Leave the tray of wet soil on a rack in a level place where it can sit undisturbed until it is dry. A warm, airy position is best. Standardise the drying conditions as much as possible by using the same part of the shed or house each time. Note that soils dried slowly give higher strengths than soils dried rapidly so it is important to use the same drying conditions each time you repeat the test on a particular soil.

Crushing the soil blocks:

The soil must be completely dry. If the soil is even slightly moist, strength will be reduced and you will underestimate the severity of structural problems in your soil. Soil must dry naturally to simulate what happens in the field, but once the soil blocks are nearly dry they can be removed from the moulds and dried completely either by a short period in a microwave oven, or in a warm oven.

Try one block first. Gently push one of the soil blocks out of the mould and place it on a clean, firm surface (hardboard or dense rubber is a good surface). Put the large (1 inch diameter) tip on the penetrometer and lay the soil block flat on the firm surface, make sure there are no sand grains below the soil block and that the tip of the penetrometer is wiped clean before each reading is taken. Hold the penetrometer vertically and gradually press down on the block until it fractures (try to apply force to the blocks at a consistent rate - 2 kg force per second is ideal) and record the scale reading when the block cracks. Return the pointer to zero by pressing the button on the side of the dial housing. If the block required a force of more than 6 units (11 kg force) to break it, discard it, and break the other blocks of the same size using the small tip (quarter inch diameter). Record each penetrometer reading and the tip size used. Note that if you are not using the test kit you can set the blocks on the pan of a set of kitchen scales and use a flat tipped rod of steel, plastic or wood to apply force to the blocks. You will, however, need the help of another person to read the scales.

Interpreting the results:

Work out the average strength reading for all blocks. Generally poor structure will be noticeably reducing the productivity of your land if block strength exceeds 2.5 units on the penetrometer scale (blocks crushed with the one inch tip) or 0.7 units (blocks crushed with the quarter inch tip). If you are using kitchen scales reading in kilograms or pounds the equivalent values are 4.5 and 1.3 kg (10 pounds and 2 pounds 12 ounces).

How can the test be used to measure the response to gypsum?

Soil wet with a salt solution will not disperse as quickly or easily as soil wet with pure water. The salty water can act in a similar fashion to the addition of gypsum to an unstable soil, inhibiting the swelling forces associated with sodic soils when wet. Therefore the test for determining how a soil will respond to gypsum involves making up one set of soil blocks wet with water and another set wet with a salt solution (1 1/2 heaped teaspoons of common salt per litre of tap water). The difference in the average strength between blocks wet with water, where dispersion takes place, and those wet with salt solution, where no dispersion occurs, is used to estimate the soil's potential response to gypsum.

To work out the average strength of soil blocks wet with salt solution, multiply by 0.6 then subtract this value from the equivalent value obtained for blocks prepared with the pure water. Multiply this value by 5.5 if the readings were in penetrometer units obtained using the one inch tip to estimate the percentage increase in wheat grain yield you could expect from a gypsum application of 2.5 to 5 t/ha on this soil (multiply by 20 if using

Source: Hunt, N. and Gilkes, B. (1992) Farm Monitoring Handbook.
Published by University of Western Australia, Land Management Society, and National Dryland Salinity Program.

the quarter inch tip). If the readings were obtained in kilograms multiply by 3 for the one inch tip and 10.5 for results obtained with the quarter inch tip.

(iii) Gypsum test strips

Another way of testing if the soil is responsive to gypsum is to use test strips on your problem soils. Choose the most uniform and representative part of the paddock. Apply the gypsum at several rates (eg. 2.5 and 5 t/ha) and leave an untreated or control strip, so that you can tell when reapplication may be needed (#25). Apply the gypsum well before sowing and be sure to treat the whole area in the same way, for example, fertilizer applications and pest control measures must be uniform, so the only difference between the strips is the gypsum rate. There may be no response in the first season, so continue observing into the 2nd year. Throughout the year you should record observations of water infiltration, seedling emergence, crop yield, soil structural stability and other properties for the gypsum treated and untreated strips. See (#29) for further information on setting up your own farm trial with test strips.

SUMMARY:

- structure decline is a problem of heavier textured soils
- visual indications - hard surface crust (pencil), wind erosion, water ponding (cloudy), boggy soil
- soil structure - what proportion of the soil is aggregates
- dispersion test - stable vs unstable soil
- soil strength test
- gypsum responsiveness
- gypsum test strips.

3.2.4 Management

Below are some brief management alternatives you can follow depending on the structural stability category your soil falls into. These notes are only brief so seek further advice before embarking on a full scale management program.

(a) Structural stability classes

(i) Class 1 soil

This is a very unstable soil and likely to be a problem, fortunately such soils are not common. Fence it off and sow a grass cover into it using minimum tillage practices, grazing it in spring. Apply gypsum with minimum tillage but first set up some trial plots before committing yourself to large scale gypsum applications. Avoid committing large fertilizer and seed banks to this soil before you have rectified the problem. Do not work the soil when it is very wet. In the long term, for example over five years, a rotation with years under pasture will improve the stability of your soil.

(ii) Class 2 soil

This soil is only partly stable and should be managed with care. These soils usually require mechanical disturbance (cultivation) as well as water to cause dispersion. Gypsum with minimum tillage may help, but first use test strips and weigh up the economics of using gypsum.

(iii) Class 3 soil

This soil is quite stable and will not be readily damaged by cultivation, provided sound management practices are used, for example, minimum tillage. Keep up the organic matter levels in the soil by practices such as stubble retention, which will maintain or even improve the stability of the soil. Do not work the soil any more than is necessary. Gypsum does not need to be applied.

(iv) Class 4 soil

This is your most stable soil. Keep up or increase the organic matter levels in the soil and maintain sound management practices.

(b) Gypsum application

Gypsum is used only to reduce surface crusting, it is not a cure for other forms of structural degradation such as traffic hardpans that occur in the subsoil. It stabilises the soil structure - it does not create it without help from organic matter, soil organisms, etc. Apply gypsum only to those soils that you know are responsive. The above tests and your own farm trials will help you identify these (Figure 3.12).

Gypsum ($CaSO_4.2H_2O$) is a naturally occurring salt and is often present in dunes at the south eastern end of salt lakes throughout the wheatbelt in W.A, where it is available from pits. It is also a by-product of fertiliser manufacture (#41). The fertilizer by-product is very fine and mined gypsum is coarse. This difference in texture affects the dissolution of the gypsum. The persistence of the gypsum also depends on the rate of application, rainfall intensity and frequency, soil type and management practices after gypsum has been applied. When buying gypsum, important qualities to look for are the purity of the sample and the salt content.

Apply gypsum to the surface soil after it has been broken up and try to keep gypsum in the top 5-10 cm as it most effective there. Minimum

Source: Hunt, N. and Gilkes, B. (1992) Farm Monitoring Handbook.
Published by University of Western Australia, Land Management Society, and National Dryland Salinity Program.

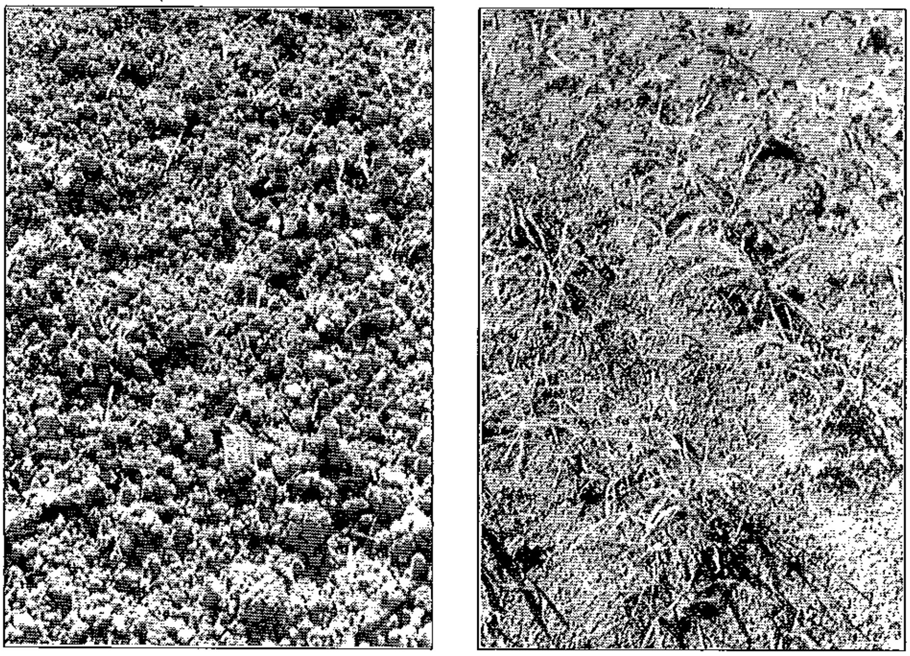


*Figure 3.12 Gypsum improving seedling emergence (*82).*

tillage does not mix it through the soil, and so it lasts longer (approximately 5 years for 2.5 t/ ha). Use a spreader to apply gypsum. If on bare soil 'scratch' in the gypsum to reduce its chances of being blown away. Apply it before the season break as it has to dissolve in rain water before it can act on the soil. Take care when applying gypsum as it can alter the crop response to nitrogen, and you may need to add additional nitrogen.

(c) Tillage practices

Minimum tillage practices such as direct drilling, can maintain or even improve soil structure. The soil is not worked as often as with conventional tillage, so the soil particles are not disturbed and retain their aggregation. It is also advisable to work soils with a poor structure when they are not wet since, as explained beforehand, such soils become less stable when wet. Thus, physical (minimum tillage) and chemical (gypsum application) techniques can sometimes be used to improve soil structure. Naturally, the success of these practices will depend upon the cause of the poor structure in the first place.

Cultivating discs, as distinct from tynes, will invert the subsoil and often bring dispersive subsoils to the surface. Stubble retention practices and maintenance of a plant cover are often necessary to prevent damage from raindrop impact, and associated wind and water erosion. Stocking rates are important in determining the amount of plant cover on your soil, and they also determine the extent of structural deterioration due to stock. You need to consider all these factors in determining the optimum management practice for your structurally unstable soils.

SUMMARY:
- gypsum application for unstable soils
- minimum tillage
- increase organic matter levels in the soil.

Source: Hunt, N. and Gilkes, B. (1992) Farm Monitoring Handbook.
Published by University of Western Australia, Land Management Society, and National Dryland Salinity Program.

3.2.5 Equipment

Equipment	Price	Suppliers
Distilled/deionised water	95c / 2 litres or $2.21/5 litres 85 c/ 2 litres	Anchor David Gray
De-Ion Pack (makes approx. 5 litres) (you supply the water and the pack purifies it)	$15.90	Crown Scientific Phone: (09) 470 3777
Balances		
5 kg capacity x1 g resolution:	$250	Phoenix Scientific 21 Roberts Rd Osborne Park Phone: (09) 443 1788
2 kg capacity x 1 g resolution	$150	
AC Adapter	$30	
Portable balance - Conso Microscale		
500 g capacity x 0.1 g resolution	$449	
5kg capacity x 1 g resolution	$178	
2 kg capacity x 1 g resolution	$114	
200 g capacity to 1 g resolution	$300	Perth Scientific Equipment 212 Abbett St Scarborough W.A. 6019 Phone: (09) 245 1930
200 g capacity to 0.1 g resolution	$500	
Pocket portable balances		
250 g capacity x 0.1g resolution	$245	
150 g capacity x 0.1 g resolution	$225	
80 g capacity x 0.1 g resolution	$195	
Penetrometer		
Pocket penetrometer Effegi, Model ST - 207	approx. $105 - $120 price depends on number ordered.	Selby Anax 21 Glassford Rd Kewdale W.A., 6105
Plastic vials (70ml)		
Unsterile, unlabeled (only in packs of 500)	approx. $80	Lancet Scientific 4 Gibberd Rd Balcatta Phone: (09) 345 4833
Unsterile, unlabeled, but may sell in smaller lots.		Allwest Scientific Phone: (09) 328 1311
General equipment		Prices quoted from: Crown Scientific Phone: (09) 470 3777 but most other suppliers have comparable prices.
washbottles	$3.00	
100 ml glass measuring cylinders	$6.30	
100 ml plastic measuring cylinders	$5.10	
100 ml plastic beakers	$2.00	
250 ml plastic beakers	$2.25	
500 ml plastic beakers	$4.00	
Gypsum costs depend on (#26): freight - distance from the source rate applied purity price	The price of gypsum can vary between $4-10/ tonne at the mine (#26). The total cost of applying gypsum can vary between $30/ha at 2.5 t/ha and at a location close to the gypsum source, up to almost a $100/ha at rates of 5 t/ha and 100 km from the gypsum source. These costs will be less if you use your own truck and spreader.	

3.3 Inspecting your soil pit - visual soil observations

(#13, #14, #27, #55)

3.3.1 Introduction

The physical examination of soil in the field provides you with invaluable information on the response of your soil to management. Many farmers tread the surface yet do not realise the wealth of information available a few centimetres below. This is the environment that plant roots, soil organisms, water and fertilizers contend with. It is therefore very important to gain an understanding of properties in the subsoil, such as structure and texture, that influence water and nutrient movement through the soil. These properties influence plant root growth and the susceptibility of the soil to erosion. A simple and efficient method of examining your subsoil is to dig a pit using either a shovel or a backhoe.

3.3.2 Examination

It is essential that you observe the soil surface first before digging a pit. Look for indications of surface crusting (see Section 3.2) and evidence of erosion, either wind or water. If many areas are to be examined, and/or you want to observe the soil below 30 cm depth, consider using a mechanical digger such as a backhoe. A backhoe can quickly expose the soil to a depth of 1.5 metres, whereas a shovel is useful to only about 30 cm unless you are feeling particularly energetic.

Source: Hunt, N. and Gilkes, B. (1992) Farm Monitoring Handbook.
Published by University of Western Australia, Land Management Society, and National Dryland Salinity Program.

3.3.3 Where?

You could use a posthole auger to examine the soil profile at several locations before choosing a good representative site for the soil pit. Choose a site representative of the area, at least 20 m away from the edges of the paddock where machines turn and firebreaks are maintained. Avoid irregular features such as gateways, roads, tracks, buildings (or where some have been in the past), ponds, etc. Mark down on your farm map or a record sheet where the pit is to be dug. Aerial photos can help to locate suitable positions for a pit in the field. Do not forget that telephone cables and water pipes need to be avoided.

The site of the pit should be chosen so that the sun shines on one side of the pit for as long as possible - especially at the time of sampling. If you want to photograph the pit face, make sure it is oriented so that it receives enough light. For a large paddock you may need to dig more than one pit, especially if there are different soil types.

Dig the pit at right angles to the direction of water flow and wheel traffic, ie: at 90 degrees to the hills where they exist, or usually along a contour (across a slope).

3.3.4 When?

Examine your soil in midseason, preferably beneath a growing crop or pasture so that root penetration can be observed. You may see variations in crop establishment and vigour that could indicate structural problems, for example, the presence of stunted plants. Pits can be dug in summer, but you will not be able to observe water movement or roots. Observing how the soil reacts to heavy rain can provide information on the stability of the soil structure, drainage, porosity and erodibility. Also, the soil is more easily dug while moist.

3.3.5 Materials

- knife
- shovel (or backhoe)
- survey peg
- camera and colour film (polaroid film may fade over time)
- aerial photograph or farm map (to mark where pit has been dug and to help in selecting sites for the pit)
- record sheet - draw one up beforehand
- any other equipment you need for sampling or measuring soil properties in the field.

3.3.6 Method

(a) Surface examination

Before you dig your pit, examine the soil surface. Is it porous or smooth? Use a blade to lever and probe the surface to see if you can lift up a crust. A crust indicates that your soil structure could be unstable. (See also Section 3.2.3)

(b) Subsurface examination

The examination of the soil surface will give a lot of information about the condition of the soil however, it is very important to look below the surface at the subsoil so as to become familiar with the environment of the plant root and the internal drainage of the soil. You should consider using a backhoe especially if many areas are to be examined. Otherwise use a clean, sharp shovel.

i) Using a backhoe

Once you have decided where you want the pit, reverse the back-hoe up to the spot so that the pit will be dug in undisturbed ground. It is important that what you see in the pit has not been changed by the back-hoe passing over the area. The backhoe will cause soil disturbance and compaction that could be put down to your previous management.

How

Cut a trench across the cultivated direction (Figure 3.13) and dig your pit deeper than the zone of interest, as spoil cut from the pit face falls back into the pit (Figure 3.14). Ideally the spoil should be thrown well clear of the pit, preferably to the side so that the prepared face can be cut further back if required. Pile the dirt on the uphill side of the pit, then if it rains heavily, the pile will stop runoff getting into the pit.

Size

Plant roots often go down well below a metre and so the depth of the backhoe pit should be about 1.5 metres. This depth allows you to examine the profile in comfort and allows for the depth decreasing as the pit fills with material pulled from the walls. However, the most important inspection area is from 0 - 50 cm (enough for a shovel). Make the pit length one reach of the back-

Source: Hunt, N. and Gilkes, B. (1992) Farm Monitoring Handbook.
Published by University of Western Australia, Land Management Society, and National Dryland Salinity Program.

hoe arm. Caution - many soils are not very stable and the walls of soil pits can collapse without warning so do not dig very deep and unsupported pits. You should not examine deep pits on your own, take a friend for safety and also to share the discoveries you make in the pit.

