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REVIEW ARTICLE

New insights into high soil strength and crop plants; implications for grain crop production in the Australian environment

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Abstract High soil strength is a problem in grain production systems worldwide. It is most severe in deep sands where the high strength occurs at greater depth, and is therefore more difficult to remedy. High strength is not an intrinsic soil physical property but the outcome of abiotic, biotic, climatic and management factors. Consequently, soil strength needs to be measured in situ with a penetrometer which, despite imperfections, provides approximate benchmarks. Following examination of laboratory, glasshouse and field literature, we hypothesise that the primary effect of high soil strength on crops is a reduction in tillering or branching, resulting in reduced radiation interception, crop transpiration and grain density (grains m^{-2}). This effect appears to be manifest *via* strigolactone hormones. While deep tillage allows deeper root growth and access to more water in deep soil layers, we contend that it is the direct effects of hormones on shoot development which has the largest effect on yield. The development of high soil strength cropping environments is not simply a function of soil properties and increased machinery mass and traffic frequency, it arises from a confluence of these with the farming system, the climate and perhaps plant breeding activities. An improved understanding of the relative importance of the unintended consequences of breeding, the effects of changes in fallowing practices, crop rotation, soil fertility, climate and traffic, along with a better understanding of the possible importance of bio- and macropores types provide avenues for improved management of high soil strength in grain crop production systems.

Keywords Compaction · Tillage · Roots · Tillering · Bulk density · Penetrometer · Strigolactones

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Introduction

Grain production is a key pillar in Australia's economy but it operates within challenging climatic and edaphic environments, with unreliable and often low rainfall. Many soils have limited capacity to store water and suffer from a range of physical, chemical or biological constraints (Dang et al. 2010; Davies et al. 2019; Nuttall et al. 2003a; Price 2010; Unkovich et al. 2020). Across much of the grain cropping region (> 20 mill. ha) soil strength emerges as an insidious and increasing problem (Davies et al. 2019) and along with a range of a range of other soil constraints, reduces crop rooting depth (Incerti and O'Leary 1990; Sale et al. 2021). Problems of high soil strength occur in cropping systems all around the world and are probably ubiquitous in cropping systems where heavy machinery is used. The problem is now exacerbated with tractor and harvester loads exceeding 20 tonnes on large Australian grain production farms (Parker et al. 2021), increasing the severity and depth of traffic induced compaction. Within this scenario positive grain yield responses to deep tillage are common, especially on sandy soils (Davies et al. 2019). However, our understanding of interactions between soil type, crop species, tillage depth and frequency, and seasonal conditions is rudimentary, leading to a limited ability to predict the immediate and ongoing benefits of deep tillage on grain production.

Soil strength is not an inherent physical property of soils but is an emergent property, an outcome of physical, chemical, biological, management and seasonal climatic factors. This review is specifically concerned with the effects of high soil strength on grain crops, the causes of high soil strength, how one might go about assessing it in the field, what effect it has on plant growth, and how crops respond to mitigation or amelioration options. With respect to measurement opportunities and the effects of high soil strength on plant growth, we canvassed the international literature, while our exploration of management options centres explicitly on the experience in the Australian soil and climatic environment.

It has been two decades since Bingham (2001) highlighted the need for more field studies on high soil strength and Passioura (2002) stated that hormonal and 'feed forward' responses were not understood. Since then, there have been significant advances in our understanding of the occurrence of high soil strength, the effects on root growth and the direct effects of soil strength on shoot growth in laboratory studies, and there have been many field studies examining grain yield responses to tillage of various forms. This review summarises our understanding of plant responses to soil physical conditions and field observations of grain crop responses to deep tillage of high strength soils, two aspects hitherto generally considered separately. We do not consider secondary effects of compacted or dense soils, such as poor drainage, water logging and low O_2 (Shaw et al. 2013), subsoil acidity (see Davies et al. 2019), or soil sodicity (Nuttall et al. 2003b).

Soils and soil strength

The soil matrix is a complex environment with many physical, chemical and biological interactions (Gregory 2022). In terms of soil strength, the primary determinant is soil pore structure, a consequence of relationships between the soil particle sizes and their packing arrangement. Compaction results in a change in soil pore structure such that there are reductions in air-filled pore space and continuity, hydraulic conductivity, soil water potential and diffusivity of water and gases, and increases in soil cohesion and shear strength. These effects work in concert (Table 1) to increase soil strength and reduce plant root elongation rates.

What soils are affected in Australia?

Essentially all soils used for grain cropping in Australia are susceptible to problems of high soil strength, due to combinations of high bulk density, traffic induced compaction or hard setting (either surface or subsurface) and loss of biopores (Table 2). The exception would be self-mulching Vertosols which are able to self-repair during wetting and drying cycles (Anon 2021; Radford et al. 2001) Davies et al. (2019) list Tenosols, Rudosols, Kandosols, Calcarosols, Sodosols and Chromosols as having poorly structured dense subsoils and being susceptible to traffic induced compaction. Jarvis et al. (2000) considered that "virtually all soils with texture loamy-sand or sandier" (6.6 M ha) in the Western Australian cropping region have compaction zones which restrict cereal root growth, and Parker et al. (2021) state that 75% of Western Australian cropping soils are susceptible to compaction. Jarvis et al. (2000) observed that sand over clay duplex soils were also considered susceptible to compaction if the depth to clay was sufficient (> 25 cm) and that the depth to the compacted layer depended on the clay content of the soil; sandy soils with a clay content of > 10% displaying compaction at 20 cm, 4–8% clay at 25 cm and < 4% clay at 30 cm or more. Compaction thus appears to occur deeper (> 30 cm) on sands (< 10% clay) than on soils with higher clay contents (Jarvis 1986). Research on

Table 1 Principal factors influencing soil strength

Realm	Factor	Influence	Exemplar
Physical	Sand/Silt/Clay	• bulk density	Kaufmann et al. (2010)
		• pore space & continuity	
	Overburden	• increases strength at depth	Gao et al. (2016a)
Chemical	Minerals	• hard setting (temporary)	Franzmeier et al. (1996)
		• cementation (permanent)	
Biological	Bioporosity	• creates voids and airspace	Kirkegaard and Lilley (2007)
Environment	Rainfall/VPD (wetting/drying)	• soil moisture matric potential (effective stress) • hard setting (temporary)	Whalley et al. (2005) Franzmeier et al. (1996)
Management	Traffic	• increases bulk density • hard setting (surface)	Radford et al. (2001)
	Tillage	• decreases bulk density	Davies et al. (2019)
	Fallowing	• increases water content	Mead and Chan (1985)
	Grazing	• near surface compaction	Proffitt et al. (1995)

