Chapter 8

Options for managing grain production on soils with subsoil constraints

Key points

- Subsoil constraints exist in most soils used for cropping in southern Australia
- Soil properties vary both spatially and in time and require site and crop specific management.
- Multiple constraints are often present and overcoming only one constraint may produce only marginal improvements in yield.
- Many amelioration strategies are often not cost-effective, even if they produce increases in grain yields. An exception is the deep sand over clay soils where subsoil placement of fertilisers may be commercially viable. This technique produces substantial and prolonged grain yield increases and may be profitable, despite high initial costs.
- Generally deep ripping is most successful on sandy soils and least on heavy clay soils.
- The most economically feasible strategy currently available for managing subsoil constraints on most soil types, especially in low to medium rainfall zones, may be to 'live with the problem' and adjust inputs to maximise profits rather than crop yields.
- Genetic solutions (varieties with tolerance to constraints such as salinity) offer considerable promise for the future.

Assessing the severity of subsoil constraints and their impact on crop productivity is difficult and this makes choosing an appropriate management strategy a complex process. As a general principal, water in the subsoil is proportionally 'more valuable' to final grain yield than surface water (Kirkegaard *et al* 2007). Consequently even small improvements in the ability of a crop to access subsoil water may produce significant yield benefits. It is very difficult to determine the impact of subsoil conditions on plant growth because it is hard to isolate the effects of the subsoil from those of the topsoil above it. Furthermore, the impact of subsoil constraints on crop yield often depends on the particular crop and seasonal conditions, making decisions about what management option to apply even more challenging. In addition to these difficulties, several constraints can exist simultaneously in the subsoil so that a 'pyramiding' of management solutions will be needed to maximise yield potential.

Soil properties are highly spatially variable (on both a regional and paddock to paddock basis). Within a single paddock, large variations in soil properties can occur in the space of a few metres as well as down the soil profile. The relative impact of subsoil constraints depends on the crop type and seasonal conditions. The 'best' management strategy will therefore likely need to be both paddock and season specific.

Like most decisions farmers make, the most appropriate strategies for managing subsoil constraints will also need to be based on financial and agronomic considerations. These decisions will vary from farm to farm and season to season and will be strongly influenced by the attitude and economic capacity of the landholder to manage risk. A high cost program of soil amelioration may not be profitable in many dryland farming environments. In many situations, the best management approach may be to 'live with the problem' and recognise a reduced yield potential, and target inputs accordingly so as to maximise profit rather than yields. The identification of the most limiting subsoil constraint and its interaction with other factors is the first step. Plant growth depends upon the interrelationships between different soil properties (in the surface and subsurface) and the environment, so managing the entire root zone becomes necessary.

There are four broad strategies that could be considered for improving the profitability of cropping on soils with subsoil constraints:

1. Amelioration of the subsoil to make it more suitable for root growth and function.

2. Altering agronomic management practises to minimise the reliance of the crop on the subsoil.
3. Selection of crop and pastures types and cultivars that are better adapted ('tolerant') to the constraint/s.
4. Recognising the inherent limitation posed by these subsoils and adjusting inputs or land use accordingly.

The choice and effectiveness (in terms of increased profitability) of each strategy depends, in part, on the nature and severity of the constraint/s, the type of farming enterprise and the extent of seasonal and spatial variability.

What amelioration strategies are being tested?

The four chemical subsoil conditions that have the greatest negative impact on crop growth on neutral and alkaline soils in south-eastern Australia are sodicity, salinity, boron toxicity and nutrient deficiencies. Implementing management strategies that reduce the impact of these conditions should improve the productivity of crops growing in these paddocks. Management strategies can be broadly grouped as either options that physically or chemically alter (or ameliorate) the subsoil constraint/s or strategies that alleviate the economic impact (including risk) of subsoil constraints.

Amelioration options to directly intervene include:

- Chemical amelioration (such as replacement of sodium (Na) and magnesium (Mg) with calcium (Ca) or adding nutrients).
- Physical amelioration (such as deep ripping or use of raised beds)
- Biological (such as use of 'primer crops' or organic matter addition).

Options to manage these constraints indirectly include:

- Agronomic practices (such as row spacing, mid row fertiliser banding, no-till and stubble retention and controlled traffic).
- Selection of tolerant plants (such as selecting crop species and cultivars adapted to subsoil constraints).

Information about managing these constraints in the subsoils is largely lacking. The options discussed here are mainly based on theory and a limited number of trials conducted in specific regions and/or soil types elsewhere, and that could now be tried in different parts of south-eastern Australia.

Which chemical ameliorants are worth trying?

The choice of chemical ameliorant depends upon the predominant constraints. The most effective and widely used ameliorants for sodic soils are those that provide a soluble source of calcium. Another new but currently very experimental approach is the use of polyacrylamides to help stabilise sodic soils (Dodd *et al*. 2004). While these materials do not presently appear to be economic for broad-acre agriculture, their potential role is being assessed in several research programmes.

Gypsum ($CaSO_4 2H_2O$) and sodicity

Applying Gypsum to ameliorate surface sodicity is common, but it is unclear how effective it is in treating subsoil sodicity. Gypsum improves sodic surface soils by:

- an electrolyte effect, which causes flocculation of the surface soil leading to improved structure and infiltration. Given the extra pressure on subsoils (from the weight of topsoil above) it is unclear if gypsum will induce flocculation of dispersed sodic subsoils.
- the exchange of Ca^{2+} for Na^+ and Mg^{2+} on the soil's exchange complex (Loveday 1976). On highly sodic soils, Na^+ ions released from the surface layers could increase the sodicity of lower subsoil layers.

Gypsum is only effective with high application rates and sufficient time. Surface-applied gypsum takes a long time to affect subsoil sodicity. Sharma (1971) reported that gypsum extended down to only 30 cm four years after application. However, more recent work in the sandy soils of the Eyre Peninsula indicates that gypsum may move through the profile much quicker.