(ii) Prepare the pit face

The next step is to prepare the vertical face so that the physical features of the soil can be identified. Carefully trim the sides with a flat edged implement eg: a knife, to expose undisturbed soil by removing the soil smeared during excavation.

Pay particular attention to the following three soil zones: the seed-bed or cultivated layer (from the surface to about 10 cm depth); the upper subsoil or bottom of the cultivated layer (say from 10 cm to 40 cm below the surface) and the deeper and generally undisturbed subsoil (say from 40 cm below the surface to the bottom of the pit). (You can generally only observe this if you have used a backhoe).

Do not be restricted to these depths, they are given as a guide only and may differ in each paddock and for each soil. Rather, decide for yourself where the different layers are and decide on the depth of the pit accordingly.

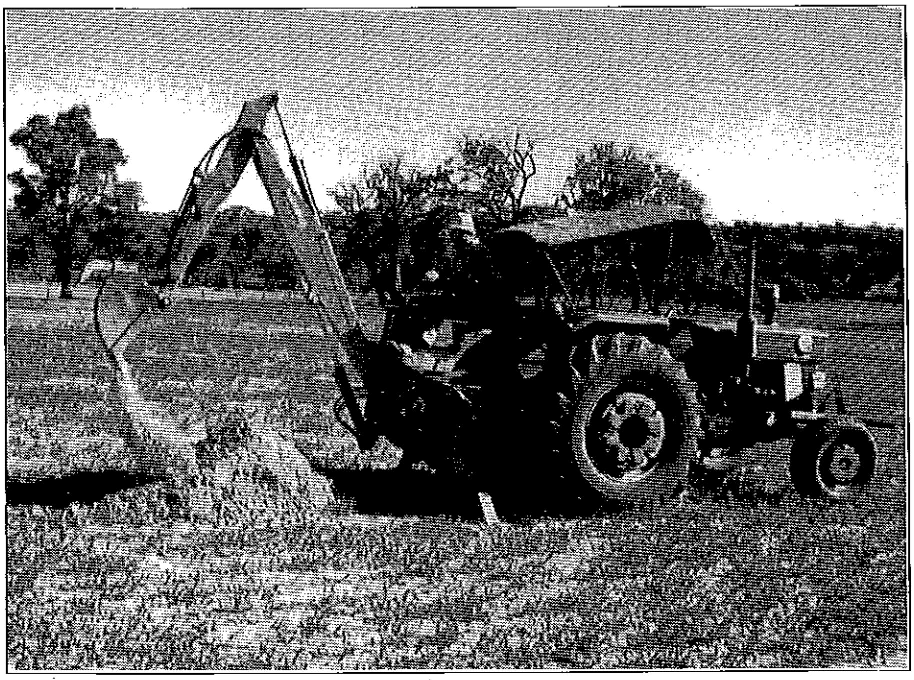


Figure 3.13 How to use a backhoe to dig a soil pit.

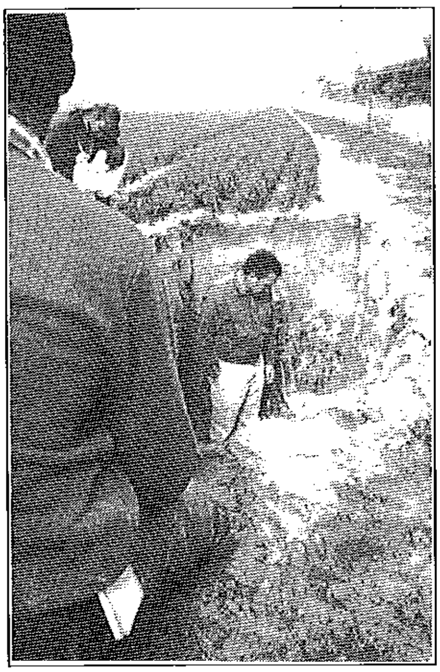


Figure 3.14 A soil pit dug by a backhoe.

For each depth or layer record the following:

- layer depths and thickness
- colour
- texture
- structure
- presence of gravels or other characteristic materials such as lime or gypsum
- pH
- roots and other biological activity

Note any marked changes in texture down the profile, for example a sandy topsoil over a clay subsoil, as this greatly influences water movement in the

Source: Hunt, N. and Gilkes, B. (1992) Farm Monitoring Handbook.
Published by University of Western Australia, Land Management Society, and National Dryland Salinity Program.

soil. (See the relevant sections on each of the above properties for methods to measure them).

(iii) What to look for

Surface crusting

If you have a clay-rich surface soil and it is dry, can you see a surface crust? (Figure 3.15) Can you prise a crust from the surface using a knife or sharp blade? Are there fine cracks? If a crust if formed, the soil may be unstable. Check the stability of the crust and soil aggregates with the Dispersion test (see Section 3.2.3).

Whilst the field observation and stability test give a good early indication of soil structural condition, soil samples could also be collected for possible laboratory testing. Chemical analysis provides more detailed advice about gypsum requirements as well as other soil properties.

When inspecting a number of pits with similar soil moisture contents, a simple method to estimate structure is to push the sharp end of a pencil into the soil at varying depths and record the strength needed to penetrate the soil. If a pencil cannot be pushed with the palm of your hand into a soil layer, then plant roots usually cannot penetrate (see Section 3.2.3).

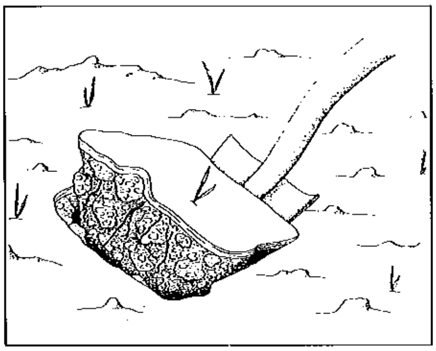


Figure 3.15 Surface crusting due to an unstable soil surface (#14)

Subsoil compaction

Soil features

One major form of compaction is due to traffic pressing the soil together (see also Section 3.5.2). This usually occurs in subsoils of sandy soils where the single sand grains and aggregates may appear to be tightly packed. This form of compaction is generally difficult to observe in a soil pit. Traffic pans can usually be readily identified with a steel probe or a penetrometer. In the absence of a penetrometer, a steel survey peg can still give a good indication. Always ensure that differences in water content are not responsible for apparent variations in strength. Soils with a uniform texture down the profile are most readily assessed in this way.

If you have a clay-rich soil (surface and subsoil) look at the size and shape of clods in the root zone. If there is a lack of pores and channels, and you can see horizontal, platey coarse clods in the soil (suggesting that the soil has been compacted), a plough pan due to smearing may have formed (see also Section 3.5.3). These pans normally cause roots to bend sideways. Plough pans form at the base of the tilled layer, so they will be most visible in the second layer. The compacted layer due to smearing of clay by ploughing, may have a smooth shiny surface on the soil. Pick at the soil profile with a trowel. If the soil above and below the plough pan is loose and friable whereas the pan is not, then water, air and plant movement will be impeded.

In extreme cases of damage due to cultivation, no clods are visible, a uniform featureless layer may be present. Such a layer will be plasticine-like when wet, and when dry it may occur as large, unfractured blocks separated by vertical shrinkage cracks.

Any evidence of a wet layer above or in some cases below the damaged (compacted) zone indicates that water movement is impeded. The water may be seeping out of the soil above this layer. Make a note of how deep and thick the damaged layer is. The shallower the pan, the more severe will be the effects on plant growth.

Dig out intact clods or spadefuls of soil to about 50 cm with as little disturbance or compaction as possible. Take these samples at random, but where you can see obvious differences in crop growth, take samples from good and bad areas and place them side by side for comparison. The soil in gateways and headlands will probably show maximum compaction, whereas the soil in fence-lines and in uncleared areas adjacent to tilled land can provide examples of least disturbance. You should suspect the presence of a plough pan or compaction layer in moist soil if the subsoil readily parts from the topsoil. Check for horizontal cracking which indicates a pan.

Source: Hunt, N. and Gilkes, B. (1992) Farm Monitoring Handbook.
Published by University of Western Australia, Land Management Society, and National Dryland Salinity Program.

If the pit is dug in summer or after a dry spell, the soil may be moist below the pan and dry above it. Plant roots may not have been able to penetrate the pan to obtain moisture. If the soil is dry below this compacted layer, roots may have been able to penetrate and extract moisture. If you are examining the soil in summer, be careful not to confuse an induced pan with the naturally hard boundary between the tilled and untilled soil.

Plant features

Examine and follow the root system of plants including crop, pasture and even weeds. Do this at least 8 weeks after sowing and when the soil is moist and the plants have grown to a reasonable size. Alternatively, you could do it in spring or early summer when roots are at their maximum extension. Taproots are good indicators of soil conditions. Note the depth to which the roots grow (Figure 3.16). Look for signs of bending and branching.

Figure 3.16 Soil pit showing inhibited rooting due to clay layer (duplex soil).

If they are bent or stunted there is evidence of a soil structural problem. Some plant roots can be bent at a 90° (right) angles. Careful interpretation is needed here, there are many reasons besides compaction why roots bend or branch. Cereals and peas will show up the compaction layer very well as their roots cannot penetrate dense soil.

To keep a permanent record of the root patterns, pin a clear plastic sheet (0.6 m x 1 m) to the vertical face of the soil pit with nails. Make sure that a narrow strip of the plastic is extended over the upper edge. Mark the soil surface with a waterproof black pen. Mark a dot where a visible root has been cut in the vertical face. Trace each root or section of root that runs within the vertical channel. Remove the plastic sheet and identify it by marking the date, location, and what the problem is. If the sheet fogs up with water from the back, first scrub the back with a fine plastic scouring sponge dipped in concentrated detergent and let it dry. Fold the sheets (treated side inside) and then take to the field.

Draw a vertical 50 cm line (marked '50 cm') on one side of the root pattern as a scale. Clean any mud or soil from the plastic after the ink has dried. The sheet can be photographed and printed at 1/5 of original size for convenient comparison and storage of data, or kept as is (#17).

If you are really keen, you may like to estimate the root density of your crop or pasture. Take a large block of soil material from each horizon and break it to produce a horizontal broken plane. Estimate the average number of roots in a number of 10 cm squares, ie: mark off 10 x 10 cm squares and count the roots. Calculate an average number of roots in a 10 cm square. Mark the depths at which the estimates were made (#17).

Water movement

Observe the water movement through the soil profile into the pit after a period of heavy rain. This will give you an indication of the infiltration rate of water, and the hydraulic conductivity (rate at which the soil will allow water to drain through it). If the water is 'spurting' into the pit, then the hydraulic conductivity of the soil will be very high in at least some of the soil profile. If the water is remaining stagnant, or moving very slowly - 'oozing' out, then you have an obstruction such as a pan, or your soil is naturally very poorly drained. The hydraulic conductivity should ideally be somewhere between spurting and oozing. Observe this water movement over at least 0.5 metre. (See also Section 3.4).

Channels

The A horizon (or the top layer where most plant activity occurs) of a tilled soil contains many large pores when first tilled, but these may collapse within a single season. Look carefully for the presence of stable continuous vertical channels (macropores). These channels may have been created by earthworms, ants, plant roots or cracking, and indicate a suitable structure for

Source: Hunt, N. and Gilkes, B. (1992) Farm Monitoring Handbook.
Published by University of Western Australia, Land Management Society, and National Dryland Salinity Program.

good plant root growth. Macropores allow roots to bypass damaged soil layers. Also look for worm casts and burrows. If you have a clay-rich topsoil, examine the clods closely, looking for macropores. They may be absent. Score: 0, none; 1, few; 2, common; 3, many. If the face of the clods are relatively smooth with a few very small pores, conditions for the extraction of water and nutrients by roots are likely to be poor.

Soil colour

Observe the soil colour. A general indication of colour is that black = humus, red = iron oxides, white = silicates such as kaolin, carbonates or salt. Examine the subsoil colour. The presence of pale, bluish tones, possibly with rusty mottling, usually indicates that impeded drainage possibly due to poor soil structure has produced serious waterlogging. Dark colouration in a subsoil usually means that plant growth has been good, leaving the soil enriched in organic matter, although some soils have a naturally dark mineral colour. Colour is a good indication of the condition of the more sandier soils. Organic matter is the major binding material for the aggregates in sandy soils, and the darker the soil colour, the more organic material present. Generally the more organic matter in a sandy soil the better the chemical and physical fertility of the soil.

The presence of some dark grey oxygen deficient (anaerobic) pockets of soil with a distinctive sewage smell can mean that crop residues have been incorporated into a wet, compacted soil.

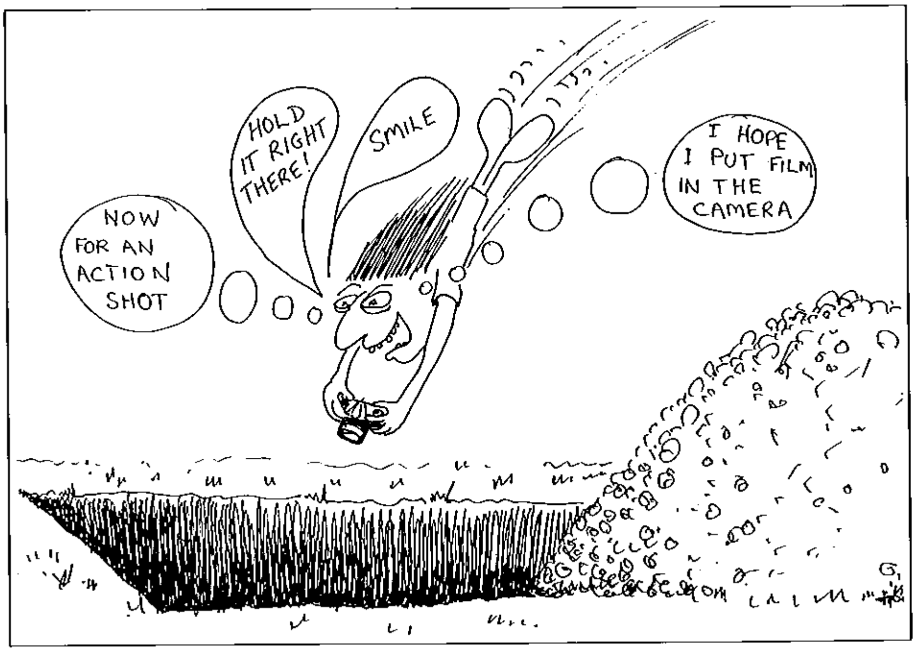
Salinity

Check for signs of salt (NaCl). If dark greasy areas appear on the soil surface when moist, followed by the presence of white crystals that taste salty, further testing is required. Don't confuse salt with $CaCO_3$ (lime) or gypsum ($CaSO_4.2H_2O$). Lime may appear as hard, white, rounded nodules or white powder, whereas gypsum appears as white or grey, needle-like or platey crystals. Check for lime by adding a few drops of 1M hydrochloric acid (HCl) - it fizzes, releasing carbon dioxide. (See also Section 9.4.3). If white salts occur on the surface or if the subsoil is unusually friable and salty to taste, salinity can be suspected. This can be confirmed by the tests outlined in Section 8.4.2.

3.3.7 Photography

An excellent method of recording the properties of the soil profile exposed in a pit is by photography. You then have a means of recording problems such as retarded root growth due to compaction, and can compare photographs from one year to the next as a test of the success of your management procedures. Photographing the soil surface is also a useful method of monitoring the condition of the soil and its stability.

Use a good camera, for example, 35 mm with a good lens, that can be accurately focused, a changeable aperture, and a choice of exposure times. You could use direct or



Source: Hunt, N. and Gilkes, B. (1992) Farm Monitoring Handbook.
Published by University of Western Australia, Land Management Society, and National Dryland Salinity Program.

bounce flash to ensure that the pit face is adequately illuminated. Pick out the profile face with a trowel to remove smeared areas before photographing.

Use colour print film but not polaroid film as it fades, also ensure the camera is dust and water proof as you do not want it to malfunction and to discover that your photographs are useless after the pit has been filled in. Write on the photograph the date, where it was taken, and what it is representing. (See also Section 10.1).

When you have completed your examination, replace the soil and level the land surface. Place any large stones dug out at the bottom of the pit. Or, to keep a permanent record fence the pit off.

SUMMARY:

- surface examination
- subsurface examination
  using a backhoe
  prepare the pit face
  look for:
  surface crusting
  subsoil compaction - soil and plant features
  water movement
  channels
  soil colour
  salinity
- photography

3.4 Soil and Surface Drainage

3.4.1 Introduction

The water content of a soil influences plant growth, structural stability including surface and subsoil compaction caused by equipment and animals, and performance and ease of manoeuvring tillage equipment. The soil is more vulnerable to break down by tillage when wet. Proper management will ensure the water is put to its most beneficial use and does not contribute to degradation.