Table 2 Approximate inherent properties of the primary soils used for agriculture in Australia as related to high soil strength

Soil order	Dominant texture	Subsoil compaction	Dense subsoil	Hard setting or cementing
Tenosols	sand	✓	✓	✓
Kandosols	loam	✓	✓	✓
Calcarosols	sand/texture contrast	✓	✓	✓
Sodosols	texture contrast	✓	✓	✓
Kurosols	texture contrast		✓	
Chromosols	texture contrast	✓	✓	
Vertosols	clay	✓		
Dermosols	clay		✓	
Ferrosols	clay		✓	

Soil orders according to Isbell and the National Committee on Soil and Terrain 2021 (following Davies et al. 2019)

sandy soils in Western Australia found that subsoils which contained transported materials (fluvial or aeolian) had lower soil strength than sandy subsoils formed from saprolitic (in situ) weathering, especially at lower soil water contents (Kew et al. 2010).

Hardsetting soils

Hardsetting in soils (the transitory appearance of an impenetrable layer) was well reviewed by Mullins et al. (1990) but progress since then appears to have been slow. In that review, they considered that hard setting in Australia was likely in loamy-sand and sandy-loam soils with low ($<2\%$) organic matter and illitic or kaolinitic clays. It occurs because the silt and clay size materials do not form water stable aggregates but become suspended in the soil water, and as the soil dries these particles settle behind the retreating meniscus and fill concavities in the sand grains and remaining aggregates. Within these layers there can be significant changes in soil strength independent of bulk density, possibly caused by iron and manganese oxides in combination with $CaCO_3$ (Cornell and Schwertmann 2003; Shaw and West 2002) or from the precipitation of Al, Fe and Si and the formation of siliceous and aluminosilicate cements (Chartres et al. 1990). It would appear that these hardsetting layers can form over just 2–3 days as the soil water content declines to a critical point (da Silva et al. 2021). Initially matric potential constitutes the major contributor to soil strength in this zone but once the soil is dry, chemical bonding creates the hard setting characteristic (Mullins et al. 1990). Relationships between soil matric potential and penetration resistance when soils dry may be different on hard setting soils compared to non-hard setting soils. The exact depth of this hard setting layer may change from year to year depending on the rise and fall of soil water.

These hard setting layers disappear on rewetting of the soil but may cause problems for crop growth during the latter part of the growing season when soil water is rapidly diminishing. The strong seasonality of rainfall in much of the southern Australian cropping region means that many soils are susceptible to repeated wetting and drying cycles, resulting in periods of hard setting in susceptible soils. The distribution and occurrence of this problem across the Australian grain belt is not yet well understood but it has major implications for both the efficacy and longevity of potential amelioration treatments. In studies in New South Wales, Sodosols with a sharp increase in pH in the subsoil were found to be more prone to hard setting than adjacent Chromosols or Vertosols (Franzmeier et al. 1996). Further west in South Australia seasonal hard setting is observed in deep sandy soils (Calcarosols, da Silva et al. 2021). Hardpans, cementing, compaction, poor structure and traffic pans are regularly referred to across a range of agricultural soils in Western Australia (Moore 2001) but it is unclear just how widespread a problem transient hard setting is in many cropping soils. Although loss of organic matter was suggested to contribute to increased hard setting (Mullins et al. 1990), no direct evidence was presented.

Texture contrast soils

Texture contrast soils (sometimes referred to as duplex), which have an abrupt (> 20%) change in clay content between A and B soil horizons, are the predominant soil form across the arable cropping lands of Australia (Chittleborough 1992; MacEwan et al. 2010; Tennant et al. 1992). In the high rainfall zones of NSW and Victoria (500-900 mm) it is thought that 90% of soils suffer from a dense ($\geq$ 1.5 g/cm^3) clay subsoil (Sale et al. 2021). Where the depth to this dense clay layer is < 30 cm, compaction is likely to be less of a problem than it is on deeper duplex soils (Crabtree 1989). However in shallow duplex soils the B horizon clays are associated with greater problems than soil strength, such as poor drainage, waterlogging, sodicity, salinity or other toxic elements (Dracup et al. 1992; Gregory et al. 1992).

How is soil strength measured?

As soil strength is an emergent property of soils it is not readily predicted to the degree required for plant root studies and thus must be directly observed or measured. Batey and McKenzie (2006) provide a method for visual assessment of soil compaction using a small pit dug into the soil and an associated series of observations of compaction and root growth which can be made with simple tools, augmented by the pre-inspection application of dilute white water-based paint. The suggested method requires some experience and a non-compacted area for comparison and includes guidance for different textured soils. The approach is useful because it also recommends observations to provide insight into processes in the soil which might contribute to high strength and identify the consequences. While the main drawbacks of the method are that it is time consuming, requires experience and training, and only provides information at one point, it has the advantage of providing direct observations on the effects of soil properties on root growth. A similar approach is provided by Parker et al. (2021). Godwin and Spoor (2015) emphasised the importance of professionally supervised visual-tactile soil assessment, *via* soil pits, to clearly understand the nature of constraints to root growth and the precise need for mechanical loosening. Emmet-Booth et al. (2016) have highlighted the growing international acceptance of a broad range of visual soil examination (VSE) techniques for farm management, including the Australian SOILpak methodologies for the assessment of subsoil compaction (Daniells et al. 1996; McKenzie 2001a, b).

Bulk density and soil matric potential

In many agronomic studies, soil bulk density is used as a measure of soil quality, with bulk densities of 1.2-1.4 g.cm^{-3} generally considered to be the desirable range for good crop production (McPhee et al. 2020). Soil bulk density is inversely proportional to the porosity of the soil, the space available in the soil for air, water, plant roots and soil fauna. Compaction results in a higher bulk density and lower soil porosity (air space). Bulk density is not a fixed soil property but may be altered by tillage operations, the action of plants and animals in the soil, changes in soil water content, and by freeze-thaw cycles in some climates. However, bulk density is only one of the contributing factors to soil strength. Soil strength is very sensitive to soil water content (Fig. 1) in addition to bulk density (Pabin et al. 1998; Whitmore and Whalley 2009).