Gypsum has little residual effect on highly sodic surface soils, even with high rates of application, suggesting that gypsum may not be a long-term solution to surface sodicity. Given that the subsoil will have lower rates of water infiltration, when compared to surface soil, gypsum may have a more prolonged residual effect in subsoils.

The commonly recommended rate of gypsum is 2.5 t/ha for wheat production on marginally sodic to sodic-clay soils (Abbott & McKenzie 1996). However given that sodicity is often much higher in the subsoil than at the surface, higher (and therefore potentially uneconomic) rates may be needed for effective amelioration of these subsoils. An example of how to calculate gypsum requirements is found in Appendix 2.

Lime ($CaCO_3$) and acidity

Lime is used mainly to increase the pH in acid soils but will also supply Ca^{2+}. Lime has been suggested as the most economical ameliorant for surface soil acidity, but surface-applied lime is unsuitable for ameliorating most acid subsoils because of its very slow rate of leaching. Deep placement of lime is effective, but difficult and costly. Gypsum has been successfully used to partially ameliorate subsoil acidity due to it being more soluble than lime.

Lime and gypsum differ in the way they ameliorate acidity. Lime reacts with the acid (H^+) to generate water and carbon dioxide and to release Ca^{2+} ions. Because acid is consumed in this reaction, the soil pH increases. Gypsum produces an ameliorative effect by decreasing acid soil infertility and the availability of toxic aluminium by:

- increasing the Ca:Al ratio in the subsoil, and

- precipitating some of the active Al as $AlSO_4$.

rather than by altering soil pH *per se*.

Lime and gypsum differ in solubility. The solubility of lime is pH dependent, whereas the solubility of gypsum is not. Lime is insoluble at pH >8.5, becoming more soluble as pH decreases below this value. The use of lime is recommended to ameliorate acid to neutral sodic soil, but is highly unlikely to have any beneficial effect on alkaline sodic soils. Gypsum is an effective source of Ca^{2+} in all soils independent of pH.

Gypsum and lime combinations

A combination of gypsum and lime has been shown to improve soil structural stability for a longer period of time, when compared to gypsum alone, in soils with near neutral or acidic pH. Valzano *et al*. (2001) suggested that gypsum acts as a useful source of Ca^{2+} during the early stages after application and its slight acidifying affect improved the dissolution rate of lime to supply Ca^{2+} for a longer period of time as compared to gypsum alone. However, lime is unlikely to be effective in soils with pH >7.5 (ie. neutral and alkaline soils).

Techniques are now being developed to apply gypsum and lime below the soil surface in the least cost and most effective ways (eg Hamza and Anderson 2003). These techniques usually involve combinations of air or belt delivery systems for gypsum and/or lime application and low draught and low disturbance deep ripping operations to apply the materials well below the soil surface.

Other calcium sources

Calcium chloride ($CaCl_2$)

This is a very soluble source of Ca^{2+} and can provide rapid amelioration. However, it is very expensive and also can create salinity and Cl^- toxicity problems due to its high solubility. Similarly, calcium nitrate ($CaNO_3$) can be an effective source of rapid amelioration (as well as a source of nitrogen for the crop), but is very expensive.

Sulphur (S)

In alkaline sodic soils (pH >8.5), carbonates and bicarbonates of Sodium dominate. In these soils, Ca^{2+} precipitates as calcium carbonate and is not available for exchange with Na^+. The most efficient means of reclaiming these soils is to bring the pH down to <8.5, so that Calcium Carbonate dissolves to release Ca^{2+}. The most common and effective means to acidify these soils is to add sulfuric acid, or elemental sulfur which is converted to sulfuric acid by soil microorganisms. However, due to the high buffering capacity (ie. ability to withstand change) of heavy clay soils, large amounts of elemental sulfur over a period of time would be required to significantly reduce soil pH. Therefore, the effectiveness and economics of S application is yet to be determined for these soils. Furthermore rainfall may not be sufficiently high to stimulate sufficient conversion of S in many areas of south-eastern Australia.

Deep placement of nutrients

Nutrient deficiencies eg. phosphorus and nitrogen are widespread throughout southern Australia. Substantial increases in crop yield have been reported by placing nutrients in the subsoil, even when seemingly adequate rates of fertilisers have been applied to the surface soil. Although there is no precise definition of 'deep placement', the nutrients are usually placed below the plough layer at depths ranging between 20 and 40 cm. For example, deep placement of nitrogen and phosphorus in wheat, and a combination of nutrients in barley, has been shown to significantly increase yields as compared to nutrients banded below the seed in a deep infertile sand (Figure 8.1). Adding zinc to the subsoil has also been shown to increase the yield of a zinc-deficient cultivar of wheat by 20% (Nable and Webb 1991).

These yield increases due to the deep placement of nutrients could be due to root proliferation in the fertilised zones, encouraging greater use of subsoil moisture and greater nutrient uptake. Although part of the response in crop growth due to deep nutrients is often due to the deep ripping operation used to apply the deep nutrients (ie from amelioration of compaction). This benefit is usually small compared to the nutrition effect.

These grain yield increases have been achieved on deep sand over clay profiles across a wide range of rainfall zones within the cropping regions of south-eastern Australia and can persist for at least 4 years after application which makes the approach far more attractive (Figure 8.2). Most of the field experiments investigating the impact of deep nutrients in south-eastern Australia have been conducted with fluid (and hence generally expensive) fertilisers. However, preliminary evidence from several field experiments recently conducted in South Australia suggest that similar impacts from deep-placed nutrients can be achieved with cheaper, granular fertilisers. Only those nutrients which are in deficient supply in the profile are required in the deep nutrient package necessary to achieve these substantial grain yield increases.

