Chapter 8

Soil Constraints: A Role for Strategic Deep Tillage

Stephen Davies, Roger Armstrong, Lynne Macdonald, Jason Condon and Elizabeth Petersen

Introduction

Despite grains productivity improvements arising from CA, the gap between yields in growers' paddocks and the physiologically determined water limited yield potential throughout many cropping regions remains large (Hochman *et al.* 2016). Although a variety of factors are responsible for this, many areas of the Australian grain belt with the largest proportional yield gaps contain a range of physicochemical soil constraints (Adcock *et al.* 2007, Dang *et al.* 2010, MacEwan *et al.* 2010, Page *et al.* 2018, Van Gool 2016, see Table 1). These constraints can result in significant reductions in grain yield potential by restricting root growth and access to soil water and nutrient supplies or directly inhibit growth via toxicities. Often a variety of constraints occur simultaneously and can be present in either the top or subsoils (or both) and are associated with both fine and coarser textured soils. In this chapter we have defined 'subsoil' as the part of the profile below normal depth of sowing or routine cultivation for weed control (ca. 0.1 m). Whilst some subsoil constraints reflect the inherent nature of the soil, those occurring in the top 0.5 m of the profile, such as acidity or compaction from machinery, result from agricultural management practices.

A range of strategies have been proposed to manage these soil constraints including:

- 'genetic solutions' involving increased tolerance to soil toxicities;
- agronomic management to maximise profitability rather than productivity;
- 'amelioration', almost inevitably involving some form of physical intervention and/or application of an amendment (Sumner *et al.* 1986, Adcock *et al.* 2007, Gill *et al.* 2008, 2012, Davies *et al.* 2015a, b).

'Biological drilling' ('primer plants') involving use of plant roots to modify subsoils has been assessed (Yunusa and Newton 2003, McCallum *et al.* 2004, Nuttall *et al.* 2008), but in recent years there has been increased attention on strategic deep tillage, which is one-off or occasional tillage typically to depths of 0.3 m or more. Strategic deep tillage includes deep ripping (Hamza and Anderson 2005), deep soil mixing (Scanlan and Davies 2019), soil inversion (Davies *et al.* 2013), deep placement, or clay spreading and delving with deep incorporation (Cann 2000, Rebbeck *et al.* 2007, Hall *et al.* 2010). The size and reliability of yield responses associated with strategic deep tillage differ across soil types and regions, but they can have significant and sustained profitability benefits (Davies *et al.* 2015b, Sale and Malcolm 2015, Davies *et al.* 2018).

If the constraint is chemical, such as sodicity, acidity or a nutrient deficiency, some form of amendment is required, either inorganic (*e.g.* gypsum or lime) or organic (*e.g.* manures, compost). Such amendments have typically been applied to the topsoil (*e.g.* Armstrong *et al.* 2007, Li *et al.* 2019) but direct placement into subsoil is gaining interest (Davies *et al.* 2008, Condon *et al.* 2018, Sale *et al.* 2019), although the mechanisms of yield improvements appear to vary with soil type and seasonal conditions and are contested (Celestina *et al.* 2018, Gill *et al.* 2019). Many subsoil amelioration practices have a high cost to implement and so are strategic in application and need to have a long residual benefit to make economic sense.

Soil constraints

In Australian dryland cropping systems, soil constraints typically align with broad soil types (Table 1). Low water holding capacity, topsoil water repellence, compaction, soil acidity and associated aluminium and manganese toxicity, and poor fertility are common on deep sands, sandy earths and sandy A-horizons of duplex (texture contrast) soils. High alkalinity, sodicity and chemical toxicities such as boron, chloride, bicarbonate and salt are common on finer textured loamy earth and clay subsoils and in the clay B-horizon of duplex profiles (Table 1).

Table 1. Association of common constraints of agricultural soils and the Australian Soil Classification soil orders (Isbell and National Committee on Soil and Terrain 2016). Dominant soil texture is shown include sand (S), texture contrast (TC), loam (L) and clay (C)

	Australian Soil Classification SOIL ORDER	**Tenosols**	**Rudosols**	**Kandosols**	**Calcarosols**	**Sodosols**	**Kurosols**	**Chromosols**	**Vertosols**	**Dermosols**	**Ferrosols**
	Soil Texture	*S*	*S*	*L*	*S, TC*	*TC*	*TC*	*TC*	*C*	*C*	*C*
COMMON SOIL CONSTRAINTS	**Water repellence**	x	x	x	x	x		x			
	Low water holding capacity	x	x		x		x				
	Subsoil compaction	x	x	x	x	x		x	x		
	Poorly structured dense subsoil	x	x	x	x	x	x	x		x	x
	Poor subsoil fertility	x	x	x	x	x	x				α
	Acidity (Al and Mn toxicity)	x	x	x			x	x			x
	Alkalinity				x	x				x	
	Sodicity					x	x		x		
	Temporary water logging					x	x	x	x	α	
	Boron toxicity				x	x			x		
	Other toxicities (e.g. Chloride)				x	x			x	x	

x = commonly occurring; α = variable occurrence

Soil water repellence occurs when hydrophobic organic compounds and waxes of plant and fungal origin coat topsoil sand particles resulting in slow and uneven water infiltration (Chan 1992, Franco *et al.* 1995, 2000, Doerr *et al.* 2000, Unkovich 2014). It is most common on sandy-topsoils with low clay content (<5 %) and has been recognised as a major constraint since land clearing in the late 1940s (Bond 1964, Roberts and Carbon 1971). Water repellence results in uneven and slow soil wetting causing:

- poor and delayed crop establishment;
- staggered weed germination;
- susceptibility to wind and water erosion;
- high leaching risk due to preferential flow; and
- inefficient use of rainfall (King 1981, Blackwell 2000, Roper *et al.* 2015).

Concentration of organic matter at the soil surface through reduced tillage (Chan 1992), a shift towards earlier and dry seeding (Fletcher *et al.* 2016), and smaller, less reliable break-of-season rainfall events, have likely contributed to increased expression of soil water repellence (Roper *et al.* 2015).

Subsoil compaction, plough pans and inherent hard layers as a result of cementation (Needham *et al.* 2004a) have long been recognised as significant soil constraints (Hamblin and Tennant 1979, Henderson *et al.* 1988). Growth in the scale of cropping enterprises has led to the use of larger, heavier machinery with resultant higher axle loads causing deeper, more severe, compaction (Henderson *et al.* 1988, Hagan *et al.* 2015, Isbister *et al.* 2016). Current agricultural machinery such as harvesters, air carts, tractors, sprayers and chaser bins have axle loads exceeding 10 tonnes, resulting in deeper compaction to 0.4 m or more (Isbister *et al.* 2016). Degree of compactibility for soils with less than 20% clay is related to the particle size distribution (Needham *et al.* 2004b). Soils with more even (well-graded) distribution of soil particles can be more susceptible to compaction than poorly-graded sand, though these may still have high bulk density (Needham *et al.* 2004b).

Agricultural practices have acidified soils. Soil acidity is a common soil constraint in cropping zones of south eastern and Western Australia (WA) and occurs in both coarse and fine textured soils. The acidification rate has increased as cropping has intensified, with higher inputs of N fertilisers and increased product export (Mason *et al.* 1994, Dolling and Porter 1994, Dolling *et al.* 1994). Where lime applications have been inadequate, there has been extensive development of subsurface acidity (Williams 1980, Tang *et al.* 2000, Tang 2004, Gazey *et al.* 2013) and associated aluminium and manganese toxicity. Whilst lime application can ameliorate acidity within the 0-10 cm layer, the slow dissolution and movement of lime limits the effectiveness of surface-applied lime to address deeper, subsoil acidity (and see Chapter 7).

Grain production in the low and medium rainfall regions of Australia is mostly conducted on neutral to alkaline soils (Adcock *et al.* 2007, Dang *et al.* 2010, van Gool *et al.* 2018). Clay content typically increases with depth (to more than 60%), often concurrent with an increase in the severity of a range of physicochemical subsoil constraints. These limit crop productivity via impeding subsoil root growth and function, leading to poor utilisation of subsoil water and nutrients (Nuttall *et al.* 2003). Lack of available water is the principal yield constraint in these environments and subsoil constraints tend to restrict grain yields in seasons with 'dry finishes' (Nuttall and Armstrong 2010) when the crop is more reliant on subsoil water reserves to complete grain fill. Most subsoils contain multiple constraints, the most common being sodicity and salinity, but many also have toxic concentrations of boron (B), chloride (Cl^-), bicarbonate (HCO_3^-) and potentially aluminium (Al) arising from high pH, as well as reduced nutrient availability (Adcock *et al.* 2007, Dang *et al.* 2010, Brautigan *et al.* 2012). Poor subsoil structure and high soil strength resulting from both sodicity (Shaw *et al.* 1994) and compaction (McGarry 1993, Hamza and Anderson 2005) is common. Poor subsoil structure often leads to restricted drainage, temporary water logging and restricted aeration (Rengasamy *et al.* 2003). Many texture contrast soils can also have alkaline clay-rich B-horizons that are sodic, poorly structured and may also be saline (Hall *et al.* 2009), restricting crop root growth and nutrient availability (Tennant *et al.* 1992, Belford *et al.* 1992).