Although soil matric potential is very closely correlated to soil strength and has been used as a proxy for it (Whitmore et al. 2010), the relationship between matric potential and soil strength appears to be much more reliable in low density than high density soils (Whalley et al. 2005). Whalley et al. (2006) noted that it is difficult to disentangle the individual effects of soil strength and volumetric water content due to their interacting relationship. Kirkegaard and Lilley (2007) found that root growth of wheat tended to be impeded at 40–50% of soil water capacity when examined across 36 agronomic field experiments. Kaufmann et al. (2010) made a theoretical comparison of three measures of soil compaction, Packing Density (PD), Least Limiting Water Range and the S parameter, the latter the inflexion point of the soil water retention curve (Dexter 2004), a function of soil pore size distribution. The results obtained by Kaufmann et al. (2010) showed that, theoretically, all three measures were in "good agreement" (well correlated) and therefore equally valid. However, these metrics are based on soil physical parameters (organic C content required for PD and S) which do not include a biological (plant) component, nor are they calculated on intact soils. They thus ignore the possible role of biopores or differences among plant genotypes and root growth.

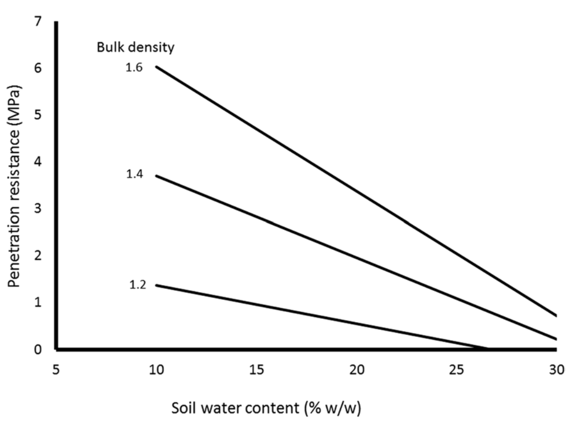

Fig. 1 Relationship between soil bulk density, soil water content and soil strength for a Loess soil (calculated from Ehlers et al. 1983)

Soil penetrometers

The cone penetrometer is probably the most practical option for field assessment of soil strength. This is a simple device consisting of a shaft of ca. ≥ 10 mm diameter which ends in a cone with a semi-angle of 30°, slightly wider than the shaft diameter. An attached force transducer measures the force required to push the probe into the soil. The measured penetration resistance (cone index) is a compound parameter involving components of shear, compressive and tensile strength and soil-metal friction (Mulqueen et al. 1977). The latter is of lesser relevance to plant roots due to the excretion of mucilages by plant roots and the fact that it is only the tip of the root which expands down through the soil (Bengough et al. 2000.) However, it is thought that where the penetrometer tip semi-angle is ≥ 30° the formation of a soil body around the tip greatly reduces friction on the following shaft (Bengough and Mullins 1990). Soil water content has an increasing influence on cone resistance as bulk density increases (Fig. 1). Although root elongation rates decrease as soil penetrometer resistance increases, the relationship depends on a number of biological and physical factors. Cone penetrometer resistances are a consequence of a plethora of variables, including both penetrometer design (cone shape thickness, material, insertion method) and soil properties at the time of measurement (bulk density, particle size distribution, particle shape and roughness, organic matter content, soil water content, soil matric potential, chemical bonding), and hence, reflect the outcome of a wide range of soil properties, methodology and environment. While Bengough (1991) concluded that there is no reliable method of accurately estimating resistance to root growth, short of direct measurement of root force, he recognised that penetrometer measurements were useful, quick and easy, and correlated with root growth.

In comparisons between laboratory and field measurements of soil strength and root growth, it would appear that the soil strength measured by a penetrometer may overestimate the strength encountered by roots by four to ten times (Bengough and Mullins 1990; Clark et al. 2003), perhaps due to (a) roots having a lubricated surface, and thus, much lower friction than a penetrometer tube (Bengough and Mullins 1991) where the whole length of the tube moves through the soil rather than just an extending tip, and (b) because the root does not have to take a completely linear route. Penetrometers with a rotating tip have been developed to overcome some of the problems associated with friction and result in resistances about half of those observed with standard penetrometers (Whalley et al. 2005). While these might provide more reliable indications of root resistance in soil, they do not solve the fundamental problem that a metal rod and a root move through the soil in different ways (Masle 2002; Bengough et al. 2000) give detailed guidance on the use and correction of penetrometer measurements in the field, including depth correction for changes in bulk density following deep tillage operations.

Because soil water content has such a strong influence on soil strength, penetrometer measurements are usually taken when the soil is at field capacity. Nearly all soils will have higher strength at low water contents (high soil water suctions). Penetrometers which have in-built soil moisture measurement have been developed (Topp et al. 2003) and might be useful.

In clay-rich Grey Vertosols in a cotton-wheat rotation, McKenzie (1996) found that penetrometers were unreliable at high soil water contents (see Fig. 2B); their work showed that (i) a shear vane distinguished compacted and non-compacted soil over a broad range of soil water contents (Fig. 2C), and shear strength in both circumstances became greater as the soil dried; (ii) penetrometer resistance became much greater as the soil dried, but it was unable to distinguish compacted and non-compacted soil under moist conditions (Fig. 2B), apparently because of the formation of soil bodies and compaction zones ahead of the probe that change probe geometry such that penetration force no longer reflects the original properties of the soil (Mulqueen et al. 1977), and (iii) core bulk density measurements distinguished compacted and non-compacted soil over a broad range of soil water contents, and bulk density in both circumstances became greater as the soil dried and shrank (Fig 2A). These data show that the worst soil water content for penetrometer measurements in clay and clay loam soil is close to field capacity ($R^2=0.57$), yet this is typically the water content that is recommended with standard penetrometer practices. Penetrometers may thus not be reliable in moist soils of high clay content when cone index becomes increasingly insensitive to shear strength or compressive strength changes as indicated above. McKenzie (1996) thus recommended that for high clay content soils, direct measurement of soil strength using shear vanes rather than penetrometers is warranted because shear vane measurements are less affected by high soil moisture content. A shear vane, a metal rod with vanes mounted on the lower end and with a gauge on top, is pushed into the soil and rotated which gives an indication of the torque required to cause "failure" of the soil.