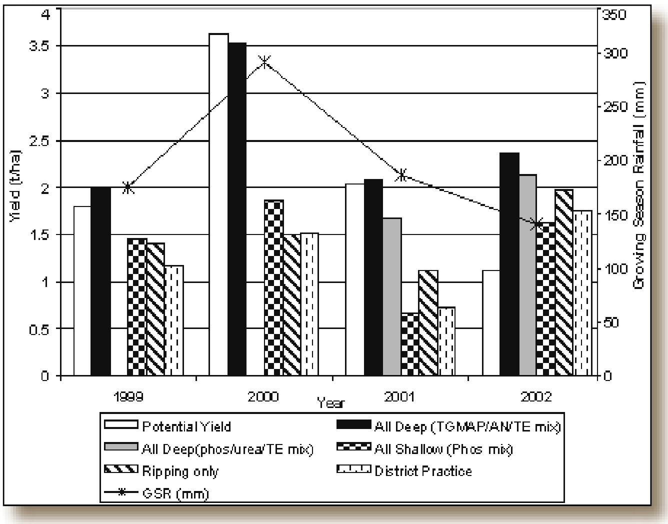

Figure 8.1: Comparison of subsoil nutrition treatments at Wharminda (Eyre Peninsula) over four years. (NB: there were no "all deep phos mix" treatments in 1999 or 2000). Average growing season rainfall (GSR) at Wharminda is 199 mm. TGMAP = tech grade MAP, AN = ammonium nitrate, phos = phosphoric acid, TE = zinc sulphate + manganese sulphate + copper sulphate (Doudle et al., 2003).

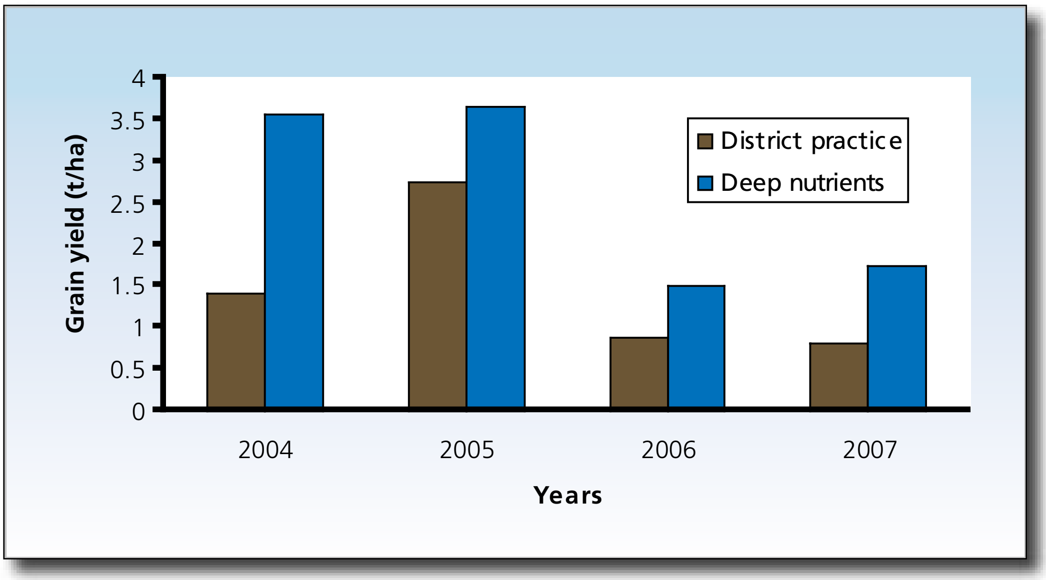

Figure 8.2: Impact of nutrients placed at 40 cm below the surface in 2004 on grain yield of wheat in that year and for the three years after application at Stansbury (Yorke Peninsula, SA). Deep nutrients were only applied in 2004.

Physical amelioration of subsoils

Physical loosening of subsoils, commonly termed 'deep ripping', can be achieved using a variety of implements. The benefit of deep ripping to crop performance varies widely between different studies reported in both Australia and overseas. Deep ripping or ploughing of compacted (high soil strength) soils has been shown to increase aeration and root growth, especially where there are no other chemical constraints such as sodicity present. For example, a study by Sadras and his colleagues in the northern Mallee of Victoria recorded yield responses in wheat of up to 40% by deep ripping on non-sodic sandy loam soils. Other studies in Western Australia (Hamza and Anderson 2003) have also demonstrated yield increases of 25% in wheat and 30% by chickpea compared to control (non ripped) treatments on lighter textured soils. However on dispersive (sodic) soils, ripping is unlikely to have a significant long-term beneficial effect unless the structure of the soil is simultaneously stabilised through amelioration with either calcium (eg. gypsum) or organic matter. Recent advances in machinery, such as slotting equipment and high pressure injection to simultaneously apply ameliorants at depth with deep ripping, could increase the effectiveness of this approach. Although deep ripping (or deep tillage) can increase water infiltration into the soil, it can also destroy the natural soil aggregation and macropores, bring sodic subsoil to the surface (resulting in poor establishment of crops), and deplete soil organic matter.

Jayawardane & Chan (1994) concluded that the effectiveness of deep ripping in improving subsoil structure depended strongly upon, implement design, soil water content and depth of ripping as well as the concurrent use of amendments. The primary aim of deep ripping should be to maximise disturbance (loosening) in the subsoil whilst minimising the draft. If soils are too dry, draft and fuel consumption are increased significantly. Ripping very dry soils can often result in large soil clods being brought to the surface. Conversely, if soils are too wet, smearing can result. A variety of tine designs have been used successfully in deep ripping including a 'winged' design (Spoor and Godwin1978), shallow tines in front of the deep tines (Hamza *et al*. 2005), and the 'Paraplough', as well as more traditional tines with straight shanks. Draft requirements increase rapidly with the depth of soil disturbance so a good knowledge of where the principal soil physical limitation is in the soil profile is required. For example, on soils with a shallow but fertile topsoil (eg. 10 cm), overlying a dense subsoil, disturbance may need only be confined to relatively shallow depths (eg. 20 cm). Once deep ripping and amelioration are completed, strategies such as stubble retention and controlled traffic should be considered to maintain any improvements in soil structure, otherwise recompaction will occur quickly on most soil types.