Water in soil is held in the pores which are spaces between and within aggregates. Due to seasonal variations or management, the water content in soil fluctuates. A plant takes water first from the larger soil pores and as these are exhausted the plant works harder to exert greater suction pressures to obtain water from smaller pores. Eventually all the remaining water is contained in very small pores and the plant is unable to extract it. The 'field capacity' of a soil is the maximum amount of water the soil can hold without it draining away under gravity. This capacity depends on soil texture and structure. At the 'wilting point', the plant can no longer extract water from the soil. The difference in water content between the values at field capacity and wilting point is the amount of water available to plants.

Water must first enter the soil before being used by plants, and the soil should drain well to prevent problems such as waterlogging. The rate of water entry into a soil is called the infiltration rate. An infiltration rate of 15 mm/ hour means that a water layer of 15 mm on the surface of the soil will take one hour to infiltrate. The infiltration rate is affected by many factors such as surface crusting, water repellence and management.

Once the water has entered the soil, the permeability of the soil determines how quickly the water will drain through to the subsoil and eventually to the ground water. The ability of a soil to transmit water is influenced by its hydraulic conductivity and is also dependent on the infiltration rate, the thickness and permeability of the soil and the pressure applied by the water.

When assessing the hydraulic conductivity of your soils it is important to pinpoint problem areas. On flat land waterlogging can often occur if the soil has a low hydraulic conductivity and receives runoff, conversely a soil with a high conductivity on a slope would lose water both by internal and surface drainage, so that less water may be retained by the soil to be available to plants. When water drains below the root zone it is called deep drainage and when this water enters a groundwater system it is termed recharge. This water has the potential to produce waterlogging and salinity when the ground water eventually meets the soil surface at positions downslope.

SUMMARY:

- water is important in soil degradation
- at field capacity the water is held in soil pores that do not drain due to gravity
- at wilting point the water is held in very small pores and the plant cannot extract water from the soil without exhibiting water stress
- infiltration rate - the rate of water entry into the soil
- hydraulic conductivity is the ability of the soil to drain water and it depends on soil properties especially texture and structure.

Source: Hunt, N. and Gilkes, B. (1992) Farm Monitoring Handbook.
Published by University of Western Australia, Land Management Society, and National Dryland Salinity Program.

3.4.2 What influences water infiltration and drainage?

The infiltration of water into a soil and its subsequent drainage through the soil is affected by a number of factors.

(a) Soil texture

Coarse textured soils have many large pores between the particles. This allows for very good infiltration and drainage. Finer textured soils have smaller pores so that infiltration is usually higher for coarse textured soils than for fine textured soils. Some representative values of infiltration rate are shown in Table 3.2.

(b) Soil structure and chemistry

In general, water infiltrates quickly into well structured soils but very slowly into massive and compact soils. A good soil structure with abundant pore spaces, allows the water to move easily through the soil. A poor soil structure can prevent this easy flow-through due to only a few and far spaced soil pore spaces being present. Finer textured soils that are prone to structural instability may form a surface crust that will greatly reduce infiltration rate. Sodic clay subsoils may also inhibit drainage through the soil because the clay disperses and clogs the pores (Figure 3.17). Gypsum and other soil conditioners can be added to some clayey soils to help maintain soil structure and therefore the drainage. Gypsum and soil conditioners help keep the clay particles aggregated so that they do not disperse and clog soil pores. Gypsum is of little value for improving the structure of sandy soils.

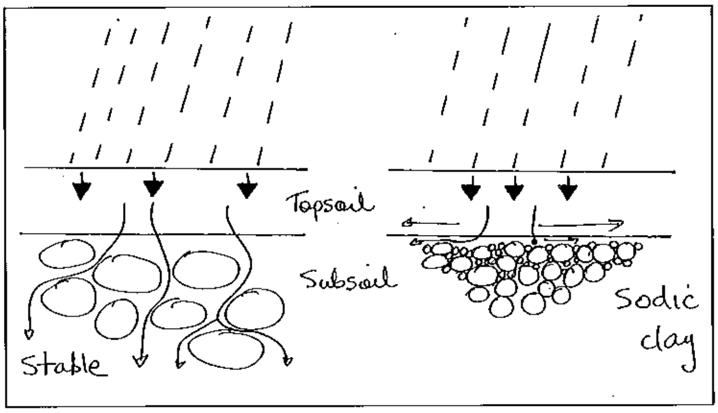


Figure 3.17 Drainage and sodicity

In some soils with a poor structure you may find that most water moves through preferred pathways and not through the bulk of the soil. These pathways are channels left by, for example, earthworms and plant roots that allow water to drain through a soil that may otherwise drain poorly, for example, in a sodic clay soil that easily disperses. It is important to realise that these channels or pathways exist when you do your monitoring - they are evident in soil pits.

(c) Water repellence

The presence of special types of organic matter in some soils, particularly the sandier soils, can lead to water repellence, or non-wetting of the soil. The water remains beaded when poured onto the soil, and will not infiltrate into the soil (see Chapter 4).

(d) Soil moisture content

Water infiltrates faster into a soil when it is dry, than when it is wet. As a consequence, when water first falls on a soil it infiltrates easily, (except when it has a surface crust or is non-wetting) but as the soil becomes wetter, the infiltration rate decreases.

Table 3.2 Infiltration rates for different soils (#53)

Soil texture	Infiltration rate (mm/hr)	
	Bare Soil	Vegetated
Clay	0-5	5-10
Clay loam	5-10	10-20
Loam	10-15	20-30
Sandy loam	15-20	30-40
Sand	20-25	40-50

(Note that infiltration rate is approximately doubled for vegetated soil).

Source: Hunt, N. and Gilkes, B. (1992) Farm Monitoring Handbook.
Published by University of Western Australia, Land Management Society, and National Dryland Salinity Program.

(e) Management

A vegetative cover on the soil (apart from water repellent residues) promotes faster water entry (see Table 3.2), due to plant roots opening up channels, and improved soil structure due to the presence of more organic matter. Vegetative cover and improved soil structure are all greatly influenced by the management of the soil.

SUMMARY:

- soil texture - sandier soils are usually better drained than clay soils
- structure and chemistry - a well structured soil is better drained than a poorly structured soil, sodic clay soils often have very poor drainage
- water repellence - water is repelled by some types of organic matter and will not enter sandy soils when sand grains are coated with this material
- management - improving soil structure and vegetative cover increases water infiltration

3.4.3 Monitoring

Is your soil likely to waterlog or be prone to surface runoff and potential erosion problems? There are some simple drainage tests that you can do on your soil, both in the paddock and in the house (or shed - depending on how messy you are!). These tests should be combined with an overall assessment of the soil structure, for example, a poor infiltration rate for your soil may be due to to a surface crust forming because of an unstable soil, or to water repellent organic matter coating the sandy soil particles.

(a) Visual - see Section 3.3.

(b) Measurements

i) Infiltration rate

Infiltration rings can used in the field to measure the infiltration rate for your soil. However, it is important to be aware of their limitations. For example, they do not simulate the effect of raindrop impact on the soil which can lead to surface sealing, especially if the soil is unstable. It is possible to use the rings to assess potential recharge areas for waterlogging or salinity problems, however be careful in this assessment as many other factors contribute to these problems.

When

Check the infiltration rate when the soil is most vulnerable to surface sealing, just prior to seeding. Carry out the test when the soils are moist. If you need to carry out the test in summer, make sure that soil below the rings is well wetted and that water is soaking in at a uniform rate before estimating infiltration rates (usually 1-2 days after a soaking rain). When you assess the infiltration rate of the soil in later years to assess the effects of management, make sure you do so at the same moisture content, as this affects the infiltration rate. If you want to compare two soils of the same texture in different parts of the farm, it is important to do the measurements at about the same water content (ie: on the same day).

Materials

- rainwater or tap water (up to 6 litres)
- steel collar or ring - you can make your own infiltration rings by using sections of 4 - 5 mm gauge steel pipe. Ensure the ring is about 30 cm diameter and 25 cm deep. Sharpen at one end so that it can be easily pushed into the soil. You can make a ring from a 60 litre steel drum, leaving the rim at the top and grind and sharpen the lower edge. Alternatively bend a piece of mild steel sheet into a cylinder and weld the seam.
- ruler
- shovel
- stopwatch
- 2 litre flagon or similar for the water, and supporting tripod (if needed)
- calculator

Method (#12, #35, #42)

Select at least 4 sites in the area you want to test to provide an estimate of variability, you may like to set a transect of several sites up a slope.

Test for water repellence:

Check your soil for water repellence. This should be done before you begin the testing as a non-wetting soil may give unreliable results. Place a spoonful or your soil into your hand. Wet the soil with a few drops of distilled water or rainwater and note whether the water beads on the surface or infiltrates quickly. The non-wetting property can be so bad that the water will remain on the surface of the soil for days! The problem can be overcome by the addition of commercial wetting agents and other measures (see Section 4.5).

Measure the area of the ring, for example, if the diameter of the ring is 30 cm, Area = π x (radius)^2 = 3.14 x15 x15 = 700 cm^2 = 0.07 m^2.

Clear the surface of vegetation. If the soil surface is compacted, then drive the ring in about 4 cm through the topsoil. If the surface is cultivated, drive the ring in below the tilled layer or the water will just escape through the sides. When the ring is

Source: Hunt, N. and Gilkes, B. (1992) Farm Monitoring Handbook.
Published by University of Western Australia, Land Management Society, and National Dryland Salinity Program.

placed into a crust on the surface, it can break up the crust and leakage can occur around the side, therefore seal the ring onto the surface with plasticine, bentonite clay or a sealing compound. A sealant could also be local clayey soil made into a slurry and poured around the rim of the ring.

There are two ways to measure the rate of water infiltration into your soil:

Surface soil:

1. Fill the ring steadily with the water. Do not splash onto the surface as this will destroy the natural structure. Measure the drop in water level at appropriate intervals until you reach a constant flow rate, for example note how much water disappears in 10 minute intervals. Pick your own time intervals depending on the rate of drainage, frequent readings if fast, every couple of hours if the drainage is very slow.
2. Alternatively, apply a depth of 25 mm of water to the base of the ring and invert a flagon of water on a tripod placing the mouth of the flagon in the water in the infiltration ring. Have another flagon of water ready to invert as soon as the first one is empty, and so on (Figure 3.18).

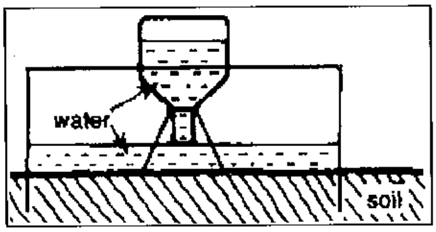


Figure 3.18 Diagram of equipment used to measure the infiltration rate of water into soil (#35).

Table 3.3 Infiltration rates and their descriptions (#53).

Description	Infiltration rate (mm/hr)
Very slow	less than 1
Slow	1 - 5
Moderately slow	5 - 20
Moderate	20 - 65
Moderately rapid	65 - 125
Rapid	125 - 250
Very rapid	greater than 250

Record the time it takes for each of the flagons to empty. Stop when there is little change in this time from one flagon to the next. Use the last time recorded to calculate the steady infiltration rate of the soil.

For example, if it took 23 minutes for 2 litres of water to infiltrate the soil, then the depth of water that has infiltrated the soil is 2/0.07 = 28.6 mm (2 litres of water would cover 1 m^2 to a depth of 2 mm). Therefore the infiltration rate is 28.6/23 x 60 = 75 mm/hr. Compare your value with Table 3.3.

In some cases, especially if you did not seal the ring onto the surface, some of the water will move sideways from the ring rather than straight down and the measured infiltration rate will be more than the actual rate for rain. You can overcome this by having two infiltration rings, one inside the other, and take the measurements within the inner ring. Water held between the rings supplies that necessary for sideways movement through the soil.

Subsoil:

1 Your surface soil may be very well drained, but your subsoil may hold up water flow. Many duplex soils have the problem of poor internal drainage in the subsoil. You can test this by digging a hole to the top of the part of the soil profile that you suspect of restricting water flow. Try to prevent the soil falling onto the freshly exposed surface. Deepen the hole by 20 - 30 mm and pour water into the hole to give a depth of about 25 mm. Invert a bottle of water into the hole as described earlier (Figure 3.19).

For deep holes use a long cylinder of clear rigid plastic tube, sealed at one end instead of a flagon. Proceed as for the measurement of infiltration rate and record the time taken for the cylinder to empty.

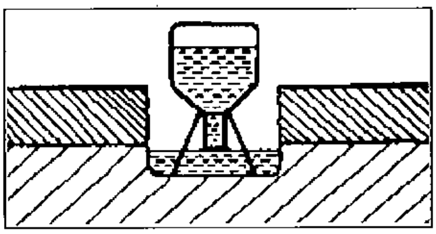


Figure 3.19 How to measure the rate of water movement into a subsoil (#35).

Source: Hunt, N. and Gilkes, B. (1992) Farm Monitoring Handbook.
Published by University of Western Australia, Land Management Society, and National Dryland Salinity Program.

2. Alternatively, you could pour a set amount of water onto the exposed subsoil in the ring and time its disappearance into the soil. Compare your value with Table 3.3 - is it a fast or slow infiltration rate?

You could also dig a soil pit after a heavy rainfall and observe water movement through the soil (see Section 3.3).

ii) Hydraulic conductivity (#42)

This test is done on collected soil inside a shed or house, as distinct from the field measurements of infiltration rate.

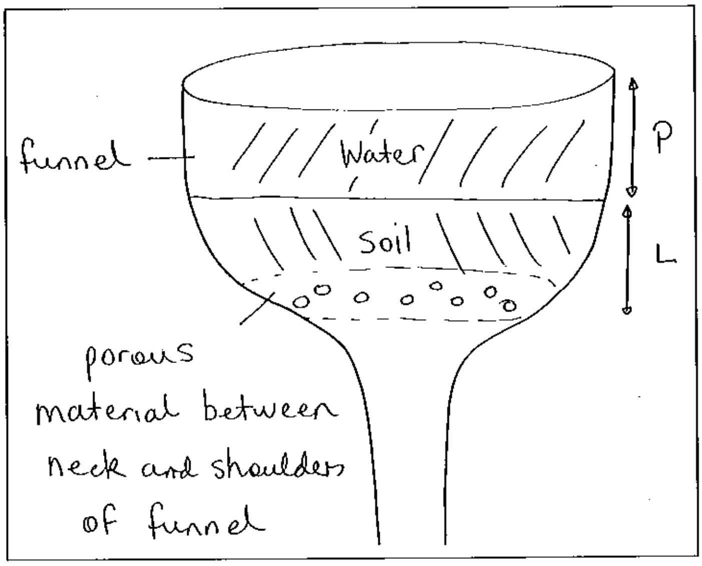


Figure 3.20 The funnels used for the measurement of hydraulic conductivity

Materials

•old plastic soft drink bottles (about 1.25 litre size). Cut the neck and shoulders off the tops of the bottles. Place some sturdy porous material such as a perforated plate between the neck and shoulder of the bottles, with many holes to allow water to freely drain through. These will be your funnels (Figure 3.20). Alternatively, any container that you can put a specific amount of soil into will do, such as plant pots or buckets. Just ensure that water can freely drain through the soil and the soil remains in place. Or, you could invest in some Buchner funnels, available from most laboratory suppliers (see Section 3.4.5).

•one measuring cylinder of about 1/2 litre capacity or any container marked in ml graduations. You could use a kitchen measure or make your own measuring cylinder from transparent tubing

•a spoon

•a balance - electronic or kitchen scales

•coarse filter paper - for example, Whatman's No. 1, but kitchen filter paper (eg: coffee filter or cloth) will do

•1 ruler

•stopwatch or clock with second hand

•distilled water or rainwater. (Some concrete rainwater collecting tanks can alter the chemistry of the rainwater, which may affect your results so avoid using water stored in these).

Gypsum:
If you have a clay soil you suspect of being unstable and would like to add gypsum to it to observe its effect on drainage, calculate the area of your funnel (in cm^2), and divide it by 20 to give the amount in grams of gypsum to add to your sample for a rate equivalent to 5 tonnes/ha. For example, if the surface area of the funnel is 44 cm^2, then 2.2 g of gypsum should be added to the soil in the funnel, which is equivalent to 5 tonnes/ha.

$$\frac{\text{Area of funnel (cm}^2)}{20} = \text{Amount of gypsum in grams equivalent to 5 tonnes/ha}$$

If you want to add the equivalent of 2.5 tonnes/ha of gypsum, then divide the area of the funnel by 40.

Method

Measure the diameter and calculate the cross-sectional area of the funnel. Record this value as it will be used in the calculation of the hydraulic conductivity. Put a disc of filter paper or coarse cloth into the funnel (this prevents soil from flowing through the funnel and clogging it). Ensure that all the holes are covered by the filter paper, and moisten the paper with distilled water or rainwater.

Measure out about 60 ml of soil to give a depth of soil of about 2 cm in the funnel. Remove all gravel and large plant fragments from the soil. Pour the soil into the funnel, on top of the filter paper. **Gently** tap

Source: Hunt, N. and Gilkes, B. (1992) Farm Monitoring Handbook.
Published by University of Western Australia, Land Management Society, and National Dryland Salinity Program.

the funnel against a flat surface (from side to side, not up and down) for 1-2 minutes, to pack the soil into the funnel. (This is to reduce boundary flow where the water will flow faster down the loosely packed boundary between the soil and the funnel). Be careful as you could shift the filter paper. Measure the height from the soil surface to the rim of the funnel with a ruler (P). Record this value. Also measure the exact depth of soil in the funnel (L) and record this value (Figure 3.20).