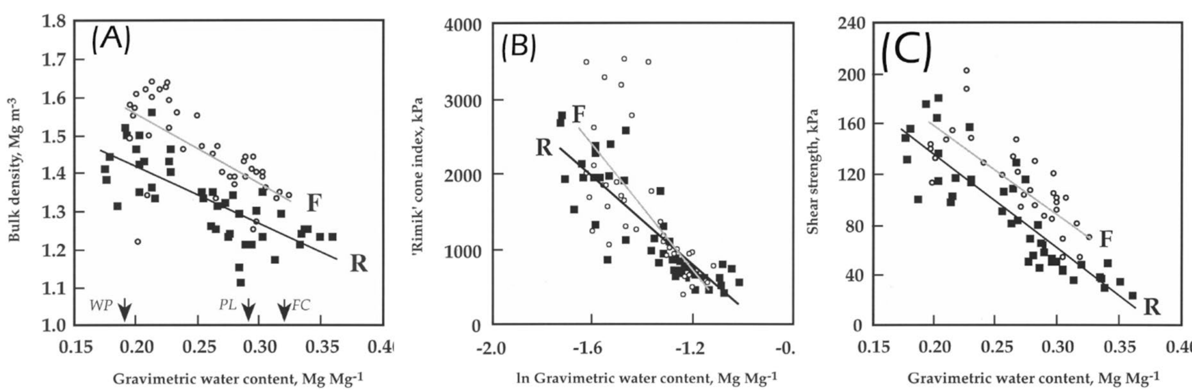

Fig. 2 Changes in **A** soil core bulk density, **B** penetrometer resistance (x axis log transformed) and **C** soil shear strength for a compacted furrow (F) and uncompacted ridge (R) in a Grey Vertosol under controlled traffic farming as the soil water content dries from field capacity (FC) to wilting point (WP) (McKenzie 1996. The 'plastic limit' corresponds with a water content that serves as a valuable reference point for shear strength and bulk density measurements in clay soil that shrinks and swells

Penetrometer measurements also do not take account of the soil overburden pressure, which might be substantial at depth. Gao et al. (2016b) concluded that this was significant below 35 cm depth and developed a mathematical model to take account of it.

Although multipoint penetrometer systems have been developed (Fountas et al. 2013) it is not yet clear what their role might be as there is a trade-off between complexity and convenience which is not yet resolved. Sensors mounted on tynes which provide 'on-the-go' measurement have also been investigated (Sharifi et al. 2007) and show some promise, but are probably more viable in the realm of research than farmer application at this stage. There is no doubt that soil density might be sensed remotely (Kuang et al. 2012), or proximally using apparatus such as the EM38 (Hoefer et al. 2010), but we appear to be some way off reliably relating these measurements directly to soil strength and crop production.

As general benchmarks, penetration resistances of about 1.5 MPa measured with a penetrometer in a moist field soil are thought to start restricting the normal functioning of most roots, and 2.5 MPa indicative of very limited root growth in the soil matrix. These values are well above those observed restricting root growth in the laboratory in artificial media (0.5 MPa) because penetrometers have resistances in soils four to ten fold those of roots. Penetrometers are nevertheless the first choice for a practical field measuring device related to root growth.

For example, Henderson (1989b) established compaction trials on nine sandy soils sites on the northern sandplains of Western Australia. Wheat was grown on plots either uncompacted or artificially compacted by tractor traffic. Soil strength was then measured and related to reductions in grain yield. A single measure of penetration resistance (mean of 0-0.4 m depth) explained 50% of the variance in wheat yield, with yield declines commencing with resistances of 0.5–1.5 MPa and a linear reduction in wheat yield with increasing penetration resistance above 1 MPa. A single regression was developed which reliably predicted yield responses to deep ripping. Shoot biomass at anthesis was also strongly correlated with penetration resistance. In other compaction studies in Western Australia soil penetration resistance and grain yield were linearly related to the number of passes of a tractor on a sandy soil (Jarvis 1986).

There is no doubt that there will be very significant differences among plant species in their ability to penetrate hard soil layers and that these will differ between soil types, but these have not been reliably related to soil penetrometer equivalents in field soils. The use of a critical penetration resistance of 2.5 MPa for all agricultural plants across a broad range of soil types is a gross oversimplification of crop root restriction in the field by high soil strength. Furthermore root:shoot signalling responses may occur at lower strengths (Whitmore and Whalley 2009) and more research is needed to understand the relationships between cone penetrometer measurements in the field, and species root and shoot responses in both structured and unstructured soils. More clarification on the soil texture and moisture ranges under which penetrometers and shear vanes are appropriate to use would be useful.

Modelling soil strength

There have been many attempts to model soil strength using algorithms based on bulk density, soil texture and soil moisture content and/or other pedotransfer functions (see e.g. Canarache 1990; Dexter et al. 2007; Whalley et al. 2007; Whitmore et al. 2011). With a typical error of > 0.5 MPa across test datasets (Gao et al. 2016b; Whitmore et al. 2011), these would be perfectly adequate for modelling purposes across a range of soils or locations, however, this does not indicate the error for a single data point (soil x moisture content) which might be relevant to an individual situation. In other words, the model might match the average of many observations well enough but might have too great an error at individual points to be useful for diagnosis and management in a specific field. Modelling nevertheless has an important role to play in assessing the possible costs and benefits of management strategies (see e.g. Roberton et al. 2021).

Effects of soil strength on crop plants

Identifying the direct effects of high soil strength on plant roots and plant shoots is most reliably done under laboratory conditions where soil conditions can be tightly controlled and the effects of soil strength can be isolated from the effects of soil drying, plant nutrition or other confounding factors. Soil strength is a problem regardless of whether it is caused by high bulk density, high soil water potential or other factors (Passioura 2002). In field experiments with wheat (*Triticum aestivum*) in the U.K., Whalley et al. (2008) found that wheat yield responses to soil strength were the same whether the soil strength was caused by soil drying or by compaction while in other laboratory experiments increasing root impedance with a weight on top of the sand had a greater effect on wheat shoot growth than did decreasing water availability (Ge et al. 2019). Below we highlight plant root responses to high soil strength from controlled experiments in the laboratory, then we move on to field observations of root growth of crops in soils. Following this we explore how the shoots of crop plants respond directly to high soil strength, independent of effects of water and nutrient supply.

How does soil strength affect plant roots?

Downward root growth in soils is achieved by root turgor pressure which pushes the expanding root tip through the soil. Provided the pressure exerted is sufficient to deform the soil around the root and friction is overcome, the root advances down the soil profile. As soil resistance increases, root growth slows in an apparently linear fashion (Whitmore and Whalley 2009). In soils with sufficient pore space soil particles are readily displaced and the root can advance, but as soil density or matric potential increase the turgor pressure may be insufficient for the root to progress through the soil matrix. Under these conditions roots favour soil cracks and biopores in order to advance. Cornish (1993) studied root growth of perennial ryegrass (*Lolium perenne*) in paired, intact and repacked soil cores, and found that (a) roots generally grew in the soil matrix rather than the macrostructure (soil pores/cracks), provided it was soft enough, (b) roots growing through a structured soil matrix grew more slowly than those in structure less repacked soils of equal bulk density and water potential, and (c) while adding macrostructure was of no advantage in unstructured soil, roots grew along macropores at lower water potential than through the soil matrix when soil strength was high. At equally high penetration resistance, roots were able to grow faster in structured soil. Thus, the macropores were important in allowing some roots to grow deeper and potentially escape drought.