Deep ripping appears to be much more successful in situations where compacted layers induced by tillage are present rather than where the subsoil is sodic and has inherently high soil strength eg. Sodosols. For example, in Western Australia, deep ripping can increase cereal yields if the soils are sandy, have a compacted layer less than 30 cm deep and the subsoil is not highly acidic (Jarvis 1984). Timing of ripping is critical but the response to ripping can last for many years. In other areas and on different soil types deep ripping has been much less reliable and benefits persist for shorter periods (Blackwell 2001, Hamza and Anderson 2003). It is not clear whether this is due to the compacted layers having less impact on crop productivity or that the deep ripping approaches have not been fully effective. Malinda and coworkers (2004) demonstrated improvements in crop and pasture productivity with tillage below the seed row in a number of environments where plough pans existed. The deep working points at seeding reduced soil strength and improved root penetration, resulting in improved crop nutrition and grain production. These improvements were found to be economic in a simulation study of their impact on a typical whole farm. The success of deep ripping in improving crop growth and yield appears to be strongly dependent on the soil type and presence of other soil chemical/physical constraints to crops.

SUMMARY OF DEEP-RIPPING RESPONSES

RELIABLE RESPONSES ››› VARIABLE RESPONSES ››› FEW RESPONSES

SOIL TYPE	DEEP ACID SAND	NEUTRAL/ ALKALINE SAND	SODIC CLAY (grey/brown vertosol)	DUPLEX-DEEP	DUPLEX-SHALLOW	RED LOAMS (Kandosol)	BLACK VERTOSOLS
CULTIVATED ZONE (0–10)			Waterlogging	Waterlogging	Waterlogging		Self mulching
COMPACT LAYER	Strength >1.5-2.0 MPa; Distorted roots	Strength >1.5-2.0 MPa; Distorted roots	Strength >1.5-2.0 MPa; Distorted roots	Strength >1.5-2.0 MPa; Distorted roots	Strength >1.5-2.0 MPa; Distorted roots	Strength >1.5-2.0 MPa; Distorted roots	
ASSOCIATED SUBSOIL PROBLEMS (25–100cm–200cm)	Acid Layer High density Low water and N holding N leaching	Low nutrient availability Salinity Boron	Waterlogging Sodic Clay Anaerobic High density Poor structure Salinity	Waterlogging Sodic Clay Anaerobic High density Poor structure Salinity	Waterlogging Sodic Clay Anaerobic High density Poor structure	Acid Layer High density Well structured	Salinity (Cl^-)
MEAN CROP RESPONSE RANGE (Wheat)	WA 20-37%	VIC/SA 23% (0-43)	NSW 33%(0-300) WA 47% VIC 25%	WA 22% NSW 0-20%	4%	Few	Few
BEST BET MANAGEMENT	Rip with lime if acid Claying	Rip with nutrition	Rip with Gypsum Avoid re-compaction	Rip if clay >30cm Gypsum/Lime?	Do not rip	Few responses	Few responses Self repairing
REFERENCES	Jarvis (2000) Davies *et al* (2006) Hamza (2003) Hall (W'shop)	Sadras *et al* (2005) Wilhelm (W'shop) Armstrong (W'shop)	Chan *et al* (2003) Armstrong (2001) McKenzie *et al* (1990) Hamza (W'shop)	Crabtree (1989) Davies (2006) Jarvis (Various) Ellington (1986) Kirkegaard (W'shop)	Crabtree (1989) Davies et al (2006)	Kirkegaard (W'shop)	Dalal (W'shop)

Figure 8.3: Summary of deep-ripping responses. (J Kirkegaard, pers comm.)

Generally ripping is most successful on sandy soils and least successful on heavy clay soils (See Figure 8.3 above). Jayawardane and Chan (1994) reviewed several options including deep ripping or deep ploughing to ameliorate sodic subsoils with gypsum. They concluded that amelioration of subsoil sodicity was very expensive, may be uneconomical and of variable effectiveness, even on similar soils. Also, if sodic subsoils have limited permeability, the Na^+ on the exchange complex replaced by Ca^{2+} cannot be moved through the profile and hence reclamation would not occur.

Biological amelioration

Roots

Studies have shown that roots of certain plants, commonly referred to as 'primer crops' alter soil conditions physically, chemically and biologically and thus benefit following crops. Root exudates of legumes generate H^+ through microbial reactions that reduce soil pH and can dissolve sodium carbonate and bicarbonates in sodic soils. This can result in localised reductions in pH and thus improve soil physical properties and nutrient availability. By reducing the pH of the soil, these crops also may assist with the dissolution of Calcite and subsequent release of calcium into the soil (Valzano *et al*. 2001).

Rooting patterns vary between crop species and some may help in modifying the subsoil environment. Biopores created by the roots of primer crops can be more effective than mechanical tillage in opening up some soils, especially the subsoils. Tap-rooted plants such as lucerne, lupin and canola can penetrate the soil (biological drilling) and create channels for the roots of subsequent crops (Elkins 1985). However, Cresswell and Kirkegaard (1995) found no difference in soil macroporosity under either canola or wheat, and concluded that canola had limited opportunity to modify soil structure. They further hypothesised that dicotyledonous perennials would be more effective than thin fibrous-rooted annuals in opening up clay soils. However, recent results (D Adcock *et al*. pers comm.) indicate that cereals have greater depth of rooting than dicots such as canola and lupin, although this does not always translate to greater water use (Table 8.1). Peoples (2003) reported that lucerne penetrated deeper into the subsoil and also created macropores wider than phalaris or canola, thereby improving permeability of the subsoil. Other potential primer crops under trial in southern Australia include Chickory and the biannual pasture species Sulla (S Davies *et al*. pers comm.)