Balance the funnel on top of the measuring cylinder. Place another piece of filter paper or cloth on top of the soil.

You will be measuring the volume of water that flows through the soil in successive 3 minute intervals. Place some distilled water or rainwater into a large cup or container.

Prepare a table to record the flow rates, for example, see Table 3.4.

Take note of the time on your watch or clock. When it has reached the time when you would like to start the experiment, **gently** pour the distilled water from the cup into the funnel. Try not to disturb the soil with the water as you do so. Fill the funnel as close to the rim as possible. **It is very important to keep the water level up to the rim throughout the test.** This height of water is known as the "pressure head", and is the same as the height from the soil surface to the rim that you measured earlier. Once you have poured the water into the funnel, begin timing and keep topping up the water in the funnel.

Three minutes later, measure the volume of water that has flowed through the soil into the measuring cylinder. Write this down in the table especially prepared for the experiment under the "Measured flow" column. **Remember to keep the funnel topped up with water throughout this experiment.**

Continue for up to 40 minutes taking measurements every three minutes and write down the results. Calculate "Q" (flow in 3 minutes measured in cubic centimetres (cm^3) which is the same as millitres (ml)) as you are taking the measurements. How to do this is outlined on the record sheet with an example. Once the rate of flow has become constant ie: approximately the same value of "Q" has been obtained for two successive measurements, you can stop the experiment, and begin to calculate the hydraulic conductivity of your soil.

If during the experiment the water collecting in the measuring cylinder looks as if it will exceed the capacity of the cylinder, take note of the volume of water, gently lift the funnel off the top of the cylinder and put it into another container. (Try not to spill any water out of the funnel or the cylinder). Tip away the water in the measuring cylinder after you

Table 3.4 Example of the measurement of rate of flow "Q".

	Soil Name	
Time (minutes)	Measured Flow (cm^3)	Q (cm^3)
3	15	-
6	32	17
9	53	21
12	84	31
15	118	34
18	150	32
21		
24		
27		

Q = 32 - 15 = 17
Q = 53 - 32 = 21
Q = 84 - 53 = 31)
Q = 118 - 84 = 34) almost constant
Q = 150 - 118 = 32)

Taking the average of these last 2 values Q = 33 cm^3

Figure 3.21 Hydraulic conductivity measurements can be fun!

Source: Hunt, N. and Gilkes, B. (1992) Farm Monitoring Handbook.
Published by University of Western Australia, Land Management Society, and National Dryland Salinity Program.

have recorded the volume of water. Very gently place the funnel back into the measuring cylinder and pour any water in the container into the **measuring cylinder**, not back into the funnel. Remember: the water in the container has already passed through the soil. Continue measuring as before, but remember that you have to add on the volume you poured down the sink to get the total flow.

Do the following calculations to obtain the hydraulic conductivity.

Hydraulic Conductivity (K), has the dimension of length per unit of time, for example, mm/hour or m/day. You have measured K in cm/minute, and should convert it to mm/day (multiply by 14,400), to enable you to approximately relate drainage to rainfall under field conditions. Rainfall is normally measured in units of mm/day and if K expressed in mm/day is much less than the rainfall then the soil will not drain and flooding may result.

Record your K value. Compare your K value with those provided in Table 3.5 to see where your soil fits. Is it well drained or likely to waterlog after heavy rainfall (eg: 40 mm/day of rain)? Rainfall often occurs in short, heavy showers with a rate of 10 - 50 mm/hr; only well drained soils can cope with such high rainfall intensities. A final word of caution; the value of K you have obtained is not a prediction of how fast rainwater will drain through the soil under particular field conditions and rainfall. It is a characteristic of the soil and its main purpose is to allow the drainage rates of different soil materials to be compared.

Hydraulic conductivity calculation

$$K = \frac{Q \times L}{A \times T \times P}$$

K = Hydraulic conductivity - a measure of the drainage performance of the soil for a standard thickness of 1 cm and pressure head of 1 cm.
L = Thickness of the bed of soil (in cm)
A = Area of the bed of soil (in square centimetres (cm^2)) - you can calculate this from the diameter (d in cm) of the funnel if it is circular.
$A = \pi r^2$ or $A = \pi d^2/4 = 0.785 \times d^2\ cm^2$
T = Time (in minutes)
P = Pressure head (in cm of water)
Q = Volume of water in (cm^3) that passed through the soil in the amount of time (T)

You have measured Q, and you know all the other measurements so you can now calculate K.

In our example (from Table 3.4):
Q = 32 cm^3 and we have measured:
P = 2 cm
L = 1.6 cm
A = 44.18 cm^2
T = 3 minutes

The calculation of hydraulic conductivity simply consists of the following:

$$K = \frac{Q \times L}{A \times T \times P} = \frac{32 \times 1.6}{44.18 \times 3 \times 2} = 0.191 \text{ cm/minute}$$

(or x 14,400 to give mm/day)
= 2,752 mm/day

(This is a high value, characteristic of a very well drained soil that is unlikely to experience waterlogging unless it has a very impermeable subsoil or occurs in a waterlogged valley floor).

Source: Hunt, N. and Gilkes, B. (1992) Farm Monitoring Handbook.
Published by University of Western Australia, Land Management Society, and National Dryland Salinity Program.

Table 3.5 **Ranges of Hydraulic Conductivity Values** (#52)

Drainage Class	What this means on your farm or garden	Hydraulic conductivity (cm/minute)	Hydraulic conductivity (mm/day)	Descriptive term for rainfall
Extremely slow Very slow	Liable to waterlog - land restricted to shallow rooted plants.	<0.0006 0.0006 - 0.002	<8.5 8.5 - 30	Fine mist Drizzle
Slow } Moderately slow }	Poor infiltration may lead to overland flow and erosion on slopes.	0.002 - 0.008 0.008 - 0.03	30 - 120 120 - 480	Slight rainfall Moderate
Moderate } Moderately rapid } Rapid } Very rapid }	No problems except on very steep slopes where erosion could occur.	0.03 - 0.104 0.104 - 0.208 0.208 - 0.417 >0.417	480 - 1,500 1,500 - 3,000 3,000 - 6,000 >6,000	Downpour Violent rainfall " "

SUMMARY:

- infiltration rings - use in the paddock
- hydraulic conductivity - soil is collected and the rate of water drainage is measured.

3.4.4 Management

To improve the drainage of your soil you first need to identify the cause of the poor infiltration and drainage. You may need to apply gypsum to stabilise a degrading clay soil surface, or apply a wetting agent if the problem is a non-wetting soil. You may need to deep rip if the problem is a compacted subsoil clay layer, such as a plough pan. For a brief outline of the management alternatives for each of these soil structure problems, see the relevant sections of this book. In general if you improve soil structure by keeping tillage down to a minimum, increase organic matter and enable soil organisms to proliferate, the soil will develop abundant stable pores and drainage will improve.

3.4.5 Equipment

Equipment	Price	Suppliers
rings made of 4 - 5 mm gauge steel 30 cm diameter and 25 cm deep or similar		
Buchner funnels or similar		can be homemade, or available from most scientific suppliers.
Distilled/deionised water	95c / 2 litres or $2.21/5 litres	Anchor
	85 c/ 2 litres	David Gray
De-Ion Pack (makes approx. 5 litres) (you supply the water and the pack purifies it)	$15.90	Crown Scientific Phone: (09) 470 3777
Balances		
5 kg capacity x1 g resolution	$250	Phoenix Scientific 396 Scarborough Beach Rd
2 kg capacity x 1 g resolution	$150	
AC Adapter	$30	Osborne Park WA 6017 Phone: (09) 443 1788
Portable balance - Conso Microscale		
500 g capacity x 0.1 g resolution	$449	
5kg capacity x 1 g resolution	$178	
2 kg capacity x 1 g resolution	$114	
200 g capacity to 1 g resolution	$300	Perth Scientific Equipment 212 Abbett St Scarborough W.A. 6019 Phone: (09) 245 1930
200 g capacity to 0.1 g resolution	$500	
Pocket portable balances		
250 g capacity x 0.1g resolution	$245	
150 g capacity x 0.1 g resolution	$225	
80 g capacity x 0.1 g resolution	$195	

Source: Hunt, N. and Gilkes, B. (1992) Farm Monitoring Handbook.
Published by University of Western Australia, Land Management Society, and National Dryland Salinity Program.

General equipment		
washbottles	$3.00	Prices quoted from:
100 ml glass measuring cylinders	$6.30	Crown Scientific
100 ml plastic measuring cylinders	$5.10	Phone: (09) 470 3777
100 ml plastic beakers	$2.00	but most other suppliers
250 ml plastic beakers	$2.25	have comparable prices.
500 ml plastic beakers	$4.00	
filter paper - Whatman's No. 1 or similar	$20/100	

3.5 Subsoil compaction

3.5.1 Introduction

Compaction is a form of soil structure deterioration and it can occur either in the surface or subsoil, and is influenced by one or more of a number of factors, depending on whether the soil is sandy or clayey.

Surface compaction, or surface crusting, occurs due to unstable soil slumping due to raindrop impact, tillage, trampling by stock and the presence of water. This topic is covered in Section 3.2.

Subsoil compaction can occur due to either physical or chemical changes in the soil. The physical changes are mainly due to machinery, both tillage and traffic, whereas there are many reasons for chemical hardpans to occur. Some of the more common chemical hardpans are outlined as follows.

(a) Chemical hardpans

(i) Coffee rock

This is a form of hardpan in subsoils. It is most prevalent in wet sandy soils that have been waterlogged. Organic matter, aluminium, silica and iron are leached down to the watertable, and precipitate to form a hard layer just above the watertable. This material is often a light brown colour and is thus referred to as coffee rock.

(ii) Ironstone (laterite)

This form of hardpan is commonly present at the top and flanks of ridges in many parts of W.A. and is a relic soils formed millions of years ago when Western Australia experienced a tropical climate. Ironstone caps are cemented by iron oxides and aluminium hydroxides, and form the familiar breakaways of many landscapes in Western Australia.

(iii) Bog iron

Bog iron is forming now in wet soils. There are two major forms of the element iron in the soil, Fe^{2+} - ferrous and Fe^{3+} - ferric, and these have very different properties. Iron dissolves into the form Fe^{2+} in the subsoil and moves through the soil. Once the Fe^{2+} reaches the air, it oxidises and changes into the insoluble Fe^{3+} form which precipitates out to form a hard layer of red/orange coloured soil (this is similar to the occurrence of mottling in seasonally waterlogged soils).

(iv) Others

Other types of hardpan are due to the chemical precipitation of carbonate, silica or iron oxides as layers in the subsoil. Where these are thin and occur close to the surface they can be broken by cultivation and do not reform. Where these chemical pans occur in the deeper subsoil and especially where they are tens of centimetres thick, they prevent root penetration and drainage. They often act as a confining layer for water stored below them in the pallid zone clay so that where they are broken by tree roots or drilling, the water is forced to the surface often causing a saline seep to develop as a consequence.

(b) Physical hardpans

Physical subsoil compaction types can be divided into those formed by tillage and traffic and those that have formed naturally. Hardpans formed by our management are called traffic and plough pans.

Traffic hardpans occur on the sandy soils and form due to the weight of the machinery simply compacting the soil particles together. Plough pans occur on the more clay-rich soils where tillage implements both smear and compact the clay just below the depth of the plough. Heavy traffic has also been reported to form hardpans on heavy clay soils in eastern Australia and overseas. Duplex soils are a form of natural subsoil compaction, where the clay-rich subsurface may act as a barrier to root growth and water and nutrient flow.

The following sections look at the major problems associated with physical subsoil compaction, and in particular those formed due to traffic and tillage.

Source: Hunt, N. and Gilkes, B. (1992) Farm Monitoring Handbook.
Published by University of Western Australia, Land Management Society, and National Dryland Salinity Program.

SUMMARY:

Compaction

- **Surface** (crusting)
  - stock
  - raindrop impact
  - water
  - cultivation
- **Subsoil**
  - **Chemical**
    - coffee rock
    - ironstone (laterite)
    - bog iron
    - carbonate silica and iron oxide
  - **Physical**
    - traffic hardpans
    - tillage plough pans
    - duplex soils

Figure 3.22 The different forms of compaction.

3.5.2 Traffic hardpans

(a) Introduction

Traffic hardpans are a form of compacted subsoil caused by heavy traffic (Figure 3.23) pressing soil particles together. In Western Australia this form of subsoil compaction is a major problem on some sand to sandy loam soils. A compacted layer is usually found 10 - 40 cm below the surface and it may take only 5 - 10 tractor runs to compact a soil and reduce cereal and pasture yields by up to a third (#47), although this is dependent on seasonal conditions. Good rains after sowing can lessen the effects of compaction, while poor soil water conditions after crop flowering can increase the effects of compaction.

Traffic hardpans have been estimated to cost the agricultural industry up to $150 million a year and over 8 million hectares of land in W.A. are affected (#10). These hardpans are mainly found in the sandplain belts stretching from Geraldton in the north through the Midlands, and the south coastal plain between Albany and Esperance and north to Jerramungup. Large areas of soils suffering from traffic hardpans are also found in the pockets of wodjil sandplain in the eastern and central wheatbelt.

Many farmers use deep ripping to break up the traffic hard pan enabling improved root penetration. Roots can penetrate faster leading to greater and more efficient water use, greater plant production and better yields. If plants are unable to use water in a compacted soil, increases in

*Figure 3.23 Heavy machinery can compact your soil (*81).*

Source: Hunt, N. and Gilkes, B. (1992) Farm Monitoring Handbook.
Published by University of Western Australia, Land Management Society, and National Dryland Salinity Program.

groundwater recharge may occur. Traffic hardpans in the eastern wheatbelt, and in particular on the wodjil soils, may not respond to amelioration (usually deep ripping) due to severe subsoil acidity (#50). The roots penetrate the layer that has been ripped but experience aluminium toxicity associated with an acid subsoil (see Chapter 9). Deep cultivation can also decrease the incidence of rhizoctonia bare-patch (*R. solani*) in wheat (#49) and lupins (#16) due to the destruction of the fungus and more rapid root growth in the looser soil. The plant is thus better able to fight the pathogen.

SUMMARY:

- traffic hardpans occur at depths of 10 - 40 cm
- they can have a severe impact on cereal yields on sandy soils in W.A.
- deep ripping is used to break up the hardpan
- the incidence of rhizoctonia bare-patch can be decreased by deep ripping.

(b) Why do traffic hardpans occur?

Traffic hardpans occur mainly on sand to sandy loam soils that have very little structure. Most of these soils contain non-aggregated soil particles, and water, air, nutrients and plant roots easily move in the spaces between the soil particles (Figure 3.24) (see Section 3.1). Compacting a soil with heavy machinery, and to a lesser extent by tillage implements, presses the particles together so that the pores are reduced in number and size (Figure 3.24). The structure becomes rigid due to interlocking and particles cannot move apart to accommodate the growing root.

As the soil volume, which reflects the amount of pores or spaces is reduced by compaction, the bulk density of the soil increases (Figure 3.25). The bulk density is the mass of soil per unit of volume, and is often used to measure soil compaction.

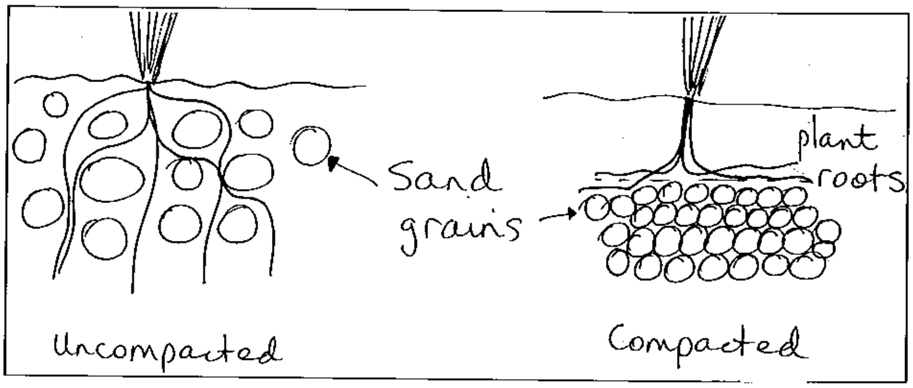


Figure 3.24 Compaction of sandy soils reduces the pore space and restricts root penetration (adapted #35).