Laboratory experiments

Laboratory experiments indicate that the maximum axial (downward) pressure exerted by impeded plant roots is about 0.5 to 0.6 MPa (Bengough and Mullins 1990; Clark et al. 2003). It would appear that roots are less sensitive to radial than axial pressures (Bengough 2012), thus constrictions from biopore walls may not be important in slowing root extension. However, roots have very limited capacity to narrow in response to soil pores smaller than their root cap or stele. Laboratory experiments with wheat, using wax layers of increasing strength (Botwright Acuna and Wade 2005), found that seminal root dry matter declined by 80% beyond a 0.5 MPa wax layer in a sand packed to a bulk density of 1.6 g/cm^3, compared to roots encountering a wax layer of only 0.1 MPa, and roots could not penetrate through a wax layer of 1.5 MPa.

In a laboratory study of 22 species (Materechera et al. 1991) where seedlings were grown in a soil of very high resistance (4 MPa), all species had reductions in root length of $\leq 90\%$ compared to controls. In the control soil there was no relationship between root width and root length (Fig. 3A), but in 4 MPa soil thicker roots were able to penetrate further into the soil ($r^2 = 0.58$, Fig. 3B) and an ability to thicken in response to 4 MPa even more strongly correlated with ability of the roots to penetrate the soil ($r^2 = 0.67$, Fig. 3C), so the ability of roots to thicken in response to high strength appeared advantageous. Whether this relates to the capacity to withstand buckling under increasing impedance (Armstrong et al. 2007a; Clark et al. 2005), or to radial thickening and resulting reduced axial resistance (Atwell 1993), is unclear.

Although it has been suggested that the thicker roots of dicotyledons generate greater axial pressures than cereals (Misra et al. 1986) and are therefore able to penetrate higher strength soils more easily (Materechera et al. 1991), comparative studies on *Pisum sativum* (field pea), *Lupinus albus* (white lupin) and *angustifolius* (narrow-leaf lupin), *Helianthus annus* (sunflower), *Zea mays* (maize), *Triticum aestivum* (wheat), *Hordeum vulgare* (barley) and *Oryza sativa* (rice), found that the dicot roots did not generate greater axial pressures than the cereals and that there was no relationship between root diameter and measured maximum axial pressure (Clark and Barraclough

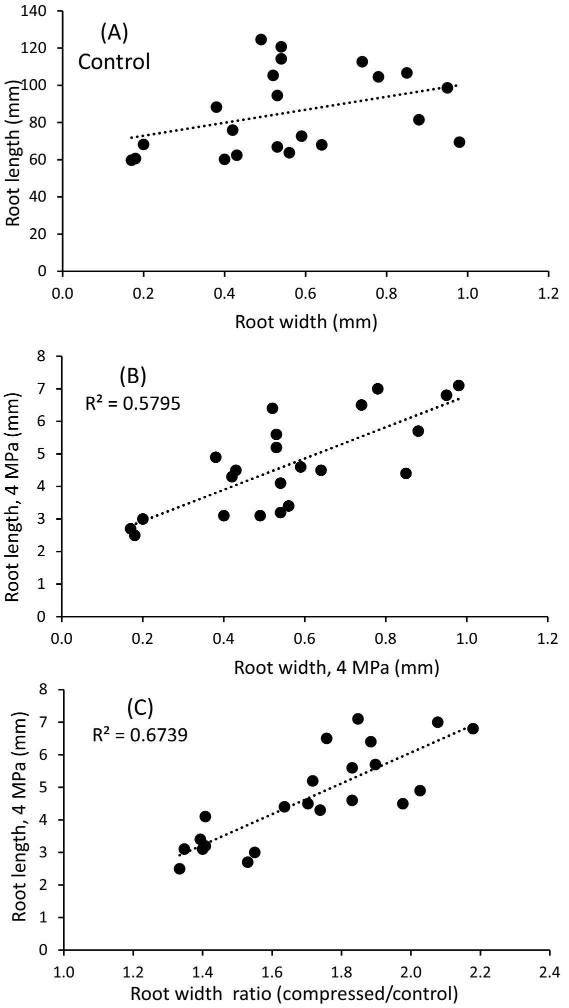

Fig. 3 Scatterplots of **A** root width versus root length for 22 species growing unconstrained in vermiculite, **B** root width and root length for the same 22 species growing in a sand with high (4 MPa) strength, and **C** ratio of root width in the vermiculite compared to that in the 4 MPa sand. Data from Materechera et al. (1991)

1999). Thus root thickness appears to be more important than root pressure. Recent research in hydroponic culture has shown that maize roots thicken in response to ethylene (Vanhees et al. 2021), that ethylene builds up in dense soils (Pandey et al. 2021) and that the roots of maize plants which are less responsive to ethylene do not thicken as much and are able to penetrate a higher strength barrier (Vanhees et al. 2021). Thus ethylene build up in high soil strength soils may be a significant signal to roots of high soil strength.

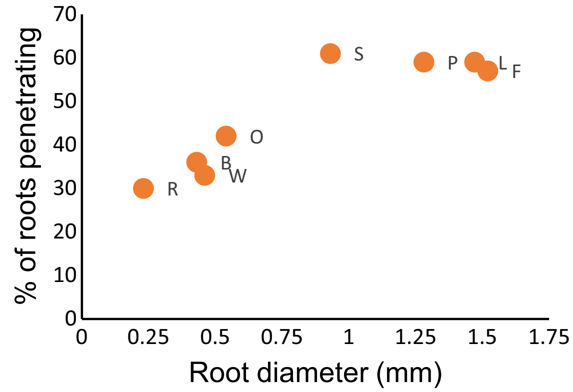

Fig. 4 Scatterplot of root diameter and percentage of roots penetrating soil with a bulk density of 1.57 g/cm^3 and 3 MPa penetrometer reading (ca. 15 cm) at the time of sampling. Data for ryegrass .(R), wheat (W), barley (B), oat (O), safflower (S), field pea (P), lupin (L) and faba bean (F) (Data plotted from Materechera et al. 1992)

Field experiments

While a cereal root may have lower capacity to penetrate dense soils than some dicotyledons, it has been postulated that because they have many more roots than dicots, they may be more successful than dicotyledons in encountering soil pores (Dexter 1986). In experiments with wax layers Whalley et al. (2013) found no difference in the penetration ability of roots from 18 different wheat lines but that the root angle and number or roots had an effect on the probability of penetration. No significant difference in root diameter was observed between the wheat genotypes, however, these observations are not consistent with those in a field experiment which found a greater number of roots from dicots with thicker roots in dense subsoils (e.g. Materechera et al. 1992). Field studies on four-week-old plants of field pea, narrow-leaf lupin, safflower (*Carthamus tinctorius*), ryegrass (*Lolium rigidum*), wheat and barley showed quite clearly that thicker roots penetrated a dense subsoil layer (3 MPa resistance at time of sampling) better than thinner roots (Fig. 4). Interestingly those species with the greatest root penetration into the high strength layer had both the thickest roots and the greatest proportional increase in root thickening when encountering the high strength layer, while the cereals had the lowest penetration and the least thickening upon encountering the high strength layer. Root diameters > 1 mm appeared to be of no advantage for increasing penetration into this soil (Fig. 4).