The roots of fibrous-rooted plants can help rip the soil (biological ploughing) through shrinkage and

Table 8.1: Grain yield, harvest index, water use and maximum rooting depth for different crops grown with and without subsoil amelioration (deep ripping, deep nutrients and composted organic matter) at Stansbury (Yorke Peninsula, South Australia) in 2005. Source D. Adcock et al. (2006).

Variable	Wheat		Canola		Lupins	
	District practice	Subsoil ameliorated	District practice	Subsoil ameliorated	District practice	Subsoil ameliorated
Grain yield (t/ha)	2.76	3.34	2.59	2.96	1.79	2.06
Harvest Index	0.46	0.44	0.43	0.38	0.47	0.46
Total water use (mm)	370	380	375	387	368	379
Water Use Efficiency (kg/ha/mm)	7.5	8.8	6.9	7.6	4.9	5.4
Maximum rooting depth (cm)	40-50	50-60	40-50	40-50	30-40	40-50

development of cracks (Hodgson & Chan 1984). This property is only important in cracking clay soils but can provide an opportunity to place nutrients and/or amendments in the subsoil. However perennial primer crops such as lucerne can also produce moisture deficits, resulting in increased risk of water stress in subsequent crops and reduced grain yields, especially in regions with low to medium rainfall.

Organic matter

Organic matter can strongly influence the physical properties of soils and minimise sodium-induced dispersion. Moreover, where organic matter has been built up by additions or growth of vigorous pastures, green manure crops, crop stubbles and/or trees, the water infiltration and structural stability of sodic soils is improved. Organic matter from plants and microorganisms acts as "glue" and helps stabilise soil aggregates (Churchman *et al*. 1993). Organic matter can be produced *in situ* (ie. from crops and pastures grown in the paddock) or can be applied as composts, mulches or amendments such as manures. For example, a single application of composted cereal straw used as pig bedding litter to a highly sodic clay soil prone to water logging in the southern Wimmera region of Victoria improved the grain yield of wheat in the first year after application by 40% (Figure 8.4). Furthermore, the composted straw produced a strong residual benefit to several subsequent grain crops. Although the underlying mechanism responsible for the yield improvement is unknown, adding composted organic matter corresponded to a significant reduction in ESP in the subsoil (Armstrong *et al*. 2007). Slattery *et al*. (2002) has speculated that Soluble organic compounds originating from applied organic matter are able to complex sodium and effectively remove some of this cation from the exchange complex. At present we have little knowledge of *how much* organic matter is required to produce noticeable reductions in the negative impact of subsoil constraints, however, it is likely to be substantial.

Are there practical alternatives to ameliorating subsoil constraints?

In many environments and grain production systems, there are currently only limited financially viable options available to ameliorate subsoil constraints. However there are two broad groups of strategies that are currently available and are financially feasible for the majority of grain growers:

(i) use of appropriate agronomic management practises and

(ii) the use of better adapted crops and cultivars.

Use of appropriate agronomic management practices

Use of appropriate crop management practices – such as stubble retention, adopting no tillage and controlled traffic systems and diverse crop rotations, including perennial legume crops and pastures and/or alternative land uses – appear to be viable, comparatively low-cost techniques to minimise yield losses resulting from subsoil constraints. Although rotations with other high value annual crops eg. pulses and canola is recommended as good agronomic practice in terms of disease and weed control, these crops are considered high risk where subsoil constraints are present and should be used with caution.

Zero-tillage and stubble retention

Zero tillage with stubble retention combined with better soil fertility management to ensure optimum production may provide a long-term solution that arrests or reverses soil sodicity and/or soil salinity. Table 8.2 shows that in a Vertosol, the combination of zero till and retained stubble resulted in a decrease in sodicity in the surface layers of the soil and also a substantial reduction in the salt load within the root zone of annual crops.

Stubble retention and no-tillage help to maintain soil structural stability and reduce both ESP and salinity. Stubble retention also helps to increase infiltration and

Table 8.2. Exchangeable Sodium Percentages (ESP, a measure of sodicity) and salt loads in a long term trial at Hermitage (QLD) after 13 years of cropping (Source: Dalal 1989).

Stubble	ESP (0-4 cm)		ESP (0-10 cm)		Salt (t/ha) 0-120 cm	
	Till	Zero till	Till	Zero till	Till	Zero till
Burned	2.8	2.0	3.5	3.2	7.3	3.2
Retained	3.1	1.3	3.8	2.2	4.9	0.8

therefore the amount of soil water available to the crop, making it less reliant on subsoil water supplies (where subsoil constraints have their greatest impact). Increasing stubble would assist soil stabilisation by decreasing clay dispersion. Further, no-till systems produces more biopores in the soil because of increased earthworm activity, thereby improving both movement of water and soil structure (Valzano *et al*. 2001). The adoption of controlled traffic systems is also likely to indirectly reduce the impact of subsoil constraints by improving soil structure (especially where amelioration such as deep ripping and/or gypsum application have been applied.

Raised beds

Raised beds have been widely adopted in the higher rainfall zones of southern Australia in the past 5 – 10 years, allowing farmers to reliably produce large increases in grain yields in environments where crops regularly failed due to water logging. This increase in grain yields results from the creation of root-zone conditions more favourable for plant growth due to a greater depth of surface soil and the formation of furrows that drain excess water, thus overcoming waterlogging. Raised beds have greater infiltration, less surface crusting, lower soil bulk density, lower shear strength and reduced penetrometer resistance compared to 'conventional' seed beds.