The major problem associated with subsoil compaction is increased soil strength. When soil strength becomes too high and root growth is impeded, for example, with a compacted layer, the roots either grow horizontally along the top of the layer, grow into the layer a short distance and stop, or grow into the layer at a slower rate. Roots expend a lot of energy to push their way through compacted soil, and this is especially damaging to young roots

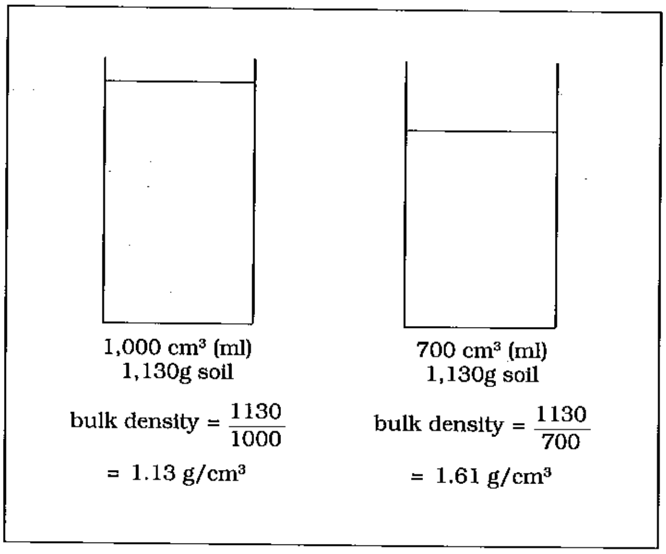
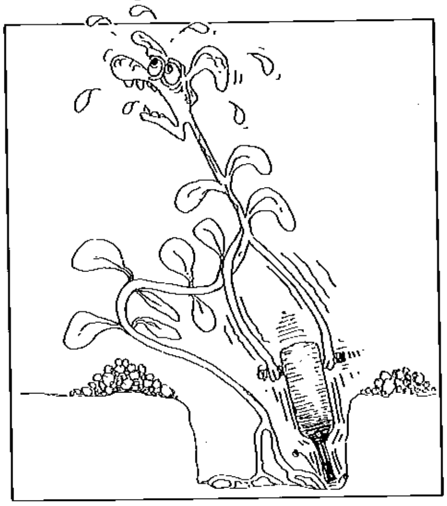


Figure 3.25 How compaction affects the bulk density of a soil (#35)

Source: Hunt, N. and Gilkes, B. (1992) Farm Monitoring Handbook.
Published by University of Western Australia, Land Management Society, and National Dryland Salinity Program.

that form the main underground network. They frequently thicken and increased branching often results. The whole root system tends to be shallow and small and less energy is available for producing leaves and flowers, leading to the characteristic stunted appearance of plants growing on compacted soils.

Yield usually decreases due to factors associated with restricted root growth through compacted soil, such as root disease, reduced water use and nutrient uptake. Even though root growth may be decreased due to a compacted layer, shoot growth and yield are not always affected. As the season progresses, plant roots grow slowly and so are unable to keep up with draining water and nutrients, especially nitrogen. It takes only one day for water and nitrogen to leach through the compacted layer, but up to weeks for the root growth to catch up. The nitrogen may be leached completely from the root zone, or in duplex soils it can be trapped by the clay at a lower depth. Towards the end of the season plants on compacted subsoils have usually taken up similar amounts of nitrogen to plants on uncompacted subsoils, however, yields are still greater on the uncompacted soils (#23).



SUMMARY:

- caused by heavy machinery compacting sandy subsoil
- root growth is hampered and soil cannot be easily explored for water and nutrients
- some yield responses to deep ripping are due to the plants tapping previously unavailable nutrient and water supplies.

(c) What soils and sites are susceptible to traffic hardpans?

(i) Soil types

Traffic hardpans can occur in most W.A. soils, however, they most seriously affect grain yields on soils with sandy to sandy loam textures (less than 10% clay) in the upper 40 m of the profile. Examples of these soils are the earthy sands and gradational yellow earths at Wongan Hills and Geraldton (#50) and the coarse duplex soils at Jerramungup (#20). Compacted layers become more shallow and thin as the clay content increases (#59). Hardpans have been found at about 20 cm depth on loamy sands and yellow earths at Wongan Hills with up to 12% clay content, and yellow earthy sands such as the Eradu sandplain with up to 8% clay have hardpans at about 25 cm depth (#59). The pan may only be a few millimetres thick yet may still affect root growth.

Most sandplain soils that have been cropped for five or more years have compaction problems (#36). Medium textured (eg. Avon valley soils) and fine textured loams are less susceptible to hardpan formation, but soil strength does increase down the profile. Deep ripping these soils sometimes gives a beneficial crop response, but this is mainly attributed to a fallowing effect as it kills the pasture (#59). White sands, with no apparent pan but increasing soil strength down the soil profile, have given positive responses to deep ripping (#59) indicating that yield was being reduced by increasing soil strength at depth.

Traffic hardpans are also present in duplex soils (sand over clay and sand over gravel) if the sand is greater than about 30 cm deep (#48). Responses to deep ripping on duplex soils also depend on the depth of clay, as the closer the clay is to the surface, the less the benefits of ripping will be (#22). If the sandy topsoil layer is shallow the mobile nutrients (nitrogen and water especially) are held in the clay layer and easily found by the plant roots, even with a traffic hardpan present in the sandy topsoil.

The effects of compaction are

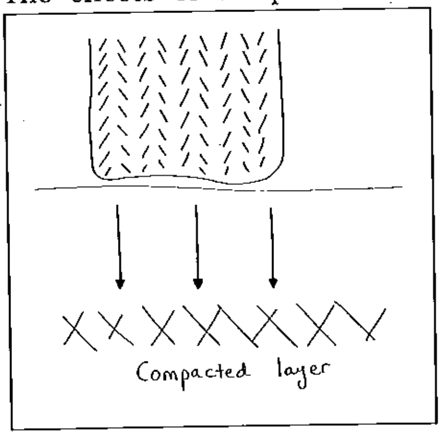


Figure 3.26 Zone of compaction beneath tyres.

Source: Hunt, N. and Gilkes, B. (1992) Farm Monitoring Handbook.
Published by University of Western Australia, Land Management Society, and National Dryland Salinity Program.

especially severe if the particles in the soil have a wide spread of sizes. Smaller particles move into the spaces between larger particles when they are forced together and form a dense interlocking fabric.

(ii) Soil water content

The soil water content is very important in determining how susceptible a soil is to compaction. Compaction by traffic is greatest when the soil is slightly wetter than field capacity (the water held in the soil that does not drain away after the soil has been saturated) (#40). The water acts as a lubricant, allowing the particles to come together easily. As the soil becomes wetter, compaction decreases as water cannot be compressed (Figure 3.27), and at some point the particles are pushed apart by the water pressure produced by heavy traffic.

(iii) Cultivation

The most critical time for compaction to occur is when the soil is moist, which is usually around seeding, when most traffic occurs.

SUMMARY:

- soil types- sands to the sandy loams (less than 30% clay) and duplex soils with clay or gravel at more than 30 cm depth
- soil water content - a soil wet to field capacity is compacted most easily
- the most critical time for traffic hardpans to be induced is around seeding when the soil is moist and a lot of traffic occurs.

(d) How do you monitor compaction or traffic hardpans?

How do you know if you have traffic hardpans? How can you test for them and monitor them over time? Be careful not to confuse compaction with natural changes in structure or texture down the profile which occur below the depth of cultivation. Some soils increase in soil strength down the soil profile, but do not have compaction pans (however, many of these still respond to deep ripping).

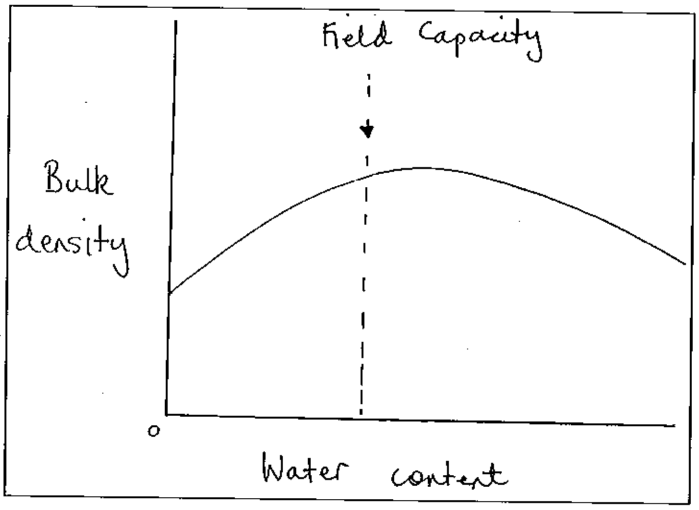


Figure 3.27 How water content affects the susceptibility of the soil to compaction. The increase in bulk density is greater for a soil water content near field capacity.

(i) Visual indications of traffic hardpans

- Varied crop height. But be careful. The whole paddock is usually evenly affected, therefore you may see little difference in crop growth or height across the paddock. You may observe differences in crop height between traffic lanes and the remainder of the paddock.
- Poor plant growth, that may be attributed to a number of factors such as moisture stress, disease or nutrient deficiencies (especially nitrogen and potassium) (see Chapter 14). Nutrients have been leached beyond the compacted layer and therefore the plant root zone. If the soil is well supplied with nutrients, but the plants look nutrient deficient, then soil physical problems such as subsoil compaction may be limiting growth.
- Dig a soil pit to examine the rooting behaviour of your crop (see Section 3.3). Look at plant root growth in the pit. Compaction will deform the roots, making them swell as they enter the hardpan (Figure 3.28), and in severe cases, can even bend them at 90° or a right angle. Compaction will not show up so readily if lupins are grown as their roots can penetrate the compacted layer more easily. Cereals show up the compacted layer well. It is best to make observations about 3 - 6 weeks after sowing when the soil is moist and the plant roots are growing rapidly.

In the soil pit in addition to the distribution of roots you may also observe if small soil particles have filled in the holes in the soil matrix to form a massive tightly packed structure. A hand lens is a great help here. In general, however, it is very

Source: Hunt, N. and Gilkes, B. (1992) Farm Monitoring Handbook.
Published by University of Western Australia, Land Management Society, and National Dryland Salinity Program.

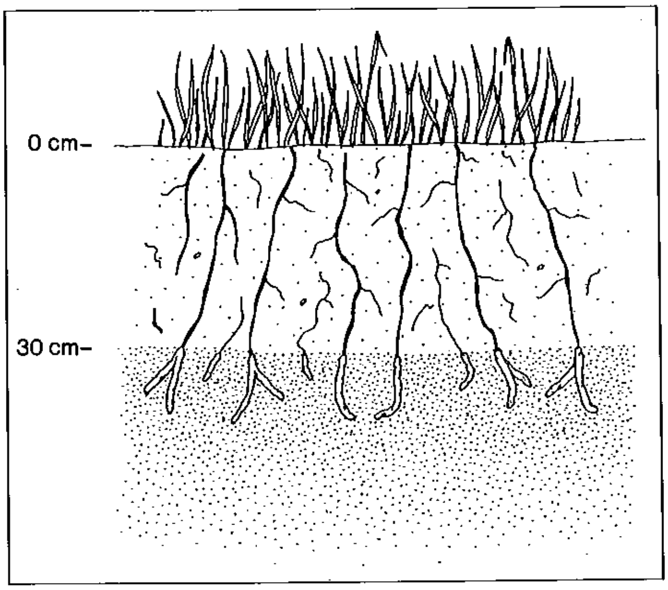


Figure 3.28 Restriction of root growth when a hardpan is encountered resulting in swollen roots (#14).

difficult to see compaction pans in sandy soils, so it is necessary to make measurements and look at plant growth.

Compaction may be only one cause of poor growth. It is best to do further measurements on your soil to test if the problem is a traffic hardpan, or another problem such as disease, nutrition, non-wetting or an acid subsoil. It is possible that there will be more than one problem, for example, some of the wodjil soils of the eastern wheatbelt suffer from both subsoil acidity and traffic hardpans.

(ii) Measurements of traffic hardpans

Bulk density
As discussed earlier, the bulk density of soil is the mass or weight of a soil per unit volume. The greater the soil volume (ie: more pore space), for a given weight of soil, the less will be the bulk density. When a soil is compacted, the volume is reduced and the bulk density increases; it is generally desirable to have soil with a low bulk density.

When
For ease of sampling, it would be best to sample when the soil is moist.

Materials

- a strong baby food tin with one end removed or a similar tin (approx. size) with a hole at the closed end for air to escape. (Alternatively you could use approx. 5 cm diameter steel pipes cut to about 5 cm in length).
- shovel
- calculator
- oven-proof pie dish or something similar
- oven (conventional or microwave)
- plastic bag (one for each sampling)
- ruler graduated in centimetres
- texta pen
- scissors
- kitchen scales or balance graduated in grams.

Method
This method of monitoring can be time consuming and works best for soils without gravel. For example, if your soil has more than 10% gravel stones, or if the stones are larger than 2 cm the bulk density readings will not be accurate.

Calculate the volume of the tin (or pipe):
Measure the diameter of the tin to the nearest tenth centimetre, and use half this value to give the radius (r) (in cm).

Volume (in cm^3)
$= \pi \times r^2 \times h$
$= 3.14 \times$ radius $\times$ radius $\times$ height of tin (in cm)

For example, if the diameter of the tin (or pipe) was 10cm, the radius would be half this value, 5cm. If the height was 4.5cm, the volume would then be

$v = 3.14 \times 5 \times 5 \times 4.5$
$= 353.25cm^3$

Alternatively fill the tin with water measuring the weight (in grams) or volume (in ml) of the water and this will be equal to the volume of the tin.

Where
Bulk density measurements can be done when you suspect that your soil has a compaction problem. When using bulk density measurements for subsoil

Source: Hunt, N. and Gilkes, B. (1992) Farm Monitoring Handbook.
Published by University of Western Australia, Land Management Society, and National Dryland Salinity Program.

compaction, the more useful results will be obtained if you take and compare measurements on the same soil over time. Compare the results from cultivated land with a similar soil that has not been cultivated, for example, under a fence. Or, compare the bulk density of the soil in an area of poor growth with that of nearby soil under more vigorous plants. But remember that if your samples come from different soil types then the critical value of bulk density for restricting root growth will vary from soil type to soil type (Table 3.6).

Table 3.6 Dry bulk density guidelines for seedbed compaction (#35)

Bulk density (g/cm3)	Sandy† soils	Loams†	Clay†soils
< 1.0	-	satisfactory	satisfactory
1.0- 1.2	-	satisfactory	satisfactory
1.2- 1.4	very open	satisfactory	some too compact
1.4- 1.6	satisfactory	some too compact	very compact
1.6- 1.8	mostly too compact above 1.7	very compact	extremely compact
> 1 .8	very compact	extremely compact	excessively compact

† See Chapter 2.

Select the site for sampling. Mark this down on your record sheet under site description, so that you can come back to exactly the same place in following years for further sampling and testing. You may need to dig a pit and take samples at 15, 35 and 40 cm depth, or whatever depth you think you have a subsoil compaction problem. It is probably best to also take samples from a similar soil that has not been cultivated, such as under a fence. Remember to take them from the same depths as for the cultivated soil.

How

With a spade prepare an undisturbed flat horizontal surface in the soil at the desired sampling depth. Push or gently hammer the tin or pipe into the soil. If you need to hammer the tin into the soil you may need to protect it by placing a wooden block on top of the tin. Be careful not to push the tin too far into the soil or it will compact the soil. Also be careful to obtain the samples with as little disturbance or loosening of the soil as possible. Excavate around the tin to remove the soil core so that you have a full tin of soil. Scrape any excess soil from the top and outside of the tin, so that you have an exactly full tin of soil. Cut off any roots with a pair of scissors. Pour the soil from the tin into the plastic bag and seal the bag. Mark on the plastic bag where the soil was sampled or allocate a site number. Collect further soil samples from other areas you would like to sample, remembering to identify the sampling site on the bags.

Take the samples back to your kitchen. Remove the soil from the bags and dry the soil samples in a microwave oven for 10 minutes, or for 2 hours in a conventional oven at 110°C. When dry, weigh each of the soil samples on your scales and mark the weights down. If the soil is in a container, remember to subtract the weight of the container to obtain the weight of the soil.

Calculate

You should now have the weight of the soil and the volume of soil you collected. These two figures will give the bulk density. Divide the weight (m) of the soil by its volume (V).

Bulk density in g/cm^3

$$= \frac{\text{weight of soil core (grams) (m)}}{\text{volume of tin (cm}^3\text{) (V)}}$$

$$= \frac{m}{V}$$

See Table 3.6 for bulk density ranges, and fit your soil into one of the 3 textural classes. Is the bulk density satisfactory, or do you have a very dense soil?

Trials

Set up your own farm trial. Use a chisel plough to penetrate as deep as you can in a strip across the paddock. Sow the seed normally in both the strip and the remainder of the paddock and observe the crop response to the chisel ploughing. If plant growth is greater in the chisel ploughed strip, subsoil compaction may be the problem.

Source: Hunt, N. and Gilkes, B. (1992) Farm Monitoring Handbook.
Published by University of Western Australia, Land Management Society, and National Dryland Salinity Program.

Steel rod penetrometer (*74)

Materials

•60 cm length of 6 mm diameter steel rod with handle at one end making it a "T" shape. At the pointed end make a tip about 2 cm long. (Figure 3.29)

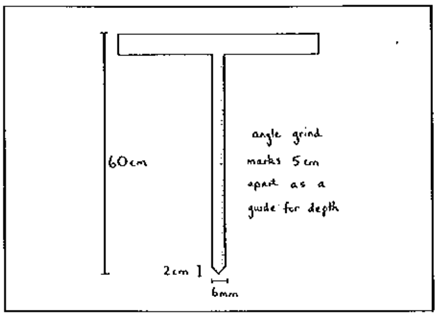


Figure 3.29 A simple rod penetrometer to test for subsoil compaction problems.