Comparative studies of wheat, barley, oat (*Avena sativa*) and triticale (x *Triticosecale*) on Western Australian sandplain soils by Henderson (1991) found all species equally sensitive to soil compaction. Field pea was also very sensitive, but narrow-leaf lupin less so. Others have found narrow-leaf lupin to be less (Moodie et al. 2022) or not sensitive to compacted soils (Delroy and Bowden 1986). In laboratory experiments the thinner roots of field pea were less successful than the thicker roots of lupin in penetrating higher strength soils (Hargreaves 2006). Root thickness and root thickening appear to be key attributes which help roots penetrate high strength soils, but overall our understanding of differences among species and cultivars in their ability to penetrate high strength soils remains poor and more comparative work is required, especially in the field.

Rooting depth, macropores and biopores Gao et al. (2016a) contend that rooting below ca. 50 cm in any soil is only possible through biopores or cracks in the soil, due primarily to the weight of soil overburden. If it were true that crop plants could not penetrate below 50 cm without biopores (cracking soils excepted) then that would mean that, excepting for the action of invertebrates, the number of biopores available cannot be increased in unstructured soils. This is difficult to reconcile with the many observations of rooting depths beyond 1 m. The rooting depth of wheat (Incerti and O'Leary 1990; Tennant and Hall 2001) and narrow-leaf lupin (Hamblin and Tennant 1987; Tennant 1983, 1986) can be up to 2 m or more in unstructured soils. It is unclear how cracks could form at these depths without roots drying the soil or how biopores at these depths might be created without roots. In addition, lucerne (*Medicago sativa*) has been observed to root to more than 10 m in Loess soil in China (Li and Huang 2008), achieving more than 5 m in two years (Shen et al. 2009) and in the U.S. to an extraordinary 34 m (Schaeffer et al. 1988).

It would appear that roots favour biopores in high strength soils but much less so in low strength soils (Atkinson et al. 2020). Zhou et al. (2021) found an increasing correlation between rooting density and soil macroporosity with depth in the soil (to 1 m) in a well structured sandy clay loam. Using endoscopic techniques in the field Athmann et al. (2013) observed vertical barley roots were associated with biopore walls, whereas in canola, tap roots moved down through the middle of biopores and had lateral roots penetrating out through the biopore walls. At 1 m depth, 85% of roots of barley and canola were associated with biopores. In detailed field studies of wheat, only 30–40% of roots in the top 100 cm were found in biopores, with the remainder in the soil matrix (Kirkegaard and Lilley 2007), with ultimate rooting depth in this soil of 140 cm. In contrast White and Kirkegaard (2010) found > 90% of wheat roots beyond 40 cm depth to be in biopores in a field soil following lucerne. This may be a consequence of deep-rooted perennial crops drying the soil profile more than annual crops (Angus et al. 2001; Latta et al. 2001), thus forcing roots of annuals following perennials into bio- and macropores. There is nevertheless some evidence of rotational crops improving rooting depth, water extraction and yield of following crops. For example, on a texture contrast soil in Western Australia, Asseng et al. (1998) found that root length density and post-anthesis water uptake and grain yield by wheat were significantly higher after narrow-leaf lupin than other legume crops. Wheat yield was not however correlated with rooting depth of the previous crops.

Henderson (1989a) conducted an interesting experiment with a narrow-leaf lupin-wheat sequence on a deep sand in Western Australia where lupin plant densities were varied from 35 to 220 plants/m^2. There was no significant difference in lupin biomass despite the different plant densities and no difference in stored soil water prior to sowing the wheat the following year. Before sowing the following wheat, half the plots were deep tilled to 30 cm. In the untilled plots soil penetration resistance was linearly related to previous lupin density but not on the tilled plots. The yield of wheat on the untilled plots increased linearly with increasing density of the previous narrow-leaf lupin crop ($R^2 = 0.55$) and equalled or exceeded yields on the deep tilled plots which were not affected by previous lupin density. Unfortunately crop water use was not reported in this study. Further more detailed experiments of this nature might provide improved understanding of the role of biological drilling in crop rotations.

The presence of deep roots alone does not ensure good water uptake. Where roots are restricted to biopores soil:root contact may not be sufficient for efficient water uptake (White and Kirkegaard 2010). However, in the field endoscopic studies of Athmann et al. (2013), barley roots were clearly seen attached to the side and spiralling down large biopores, so some water uptake might have occurred. There is also evidence that roots can move down through hard soil layers via biopores and then re-enter the deeper soil matrix (chicory and tall fescue, Han et al. 2015).

While biopores can be produced by different plant species (Yunusa et al. 2002) and increase the number of soil macropores and water infiltration (McCallum et al. 2004), examples of increases in soil water uptake by following annual crops are not very apparent. Cresswell and Kirkegaard (1995) conducted two field experiments on a red-brown earth with a dense B horizon and concluded that canola was not able to penetrate the B horizon and create useful biopores, and that in general there was little evidence that annual crop species might be effective in this regard. They suggested that a perennial plant such as lucerne might be more effective due to its strong tap root and extended growth period. However, it may take longer (1–2 years) for woody roots to decompose and create biopores after the removal of such species, and in the short term, low soil water contents after extended periods of perennial species may increase soil strength (Yunusa et al. 2002). There are some examples of perennial grasses providing improved conditions for following crops (e.g. Elkins et al. 1977), perhaps because being perennial they have more time and opportunity to penetrate further into the soil. Bell et al. (1997) found that perennial grasses could increased infiltration and hydraulic conductivity of a degraded soil, but they did not change the bulk density of a compacted layer. In studies on a Sodosol in New South Wales comparing lucerne with phalaris, wheat and canola, McCallum et al. (2004) considered that the greater number of biopores observed after lucerne or phalaris than after wheat or canola may have been due to destruction of biopores in the annual cropping system as much to generation of new biopores by the perennial systems. Soil water infiltration was greater following lucerne and phalaris than the annual crops.