Strategic deep tillage tools and approaches

Deep ripping, also known as subsoiling, involves the loosening of soils for the purpose of removing hardpans, either natural or induced, and loosening dense subsoils to improve soil structure, porosity and water infiltration (Spoor 2006). Deep ripping is undertaken using deep working tynes which may be rigid or have high-breakout pressure. Typically, deep rippers do not intentionally incorporate much topsoil into the subsoil (Scanlan and Davies 2019). The type and geometry of the deep ripper can influence soil mixing as rippers with parabolic, wider or angled chisel-point tynes can delve and mix the soil more than narrow-tyned rippers (Spoor 2006). Addition of wings or wider points can also result in more breakout and soil disturbance, depending on working depth and soil conditions, especially moisture content (Spoor 2006). Narrow-tyned rippers can incorporate around 5-10% of the topsoil into soil layers below 0.1 m, but this would typically only be to a maximum depth of 0.15 m (Scanlan and Davies 2019; Table 2). This 'mixing' is passive with topsoil falling into temporary voids around and behind the ripping tynes as they pass through the soil.

In Australia, deep ripping has been practised for more than 40-years (Jarvis 1983, 1986a, Ellington 1986) and has long included the possibility of incorporating or deep placing soil amendments, such as lime, nutrients and organic matter (Robertson *et al.* 1957, Parr 1959). In continuous or intensive grain cropping systems of WA, deep sandy-textured soils have been the most responsive to deep ripping (Jarvis 1986b) and consequently the most commonly ripped soils. Ripping depths have traditionally been 0.3-0.4 m (Jarvis 1986b) but in recent years ripping depths on deep sands and sandy earths have increased to 0.7-0.8 m (Blackwell *et al.* 2016). The move to even deeper ripping has been driven by:

- recognition of deeper and more severe compaction layers arising from larger and heavier machinery (Isbister *et al.* 2016) coupled with increased cropping intensity;
- increased availability of high horsepower tractors and deeper working rippers; and
- larger yield and potential profit benefits when used on responsive soil types.

Table 2. Summary of strategic deep tillage approaches, working depth, incorporation characteristics, soil constraints addressed and approximate cost

Strategic deep tillage method	Implement working depth (m)	Implement impact on incorporation of soil amendment and/or topsoil	% topsoil buried below 0.1 m*	Constraints addressed	Approximate cost ($/ha)
Deep ripping	0.3-0.7	Minimal incorporation, depending on ripper type. Backfill to 0.15 m.	5-10	Compaction Hardpans	$45-100
Deep ripping with topsoil slotting	0.3-0.7	Topsoil slots from surface typically to depths of 0.35-0.40 m, but ripping depths can extend to 0.70 m. Can partially incorporate surface spread amendments (*e.g.* lime, nutrients, organic matter).	10-15	Compaction Hardpans Subsoil acidity Subsoil sodicity	$55-120
Deep subsoil placement, using ripper	0.3-0.7	Direct deep placement of amendments (*e.g.* organic matter, lime, gypsum, nutrients) in bands at depths up to 0.70 m.	5-15	Compaction Hardpans Subsoil acidity Subsoil fertility	$300-1400
Subsoil clay Delving + incorporation	0.6-1.2	Backfill likely due to wide tynes and high disturbance, subsequent clay incorporation will mix soils to 0.15-0.45 m. Soil amendments can be mixed into soil profile by incorporation process.	n.m.	Water repellence Compaction Fertility of A-horizon	$300-450
Soil mixing – large offset discs	0.2-0.3	Offsets throw soil one way then back again, mixing of topsoil and surface spread amendments, (*e.g.* lime, subsoil clay, organic matter) typically occurs between 0.15-0.25 m.	n.m.	Subsoil acidity Water repellence Compaction	$50-70
Soil mixing - one pass tillage	0.3-0.35	Mixing of topsoil and surface spread amendments to 0.15 m and some deeper inclusion to 0.30 m possible depending on tyne design.	n.m.	Subsoil acidity Compaction	$70-100
Soil mixing – rotary spader	0.35-0.4	Mixes to maximum working depth of 0.35-40 m. Can incorporate a range of surface spread amendments (*e.g.* lime, gypsum, organic matter, subsoil clay, nutrients etc.)	50-60	Subsoil acidity Compaction Water repellence Fertility of A-horizon	$120-150
Soil inversion - mouldboard plough	0.35-0.45	Buries a layer typically between 0.15-0.40 m. Can bury surface applied amendments (*e.g.* lime, organic matter, nutrients etc.) at depth. For subsoil acidity low pH subsoil brought to the surface after ploughing will need to be limed.	80-90	Water repellence Compaction Subsoil fertility Weeds	$100-150
Soil inversion – modified one way disc plough	0.3-0.4	Buries topsoil or surface applied amendments, such as lime or organic matter, in an arc from surface down to a depth of 0.25-0.35 m.	60	Water repellence Compaction Subsoil fertility Weeds	$40-60

* The proportion of topsoil buried below 0.1 m based on Scanlan and Davies 2019, Ucgul *et al.* 2017, 2018, 2019.
n.m. = not measured.

Costs of 'deeper' ripping are considerably higher with greater fuel use as a result of increased draft force, reduced work rate with narrower rippers and slower operating speeds and greater wear and fatigue of engines and machinery components working under high load (Blackwell *et al.* 2016, Isbister *et al.* 2016). Blackwell *et al.* (2016) found that fuel use at least doubled when ripping to 0.55 m on sand compared with ripping to 0.3 m. Shallow leading tynes can reduce the deeper ripping draft force and fuel use compared with conventional ripping and provide more effective removal of deep compaction

(Hamza *et al.* 2013). Depending on the tyne arrangement, shallow-leading tynes were shown to reduce draft by up to 11-25% on deep loamy sand and by up to 18% on a clay soil (Hamza *et al.* 2013).

Other developments in deep ripping include topsoil slotting (Blackwell *et al.* 2016, Davies *et al.* 2015a, Parker *et al.* 2017) and direct deep placement of amendment (Gill *et al.* 2008, Davies *et al.* 2008, Sale *et al.* 2019). Topsoil slotting is achieved through placement of an opener behind the ripping tyne which operates just below the topsoil, holding the subsoil open to allow loosened topsoil and surface applied amendment to fall into slots (Davies *et al.* 2015a, Blackwell *et al.* 2016, see Figure 1). Deeper inclusion of surface organic matter to depths up to 0.35-0.40 m may help maintain the ripping slot in softer condition for a longer time (Blackwell *et al.* 2016).

Direct placement of organic or other soil amendments directly into the subsoil typically involves placement of pipes directly behind deep ripper tynes (Gill *et al.* 2008, Davies *et al.* 2008). Large diameter pipes are used for deep placement of dry, sometimes pelletised, amendments which flow via gravity or are blown into the subsoil (Gill *et al.* 2008, Davies *et al.* 2008). Liquid amendments can be pumped through smaller diameter tubes, although the volume of amendment that can be applied is restricted (Anderson and Hendrick 1983).

Clay delving, like deep ripping, uses deep working tynes to interact with the subsoil. In this instance tynes are fixed, often angled at ~45°, broad-faced and typically work at depths of at least 0.6 m or more, typically with only 2-3 tynes spaced about 1 m apart (Desbiolles *et al.* 1997, Bailey and Hughes 2012, Betti *et al.* 2015). Delving tynes penetrate the clay B-horizon of texture contrast, or duplex, soils and lift clay-rich subsoil into the sandy A-horizon (Bailey and Hughes 2012) while at the same time physically breaking up compacted and cemented layers (Figure 1). Following delving, soils are typically worked with offset discs or a rotary spader (described below) to mix further and incorporate the clay (Bailey and Hughes 2012). Increasing the clay content of sandy topsoils can reduce soil water repellence and improve soil wettability (Betti *et al.* 2015, 2016), while also improving fertility (Hall *et al.* 2010), soil carbon storage (Schapel *et al.* 2017, 2018) and crop yield (Bailey *et al.* 2010, Hall *et al.* 2010, Betti *et al.* 2017).

Deep soil mixing involves occasional cultivation of soils to depths of 0.2 m or more (Scanlan and Davies 2019), as opposed to traditional ploughing or cultivation practices that are shallower and were traditionally practised regularly, rather than as a strategic or one-off practice. Deep soil mixing can be beneficial by reducing topsoil water repellence and partial weed seed burial (Davies *et al.* 2013). Deep mixing can also be effective to incorporate stubbles and place surface organic matter and associated nutrients deeper into the soil profile. In Australia, deep mixing is typically undertaken using large, deep working, offset disc ploughs, one-pass tillage system implements or, more recently, rotary spaders (Davies *et al.* 2010, 2013, 2015a, see Table 2).

One-pass tillage implements combine a series of tillage tools on the one implement, typically a leading set of shallow working offset discs followed by ripping tynes and then levelling discs or harrows and a soil packer (Davies *et al.* 2015a). While they may have a working depth of 0.3-0.35 m, depth of incorporation is often 0.25 m or less. Large offset discs can also have disc diameters up to 0.8-1.0 m and work as deep as 0.3 m; however effective incorporation of the surface often only occurs to a depth of 0.2-0.25 m (Davies *et al.* 2015a, see Table 2). Rotary spading typically follows deep ripping and has a working depth of 0.35-0.4 m (Scanlan and Davies 2019, Ucgul *et al.* 2018, see Table 2).

Rotary spaders have a shaft which rotates, typically at ~90 revolutions per minute in the direction of travel. Attached are sets of curved tynes, on the end of which are, typically, triangular-shaped spades that help bury topsoil at depth while also lifting some subsoil to the surface (Scanlan and Davies 2019, Ucgul *et al.* 2018). Incorporation by a spader is not uniform; rather the spades bury deeper 'pockets' of topsoil (Figure 1) in a grid pattern when viewed from above, through various soil layers (Ucgul *et al.* 2018). Rotary spaders typically bury about 50-60% of the topsoil (Ucgul *et al.* 2018, Scanlan and Davies 2019, see Table 2).