Recent research has also indicated the potential for raised beds to improve grain yields in lower rainfall zones (350 – 550 mm annual rainfall) where temporary water logging can result from perched water tables overlaying poorly structured clay subsoils with low porosity. For example grain yields of wheat in the southern Wimmera region (annual rainfall < 500 mm) were increased by up to 2 t/ha (40%) compared to conventional seed beds, even in years where the in-crop rainfall was less than average (see Figure 8.4).

However not all landscapes are suitable for the development of raised beds. Raised beds will result in crop losses if inadequate provision is made to allow excess water to drain away and it is strongly recommended that paddocks be properly surveyed before the beds are created. Furthermore, experience in western Victoria has shown that it is very difficult to form and maintain raised beds on soil types that are prone to slumping when wet (eg. sandy topsoils). Raised beds should not be used if the soil is saline or in regions with shallow watertables because salt can concentrate on the surface of the beds.

Row spacing and fallowing

There is increasing evidence that subsoil constraints have their greatest impact during the grain filling period rather than during earlier vegetative stages. This finding appears to be due to crops being most reliant on water stored deeper in the subsoil during latter stages of crop development, whereas earlier in the growing season, crops have better access to water nearer the soil surface. However, as the severity of subsoil constraints tend to increase with depth in most soils, the ability of crops to access water at the greatest depths in the profile also decreases as the severity of subsoil constraints increases.

In soils with low plant-available water, the use of wide row spacing and/or low plant densities should, in theory, conserve more soil water for the grain filling stages, and thus maximise the harvest index (ie. ratio of grain produced compared to the total dry matter of the crop). This effect can also be achieved by selecting earlier maturing cultivars and early sowing (although the impact of greater frost risk needs to be considered). The success of this strategy in the paddock however will depend on a number of factors including the soil type (wider row spacing tends to be more effective on heavier textured soils), the type and extent of weeds present (wider row spacing, whilst making weed control between rows

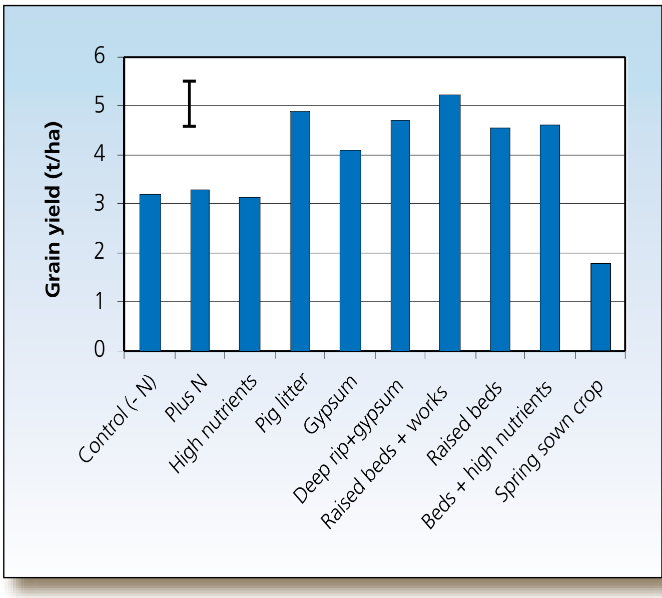

Figure 8.4: Yield responses of Frame wheat in 1999 to various amelioration practices including raised beds, deep ripping + gypsum and application of composted bedding litter (straw) on a Sodosol at Brimpaen in the southern Wimmera region of Victoria (Source: Armstrong et al. 2001).

easier, also reduces the ability of the crop to compete with weeds), seasonal conditions experienced and the management of the inter row to minimise evaporation of water (eg retention of standing stubble).

Fallowing is a widely used strategy to minimise risk in environments characterised by terminal drought. The value of fallowing – especially long fallowing – is questionable given that it is now recognised as a major contributor to increased recharge and the development of dryland salinity as well as wind erosion, and that severe subsoil constraints often limit the ability of a crop to exploit deep soil water reserves. Research in the Victorian Mallee (B Jones and N O'Halloran, pers. comm.) has trialled a novel system of wide row spacing whereby alternative rows only are fallowed in any one year rather than the whole paddock. This system aims to maximise the beneficial aspects of fallowing (increased water supply to the crop) whilst minimising some of the negative environmental aspects. Results to date suggest that this novel system offers some clear production benefits under some circumstances.

Genetic Variation in Adaptation

Plants vary significantly in their ability to grow in soils containing subsoil constraints. For example, a survey of the growth, yield and water use of crops over 3 consecutive years noted a large interaction between the relative yield at a particular point in a paddock (with moderate to strong subsoil constraints) and the crop type and/or seasonal conditions (Nuttall *et al*. 2006; Figure 8.5). In 2004 the grain yield of wheat monitored at Points 4, 6, and 8 was significantly above the paddock average of 1 t/ha across the other 7 points. This contrasts to the yield of chickpeas the previous year (2003) and fieldpea in 2005, which was characterised by relatively good seasonal conditions, where yields at these same points in the paddock were much closer to the paddock average.