While differences in soil strength and macroporosity following different crops have been observed, it is difficult to determine the relative importance of changed soil strength from the many other potential effects of rotational crops, especially legumes (e.g. Rochester et al. 2001). No doubt more experiments employing careful penetrometer measurements would provide further insight. At this point it remains unclear how important biopores are to root growth and effective soil water uptake.

How does soil strength affect crop shoot growth?

While there is a substantial literature on the effect of high soil strength on plant roots there is somewhat less on the effects of high soil strength on shoots, particularly from field studies. Although slower growth and development in response to high strength has been recognised for some time, growth reductions have consistently been assumed to be a consequence of reduced access to soil water and nutrients, and positive responses to deep tillage attributed to increased access to deep soil water. However, direct effects of high soil strength on shoots, independent of soil water and nutrient supply, were clearly demonstrated in pot studies with wheat more than thirty years ago (Peterson et al. 1984). Masle and Passioura (1987) grew wheat seedlings in soils of various strength, either by changing the bulk density or the soil water content, and found that shoot growth was reduced more than root growth. The changes were independent of leaf water potential, seed C reserves or soil P content, which led the authors to conclude that a hormonal signal from the root was the primary cause of reduced shoot growth in response to high soil strength. Other research where bulk density was increased but soil water and nutrition kept non-limiting, has very clearly demonstrated an effect of high penetration resistance on tillering in wheat independent of water and nutrient supply (Coelho Filho et al. 2013; Jin et al. 2015).

Similarly, in field experiments with wheat in Australia (Atwell 1990) 78% of plants grown on loosened soil had a third tiller visible while on the compacted soil only 48% of plants had three tillers. While it is tempting to assume that increased tiller number was due to better root exploration of soil and therefore increased crop water uptake and growth, this was not evident and direct effects of high soil strength on shoot development were suggested as a possibility. In field experiments with wheat in the U.S. and Morocco, tillering was reduced following soil compaction but this was not overcome with additional nitrogen application (Oussible et al. 1993). In field experiments with wheat in the U.K. (Whalley et al. 2006), tillering was strongly correlated with soil strength and this was also illustrated in parallel controlled environment studies where tiller number per plant was halved in compacted soil. When grown in pots of increasing volume, the number of tillers on wheat was linearly related to pot volume (Wheeldon et al. 2021), with no response to additional nutrients. Rates of tillering diverged from the commencement of tillering and this effect could not be overcome with additional N. Rates of root growth in the pots did not appear to be correlated with the tiller production rates. In some of their experiments a later phase indicated that restricted root volume did have an effect, but this was secondary to the direct effect on shoots that had occurred earlier in the life of the crop.

There are very few reports of effects of soil compaction on non-cereal annual grain crops, but in a field experiment in the U.K., reductions in grain yields of faba bean following compaction were a consequence of reduced grain density due to fewer podding nodes, with grains per pod and grain size unaffected (Brereton et al. 1986). In a pot study on chickpea, plants grown in compacted soils had fewer branches (nodes) than those growing in uncompacted soil (Choudhary et al. 2015). In other glasshouse studies on lucerne, tertiary branching was the parameter most sensitive to increasing soil strength, more so than reductions in root growth (Mapfumo et al. 1998). There are other studies which have examined restrictions to rooting volume and these are also relevant and insightful. In glasshouse studies of narrow-leaf lupin, plants growing in reduced soil volumes displayed decreased orders of branching in shoots with the end result that shoot dry matter was reduced more than root dry matter, with harvest index increased (Pigeaire et al. 1990). The authors alluded to potential consequences of high soil strength, but this does not appear to have been followed up. Interestingly when reduced branching narrow-leaf lupins were developed they were found to display reduced root branching as well (Bishop and Delane 1986). Whether reduced root branching also occurs in cereals exposed to high soil strength is unclear. In the glass bead experiments of Goss (1977), root branching of barley decreased as impedance increased, and in an assessment of historical wheat cultivars (Aziz et al. 2017) root length and root length density were lower in modern than older cultivars. In soybean, growing plants in restricted volumes supressed the growth of leaves and stems on auxiliary shoots (Krizek et al. 1985). When Phaseolus beans were grown in small pots the shoots had small leaves and reduced internode lengths, an effect which appeared to be very much reduced by the application of both gibberellins and cytokinins (Carmi and Heuer 1981). When bean (*Phaseolus*) and cowpea (*Vigna unguiculata*) were grown in restricted rooting volumes, leaf initiation and development of trifoliates were delayed (Izaguirre-Mayoral and de Mallorca 1999). These numerous laboratory observations clearly demonstrate direct effects of rooting volume/growth on the branching of non-cereals, independent of water and nutrient supply, and so we assume that effects of high soil strength in legumes is similar to that observed for tillering in cereals. We have not yet identified any similar studies on canola/rapeseed. Observations of increased early soil water extraction following ripping are often attributed to increased root growth (see e.g. Holloway and Dexter 1991) but might they also be a result of increased tillering/branching and leaf area, driving radiation interception and higher transpiration (feed forward vs. feedback)?

The hormones responsible for controlling tillering and branching in plants have only very recently been elucidated, with strigolactones, auxin and cytokinins considered to work in concert (Barbier et al. 2019). However, it is the identification of the role of strigolactones that appears to be a significant turning point to understanding both tillering in cereals and branching in dicotyledonous plants (Dun et al. 2009; Gomez-Roldan et al. 2008). Furthermore Lloyd (2016) found that the concentration of strigolactones in roots of rice plants increased in response to high soil strength and that mutants deficient in either biosynthesis or perception of strigolactones, displayed a reduced effect of high soil strength on tillering. These findings open up new possibilities for managing crop growth (tillering/branching) under high soil strength. Interestingly other recent laboratory work has shown that reduced tillering of wheat under high soil strength is observed under higher (250 µm) but not lower (10 µm) phosphorus supply (Wang et al. 2021). Low phosphorus supply is generally thought to stimulate strigolactone production and exudation in roots and result in arbuscular mycorrhizal branching and the increased uptake of phosphorus (Bouwmeester et al. 2007), as well as reduced tillering (Umehara et al. 2010). Interestingly non-mycorrhizal white lupin did not upregulate strigolactone production in response to low phosphorus or nitrogen supply, whereas mycorrhizal legume species did (Yoneyama et al. 2008). Whether this might be the reason for the maintenance of growth of narrow-leaf lupin often observed under high soil strength conditions is yet to be examined. Clearly there is some way to go before these factors are untangled, but the recognition of the role of strigolactones provides an avenue for increasing our understanding of the response of crop shoots to high strength soil conditions.