Figure 1. Images demonstrating a range of strategic deep tillage implements and the impact they have on the soil profile. Note incorporation dark coloured topsoil caused by each implement (Photos: Stephen Davies, Department of Primary Industries and Regional Development WA and Erin Cahill, agVivo image modified one-way plough).

Soil inversion is perhaps the most extreme strategic deep tillage option, resulting in the topsoil being nearly completely buried underneath a layer of subsoil 0.15-0.35 m deep (Figure 1). This provides an opportunity to:

- bury water repellent topsoil and lift wettable subsurface soil to the surface;
- incorporate lime, deeper into the soil profile;
- redistribute topsoil nutrients and organic matter into the crop root zone; and
- lift higher clay content subsoil to the surface, depending on soil type (Davies *et al.* 2013).

The principal advantage of inversion over soil mixing is more effective amelioration of topsoil water repellence (Roper *et al.* 2015) and the near complete burial of weed seeds (Peltzer and Matson 2006, Davies *et al.* 2010, Newman and Davies 2010, Aulakh *et al.* 2012) which can slow the evolution of herbicide resistance (Renton and Flower 2015). Soil inversion is typically undertaken with a mouldboard or 'square' plough but more recently modified one-way disc ploughs have also been used. The modifications involve removal of every second disc and fitment of larger and often more concave discs, increased break-out pressure on the jump arms and may involve adding more weight to the plough, depending on the model used. These modifications allow deeper working, more space for soil to turn over and a greater degree of inversion. Mouldboard ploughs provide the most complete inversion (Ucgul *et al.* 2017, Scanlan and Davies 2019), but square and one-way ploughs are cheaper to purchase and effective with good setup and soil conditions (Ucgul *et al.* 2019), though weed seed burial is inferior to the mouldboard plough. Mouldboard ploughs typically bury 80-95% of the topsoil below the top 0.1 m (Ucgul *et al.* 2017, Scanlan and Davies 2019, see Table 2) while one-way ploughs bury 60-75% of the topsoil (Scanlan and Davies 2019, Ucgul *et al.* 2019, see Table 2).

Strategic deep tillage practices are often implemented in combination, either at the same time or in series over several years (Davies *et al.* 2018). The most common combinations involve deep ripping together with either soil mixing or inversion (Davies *et al.* 2018) or clay delving with subsequent incorporation. Timing of this ripping after inversion can vary, but generally occurs within 2-4 years. Use of controlled traffic farming systems can increase the longevity of soil loosening benefit from strategic deep tillage by confining machinery compaction to permanent wheel-tracks (Ellington 1986, Chan *et al.* 2006). However, some subsoils naturally 're-compact' after loosening and may require occasional deep ripping (Needham *et al.* 2004a).

Effects on crop growth and yield

Deep ripping to alleviate subsoil hardpans is most beneficial on deep sands and deep sandy duplex soils (Jarvis 1986b, Hamza and Anderson 2003), with responses on heavier-textured soils more variable and less reliable (Ellington 1986, Kirkegaard *et al.* 2008, Armstrong *et al.* 2009). Yield benefits from ripping result from improved root growth extension rates and final rooting depth which contribute to subsoil water access and more efficient nitrogen capture (Delroy and Bowden 1986). In sandy soils, deep ripping typically results in substantial increases in grain yield, of the order of 20-40% in the first season after ripping (Hamza and Anderson 2003, Armstrong *et al.* 2009). Yield benefits from deep ripping typically decline substantially in subsequent seasons. Despite yield increases of 19% in the year of ripping (sandy duplex), Hamza and Anderson (2003) report that by the third year the yield benefit had disappeared. Reasons for a neutral or negative response to ripping include:

- enhanced vegetative crop growth driving greater water use with insufficient moisture left for grain filling (Delroy and Bowden 1986);
- bringing excessive clay or hostile subsoil to the surface on heavier-textured soils (Kirkegaard *et al.* 2008, Armstrong *et al.* 2009, Blackwell *et al.* 2016);
- loss of soil structure; or
- not fully overcoming compaction or other soil constraints present, such as acidity (Coventry *et al.* 1987).

On deeper sands, increasing ripping depth up to 0.8 m to remove deeper compaction can substantially increase the crop yield benefit in situations where traditional ripping depths of 0.3-0.4 m have not improved yield (Blackwell *et al.* 2016, Isbister *et al.* 2016, Davies *et al.* 2018). Blackwell *et al.* (2016) reported yield increases of 83-137% following ripping to 0.55 m, compared with minimal response following ripping to 0.3 m.

Crop response to ripping with topsoil slotting to incorporate surface organic matter and amendments deeper into the profile have been mixed (Blackwell *et al.* 2016, Davies *et al.* 2015a). Blackwell *et al.* (2016) reported that, for deep ripping to 0.55 m following spreading of surface-applied lime on deep sand and sandy duplex sites, wheat yield benefits from topsoil slotting ranged from 16-32% over deep ripping with no slotting. Lime addition improved the benefit at several of the more acidic sites, consistent with previous research (Coventry *et al.* 1987, Davies *et al.* 2008). In contrast Davies *et al.* (2018) found no significant benefit to wheat yields (-12-10%) from topsoil slotting across two sites and two ripping depths compared with ripping alone. Parker *et al.* (2017) reported reduced yields from topsoil slotting for lupin in the second season, noting that the soil opener which facilitates topsoil slotting had also acted to re-compact the soil between the tynes. On heavier soil types, including a calcareous loam, loamy duplex and grey clay, crop yield response to topsoil slotting showed no positive yield responses in the first year (Blackwell *et al.* 2016) but on the grey clay in the second season increased barley yield by 0.67 t/ha over ripping only (Parker *et al.* 2017).

Broad-faced ripping tynes can delve (lift) clay-rich subsoil within the 0.3-0.6 m layer into the sandy textured surface A-horizon of duplex (texture contrast) soils. This results in benefits from deep subsoil loosening and removal of hardpans and topsoil water repellence but can also improve the fertility, pH and moisture holding of the sandy A-horizon (Bailey *et al.* 2010, Bailey and Hughes 2012, Betti *et al.* 2015, 2016, 2017). Variability in crop response to delving has been attributed to differences in the machinery used, the depth and extent of mixing between the soil horizons, and the timing of operation.

Cereal grain yields are increased by around 50% on average in the first two years following rotary spading on deep sands and deep sandy duplex soils (Davies *et al.* 2019). This represents a yield increase of 0.42-0.73 t/ha depending on soil type. Growth and yield increases are in part driven by increased mineralisation of organic matter, leading to greater nutrient supply, along with nutrient redistribution, establishment, soil loosening and soil pH benefits. Once these effects subside, residual yield responses appear soil type dependent, falling to 11% (0.22 t/ha) on average for pale deep sands but remaining at 33% (0.55 t/ha) for stronger deep sands, sandy earths and deep duplex soils (Davies *et al.* 2019). Current research indicates that benefits from rotary spading can last at least 4-5 years on better sands but may be more limited on infertile and low clay content deep sands (Davies *et al.* 2019).

Crop grain yield responses to soil inversion can be large and sustained for 8 or more years (Davies *et al.* 2015b, Davies *et al.* 2019). Soil inversion on average increases cereal grain yield by 30-60% (0.54-0.88 t/ha) in the first 2-years depending on soil type (Davies *et al.* 2019). As with deep soil mixing, responses tend to be lower on low fertility deep sands, and higher on deep sandy duplex and repellent gravel soils. Residual cereal yield benefits average 21-27% (0.51-0.68 t/ha) for most soils. For pale deep sands residual yield benefits typically decline after several years except for severely repellent deep sands where the untreated condition is particularly poor (Davies *et al.* 2019).

While benefits of ameliorating sands through deep soil mixing and soil inversion are apparent, there are numerous substantive risks, including:

- acute short-term wind erosion risk with complete stubble burial;
- surface crusting from lifting higher clay content subsoil to the surface with low organic matter;
- increased activity of pre-emergent herbicides resulting in greater risk of crop damage (Edwards *et al*. 2018) as well as opportunity for improved weed control;
- loss of soil organic carbon from tillage effect;
- poor seed depth control on loosened soils;
- re-compaction, especially if traffic is not controlled; and
- run-down of soil fertility.

These risks can be managed by growers but highlight the complexity and management required to achieve an ‘optimal’ outcome.

Strategic deep tillage with soil amendments

For soils with a combination of soil physicochemical constraints, soil amendments together with strategic deep tillage may be needed to address the interacting constraints, stabilise or improve soil structure or improve subsoil fertility all of which may improve the size and longevity of the amelioration benefit (Ellington 1986, Coventry *et al.* 1987, Hamza and Anderson 2003).

Lime incorporation into acidic subsoils

Movement of lime to depth is influenced by soil properties (texture, initial pH, pH buffering capacity), rainfall (duration and intensity) and lime (quality, particle size and rate of application, Whitten *et al.* 2000) but is generally very slow without physical intervention (Li *et al.* 2019). Conyers and Scott (1989) demonstrated that application rates of 8 t/ha were required to increase pH several centimetres below the depth of incorporation in loam topsoil of a southern NSW duplex soil. However, the mechanism of alkali movement is related to the pH following liming and not the rate of lime itself (Scott and Conyers 1995). They recommended liming to a pH_{Ca} >5.5 to facilitate alkali movement below the incorporation layer to the 0.1-0.2 m layer in their example. However long-term field experimentation demonstrates that the rate of subsoil pH increase remains slow, 0.04 pH units per year in the 0.1-0.2 m layer (Li *et al.* 2019).