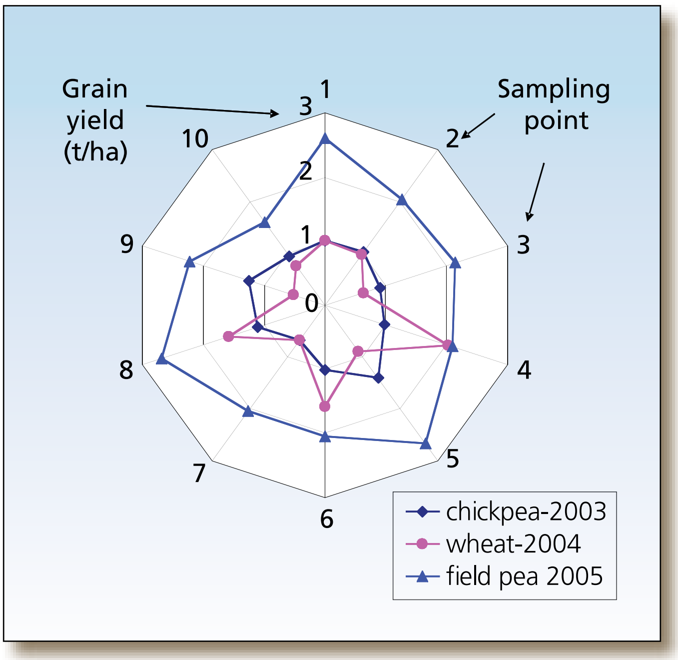

Figure 8.5: Grain yield (t/ha) of different crops at 10 fixed points in a paddock at Brim in the Victorian Mallee for chickpea (2003), wheat (2004) and field peas (2005). Numbers (1 to 10) on the outside circumference of graph represent fixed sampling points in the paddock. Numbers (1 – 3) on the vertical contours are grain yield (t/ha). Source: Nuttall et al. (2006)

Although this variation in relative tolerance of different crops to various constraints increases the difficulty in assessing the relative severity of subsoil constraints in a particular paddock, and developing appropriate management solutions, it also offers a potential solution. Genetic variation between species and within species may mean that plant breeding could ultimately provide the most feasible long-term economic solution for overcoming many subsoil constraints.

The potential success of a breeding solution to a subsoil constraint depends on several factors, including a clear understanding of what factor/s is limiting the crop, whether sufficient natural variation exists in the germplasm for tolerance to this limitation, whether the desired features can be readily incorporated into existing cultivars without compromising desirable traits, and the nature of the particular adaptation and constraint/s. Plants have evolved a variety of strategies to cope with unfavourable growing conditions such as nutrient deficiencies and chemical toxicities. These strategies can be broadly classified as 'tolerance', 'exclusion' and 'avoidance'.

Although many 'native species' have adapted to a range of soil constraints, these adaptations may be undesirable for agricultural species. For example, many native species have adapted to surviving on extremely nutrient deficient soils by having very slow rates of growth; this may be a good strategy if the aim is survival ('evolutionary success') but not when the primary goal is to maximise growth rates and the commercial production of a commodity such as grain.

Crops

There is significant variation in the relative tolerance of different crops to many subsoil constraints. It is generally accepted that pulses are extremely sensitive to subsoil constraints, especially salinity and boron, whereas cereals are more tolerant. Oilseeds such as canola appear to have intermediate tolerance, at least for boron toxicity (Kaur 2003). Within crop types there is also significant variation in their tolerance of subsoil constraints. For example, durum wheat has greater salt uptake and much lower salt tolerance compared to bread wheat. Durum lacks the Na^+ exclusion trait, which accounts for the better performance of bread wheat than durum wheat on saline soils (Munns *et al* 2000). Similarly, barley is generally more susceptible to boron toxicity than wheat. However, it is important to note that tolerance to one particular subsoil constraint (eg. boron), does not always correspond to greater tolerance to another constraint (eg. salinity), due to the different impact of each subsoil constraint on the physiology of the crop and the range of adaptive mechanisms utilised by different species.

Plant breeding has provided improved adaptation of new crop cultivars to subsoil constraints. In southern Australia the best example is the incorporation of boron tolerance into all the major wheat cultivars (eg. Frame) and barley (eg. Sloop Vic), targeted for alkaline soils in southern Australia. In recent years there has also been major advances in the identification and development of tolerance to subsoil constraints such as boron and salinity in highly sensitive crops such as lentils (Figure 8.6). This new germplasm offers potential to improve the adaptation of lentil to subsoil constraints, as demonstrated in Figure 8.7. The growth of new lentil lines possessing moderate tolerance to salinity (CIPAL415) or tolerance to both high B and salinity (02-355L*03HS005) were compared to that of widely grown variety Nugget (Armstrong *et al*. 2008). All three lines were grown in intact cores collected from paddocks in the Victorian Mallee exhibiting either relatively benign subsoil constraints (Site 1) or severe subsoil constraints (Site 2). Crop growth was significantly better (25% for dry matter and 64% for grain yield) by all lentil lines at Site 1 compared to the soil with severe subsoil constraints (Site 2). Nugget, which was classified as 'intolerant' to high B and salinity produced less yield and dry matter compared to the other two lines on both soil types. CIPAL415 (moderate NaCl tolerant) produced significantly higher grain yield than 02-355L*03HS005 (NaCl and B tolerant) on the relatively benign soil but this pattern was reversed on the soil with severe SSCs. The yield advantage of the two SSC tolerant lines compared to Nugget resulted primarily from a higher harvest index across both soil types with 02-355L*03HS005 having significantly smaller ($P < 0.001$) seed size than the two other lines as well as better use of water in the subsoil (data not presented). It is anticipated that these tolerant lines will form the basis of new cultivars (M Materne pers comm.). Cereal germplasm with tolerance to a range of subsoil constraints such as salinity, aluminium, water-logging and bicarbonate toxicity has been identified so that cultivars with tolerance to these subsoil constraints are likely to be available in the future.