Method

The depth to which a person of average strength can push the rod into the soil is a good measure of compaction. Push the simple penetrometer into the soil (Figure 3.30) and feel the soil get firmer then become softer as you go through the compacted layer into the softer soil underneath. Do this one day after soaking rain for sands, and after 3 days for loams (approximates to field capacity water content). Record the depth to which you are able to push the rod into the soil in different parts of the paddock. It may be interesting to compare soil under a fenceline or native bushland where the soil has not been compacted, with a cultivated soil.

Penetrometers

Penetrometers measure the force required to penetrate the soil at a series of depth intervals. The penetrometer is a cone pointed metal rod driven into the soil by either a steady force (steady rate) or through consecutive blows of a load (impact). The force necessary for the rod to penetrate to a certain depth or the depth of penetration under a given load is recorded.

Figure 3.30 How to use a steel rod penetrometer.

Units Used

Ease of penetration is mostly measured using one of two units of pressure - pascal (Pa) or bar. Multiples of ten for the pascal unit of measurement are often used, such as kPa (1,000 Pa) or MPa (1,000 kPa). To convert one measure of penetration to the other is very simple since 100 kPa = 1 bar.

Where not to use penetrometers

Penetrometers, particularly steady rate penetrometers, are better indicators of compaction than is bulk density. They provide a more rapid assessment of compaction problems and also are more sensitive to changes in soil condition than are other methods. For example, at one site compaction by traffic increased bulk density by 20%, but the penetrometer resistance increased four fold (#68). Do not use penetrometers on heavy (clay) soils where you suspect the presence of plough pans, because differences in soil water content could lead to readings that are inaccurate. Do not use penetrometers on gravelly soils (unless stones are less than 5 mm in size). The readings are strongly affected by the probe hitting gravel or rock.

Wheel tracks are obvious areas for development of compaction problems, so you may like to measure the soil strength under tracks, and at a distance from the track, especially if plant growth on tracks seems to be affected.

Steady Rate Penetrometer

Some steady rate penetrometers are now made with electronic devices that take consecutive readings of the force required to penetrate the subsoil layers, and store them in a small computer attached to the probe. They are, however, quite expensive, and so if you would like to use them, it may be best to purchase them on a district basis, or through your local Land Conservation District Committee. The most popular steady rate penetrometers are the Remik and the Bush penetrometers (Figure 3.31). (See also Section 3.5.4).

Source: Hunt, N. and Gilkes, B. (1992) Farm Monitoring Handbook.
Published by University of Western Australia, Land Management Society, and National Dryland Salinity Program.

The soil moisture content is very important. These penetrometers usually have a small probe that can be easily broken by hard dry soils, and so measurement is best done when the soil is moist, ideally a day after a substantial (greater than 10 mm) rainfall event. If the soil is any drier, then penetrometer readings can be affected (#40) and they may indicate traffic hardpans that are not there. Gradational or duplex soils are naturally more variable in penetration resistance than more uniform sands.

Slowly push the penetrometer vertically into the soil at a constant speed, to the full depth of measurement. Withdraw the penetrometer and record the data (see Table 3.7 for an example of data recording). You may need to take a large number of measurements to counter the soil variability, for example, up to 20 readings per hectare. Remember to take note of the sites measured for future readings. It may help to mark on a map the sites where readings were taken.This example shows that you can compare between sites and between years before and after implementing a management strategy such as deep ripping.

You could also graph your results against depth and get a better indication of where the traffic hard pan is in the soil profile.

What is the maximum penetration resistance recorded and where in your soil profile does it occur? Was it within the plant rooting depth? It is important to realise that under ideal conditions plant roots can grow down to 3 metres. Root growth is restricted by up to 50% in subsoil compacted at a pressure of 1MPa (10 bar), and for 2MPa (20 bar), root growth is almost totally reduced (#64, #66). Compare your results with Table 3.8.

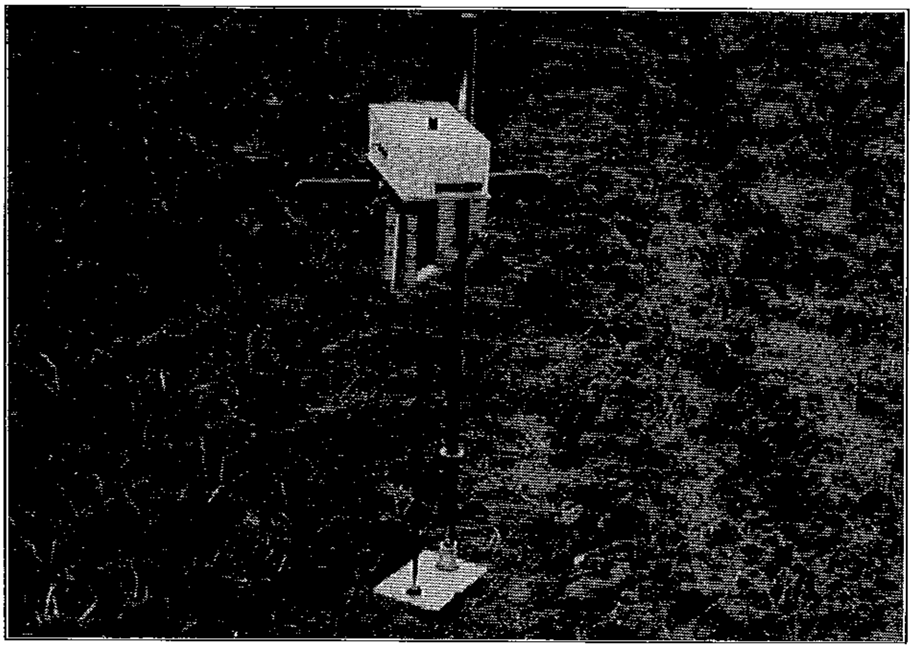


*Figure 3.31 The Bush recording penetrometer (*73)*

Table 3.7 Example of recording using a steady rate penetrometer

Site Description:
Site 1: Wheel tracks 20 m in from fence in Hill paddock.
Site 2: Under fenceline 30 m north from Site 1.

Depth (cm)	1989		1990	
	Site 1	Site 2	Site 1 (after 30 cm deep ripping)	Site 2
	Penetration (bar†)	Penetration (bar†)	Penetration (bar†)	Penetration (bar†)
0	0	0	0	0
5	3	2	2	2
10	10	3	3	4
15	13	5	3	4
20	28	5	4	5
25	32	4	3	5
30	34	3	10	4
35	29	3	29	3
40	25	3	25	3

†10 bar = 1MPa = 1,000 kPa.

Source: Hunt, N. and Gilkes, B. (1992) Farm Monitoring Handbook.
Published by University of Western Australia, Land Management Society, and National Dryland Salinity Program.

Table 3.8 Penetration resistance (MPa) (adapted #4)

Penetration resistance (MPa)	Degree of soil consolidation	Effect on root growth
< 0.5	Loose	Not affected
0.5 - 1.25	Medium	Root growth of some cereal plants may be affected.
1.25 - 2	Dense	Cereal root growth badly affected.
> 2	Very dense	Very few plant roots penetrate the soil.

Impact penetrometers
Another method of monitoring subsoil compaction uses a hammer (impact) penetrometer (#67). The specifications are given so you can make one yourself. These penetrometers are best used when the soil strength is very high.

The hammer penetrometer measures the force necessary to penetrate the soil to a certain depth using a weight that is dropped from a standard height.

When?
When is the best time to use the hammer penetrometer? The hammer penetrometer is useful when the ground is quite hard and dry, whereas the dynamic penetrometers are quite fragile and will not penetrate hard soil easily. When you use a penetrometer, remember to use it for the same soil moisture content each year as the amount of water in the soil greatly affects soil strength.

Materials (#67) (see Figures 3.32 and 3.33).

•a calibrated lower rod, 1 m long is fitted with an anvil. Set markings at 1 cm intervals, and try to engrave rather than paint them as they last longer. The rod diameter should be 1 to 1.5 cm (Figure 3.32).

•an upper rod, 1m long, along which the hammer slides. A stop at the top of the rod ensures a uniform dropping height (Figure 3.32).

•a hammer of 2 kg weight (or any chosen value between 0.5 - 20 kg).

•cone-shaped probe, with a cross section area of 3 cm^2 and a 90° angle (Figure 3.33). If the diameter is 2 cm this equates to almost a 3 cm^2 cross section. Make the cone of very hard steel, and make spare ones. If the rod is 1 - 1.5 cm in diameter, then the cone will form an arrow head when attached to the rod. (Figure 3.32).

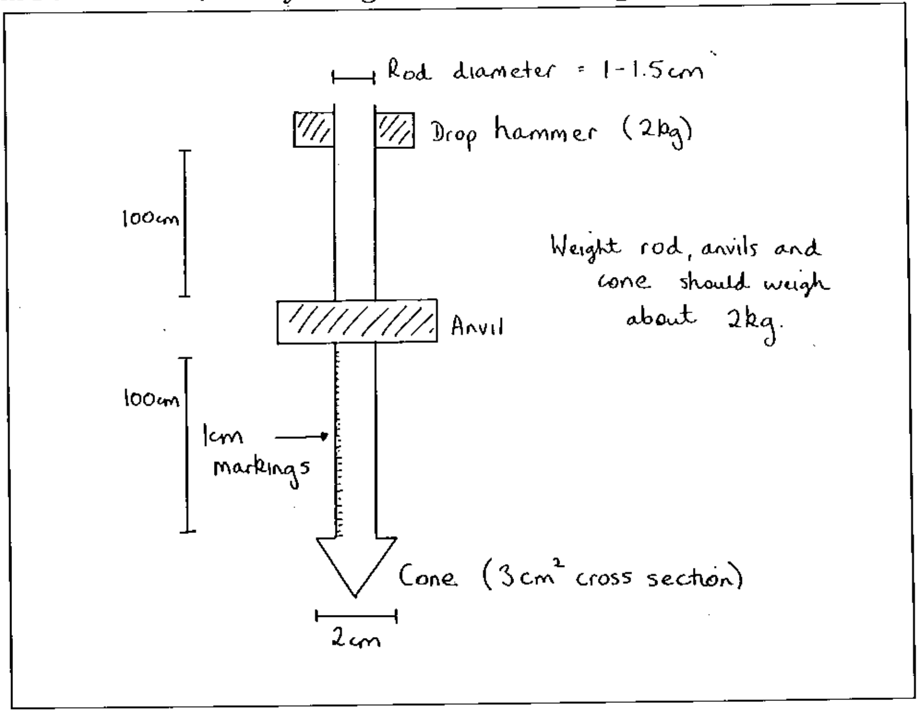


Figure 3.32 Specifications for making your own drop hammer penetrometer (#68)

Source: Hunt, N. and Gilkes, B. (1992) Farm Monitoring Handbook.
Published by University of Western Australia, Land Management Society, and National Dryland Salinity Program.

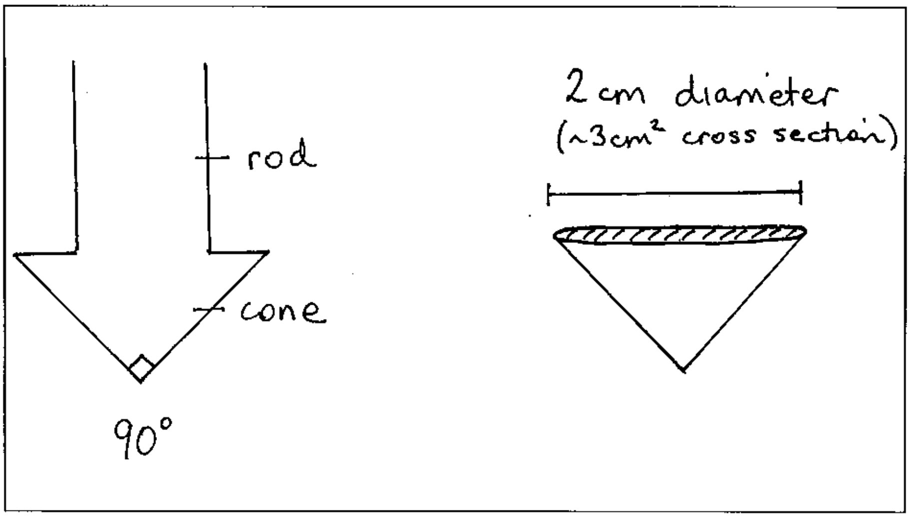


Figure 3.33 How to make the cone

- Try to make the total weight of the rods, anvil and cone 2 kg, but it may vary according to the type of cone.

If you have followed the above specifications, with the given weights and sizes of the equipment, use formula 1 to calculate the resistance to penetration. If you made the hammer penetrometer with different specifications, formula 2 can be used.

Formula 1:

$$R = \frac{16 \times n}{z} = \frac{16 . \text{number of blows}}{\text{depth of penetration (cm)}}$$

Formula 2:

$$R = \frac{M^2 \times h \times n}{2 \times (M+m) \times S \times z}$$

where:

R	=	resistance to penetration (in bar)
M	=	weight of hammer in kg (usually 2 kg) .
m	=	weight of the rod, anvil and cone in kg (usually 2 kg; if not, weigh and record and use formula 2).
h	=	height above anvil from which the weight is dropped in cm (usually about 95 cm)
S	=	cross section of the head or cone in cm^2 (usually 3 cm^2) -
n	=	number of blows
z	=	depth of penetration after n blows (cm)

Method

Select the site you want to monitor. Set up the hammer penetrometer and measure the number of blows (n) the penetrometer takes to go down 5 cm. Use the formula to calculate the average force required to enter this 5 cm. In some cases the ground may be very hard and you may not be able to penetrate more than a few millimetres after a large number of blows. Excavate to 5 or 10 cm and then start to hammer again to measure the strength of different soil horizons. Record the number of blows it takes for the penetrometer to enter the soil at 5 cm intervals. Table 3.9 is an example of how to record your results.

Take care that the penetration is vertical and the dropping height does not allow the hammer to rebound against your hands. It may be easier to have two people doing the measuring; one to hold the rods straight and drop the hammer and count the number of blows, and the other to check the penetration depth and note the number of blows per given depth.

You may find it useful to graph your results, and see if a traffic hardpan is present. Plot the depth of the cone in the soil against the force required to penetrate the soil (Figure 3.34), or the number of blows taken to penetrate 5 cm at that depth. It may even be useful to plot the data for the following year on the same graph, for easy comparison between years.

It is best to do several penetrations in a sampling area to establish the variability of the property, and it may also be interesting to make visual observations such as the root penetration pattern at the same time.

Source: Hunt, N. and Gilkes, B. (1992) Farm Monitoring Handbook.
Published by University of Western Australia, Land Management Society, and National Dryland Salinity Program.

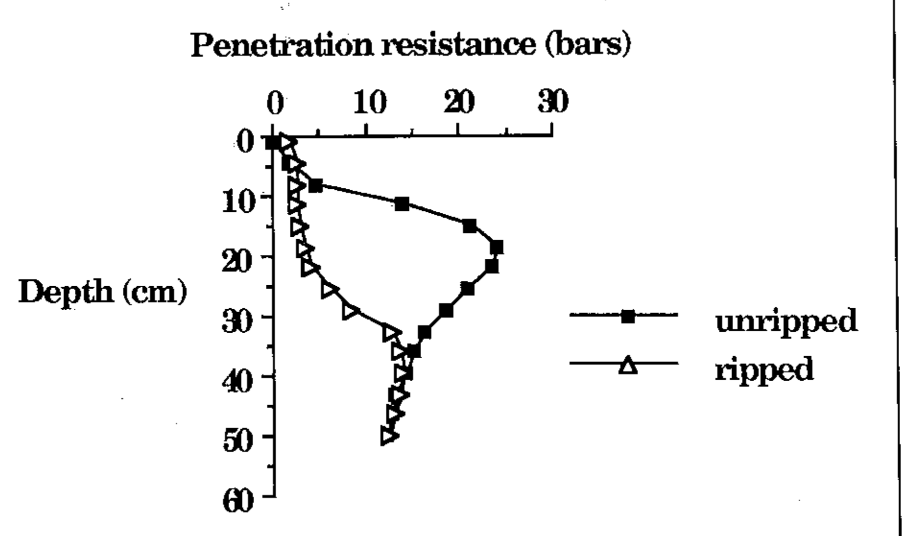
Table 3.9 An example of measurements taken using a hammer penetrometer

Depth penetrated (cm)	Number of blows to penetrate 5 cm	Resistance to penetration (bar)
0-5	1	3
5-10	4	13
10-15	7	22
15-20	8	26
20-25	7	22
25-30	6	19
30-35	5	16
35-40	4	14
40-45	4	14
45-50	4	14

10 bar = 1MPa = 1,000 kPa.

Be careful when you do your testing. Some sandy soils suffering from subsoil compaction have formed chemical bonds between particles due to drying. When the soil is wet, this bond is weakened, and the pan disappears.

*Figure 3.34 Example of plotting your penetrometer data. Yellow Wongan loamy sand at field capacity, ripped and measured a week later (*80).*



SUMMARY:

- visual
  plant symptoms
  soil pit
- measurements
  steel rod
  bulk density measurements
  penetrometers
  steady rate and impact
  farm trials

(e) Management

If you have a subsoil compaction problem caused by heavy traffic, what can you do about it? There are a range of alternatives available depending on the type of compaction and the soil type, and they are briefly outlined below. Before embarking on a full scale management program to ameliorate your subsoil compaction problems, consult your WADA officers, consultants and farmers in the district, etc., for up-to-date local information. It is best to have all the relevant information before you make a decision.