Use of tillage to incorporate liming products to greater depth allows for more immediate amelioration of soil acidity in the subsoil. On acidic deep sandy textured soils with low pH buffering capacity, compaction and minimal subsoil structure, surface liming followed by incorporation using strategic deep tillage is an effective amelioration intervention (Gazey and Davies 2009). Rotary spaders, large offset discs and mouldboard ploughs have been used to incorporate lime into acidic sands (Davies *et al.* 2015a). The interaction of soil inversion with a mouldboard plough and lime application improved barley yield and reduced ryegrass biomass in a replicated experiment on deep yellow sand in WA, eight seasons after the amelioration was applied (Figure 2, Davies *et al.* 2015b).

For soils with higher clay content, deep tillage to depths of 0.3-0.4 m requires large energy inputs, can damage soil structure and increase erosion risk, especially if poorly structured A_2 horizons are brought to the soil surface (Kirchhof *et al.* 1995). For example, broadcasting lime at high rates (20 t lime/ha) prior to ripping or delving was shown to have limited benefit in ameliorating subsoil acidity (Kirchhof *et al.* 1995, see Figure 3a). Thus, deep tillage to incorporate lime into bulk soil is not commonly used on the loam and clay soils of south-eastern Australia, though beneficial interactions have been measured (Coventry *et al.* 1987). On sandy clay loam with a dense hardpan and subsoil acidity in north-east Victoria, lime application was necessary to achieve a deep ripping response and the ripping was still effective after 4-years (Coventry *et al.* 1987).

Where deep tillage of bulk soil may be uneconomic or impractical, techniques that amend specific portions of the soil profile or areas under or adjacent to seeding rows have been assessed (*e.g.* Davies *et al.* 2008, Blackwell *et al.* 2016, Sale *et al.* 2019). Lime slotting by mechanically cutting slots, 0.15 m wide and 0.8 m deep, in the profile to remove soil, mixing that soil with lime at 20 t lime/ha and then replacing the amended soil back to the slot, was effective in increasing soil pH (Figure 3a) in the slot (Kirchhof *et al.* 1995) and resulted in 46% of the yield of a completely amended soil (Jayawardane *et al.* 1995). However the use of such high lime rates and specialised intensive machinery limit the practicality of this method in dryland cropping systems.

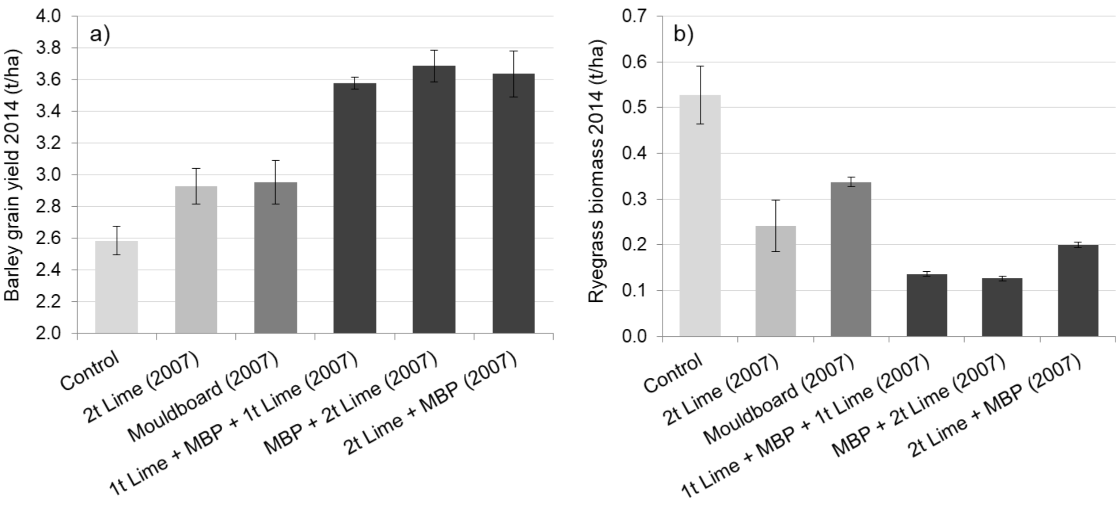

Figure 2. Impact of lime application and mouldboard ploughing (MBP) applied in 2007 on: a) barley grain yield (t/ha); b) above-ground ryegrass biomass (t/ha, right) in 2014. For treatments with lime, all were surface applied at total rate of 2 t/ha either without incorporation (2t Lime); split with half (1 t/ha) before and after MBP (1t + MBP + 1t); all applied before MBP (2t + MBP); or all applied after MBP (MBP + 2t). Bars show standard error of the mean of 4 replicates (adapted from Davies *et al*. 2015b)

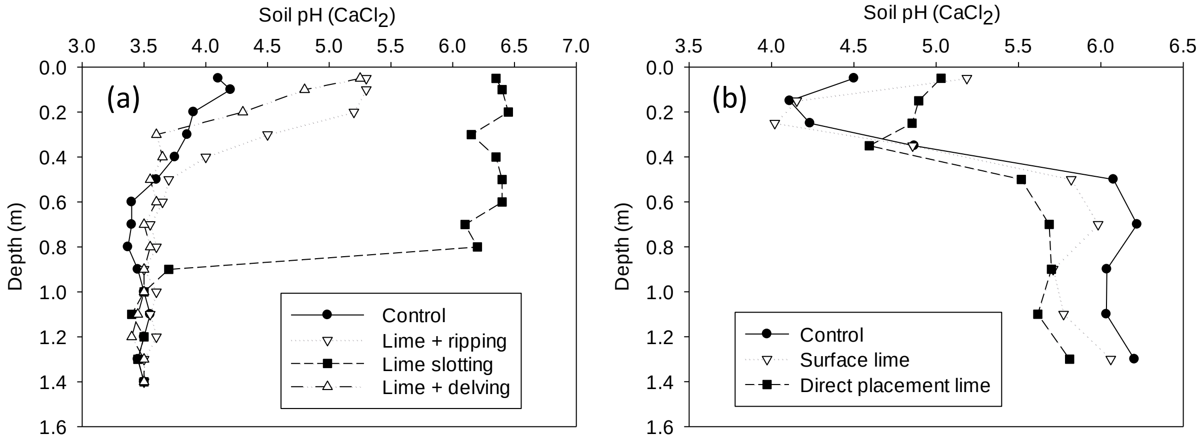

Figure 3. Impact of lime application and placement on soil pH profiles for: a) a yellow Podosol showing untreated (control), lime followed by ripping or delving and slotting of lime amended soil (adapted from Kirchhof *et al.* 1995); and b) a Chromosol at Rutherglen, Victoria, showing untreated (control), surface lime and direct deep (0.3 m) lime placement (adapted from Condon *et al.* 2018)

Direct placement of lime has been achieved with modified deep rippers, fertiliser spreaders and air delivery systems to create machines that blow lime into subsoil seams to a depth of 0.3 to 0.4 m (Davies *et al.* 2008, Li and Burns 2016). This machinery can ameliorate subsoil acidity to the depth of placement (Figure 3b) and also decrease soil strength (Davies *et al.* 2008, Li and Burns 2016, Condon *et al.* 2018). Yield responses from this approach have been mixed, with crop yields failing to respond at a range of sites in southern NSW (Swan *et al.* 2011, Li and Burns 2016) but was shown to increase wheat yield by 20-30% in WA deep sands with acidic subsoils (Davies *et al.* 2008, Gazey and Davies 2009). For the southern NSW sites, drought conditions experienced during the trial years 2007-9 may have limited the opportunity for a crop response (Swan *et al.* 2011). Direct lime placement and partial amelioration of acidic subsoils enables lime application rates to be decreased, potentially to economically viable rates.

Application rates of dolomite or lime of 2.3 and 2.5 t/ha, respectively, ameliorated the acidity in the 10-30 cm of a Chromosol at Rutherglen, Victoria (Figure 3b) resulting in more than a 10% increase in canola yield compared with an unlimed control (Condon *et al.* 2018). Some versions of direct placement equipment can apply organic material and other inorganic amendments to specific layers of the soil, allowing amelioration of acidity and provision of subsoil nutrition, thereby addressing multiple crop productivity constraints (Condon *et al.* 2018). Apart from the need of specialised equipment and slow application process, a major limitation to success of direct deep lime placement is poor vertical distribution and a discontinuity of the ameliorated subsoil which would likely limit the benefit obtained.

Clay spreading and incorporation on sands

Addition of clay-rich subsoil to sands, known as claying, was first trialled in 1968 by South Australian farmer, Clem Obst, near Bordertown. After spreading a clay-rich subsoil on a sandy rise following excavation of a new dam, Obst (1994) recalls an immediate and long-lasting improvement in soil wettability, successfully growing clover and lucerne on clay-spread areas in following years. It is now estimated that 0.16 Mha of land have been clay modified in southern and Western Australia (Churchman *et al*. 2014).

Where available, incorporation of clay subsoil provides a permanent amelioration of soil water repellence but can also modify soil pH, nutritional status, moisture dynamics, carbon sequestration, soil stability and biological activity. Improved plant nutrition, particularly potassium from the applied clay, and greater water infiltration are key factors behind improved productivity on clayed soils (Hall *et al.* 2010). Substantial benefits (up to 22 t/ha increases) to soil organic carbon (SOC) stocks (0-30 cm) have also been associated with increased clay content (Schapel *et al.* 2017, 2018), although the benefits of this on improved biological fertility and nutrient retention and supply have been poorly quantified to date.