Figure 8.6: Variation in tolerance to moderate concentrations of soil Boron by different lentil germplasm. (Picture courtesy of K Hobson)

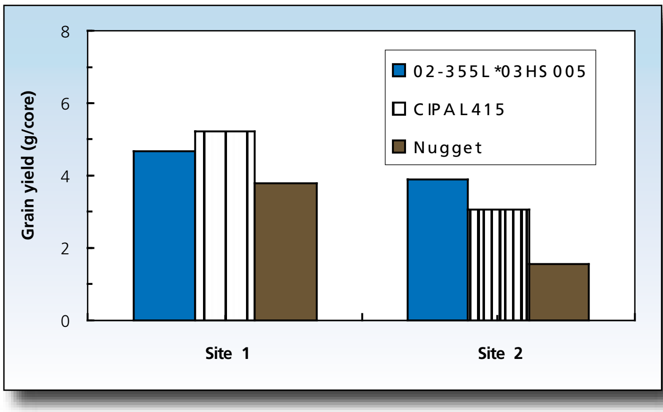

*Figure 8.7: Grain yield of different lentil genotypes with either NaCl (CIPAL415) or both B and NaCl tolerance (02-335*03HS005) compared to the parent Nugget when grown on either aa relatively benign (Site 1) or severe (Site 2) SSCs. Vertical bar represents lsd (5%). Source: Armstrong et al. (2008).*

Identification of genetic variability in crops and cultivars adapted to hostile subsoils represents a real challenge, requiring collaboration between different disciplines such as agronomists, soil scientists and plant breeders. However, despite some good successes such as the incorporation of boron tolerance into cereals, plant breeding will not be a complete solution for overcoming all subsoil constraints. For example, there appears to be little opportunity for improving the adaptation of annual crops to high soil strength (Materechera *et al*. 1991).

Pasture.

Many pasture species, especially perennials, appear to be better adapted to soils with subsoil constraints than annual grain crops. Armstrong *et al*. (1999) showed that perennial pastures were able to extract more water from the soil than annual legumes or sorghum in central Queensland. Similarly Ridley *et al*. (2001) demonstrated the potential of lucerne grown in rotation with crops to reduce the losses to deep drainage compared with annual crops and pasture. However this perception of better growth by perennial pasture species may not necessarily represent better adaptation per se as many annual crops, especially cereals, as perennial pasture species display only relatively minor reductions in dry matter during the vegetative stages of growth and suffer significant yield losses.

Replacing annual crops with salt-tolerant pasture grasses, fodder shrubs or trees can also help manage subsoil constraints. Pasture provides organic matter and fertility to the topsoil. There is anecdotal evidence that paddocks in parts of the Wimmera, which had previously been unsuitable for cropping due to waterlogging and salinisation, have been rehabilitated over several years through the use of tall wheatgrass. Lucerne can grow through highly sodic and saline layers and create big cracks in the soil (*Salinity Management Handbook* 1997), opening up the subsoil for water and root penetration by following cereal crops (Cresswell & Kirkegaard 1995). Forage shrubs such as saltbush, bluebush and related plants can raise the feed value of grazing pastures and can tolerate higher salinity in the soil.

Agroforestry

Many trees, including *Acacia* and *Eucalyptus* species, have long been used to manage salts and provide other benefits such as enhancing the farm environment, boosting returns and providing opportunities for diversification into forestry (*Salinity Management Handbook* 1997). Trees are also a good source of organic matter in leaves, bark and wood. Their deep roots help break up large aggregates and provide channels for water entry and drainage and there are examples of *Acacia* species being used as effective primer crops (Yunusa and Newton 2003).

The future

Our ability to effectively manage subsoil constraints depends on knowledge of the specific constraints operating, the interactions between these constraints, their relative impacts on yields and their potential interaction with crop types and seasonal conditions. The subsoil environment is highly complex and although we currently have some knowledge of the effectiveness of management strategies on specific constraints under particular circumstances (crops, soils and seasons), the challenge is to extrapolate this to a greater range of conditions across southern Australia.

Because many potential subsoil constraints can occur simultaneously, overcoming one constraint (eg. boron toxicity using a tolerant cultivar), may only produce a small improvement in crop production because the next most limiting constraint is then restricting growth. In order to significantly improve grain production in many environments, a 'pyramiding' of solutions may be required.

Subsoils are extremely heterogeneous so it is often difficult to determine which is the major limitation to root growth and where and when it occurs in a paddock. Soil properties can vary within paddocks (over distances as little as a few metres), between paddocks and across the landscape. Identifying variations that occur throughout the root zone to construct a subsoil constraints map at paddock or catchment level would be the starting point to overcoming the subsoil limitations. Collecting large numbers of soil samples from the root zone to account for this variability is usually prohibitively expensive. However the development of simple, practical and cost effective methods of soil testing based on ground based and remote sensing technologies eg. EM38 will assist growers to undertake the soil analysis for the entire root zone e.g. O'Leary *et al*. (2006). This knowledge can then be used to improve the selection and targeting of suitable management responses.

The threshold limits of many subsoil constraints are currently poorly defined. Better threshold values for the various subsoil constraints would provide an improved ability to assess the potential economic loss from subsoil constraints and the effectiveness of management solutions. However there is strong evidence that there are often significant interactions between different subsoil constraints (Nuttall *et al*. 2005) and this needs to be accounted for.

This chapter has suggested a range of management options that may be suitable for testing by farmers. Whatever strategy or strategies are chosen, they should first be trialed in a series of small scale test strips on farm prior to major investment or change in practice. The effectiveness of any management technique, or combination of techniques, depends upon its long-term impact on the soil, the crop and crop variety, the farming system, the landscape, the environment and the economic issues such as comparative value of land and the cost of implementing amelioration strategies, and the landholder's own desires and needs. The key requirement for profitably managing any subsoil constraint is the need to identify the extent and severity of a range of potential constraints. Recent developments in remote sensing, such as the satellite based NDVI (Normalised Difference Vegetation Index) images (Fisher and Abuzar 2006) offer the potential to relatively easily and cheaply identify parts of paddocks (or whole paddocks) that consistently perform poorly. Given our current state of knowledge, the most economically feasible strategy currently available for many farmers when managing subsoil constraints, especially in the low to medium rainfall zones of the Australian grain belt, may be to either remove these paddocks from grain production (eg. return to pasture) or to 'live with the problem'. This latter strategy is based on understanding the extent and severity of subsoil constraints in a particular paddock and reducing inputs eg. nitrogen fertiliser, to account for the true yield potential rather than one based on likely rainfall alone, leading to maximum profitability rather than maximum biological productivity.

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