(i) Deep ripping where possible and practical

Consider these points before you deep rip:

Soil type
Light soils are more responsive to deep ripping than are heavier soils. In the drier parts of the agricultural regions (eg: Merredin) there may be no grain yield response to deep ripping of compacted sandy soils due to a lack of water or if the subsoils are very acid. It may be best to trial deep ripping on a particular part of your paddock prior to using it extensively.

Source: Hunt, N. and Gilkes, B. (1992) Farm Monitoring Handbook.
Published by University of Western Australia, Land Management Society, and National Dryland Salinity Program.

Some sands, fine textured soils (salmon gum/gimlet soils) and medium textured soils (Avon Valley loams), have no hardpans, but the soil strength increases with depth. The sands may show a response to ripping but the finer and medium textured soils usually do not economically respond to deep ripping. Weigh up the costs and benefits yourself before embarking on a deep ripping program. Once again, trial the practice on a strip in the paddock before using it full scale.

Duplex soils such as sand over gravelly clays and sand over clay can form hard pans in the sandy horizon if the sand is deep enough (#48). These soils are unlikely to give economic responses to deep ripping unless the clay occurs at a depth of at least 30 cm, although a 20 cm deep ripping depth may be economical (#21). Sand over gravel soils will respond if the gravel does not restrict root growth (#48). If the gravel is close to the surface and the stones are greater than 10 cm in diameter, there will be no response to deep ripping (#21).

Crop type
All cereals, (wheat, oats, barley, triticale), can respond to deep ripping. Lupins generally do not respond to ripping. Lupin yields can even be decreased if the seed is sown too deep in soft soil after ripping. This can be due to reduced nodulation or herbicide dilution leading to inadequate weed control (#48).

Depth of ripping
Ripping to 30 cm is standard, although benefits from 20 cm ripping also usually occur, but first check at what depth your traffic hardpan occurs and the depth to clay (#20).

Shank spacing
Soil softening is not as deep between the tynes as near the points, and therefore a wider tyne spacing softens less soil. Wider spaced tynes require deeper working to achieve the same response (#48).

Speed of working (#48)
Fuel consumption increases as speed increases. At slower speeds, less fuel is used, but greater implement wear occurs. Work out if speed or the implements are the most important.

Residual benefits from one ripping (#48)
The effects of deep tillage can last up to four seasons, but with a declining response. Direct drilling reduces the risk of erosion and helps the effect of ripping to last longer, as hardpans can be re-established very quickly.

Tools to use
For deep tillage it is best to use tools such as the Agrowplow or the Paraplow (Figure 3.35). Chisel ploughs are probably more economical on a dollar for dollar basis compared to the Agroplow or the Paraplow, however, the Agrowplow softens the soil better (with its closer shank spacing) and can achieve greater yield increases compared to the chisel plough (#21). Most chisel ploughs cannot reach the depth required to deep till without the tynes dragging back, so the soil between the tynes is not loosened effectively, however, they can be strengthened and narrow tips put on them.

Time
It is best to rip moist soil - it is cheaper on fuel and points, disturbs less surface soil and softens the subsoil profile evenly. Deep tillage prior to cereal cropping will give the best economic returns, and ripping within 3 days of sowing with narrow tyned implements is popular. The time of sowing may be affected and this could decrease grain yield more than the increase due to ripping.

Problems (*74)
Deep ripping can cause farm machinery to become bogged particularly if rain falls soon after ripping, delaying sowing because the ripped soil is too soft and boggy to seed. Up to 6 weeks can be lost, leading to 50% yield reductions. Do not rip headlands so as to allow access for trucks with grain and fertilisers. Rocks may be ripped up if soils are shallow and so it is best to avoid such paddocks.

Costs
Deep ripping cost between \$25-\$40 per ha in 1986 (#40), thus the cost:benefit ratio may be tight, with little margin for error. Most sandplain soils which have had approximately 10 crops will have compaction pans which may or may not give an economic response to deep ripping depending on the season. It may be best to trial deep ripping on a representative part of the paddock before embarking on a full scale program.

There are different suggestions for deep ripping during pasture/crop rotations and continuous cropping programs. Check with your consultant, adviser or farmers in your district who have undergone a similar program as to which would be the best method for you to follow. The factors to consider in deep ripping are summarised in Figure 3.36.

Source: Hunt, N. and Gilkes, B. (1992) Farm Monitoring Handbook.
Published by University of Western Australia, Land Management Society, and National Dryland Salinity Program.

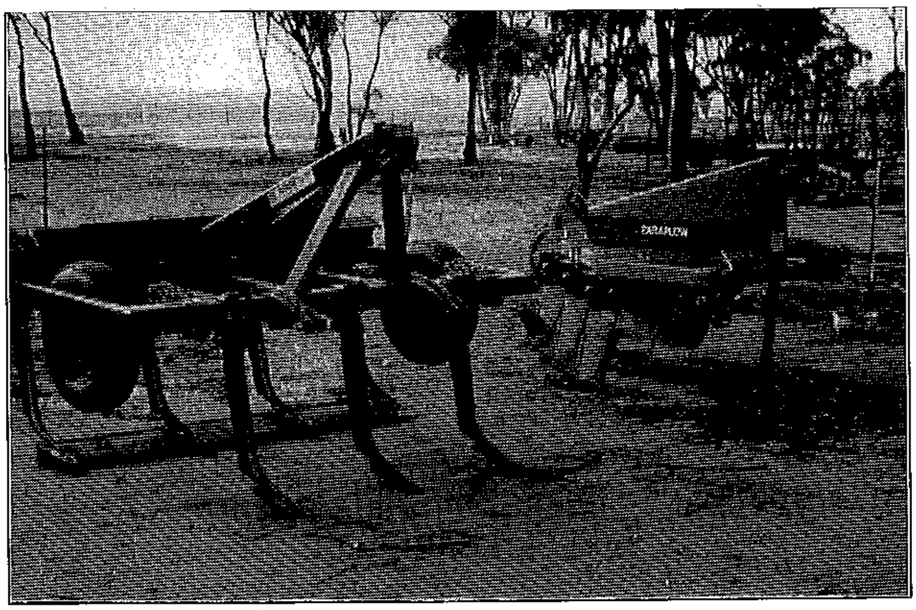


*Figure 3.35 An Agrowplow (left) and a Paraplow (right) are tools used for deep ripping (*80)*

(iv) Tyres
Use wider and larger radial tyres running at lower inflation pressures, although the total axle load has more influence on compaction than the ground contact pressure of the vehicle. You can also use low ground pressure vehicles with balloon tyres, rubber tracks and 'cage' wheels.

(v) Biological activity
Plant crops such as lupins using high seeding rates, lupins have roots that create pathways through the compacted layer. However, only plant lupins for favourable soil and climatic conditions. The decomposed lupin roots become channels for subsequent wheat roots, although for this to be most beneficial, higher sowing densities than normal are necessary. Lupins are usually planted at rates of 20-45 seeds/m^2,

(ii) Traffic frequency
Minimise traffic frequency especially when the soil is wet. Minimum tillage is one alternative and the use of permanent traffic lanes for all paddock operations is another viable alternative. These reduce the area compacted and increase accessibility as tracks become very firm.

(iii) Traffic weight
Minimise traffic weight (use light equipment) for example, utilities and small trucks can be used as spraying vehicles and fertilizer spreaders instead of heavy tractors. Other helpful practices include aerial application of compound fertilizers at seeding. If the contact pressure can be kept below 100 kPa, compaction is greatly reduced (#63).

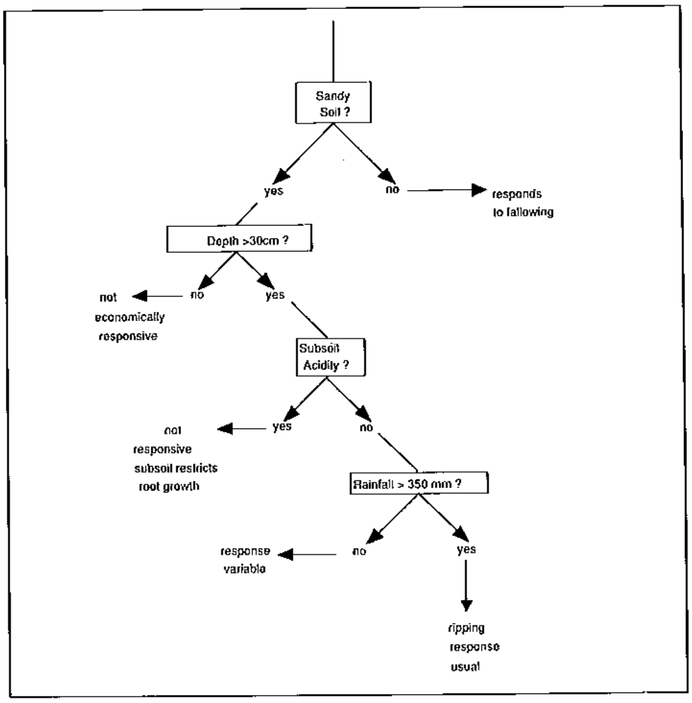


Figure 3.36 What to consider when deciding whether to deep rip (#59)

Source: Hunt, N. and Gilkes, B. (1992) Farm Monitoring Handbook.
Published by University of Western Australia, Land Management Society, and National Dryland Salinity Program.

whereas wheat is sown at approximately 110/m^2, therefore there may not be enough channels made by the lupin roots for all the wheat plants. The greatest benefit from lupins may be from nitrogen fixation and their use as a disease break rather than the amelioration of subsoil compaction problems (#39).

Soil animals, in particular earthworms, increase the number of preferred pathways in the soil (#39). Old earthworm channels often act as pathways for plant roots.

(vi) Others
Dry seeding is a possible alternative but be aware of potential wind erosion problems. Also the use of misters for herbicide application rather than boomsprays can reduce the possibility of subsoil compaction.

SUMMARY:
- use deep ripping to break up the pan
- minimise traffic frequency and weight with narrow permanent traffic lanes for paddock operations
- use wider, larger radial tyres at lower inflation pressures
- plant lupins and other deep rooting plants
- dry seeding is a possibility, but beware of potential wind erosion problems

3.5.3 Plough Pans

(a) Introduction

The finer textured or clay soils are susceptible to compaction from tillage, and can form what are commonly known as plough pans. Some areas of Western Australia experience plough pans, including clay soils which occur in valley floors. This form of hardpan is more prevalent in eastern Australia and overseas.

(b) Why plough pans form

A well structured soil consists of aggregates and a range of pores or spaces between the aggregates (Figure 3.37). These pores allow water, air, nutrients and plant roots to move easily through the soil.

When wet clay soils are cultivated, the aggregate structure in the subsoil can be broken down and smeared by cultivating implements, the soil hardens to a pan which forms just below the cultivated layer. The aggregates may also become aligned (Figure 3.38) due to heavy traffic and form a characteristic 'platey' structure.

The pores become sealed, reducing water and air infiltration and form

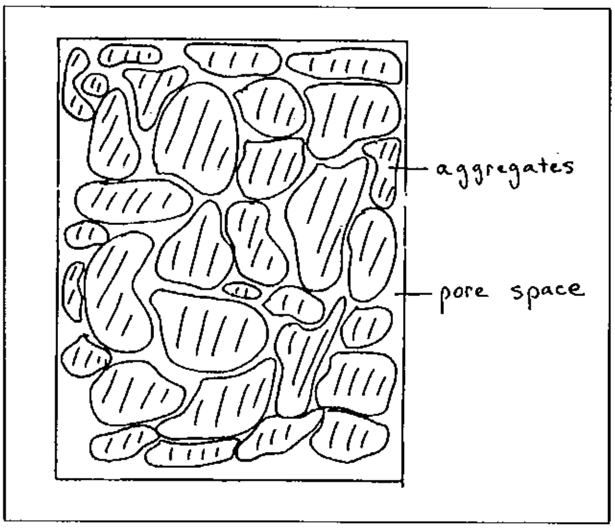
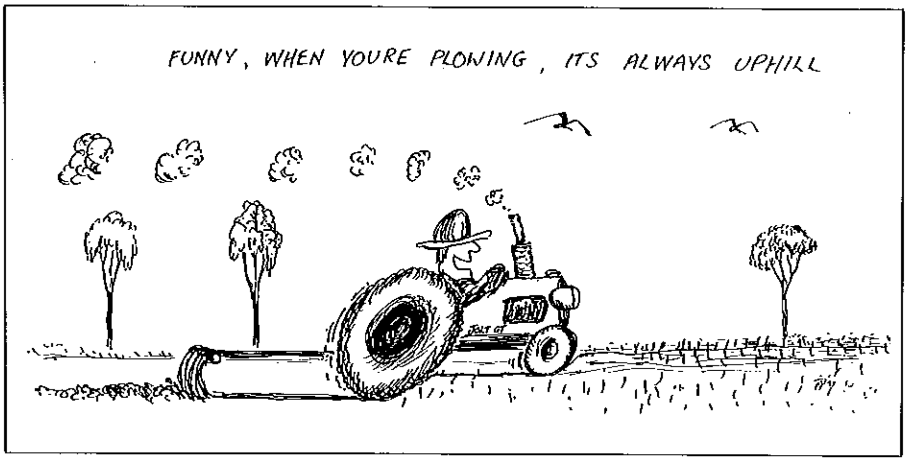


Figure 3.37 Well structured soil with aggregates and pore space.



Source: Hunt, N. and Gilkes, B. (1992) Farm Monitoring Handbook.
Published by University of Western Australia, Land Management Society, and National Dryland Salinity Program.

a layer or pan that is not readily penetrated by roots. As with traffic hardpans, roots expend a lot of energy to force their way through the ploughpan, and so less energy is available for producing leaves and grain. Stunted growth therefore, is often an indication of plants growing in soils suffering from plough pans. Water drainage through the soil is hampered and can result in waterlogging or erosion if on sloping land.

Do not confuse this form of subsoil compaction with surface crusting. Both are formed by cultivating wet clay soils, but one occurs in the surface and prevents seedling emergence when the soil dries, whereas plough pans occur below the cultivated layer and inhibit plant root development (see Section 3.2). Traffic hardpans and plough pans also have different effects on root growth. Plough pans inhibit both water and root entry into the subsoil, leading to stunted and often waterlogged plants. Traffic hardpans inhibit only root growth, and allow water and nutrients to drain beyond the plant root zone. (Figure 3.39).

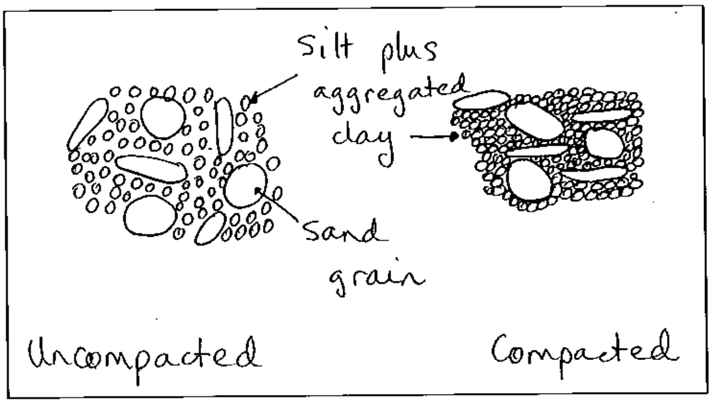


Figure 3.38 Compacting clay soils rearranges the fine particles and orients the larger particles (#61).

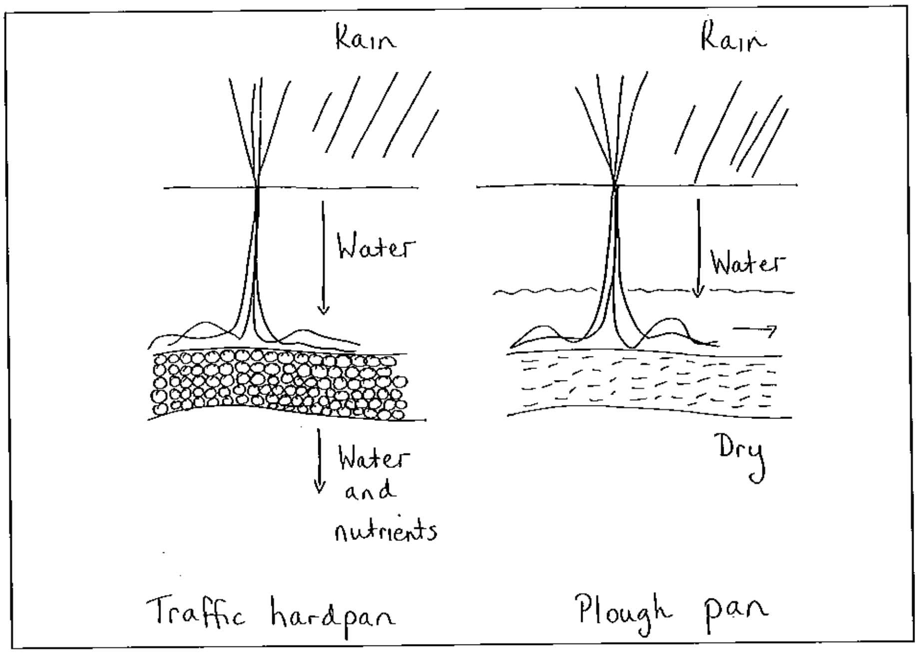


Figure 3.39 How plough pans and traffic hardpans affect plant root growth.