Surface spreading of clay is undertaken when clay B-horizon subsoils are too deep to be delved effectively. Clay spreading involves excavation and broadcast spreading of a clay-rich subsoil from a large pit over deep, typically repellent, sands (Davenport *et al.* 2011). Spreading is typically undertaken using carry graders, purpose-built spreaders or heavy-duty multi-spreaders. Once spread, a range of deep cultivation approaches (*e.g.* tynes, off-set discs, harrows, rotary hoe) are used to incorporate the clay into the top 0.1 to 0.2 m. Subsoil clays are typically spread at rates of 100-300 t/ha, aiming to increase the topsoil clay content to the 3-6% clay required to overcome repellence (Hall *et al.* 2010, Davenport *et al.* 2011). High rates (200 t/ha or more) can be difficult to incorporate effectively and can lead to negative impacts, such as soil sealing, poor emergence and restricted root development (Davenport *et al.* 2011). Implements for deeper incorporation, such as rotary spaders and large-diameter deep working offset discs help minimise this risk.

Although expensive, claying practices have been shown to double crop yields, with an expectation of permanence (Cann 2000). Yield increases of 0.3-0.6 t/ha have been reported on a WA sandplain soil (Hall *et al.* 2010).

Incorporation of organic amendments

Organic amendments have the potential to provide benefits over and above their nutritional value alone including altering:

- physical condition through changing structural stability, porosity and bulk density, which impact root growth and water dynamics;
- chemical condition through changing pH buffering, cation exchange capacity, and chelation which affect nutrient supply and retention; and
- biological functions including nutrient cycling rates, and the balance between beneficial and pathogenic organisms.

The use of organic amendments in agriculture has been reviewed previously (Edmeades 2003, Quilty and Cattle 2011, Abbott *et al.* 2018). In general, these reviews focus on results from surface application of amendments, often in terms of disposal of 'wastes', where there has been a focus on nutrient budgets. These overseas studies have often failed to account for other potential benefits to productivity by using these organic amendments if soil physicochemical constraints are present. A recent Australian study (Celestina *et al.* 2018) compared surface and subsoil application of organic amendments or additional matching inorganic fertiliser applications and found that over the first two years following application the yield response could generally be attributed to additional nutrient supply, particularly nitrogen. The impact of any amendment in overcoming a physicochemical constraint in the subsoil will be negated if there is either no subsoil water , as occurs in very low rainfall years, or when the crop can rely on water in the topsoil and so can be highly season-dependant (Nuttall and Armstrong 2010). Similarly, no long-term beneficial effect of the amendments will occur if there are no physical constraints present, such as occurs on many well-structured soils, such as vertosols. Furthermore, it may take several years for the benefits of organic amendments to become evident, as they result not only from the short-term direct nutrient effects, but longer-term indirect effects. Indirect effects include those resulting from altered root growth and distribution, as well as enhanced aggregation resulting from microbial processes (hyphal binding, extracellular polymer binding, Six *et al*. 2004, Tisdall and Oades 1978). This has been demonstrated in recent research targeting poorly structured sodic subsoils where subsoil manuring (chicken litter placed at 0.3-0.4 m) improved grain yields through both improved crop nutrition and soil structure (Gill *et al.* 2019, Sale *et al*. 2019). Gill *et al.* (2019) demonstrated seasonal impacts on response with no difference between surface and subsoil manuring at one site in an 'average' rainfall season but a significant advantage of subsoil manuring over surface manuring in a season with a dry spring, where the crop was reliant on subsoil water reserves during grain filling. Transport and application costs can be challenging for profitability of organic amendments although, where successfully applied to overcome subsoil constraints, the potential for profitable outcomes has been demonstrated (Sale and

Malcolm 2015, Trengove and Sherriff 2018, Gill *et al.* 2019). Further work appears necessary to attribute growth and yield impacts from deep organic amendments to nutritional or other mechanisms and to assess economic feasibility (Gill *et al.* 2019, Celestina *et al.* 2018, 2019).

In sands, rotary spading, topsoil slotting, soil inversion or direct deep placement can be used to incorporate organic amendments into the profile. In South Australia (SA) the combination of deep ripping to 0.3 m with surface applied chicken litter (5 t/ha) and/or high fertiliser rates has been evaluated (Trengove and Sherriff 2018). The outcomes demonstrate strong seasonal and rotational effects, with barley (2016) responding to increased nutrition, and lentils (2017) responding to ripping. Overall, the cumulative three-year yield gains for a wheat-barley-lentil rotation above the 4.4 t/ha control were +3 t/ha, +2.4 t/ha, and +2 t/ha under high annual fertiliser rates, deep ripping and chicken litter treatments, respectively. The costs associated with high fertiliser treatments, compared with lower costs of ripping or chicken litter, result in ripping alone having the highest return on investment, followed by ripping with chicken litter (Trengove and Sherriff 2018).

For neutral-to-alkaline soils with clay subsoils and multiple physicochemical constraints, it is generally necessary to ameliorate chemically these subsoils using amendments such as gypsum or nutrient-rich organic matter. Purely physical amelioration of these soils, such as deep ripping, are often ineffective (Nuttall *et al.* 2005, Armstrong *et al.* 2009). Use of nutrient-rich organic matter has proven effective but the processes underpinning this remains unclear. Improved productivity is associated with additional nutrition (Celestina *et al.* 2018) and increased use of subsoil water from improvements in both physical structure and fertility of the subsoil (Gill *et al.* 2012, Gill *et al.* 2019). Yield responses of 27 up to 250% over an untreated control have been achieved in the Victorian High Rainfall Zone (Sale *et al.* 2019, Gill *et al.* 2019). These yield increases arising from deep placement of amendments generally last several years, which is an important consideration when needing to offset high upfront costs of implementation (Sale and Malcolm 2015).

Economic consequences of strategic deep tillage

For the purpose of understanding the economic impacts of strategic deep tillage, tillage treatments have been categorised as either deep ripping or soil mixing/inversion.

Deep ripping is most effective on deep sandy-textured soils and less effective on heavy clay soils. Armstrong *et al.* (2009) provides a summary of yield responses to deep ripping by soil type. On responsive soils, average wheat yield responses were found to be 33% in New South Wales, 10-23% in SA, 23-25% in Victoria and 20-47% in WA.

Deep ripping generally costs $40-100/ha depending on soil type (Table 2), with benefits lasting about 3 seasons (Isbister 2017). Deep ripping is generally not cost-effective unless conducted on a soil with high productive potential, or in conjunction with other amelioration options to address other soil constraints, such as acidity, nutrient deficiency or toxicity, sodicity or topsoil water repellence (Armstrong *et al.* 2009, Petersen *et al.* 2019).

Soil mixing or inversion provides long-term and reliable benefits for most repellent soils. Davies *et al.* (2019) reviewed trial data from WA during 2009-2018 and found that cereal responses to soil mixing/inversion range from 56-86% in the first and second year after treatment, and 11-49% in the third and subsequent years. Yield response for canola was approximately 24%, and that for lupin 20-50%. Field research results in SA are similar, although soil mixing/inversion resulted in very high yield increases (200%) on some soils with low (0.5 t/ha) control yields (Fraser *et al.* 2016, Macdonald *et al.* 2019).

Soil mixing/inversion can cost $50-150/ha depending on the soil type and technique (Table 2) and benefits last more than 10 years (Davies *et al.* 2015b). Soil mixing or inversion is generally worthwhile even when yield potential is low and other soil constraints are present.

Significantly higher benefits are generated when strategic deep tillage and other amelioration options are combined to address limiting constraints within a soil. This may include use of more than one strategic deep tillage method (*e.g*. deep ripping as well soil mixing/inversion) as well as incorporating amendments such as fertilisers, clay, lime, and/or organic matter.

Recent research in Victoria on a Sodosol in a High Rainfall environment (550 mm annual rainfall) showed deep ripping alone to have little impact on yields, but deep ripping in conjunction with gypsum, nutrients, wheat straw+ nutrients or chicken manure resulted in yield responses of 12-16% on high yielding soils (mean grain yield of control = 6.3 t/ha, unpublished data). Even higher yield responses (up to 200%) have been recorded following application of nutrient-rich organic matter to clay soils in high rainfall environments in South Australia and southern NSW (unpublished data). Assuming a $300/t grain price, this is a gross benefit of $225-300/ha. Sale and Malcolm (2015) found amending sodic soils by subsoil manuring (20 t/ha) to be expensive ($1,300-$1,400/ha) but cost effective, generating a net present value over 4 years of $1,390-$1,810/ha. The question about whether similar or better returns could be achieved with improved nutrition alone remains open (Celestine *et al.* 2019).

Higher profits are generally gained by spending a limited budget addressing all constraints within an area of the farm, rather than addressing one constraint over a larger area. This is because the full yield benefit of any one soil amelioration technique cannot be realised until other limiting constraints are addressed. However, it can also be profitable to undertake low cost and easy to implement partial-amelioration options if they can be applied to larger areas of the farm in a given year, and still provide a portion of the yield benefit (Blackwell *et al.* 2014). Prioritising constraints to be addressed, or regions of the farm to ameliorate, depends on local soil conditions, the cost of amelioration, the attainable yield and the price of grain. The WA Department of Primary Industries and Regional Development have developed a decision tool called ROSA (Ranking Options for Soil Amelioration) to help consultants and farmers make this comparison (Petersen *et al.* 2019).

ROSA can be used to illustrate the benefits of addressing multiple constraints rather than single constraints in WA. For example, a sandy or deep sandy duplex soil with significant topsoil water repellence, subsoil compaction and acidity (pH: 0-0.1 m = 4.8, pH: 0.1-0.3 m = 4.5) issues. The net present value (NPV) over a five-year period of addressing single constraints of water repellence (through soil mixing/inversion) or subsoil compaction (through deep ripping) is approximately $140/ha and $30/ha, respectively. However, addressing multiple constraints of water repellence, subsoil compaction and acidity (through soil mixing, deep ripping and liming) results in a 5-year NPV of approximately $1,440/ha.

It is important to note that the benefits and costs of strategic deep tillage differ significantly across regions of Australia; these examples should be considered as indicative only of the benefits that can be gained from strategic deep tillage for soil amelioration.

Future directions in strategic deep tillage

Strategic deep tillage, often in conjunction with an amendment, can be used successfully to overcome a range of soil physicochemical constraints. The high cost of such approaches are a barrier and grain growers need greater confidence that the interventions will likely result in profitable productivity increases over the medium to long-term. Following amelioration with strategic deep tillage, management strategies based on long-term controlled traffic, no-till and stubble retention will enable the improved yield potential from overcoming soil constraints to be maximised and sustained and reduce the risk of negative environmental impacts.

The most convincing current evidence for strategic deep tillage exists for deep sandy-textured soils or texture contrast soils with deep A-horizons. On these soils, improved rooting depths can be obtained by removal of constraints and the weakly developed soil structure is less susceptible to damage from deep tillage intervention. There is a need to better understand how soil fertility and biological activity can be improved and maintained following amelioration to sustain higher potential yields on these soils. Soil amelioration may provide an opportunity to build soil organic carbon levels as more of the soil profile becomes biologically active, soils are mixed and production of above- and below-ground plant biomass increases. However, apart from clay addition to sands, a cost-effective system or strategy to build soil carbon on many dryland cropping soils remains elusive.

The nature of physicochemical constraints associated with higher clay content neutral-alkaline soils used for grain production presents particular challenges. High clay content, combined with low rainfall and high evaporation environments, results in high soil strengths and increased energy costs to physically alter the subsoils. Furthermore, many of the constraints are chemical, such as high sodicity, leading to dispersion and poor structure when soils are wet and high penetrometer resistance when dry. The severity also usually increases with depth. Amelioration then almost always requires amendment addition, likely at depth, further increasing cost and reducing the feasibility of such approaches. In regions with higher, more reliable rainfall, large increases in yields may sometimes justify the initial significant financial investment required, but there remains considerable uncertainty in predicting when such interventions will improve yield and profit. Targeted subsoil interventions and the promise of stimulating further 'biological' improvement of the subsoil condition following intervention requires further research. Where amelioration is not financially or logistically feasible, growers will need use better adapted, more tolerant crop varieties or species and manage agronomic inputs to match the constrained yield potential.

Amelioration of soil constraints can, in part, enable a reduction in the gap between current and potential water limited grain yields but capturing and sustaining this benefit will require the simultaneous implementation of a range of management strategies to reduce the range of abiotic and biotic constraints that limit grains productivity.

References

Abbott LK, Macdonald LM, Wong MTF *et al.* (2018) Potential roles of biological amendments for profitable grain production – A review. *Agriculture, Ecosystems and Environment* **265**, 34-50

Adcock D, McNeill AM, McDonald GK, Armstrong RD (2007) Subsoil constraints to crop production on neutral and alkaline soils in south-eastern Australia: A review of current knowledge and management strategies. *Australian Journal of Experimental Agriculture* **47**, 1245-1261

Anderson DL, Hendrick JG (1983) Subsoil lime injector. *Soil Science Society of America Journal* **47**, 337-339

Armstrong RD, Eagle C, Jarwal SD (2007) Application of composted pig bedding litter on a Vertosol and Sodosol soil. 1. Effect on crop growth and soil water. *Australian Journal of Experimental Agriculture* **47**, 689-699

Armstrong RD, Davies SL, Kirkegaard JA (2009) Deep ripping not appropriate for all soil types. Deep Ripping Factsheet (Grains Research and Development Corporation: Canberra) www.grdc.com.au/resources-and-publications/all-publications/factsheets/2009/06/grdc-fs-deepripping

Aulakh JS, Price AJ, Enloe SF *et al.* (2012) Integrated Palmer amaranth management in glufosinate-resistant cotton: I. Soil inversion, high residue cover crops and herbicide regimes. *Agronomy* **2**, 295-311

Bailey G, Hughes B, Tonkin R *et al.* (2010) Gross soil modification of duplex soils through delving and spading. *Proceedings of 19th World Congress of Soil Science*, Brisbane, Queensland p 4

Bailey G, Hughes B (2012) An observational study of clay delving and its impact on the A2 horizon in sand over clay soils. *Proceedings of 5th Joint Australian and New Zealand Soil Science Conference* Hobart, Tasmania

Belford RK, Dracup M, Tennant D (1992) Limitations to growth and yield of cereal and lupin crops on duplex soils. *Australian Journal of Experimental Agriculture* **32**, 929-945

Betti G, Grant C, Churchman G, Murray R (2015) Increased profile wettability in texture-contrast soils from clay delving: case studies in South Australia. *Soil Research* **53**, 125-136

Betti G, Grant CD, Murray RS, Churchman GJ (2016) Size of subsoil clods affects soil-water availability in sand-clay mixtures. *Soil Research* **54**, 27-290

Betti G, Hall D, Davies S, Edwards T (2017) Clay delving for the amelioration of water repellent soils: first year results from a site near Esperance. *GRDC Grains Research Updates*, Perth, Western Australia www.giwa.org.au/2017researchupdates

Blackwell PS (2000) Management of water repellency in Australia, and risks associated with preferential flow, pesticide concentration and leaching. *Journal of Hydrology* **231-232**, 384-395

Blackwell P, Hagan J, Davies S *et al.* (2014) Smart no-till furrow sowing to optimise whole-farm profit on non-wetting soil. *Agribusiness Crop Updates*, Perth, Western Australia (Department of Agriculture and Food WA and Grains Research and Development Corporation) www.giwa.org.au/2014-crop-updates

Blackwell PS, Isbister B, Riethmuller G *et al*. (2016) Deeper ripping and topsoil slotting to overcome subsoil compaction and other constraints more economically: way to go! *GRDC Grains Research Updates* Perth, Western Australia www.giwa.org.au/2016researchupdates

Bond RD (1964) The influence of the microflora on the physical properties of soils. II. Field studies on water repellent sands. *Australian Journal of Soil Research* **2**, 123-131

Brautigan DJ, Rengasamy P, Chittleborough DJ (2012) Aluminium speciation and phytotoxicity in alkaline soils. *Plant and Soil* **360**, 187-196

Cann MA (2000) Clay spreading on water repellent sands in the south east of South Australia – promoting sustainable agriculture. *Journal of Hydrology* 231-232, 333-341

Celestina C, Midwood J Sherriff S *et al.* (2018) Crop yield responses to surface and subsoil applications of poultry litter and inorganic fertiliser in south-eastern Australia, *Crop and Pasture Science* **69**, 303-316

Celestina C, Hunt JR, Sale PWG, Franks AE (2019) Attribution of crop yield responses to application of organic amendments: A critical review. *Soil and Tillage Research* **186**, 135-145

Chan KY (1992) Development of seasonal water repellence under direct drilling. *Soil Science Society of America Journal* **56**, 326-329

Chan KY, Oates A, Swan AD *et al*. (2006) Agronomic consequences of tractor wheel compaction on a clay soil. *Soil and Tillage Research* **89**, 13-21

Churchman GJ, Noble A, Bailey G *et al.* (2014) Clay addition and redistribution to enhance carbon sequestration in soils. In (Eds. A Hartemink, K McSweeney) "Soil Carbon", Progress in Soil Science (Springer: Cham)

Condon JR, Moroni JS, Zander A *et al.* (2018) Deep ripping incorporation of novel amendments to ameliorate subsurface acidity. *Proceedings of National Soils Conference* Canberra, ACT www.soilscienceaustralia.org.au/media/content/files/Proceedings_Natl._Soil_Sci_Conf-_Canberra_18-23_Nov_2018_FINAL_reduced_size.pdf

Conyers MK, Scott BJ (1989) The influence of surface incorporated lime on subsurface soil acidity. *Australian Journal of Experimental Agriculture* **29**, 201-207

Coventry DR, Reeves TG, Brooke HD *et al.* (1987) Increasing wheat yields in north-eastern Victoria by liming and deep ripping. *Australian Journal of Experimental Agriculture* **27**, 679-685

Dang YP, Dalal RC, Buck SR *et al*. (2010) Diagnosis, extent, impacts, and management of subsoil constraints in the northern grains cropping region of Australia. *Australian Journal of Soil Research* **48**, 105-119

Davenport D, Hughes B, Davies S, Hall D (2011) Spread, delve, spade, invert: a best practice guide to the addition of clay to sandy soils. (Grains Research and Development Corporation and the Agricultural Bureau of South Australia Incorporated) www.grdc.com.au/resources-and-publications/all-publications/bookshop/2011/09/grdc-booklet-spreaddelvespadeinvert

Davies SL, Gazey C, Gartner D (2008) Long-term effect of lime incorporated directly into acid subsoils on soil properties and growth of wheat. *Proceedings of Australia and New Zealand Soil Societies Conference*. Massey University, Palmerston North, NZ

Davies SL, Newman P, Best B (2010) Impact of soil inversion, soil dilution and claying on non-wetting sandplain soils. *Proceedings of 2010 Agribusiness Crop Updates* Perth Western Australia (Department of Agriculture and Food, Western Australia and Grains Research and Development Corporation)

Davies SL, Blackwell PS, Bakker DM *et al.* (2013) Deep soil cultivation to create improved soil profiles for dryland crop production. *Proceedings of 2013 Society for Engineering in Agriculture (SEAg) Conference* Mandurah, Western Australia.