In finer textured soils compaction can increase fungal activity due to the increased water content, and, as the plant is growing poorly it is more susceptible to infection. Compacted soils also affect the power required to till the soil and the performance of tillage tools.

In soils susceptible to plough pans, bulk density tends to increase with depth down the soil profile due to clay particles leaching down the profile to the lower horizons and to less soil disturbance due to cultivation. The clay particles fill up the pore spaces in the soil and there is less organic matter in the lower horizons compared to the topsoil resulting in less aggregation, more compaction, and an increased bulk density. Some soils increase in bulk density as the soil dries out and shrinks.

(c) What areas on the farm could experience plough pans?

If you have cultivated finer textured (clay) soil at the same depth over a number of years, then there is a high probability that a plough pan has formed.

Source: Hunt, N. and Gilkes, B. (1992) Farm Monitoring Handbook.
Published by University of Western Australia, Land Management Society, and National Dryland Salinity Program.

(d) Monitoring

(i) Visual

Dig a pit when the soil is moist - a bit drier than when you would work the soil. If the soil is too wet, then any differences in smearing will not show up well. See also Section 3.3.

In the soil pit you may observe the following indications of compacted layers:

- Water held up and oozing out of the pit above the pan.
- Smeared, shiny surfaces on soil.
- Grey anaerobic (oxygen deficient) soil in the topsoil.
- A lack of pores, cracks, roots or earthworm holes.
- Crusting, ponded water, increased erosion.
- Mottling due to impeded water movement (see Section 6.4.1)
- A platey soil structure, where the aggregates are lined up horizontally.

Another good method of observing a platey structure is to remove a spadeful of dry soil very carefully and lay it on its side. Blow to remove the loose soil. If compact layers are there, you will see "ribs" of soil lying parallel to the surface (#14).

Also observe changes in structure in parts of the paddock with different levels of traffic (gate areas, headlands, fence-lines) and tillage history.

(ii) Measurements

It is best not to use a penetrometer to detect plough pans on clay soils because the water content of the soil is very important in determining the accuracy of the penetrometer. It is difficult to select the correct moisture content for clay soils, whereas for sandy soils and traffic hardpans this is much less of a problem.

Bulk density measurements on the finer textured clay soils can be done (see Section 3.5.2 (d)), however, observing the presence or absence of a plough pan and the behaviour of roots and water in a soil pit is the most useful method of monitoring.

(e) Management

If you have a subsoil compaction problem caused by tillage implements, what can you do about it?

1. Increase the organic matter in the soil to help improve aggregation and structure. If the soil is sodic applying gypsum may also help the clay aggregates to remain more stable when worked. (see Section 3.2.4).
2. Try to minimise the number of cultivations, and do not till the soil when it is very wet. Also, if you till the soil at the same depth over a number of years, this is a major contributor to plough pan development.
3. Use deep rooted crops and pastures to penetrate the pan, for example, phalaris, lucerne, rape and lupins.
4. Use deep ripping to mechanically break up the pan. However the pan can easily reform, so reduced tillage is advised to prolong the benefits of the deep ripping.

SUMMARY:

- finer textured (clay) soils
- smeared and compacted just below level of cultivation by tillage implements
- visual monitoring - soil pits
- measurements - bulk density
- manage the problem by increasing organic matter, applying gypsum, reducing the number of cultivations and not cultivating when wet, plant deep rooting crops and deep rip.

Source: Hunt, N. and Gilkes, B. (1992) Farm Monitoring Handbook.
Published by University of Western Australia, Land Management Society, and National Dryland Salinity Program.

3.5.4 Equipment

Equipment	Price	Suppliers
Penetrometers		
Bush Recording penetrometer, with electronic digital readout of depth and force units to a maximum depth of 52.5 cm.	approx. $5,000	Manufacturer: Findlay, Irvine Ltd, Penicuik, Scotland.
Remik Cone Penetrometer, with digital readout and in built data logging of depth and force values to a maximum of 45 cm. Some staff at WADA use these - contact them for information on where to purchase them.	approx. $3, 500.	
Bulk density		
Steel pipes		from most hardware stores.
Balances		
5 kg capacity x1 g resolution	$250	Phoenix Scientific
2 kg capacity x 1 g resolution	$150	396 Scarborough
AC Adapter	$30	Beach Rd
Portable balance - Conso Microscale		Osborne Park
500 g capacity x 0.1 g resolution	$449	W.A. 6017
5kg capacity x 1 g resolution	$178	Phone: (09) 4431788
2 kg capacity x 1 g resolution	$114	
200 g capacity to 1 g resolution	$300	Perth Scientific Equipment
200 g capacity to 0.1 g resolution	$500	212 Abbett St
Pocket portable balances		Scarborough W.A. 6019
250 g capacity x 0.1g resolution	$245	Phone: (09) 245 1930
150 g capacity x 0.1 g resolution	$225	
80 g capacity x 0.1 g resolution	$195	
Deep ripping	$25 - $40/ha	

3.6 Further Reading

1. Abadi, A. and Bathgate, A. (1991). Deep tillage: keep an eye on costs as well as yields. J.Agric. (W.A.)., Vol. 32, No. 1, 36-39.
2. Abbott, T.S. and McKenzie, D.C. (1986). Improving soil structure with gypsum. Agfact No. A.C. 10, Department of Agriculture, NSW.
3. Anderson, G., Pidgeon, J.D., Spencer, H.B. and Parks, R. (1980). A new hand-held recording penetrometer for soil studies. J. Soil Science, 31, 279-296.
4. Anon. (1982). Techniques for measuring soil physical properties. Ministry of Agriculture, Fisheries and Food, Reference Book 441 (Formerly Advisory Paper 18), p. 66-71. London: Her Majesty's Stationary Office.
5. Anon. (1985). Conservation Farming - Extending the principles of soil conservation to cropping. ed. P.E.V. Charman, Soil Conservation Service of NSW.
6. Anon. (1985). video. Soil structure decline. (duration 17 mins). NSCP/WADA.
7. Anon. (1987). video. The Gypsum Story. (duration 12 minutes). NSCP/WADA.
8. Anon. (1987). video. The Deep Ripping Story. (duration 10 mins). NSCP/WADA.
9. Anon. (1987). video. Direct drilling, soil structure and crop yield. (duration 20 mins). NSCP/WADA.
10. Anon. (1988). Submission to the House of Representatives Inquiry into Land Degradation. WADA. Western Australian Legislative Council.
11. Anon. (1988). Soil - Protecting our greatest asset. Monsanto Aust. Ltd.
12. Anon. (1989). SALTWATCH package. Department of Conservation, Forests and Lands, Victoria.
13. Batey, T. (1975). Soil examination in the field. from Soil conditions and crop production, Great Britain, (ANAS). Technical Bulletin 29.
14. Batey, T. (1988). Soil Husbandry - A practical guide to the Use and Management of soils. Soil and Land Use Consultants Ltd. Aberdeen.
15. Bowden, J. W. and Jarvis, R.J. (1985). Soil hardpans and plant growth. J. Agric. (W.A.), Vol. 26, No. 1. p 16-17.
16. Brennan, R.F. and Crabtree, W. (1989). Deep cultivation of a sandy soil, near Esperance, reduced the incidence of rhizoctonia bare patch and increased grain yield of lupins.

Source: Hunt, N. and Gilkes, B. (1992) Farm Monitoring Handbook.
Published by University of Western Australia, Land Management Society, and National Dryland Salinity Program.

Aust. J. Exp. Agric., 29, 803-806.
17. Brinkman, R., Mamaril, C.P. and Aragon, E. (1982). Land Characteristics for experiments on wetland rice: Hydrology, Landform and soil. IRRI, Philippines, FAO.
18. Brouwer, C., Goffeau, A. and Heibloem, M. (1985). Introduction to Irrigation. Irrigation Water Management Training Manual No. 1, Food and Agriculture Organisation of the United Nations.
19. Cannell, R. Q. (1977). Soil aeration and compaction in relation to root growth and soil management. Appl. Biol. Vol 2, p 1-86.
20. Crabtree, W.L. (1989). Cereal grain yield responses to deep ripping on duplex soils. Aust. J. Exp. Agric., 29, 691-694.
21. Crabtree, W.L. (1990). Toward better minimum tillage for south-coastal sandplain soils. Technical Report No. 111, Division of Resource Management, WADA.
22. Crabtree, W.L. and Jarvis, R.J. (1986). Depth to clay affects grain yield response to ripping on duplex soils. Aust. Field Crops Newsletter, No. 21, 76-78.
23. Delroy, N.D. and Bowden, J.W. (1986). Effect of deep ripping, the previous crop, and applied nitrogen on the growth and yield of a wheat crop. Aust. J. Exp. Agric., 26, 469-79.
24. Emerson, W.W. (1967). A classification of soil aggregates based on thei: coherence in water. Aust. J. Soil Res., 5. 47-57.
25. Fosberry, G. and Howell, M. (1985). Gypsum improves soil stability. Farmnote No. 32/85, WADA.
26. Frost, F. and Orr, G. (1990). Identifying gypsum-responsive soils. Farmnote No. 57/90, WADA.
27. Hamblin, A. (1987). The effect of tillage on soil physical conditions. Chapter 6 from: Tillage - New Directions in Australian Agriculture. ed. P.S. Cornish and J.E. Pratley, Inkata Press, Aust. Society of Agronomy.
28. Hamblin, A.P., Tennant, D. and Cochrane, H. (1982). Tillage and the growth of a wheat crop in a loamy sand. Aust. J. Agric. Res, 33, 887-897.
29. Hamblin, J. and Hillman, B. (1986). So you want to do a farm trial. Farmnote No. 24/86, WADA.
30. Handreck, K.A. (1986). When should I water? Discovering Soils No. 8. CSIRO Division of Soils and Rellim Technical Publications.
31. Handreck, K.A. (1987). Soils - An outline of their properties and management. Discovering Soils No. 1. CSIRO Division of Soils .
32. Handreck, K.A. (1987). What's wrong with my soil? Discovering Soils No. 4. CSIRO Division of Soils .
33. Handreck, K.A. (1987). Earthworms for gardeners and fishermen. Discovering Soils No. 5. CSIRO Division of Soils.
34. Handreck, K.A. (1987). Organic matter and soils. Discovering Soils No. 7. CSIRO Division of Soils .
35. Handreck, K.A. & Black, N.D. (1984). Growing Media for Ornamental Plants and Turf. NSW University Press.
36. Henderson, C.W.L. (1985). Compaction of sandy soils and its effect on crop yields. Proc. Fourth Australian Soil Conservation Conference, Maroochydore, Qld.
37. Henderson, C. (1987). Using penetrometer data to predict the effects of compaction of earthy sands on wheat yields. In Effects of Management Practices on Soil Physical Properties. Proceedings of a national workshop held Toowoomba, Qld. ed. K.J. Coughlan and P.N. Truong. Qld Dept. Primary Industries .
38. Henderson, C.W.L. (1989). Using a penetrometer to predict the effects of soil compaction on the growth and yield of wheat on uniform, sandy soils. Aust. J. Agric. Res. 40, 497-508.
39. Henderson, C. W. L. (1989). The diagnosis, prediction and amelioration of subsoil compaction on the sandplains of the Northern Agricultural Region of Western Australia. Master of Science (Agric.) thesis, School of Agriculture, University of Western Australia.
40. Henderson, C., Levett, A. and Lisle, D. (1988). The effects of soil water content and bulk density on the compatibility and soil penetration resistance of some Western Australian sandy soils. Aust. J. Soil Res. 26, 391-400.
41. Howell, M. (1987). Gypsum use in the wheatbelt. J. Agric. (W.A.). Vol. 28, No. 2, pp 40-43. WADA.
42. Hunt, N.M. and Gilkes, R.J. (1989). Know Your Soils course notes. LMS/NSCP.
43. Jarvis, R.J. (1983). Deep ripping produces wheat yield responses. Aust. Field Crops Newsletter, No. 18, 104-105.

Source: Hunt, N. and Gilkes, B. (1992) Farm Monitoring Handbook.
Published by University of Western Australia, Land Management Society, and National Dryland Salinity Program.

44. Jarvis, R.J. (1985). Deep ripping with an Agrowplow and Paraplow at two speeds. Aust. Field Crops Newsletter, No. 20.
45. Jarvis, R.J (1985). Direct drilling: soil type recommendations. Farmnote No. 39/85, WADA.
46. Jarvis, R. (1988). Tillage systems and soil stability. Journal of Agriculture (W.A.). Vol. 29, No. 2, 54-57, WADA.
47. Jarvis, R.J. and Porritt, S.E. (1985). Soil compaction and its effect on wheat yield. Aust. Field Crops Newsletter, No. 20, 122-125.
48. Jarvis, R.J., Riethmuller, G.P., Henderson, C., Hamblin, J. and Hillman, B.J. (1985). Deep ripping. Farmnote No. 61/85. WADA.
49. Jarvis, R.J. and Brennan, R.F. (1986). Timing and intensity of surface cultivation and depth of cultivation affect rhizoctonia patch and wheat yield. Aust. J. Exp. Agric. 26, 703-708.
50. Jarvis, R.J., Hamblin, A.P. and Delroy, N.D. (1986). Continuous cereal cropping with alternative tillage systems in Western Australia. Technical Bulletin No. 71, WADA.
51. Kay, A. (1988). Soil pits and how to use them. The Australian Cotton Grower, Feb. - April, pp 39-40.
52. Klute, A. (1965). Laboratory measurement of hydraulic conductivity of saturated soil. Chapter 13 in: Methods of Soil Analysis, Part 1. ed. Black, C.A., et. al. American Society of Agronomy.
53. Kohnke, H. (1968). Soil physics. New York. McGraw - Hill.
54. McDonald, R.C., Isbell, R.F., Speight, J.G., Walker, J. and Hopkins, M.S., (1984). Australian Soil and Land Survey Field Handbook, Inkata Press, Melbourne.
55. McKenzie, D. (1989). SOILpak - A soil management package for cotton production on cracking clays.
56 Negus, T.R. (1984). Direct-drilling on the contour for controlling erosion. Farmnote No., 99/84, WADA.
57. Northcote, K.H. (1979). A factual key for the recognition of Australian Soils. Rellim Technical Publications, Adelaide.
58. Perry, M.W. (ed). (1986). A review of deep tillage research in W.A. Technical Report No. 3, Division of Plant Research, WADA, August.
59. Perry, M. and Hillman, B. (1991). The Wheat book. A technical manual for wheat producers. Bulletin No. 4196, WADA.
60. Riethmuller, G. P. (1986). The effect of tine spacing and tillage depth on a subsoiler's energy requirements on a deep yellow loamy sand. From Conference on Agricultural Engineering, Adelaide 24-28 August, The Institution of Engineers, Australia, 315-319.
61. Singer, M.J. and Munns, D.N. (1987). Soils - An Introduction. MacMillan Publishing Co. New York.
62. Soane, B.D., Blackwell, P.S., Dickson, J.W. and Painter, D.J. (1980/81). Compaction by agricultural vehicles: A review. I. Soil and wheel characteristics. Soil and Tillage Research, 1, 207-237.
63. Soane, B.D., Blackwell, P.S., Dickson, J.W. and Painter, D.J. (1980/81). Compaction by agricultural vehicles: A review. II. Compaction under tyres and other running gear. Soil and Tillage Research, 1, 373-400.
64. Soane, B.D., Blackwell, P.S., Dickson, J.W. and Painter, D.J. (1982). Compaction by agricultural vehicles: A review. III. Incidence and control of compaction in crop production. Soil and Tillage Research, 2, 3-36.
65. Sullivan, L.A., Henderson, C.W.L. and Stoneman, T.C. (1983). Farming practices and soil structure, J. Agric. (W.A.). Vol. 24, No. 2, pp 62-64. WADA.
66. Taylor, H.M., Roberson, G.M. and Parker, J.J. Jnr. (1966). Soil strength root penetration relations for medium to coarse textured soil materials. Soil Sci., 102, 18-22.
67. Valentin, C., (1989). Soil structure and rooting. In: Asialand Workshop on the Establishment of Soil Management Experiments on Sloping Lands, 264-267. IBSRAM Technical Notes No. 3, Bangkok, IBSRAM.
68. Voorhees, W.B., Senst, C.G., and Nelson, W.W. (1978). Soil and Water Management in Conservation. Compaction and soil structure modification by wheel traffic in the northern corn belt. Soil Sci. Am. J. Vol. 42, p 344-349.
69. Wild, J. (1985). Murrumbidgee College of Agriculture, Agriculture and Fisheries, NSW, Soil structure notes. Level I.
70. White, P. and Robson, A.D. (1989). Emergence of lupins from a hard setting soil compared with peas, wheat and medic. Aust. J. Agric. Res. 40, 529-37.

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3.7 Contributors and Acknowledgements

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