Davies SL, Gazey C, Parker W *et al.* (2015a) Lime incorporation into acidic soils: assessing cost, efficacy, value and novel approaches. *Proceedings 2015 Agribusiness Crop Updates* Perth Western Australia www.giwa.org.au/2015-crop-updates

Davies SL, Hagan J, Reynolds C *et al*. (2015b) Long-term responses to soil amelioration – benefits will last more than 10 years! *Proceedings 2015 Agribusiness Crop Updates* Perth Western Australia www.giwa.org.au/2015-crop-updates

Davies S, Boyes T, Reynolds C *et al*. (2018) Understanding the impact of a comprehensive range of deep tillage practices on crop performance and soil properties for two water repellent soil types. *GRDC Grains Research Updates*, Perth, Western Australia www.giwa.org.au/2018researchupdates

Davies S, Betti G, Edwards T, McDonald G *et al*. (2019) Ten years of managing water repellent soils research in Western Australia – a review of current progress and future opportunities. *GRDC Grains Research Updates*, Perth, Western Australia. www.giwa.org.au/2019researchupdates

Delroy ND, Bowden JW (1986) Effect of deep ripping the previous crop, and applied nitrogen on the growth and yield of a wheat crop. *Australian Journal of Experimental Agriculture* **26**, 469-479

Desbiolles JMA, Fielke JM, Chaplin P (1997) An application of tine configuration to obtain subsoil delving for the management of non-wetting sands. *Proceedings of Third International Conference on Soil Dynamics* (ICSD III) Tiberias, Israel pp. 201-210

Doerr SH, Shakesby RA, Walsh RPD (2000) Soil water repellency: its causes, characteristics and hydro-geomorphological significance. *Earth Science Reviews* **51**, 33-65

Dolling PJ, Porter WM (1994) Acidification rates in the central wheatbelt of Western Australia. 1. On a deep yellow sand. *Australian Journal of Experimental Agriculture* **34**, 1155-1164

Dolling PJ, Porter WM, Rowland IC (1994) Acidification rates in the central wheatbelt of Western Australia. 2. On a sandy duplex soil. *Australian Journal of Experimental Agriculture* **34**, 1165-1172

Edmeades DC (2003) The long-term effects of manures and fertilisers on soil productivity and quality: a review. *Nutrient Cycling in Agroecosystems* **66**, 165-180

Edwards T, Davies S, McDonald G *et al.* (2018) Understanding interactions between pre-emergent herbicides and inversion tillage. *GRDC Grains Research Updates*, Perth, Western Australia www.giwa.org.au/2018researchupdates

Ellington A (1986) Effects of deep ripping, direct drilling, gypsum and lime on soils, wheat growth and yield. *Soil and Tillage Research* **8**, 29-49

Fletcher A, Lawes R, Weeks C (2016) Crop area increases drive earlier and dry sowing in Western Australia: implications for farming systems. *Crop and Pasture Science* **67**, 1268-1280

Franco CMM, Tate ME, Oades JM (1995) Studies on non-wetting sands. I. The role of intrinsic particulate organic matter in the development of water-repellency in non-wetting sands. *Australian Journal of Soil Research* **33**, 253-263

Franco CM, Clarke PJ,Tate ME, Oades JM (2000) Hydrophobic properties and chemical characterisation of natural water repellent materials in Australian Sands. *Journal of Hydrology* **231-232**, 47-58

Fraser M, Davenport D, Bartel B, Wilhelm N (2016) Overcoming constraints on sandy soils – amelioration strategies to boost crop production. *GRDC Grains Research Updates* www.grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2016/02/overcoming-constraints-on-sandy-soils-amelioration-strategies-to-boost-crop-production

Gazey C, Davies S (2009) “Soil acidity: a guide for WA farmers and consultants” Bulletin 4784 (Department of Agriculture and Food, Western Australia, Perth)

Gazey C, Andrew J, Griffen E (2013) Soil acidity. In “Report card on sustainable natural resource use in agriculture” (Department of Agriculture and Food, Western Australia) www.agric.wa.gov.au/climate-land-water/resource-assessment/report-card-conditions-and-trends

Gill JS, Sale PWG, Tang C (2008) Amelioration of dense sodic subsoil using organic amendments increases wheat yield more than using gypsum in a high rainfall zone of southern Australia. *Field Crops Research* **107**, 265-275

Gill JS, Clark GJ, Sale PW *et al.* (2012) Deep placement of organic amendments in dense sodic subsoil increases summer fallow efficiency and the use of deep soil water by crops. *Plant and Soil* **359**, 57-69

Gill JS, Sale PW, Peries RR, Tang C (2019) Crop responses to subsoil manuring. II. Comparing surface and subsoil manuring in north-eastern Victoria from 2011 to 2012. *Crop and Pasture Science* **70**, 318-326

Hagan J, Blackwell P, Davies S, Isbister B (2015) Tools and planning to ease the transition to Controlled Traffic Farming. *Proceedings 2015 Agribusiness Crop Updates* Perth Western Australia. (Department of Agriculture and Food, WA and Grains Research and Development Corporation) www.giwa.org.au/2015-crop-updates

Hall DJM, Jones HR, Crabtree WL, Daniels T (2010) Claying and deep ripping can increase crop yields and profits on water repellent sands with marginal fertility in southern Western Australia. *Australian Journal of Soil Research* **48**, 178-187

Hall JAS, Maschmedt DJ, Billing NB (2009) The soils of southern South Australia. The South Australian Land and Soil Book Series, Volume 1; “Geological Survey of South Australia” Bulletin 56 (Department of Water, Land and Biodiversity Conservation: Government of South Australia)

Hamblin AP, Tennant D (1979) Interaction between soil type and tillage level in a dryland situation. *Australian Journal of Soil Research* **17**, 177-189

Hamza MA, Anderson WK (2003) Responses of soil properties and grain yields to deep ripping and gypsum application in a compacted loamy sand soil contrasted with a sandy clay loam soil in Western Australia. *Australian Journal of Agricultural Research* **54**, 273-282

Hamza MA, Anderson WK (2005) Soil compaction in cropping systems: a review of the nature, causes and possible solutions. *Soil and Tillage Research* **82**, 121-145

Hamza MA, Riethmuller GP, Anderson WK (2013) Experimental subsoiling by in-line and shallow deep tines. *Soil Research* **51**, 477-483

Henderson C, Levett A, Lisle D (1988) The effects of soil water content and bulk density on the compactibility and soil penetration resistance of some Western Australian sandy soils. *Australian Journal of Soil Research* **26**, 391-400

Hochman Z, Gobbett D, Horana H, Navarro Garciac J (2016) Data rich yield gap analysis of wheat in Australia. *Field Crops Research* **197**, 97-106

Isbell RF and National Committee on Soil and Terrain (2016) "The Australian Soil Classification" Second Edition (CSIRO Publishing: Canberra)

Isbister B, Hagan J, Blackwell PS (2016) The changing options for soil compaction management in the WA wheatbelt. *GRDC Grains Research Updates*, Perth, Western Australia www.giwa.org.au/2016researchupdates

Isbister B (2017) Deep-ripping explained. *Ground Cover* Issue 126 www.grdc.com.au/resources-and-publications/groundcover/ground-cover-issue-126-january-february-2017/deep-ripping-explained

Jarvis RJ (1983) Deep ripping produces wheat yield responses. *Australasian Field Crops Newsletter* **18**, 104-106

Jarvis RJ (1986a) The history of deep tillage research in Western Australia. In (Ed. MW Perry) "A review of deep tillage research in Western Australia" Report 3, pp 1-5 (Department of Agriculture and Food: Perth, Western Australia)

Jarvis RJ (1986b) Crop response to deep tillage. In (Ed. MW Perry) "A review of deep tillage research in Western Australia" Report 3 pp 40-51 (Department of Agriculture and Food: Perth, Western Australia)

Jayawardane NS, Barrs HD, Muirhead WA *et al.* (1995) Lime-slotting technique to ameliorate subsoil acidity in a clay soil II. Effects on medic root-growth, water extraction and yield. *Soil Research* **33**, 443-459

King PM (1981) Comparison of methods for measuring severity of water repellence of sandy soils and assessment of some factors that affect its measurement. *Australian Journal of Soil Research* **19**, 275-285

Kirchhof G, Jayawardane NS, Blackwell J, Murray E (1995) Lime-slotting technique to ameliorate subsoil acidity in a clay soil 1. Effects on soil-pH and physical characteristics. *Soil Research* **33**, 425-441

Kirkegaard JA, Angus J, Swan T *et al*. (2008) Ripping yarns: 25 years of variable responses to ripping clay soils in south-eastern Australia. *Proceedings of 14th Australian Agronomy Conference* Adelaide, South Australia agronomyaustraliaproceedings.org/index.php/2008

Li GD, Burns H (2016) Managing Subsoil Acidity: 3-D Ripping Machine. GRDC DAN00206, NSW Department of Primary Industries www.dpi.nsw.gov.au/agriculture/soils/acidity

Li GD, Conyers MK, Heylar KR *et al.* (2019) Long-term surface application of lime ameliorates subsurface soil acidity in the mixed farming zone of south-eastern Australia. *Geoderma*, **338**, 236-246

Macdonald L, McBeath T, Moodie M *et al*. (2019) Underperforming sandy soils – targeting constraints for cost effective amelioration. *GRDC Grains Research Updates* Adelaide, South Australia

MacEwan RJ, Crawford DM, Newton PJ, Clune TS (2010) High clay contents, dense soils, and spatial variability are the principal subsoil constraints to cropping the higher rainfall land in south-eastern Australia. *Australian Journal of Soils Research* **48**, 150-166

Mason MG, Porter WM and Cox WJ (1994) Effect of an acidifying nitrogen fertiliser and lime on soil pH and wheat yields 1. Soil effects. *Australian Journal of Experimental Agriculture* **34**, 237-246

McCallum MH, Kikegaard JA, Green T *et al.* (2004) Evidence of improved macro-porosity following perennial pasture on a duplex soil. *Australian Journal of Experimental Agriculture* **44**, 299-307

McGarry D (1993) Degradation of soil structure. In (Eds. G McTanish, W Boughton) "Degradation Processes in Australia" pp 271-305 (Longman Cheshire: Australia)

Needham P, Scholz G, Moore G (2004a) Hard layers in soils. In (Ed. G Moore) "Soilguide. A handbook for understanding and managing agricultural soils" Bulletin 4343 (Department of Agriculture, Western Australia) pp 111-115

Needham P, Moore G, Scholz G (2004b) Subsurface compaction. In (Ed. G Moore) "Soilguide. A handbook for understanding and managing agricultural soils" Bulletin 4343 (Department of Agriculture, Western Australia) pp 116-124

Newman PD, Davies SL (2010) Mouldboard plough continues to kick goals. *2010 Agribusiness Crop Updates*, Perth (Western Australia. Department of Agriculture and Food Western Australia and Grains Research and Development Corporation)

Nuttall, JG, Armstrong, RD, Connor DJ, Matassa VJ (2003) Interrelationships between soil factors potentially limiting cereal growth on alkaline soils in NW Victoria *Australian Journal of Soil Research* **41**, 277-292

Nuttall JG, Armstrong RD, Connor DJ (2005) The effect of boron tolerance, deep ripping with gypsum, and water supply on subsoil water extraction of cereals on an alkaline soil. *Australian Journal of Agricultural Research* **56**, 113-122

Nuttall JG, Davies SL, Armstrong RA, Peoples MB (2008) Testing the primer-plant concept: wheat yields can be increased on alkaline sodic soils when an effective primer phase is used. *Australian Journal of Agricultural Research* **59**, 331-338

Nuttall JG, Armstrong RD (2010) Impact of subsoil physicochemical constraints on crops grown in the Wimmera and Mallee is reduced during dry seasonal conditions. *Australian Journal of Soil Research* **48**, 125-139

Obst C (1994) Non-wetting soils: management problems and solutions at 'Pineview', Mundulla. *Proceedings of 2nd National Water Repellency Workshop*, Perth, Western Australia pp 137-139 (Grains Research and Development Corporation and the Western Australian Department of Agriculture)

Page KL, Dalal RC, Wehr JB *et al.* (2018). Management of the major chemical soil constraints affecting yields in the grain growing region of Queensland and New South Wales, Australia – a review. *Soil Research* **56**, 756-779

Parker W, Isbister B, Hall D *et al*. (2017) Longevity of deep ripping and topsoil inclusion in soils under traffic farming; evidence from the second season. *GRDC Grains Research Updates*, Perth, Western Australia. www.giwa.org.au/2017researchupdates

Parr JF (1959) Effects of vertical mulching and subsoiling on soil physical properties. *Agronomy Journal* **51,** 412-414

Peltzer SC, Matson P (2006) Windrow management for annual ryegrass control: bury, burn or bomb? *Proceedings 15th Australian Weed Conference*, Adelaide, South Australia www.weedinfo.com.au/bk_15awc.html

Petersen EH, Lemon J, Xayavong V (2019) Ranking Options for Soil Amelioration spreadsheet (ROSA). (Department of Primary Industries and Regional Development) www.agric.wa.gov.au/managing-soils/ranking-options-soil-amendments-tool

Quilty JR, Cattle SR (2011) Use and understanding of organic amendments in Australian agriculture: a review. *Soil Research* **49**, 1-26

Rebbeck M, Lynch C, Hayman PT, Sadras VO (2007) Delving of sandy surfaced soils reduces frost damage in wheat crops. *Australian Journal of Agricultural Research* **58**, 105-112

Rengasamy P, Chittleborough D, Helyar K (2003) Root-zone constraints and plant-based solutions for dryland salinity**.** *Plant and Soil* **257**, 249-260

Renton M, Flower K (2015) Occasional mouldboard ploughing slows evolution of resistance and reduces long-term weed populations in no-till systems. *Agricultural Systems* **139**, 66-75

Roberts FJ, Carbon BA (1971) Water repellence in sandy soils of south-western Australia. 1. Some studies related to field occurrence. *Field Station Record Division of Plant Industry, CSIRO* **10**, 13-20

Robertson WK, Fiskell JGA, Hutton CE *et al*. (1957) Results from subsoiling and deep fertilization of corn for 2 years. *Soil Science Society of America Journal* **21**, 340-346

Roper MM, Davies SL, Blackwell PS *et al*. (2015) Management options for water-repellent soils in Australian dryland agriculture. *Soil Research* **53**, 786-806

Sale P, Malcolm B (2015) Amending sodic soils using sub-soil manure: economic analysis of crop trials in the high rainfall zone of Victoria. *AFBM Journal* **12**, 22-31

Sale PW, Gill JS, Peries RR, Tang C (2019) Crop responses to subsoil manuring. I. Results in south-western Victoria from 2009 to 2012. *Crop and Pasture Science* **70**, 44-54

Scanlan CA, Davies SL (2019) Soil mixing and redistribution by strategic deep tillage in a sandy soil. *Soil and Tillage Research* **185**, 139-145

Schapel A, Davenport D, Marschner P (2017) Increases in organic carbon concentration and stock after clay addition to sands: validation of sampling methodology and effects of modification method. *Soil Research* **55**, 124-133

Schapel A, Marschner P, Churchman J (2018) Clay amount and distribution influence organic carbon content in sand with subsoil clay addition. *Soil and Tillage Research* **184**, 253-260

Scott BJ, Conyers MK (1995) Magnesium nutrition and lime movement down the profile. "*Making better fertiliser, lime & gypsum recommendations"* (Eds. IG Fenton, PW Orchard) pp 1-18 (Agricultural Research Institute: Wagga Wagga, Australia)

Shaw RJ, Brebber L, Ahern CR, Weinand MMG (1994) A review of sodicity and sodic soil behaviour in Queensland. *Australian Journal of Soil Research* **32**, 143-172

Spoor G (2006) Alleviation of soil compaction: requirements, equipment and techniques. *Soil Use and Management* **22**, 113-122

Six J, Bossuyt H, Degryze S, Denef K (2004) A history of research on the link between microaggregates, soil biota, and soil organic matter dynamics. *Soil and Tillage Research* **79**, 7-31

Sumner ME, Shahandeh H, Bouton J, Hammel J (1986) Amelioration of an acid profile through deep liming and surface application of gypsum. *Soil Science Society of America Journal* **50**, 1254-1258

Swan T, Kirkegaard J, Angus J *et al.* (2011) Potential impacts of subsoils constraints on canola production in southern NSW. *Proceedings of 17th Australian Research Assembly on Brassicas (ARAB)*, Wagga Wagga, NSW www.australianoilseeds.com/conferences_workshops/ARAB/arab_2011

Tang C, Raphael C, Rengel Z, Bowden JW (2000) Understanding subsoil acidification: effect of nitrogen transformation and nitrogen leaching. *Australian Journal of Soil Research* **38**, 837-849

Tang C (2004) Causes and management of subsoil acidity. *SuperSoil 2004: 3rd Australian New Zealand Soils Conference* University of Sydney, Australia www.regional.org.au/au/asssi/supersoil2004

Tennant D, Scholz G, Dixon J, Purdie B (1992) Physical and chemical characteristics of duplex soils and their distribution in the south-west of Western Australia. *Australian Journal of Experimental Agriculture* **32**, 827-843

Tisdall JM, Oades JM (1978) Organic matter and water-stable aggregates in soils. *Journal of Soil Science* **33**, 141-163

Trengove S, Sherriff S (2018) Amelioration of sandy soils – opportunities for long term improvement. *GRDC Grains Research Updates* Adelaide, South Australia www.grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/past-update-proceedings/2018/grdc-grains-research-update-adelaide-2018

Ucgul M, Saunders C, Fielke JM (2017) Discrete element modelling of top soil burial using a full scale mouldboard plough under field conditions. *Biosystems Engineering* **160**, 140-153

Ucgul M, Saunders C, Li P *et al.* (2018) Analyzing the mixing performance of a rotary spader using digital image processing and discrete element modelling (DEM). *Computers and Electronics in Agriculture* **151**, 1-10

Ucgul M, Saunders C, Desbiolles JMA *et al*. (2019) Improving the effectiveness of overcoming constraints by optimising soil amelioration practices. GRDC Grains Research Updates Perth, Western Australia. (Grains Research and Development Corporation) www.giwa.org.au/2019researchupdates

Unkovich M (2014) A review of the potential constraints to crop production on sandy soils in low rainfall south-eastern Australia and priorities for research. Report for GRDC Low Rainfall Zone Regional Cropping Solutions Network (Grains Research and Development Corporation) www.grdc.com.au/research/reports/report?id=5999

van Gool D (2016) Identifying soil constraints that limit wheat yield in South-West Western Australia. Resource Management technical report 399 (Department of Agriculture & Food, Western Australia, Perth) www.agric.wa.gov.au/managing-soils/soil-constraints-limit-wheat-yield-south-west-western-australia

van Gool D, Stuart-Street A, Tille P (2018) Distribution of classified soils in south-west Western Australia. Resource Management Technical Report 401 (Department of Primary Industries and Regional Development: Perth) www.agric.wa.gov.au/identifying-wa-soils/soil-classification

Whitten MG, Wong MTF, Rate AW (2000) Amelioration of subsurface acidity in the south-west of Western Australia: downward movement and mass balance of surface-incorporated lime after 2-15 years. *Soil Research* **38**, 711-728

Williams CH (1980). Soil acidification under clover pasture. *Australian Journal of Experimental Agriculture and Animal Husbandry*. **20**, 561-67

Yunusa IA, Newton PJ (2003) Plants for amelioration of subsoil constraints and hydrological control: the primer-plant concept. *Plant and Soil* 257, 261-281