Deep tillage to reduce soil strength and increase crop growth

Deep tillage is currently the only practical approach to reducing high soil strength and while grain crop responses are usually positive, effects are typically not long lived nor well predicted. Here we focus solely on the Australian experience with deep tillage due to the important and complex nature of regional interactions of soil, climate, season, genotype and management. We consider deep tillage specifically for the purpose of remediating hard subsoil layers (Fig. 5), whether they be natural or induced by agricultural practices. We do not consider the many reports where deep tillage has been used in conjunction with ameliorants (organic amendments, lime, clay etc.) to improve soil structure or function unless they have a deep tillage only control so that the effects of tillage are not confounded by ameliorant. In many cases there is no such control and this confounds an understanding of the role of tillage versus other factors (Celestina et al. 2019). We also restrict our analysis to reports from which we can assess the evidence which might explain the reasons for responses to ripping. For example, if soil water is not measured then one cannot make any conclusions about changes in the amount or timing of crop water use. Thus, we restrict our analysis to the available data rather than to previously published conclusions based on inference and only consider reports where responses to intervention include more than grain yield. For those looking for practical advice on implementing deep tillage, this can be found in Jarvis et al. (2000), Davies et al. (2019) and Fraser (2020). Clay delving (i.e. tillage that lifts clay from subsoil layers in duplex soils) to reduce topsoil water repellency and improve soil structure is also considered elsewhere (Leonard 2011; Unkovich et al. 2020). Sale et al. (2021) have recently reviewed amelioration options for dense clay subsoils with poor drainage and a range of associated chemical constraints, which are not covered here.

Davies et al. (2019) reviewed the role of strategic deep tillage to loosen soil in Australia. These authors indicated that in Western Australia deep tillage (typically 0.3-0.6 m) has been practiced for decades on

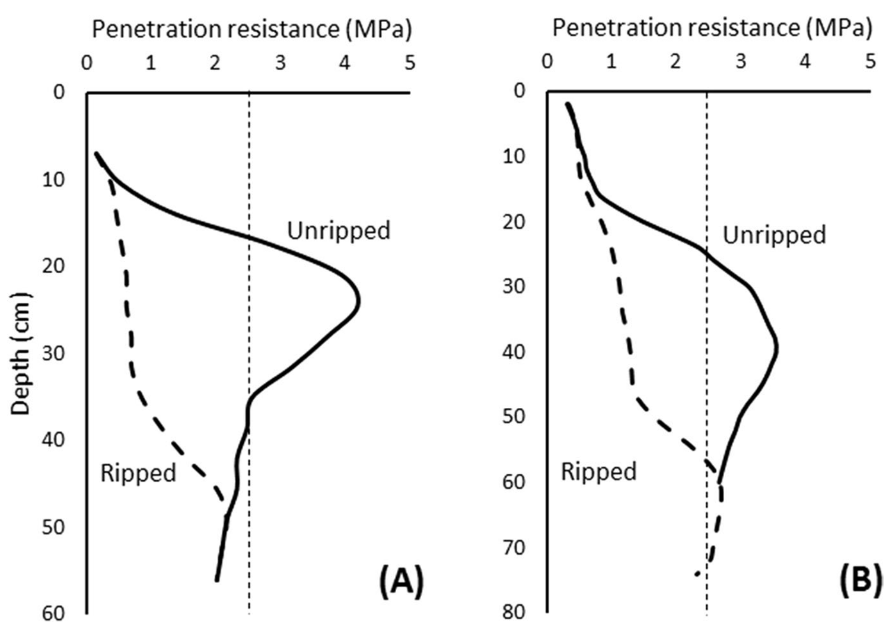

Fig. 5 Soil strength as measured by a cone penetrometer for **A** a deep loamy sand (10–20% clay) cropping soil at Wongan Hills (1983) and **B** deep sand (4–6% clay) at Binnu in Western Australia following deep ripping to 35 (**A**) and 55 cm (**B**) (from Tennant 1986 and Parker unpublished)

deep sandy soils, but recent increases in machinery weight and more frequent cropping have resulted in greater and deeper compaction. Consequently, ripping to 0.7-0.8 m is now required with more powerful tractors. It is quite clear that positive crop responses are very common on deep sandy soils and on sands over clay with a deep A horizon containing a compacted or hard setting layer, and such operations appear profitable (Parker and Isbister 2020). Responses to deep tillage in clay soils have been very much less consistent.

Tennant (1986) reported increased root growth for wheat and increased total water use (24 mm) following deep tillage to 35 cm on a sandy loam at Wongan Hills in Western Australia, but no such increase in root growth or water use in narrow-leaf lupin. There was an increase in shoot dry matter (+900 kg/ha) and grain density (+900 g/m^2), but a reduction in grain size (-2 mg) following deep ripping. Water extraction by wheat occurred down to 170 cm under ripping and 130 cm without ripping compared to 240 cm (ripped) and 230 cm (unripped) for narrow-leaf lupin (Tennant 1986).

Although deep ripping responses are very common they are not assured. Celestina et al. (2018) established ripping x nutrition treatments across eight locations in the south-east Australian cropping belt. Out of 15 site x year combinations there were no yield improvements from any of the ripping treatments, but one negative response was recorded. Most of the sites used in the experiments had subsoils that were either sodic and/or contained toxic concentrations of boron, so presumably these confounded potential responses to deep tillage. Soil strength was not reported for these experiments. This work highlights that some knowledge of the potential constraints within the soil profile is needed prior to exploring possible responses to deep ripping. In many situations soil strength is not the sole or even principal factor limiting crop production in a given field, and hence, responses to management practices may be multifarious and difficult to attribute to each of the possible constraints (Hall et al. 2010). Nevertheless, high soil strength appears to be a common underlying condition on coarse textured soils (Hall et al. 2020; Macdonald et al. 2019).

On soils with a sodic clay subsoil, Armstrong et al. (2015) found that increases in yield were achieved through increases in tiller number and grain density, but not by grain size or increased crop water use. Raised bed and deep ripped treatments generally showed the same effects, with increased rooting depth observed along with reduced penetration resistance in the rooting zone. The application of pig bedding litter into the sodic subsoil manifest as increased drainage and decreased waterlogging. Earlier work had shown that responses to surface applications of pig bedding litter appeared to be related to increased N uptake (Armstrong et al. 2007a), although significant reductions (1–1.5 MPa) in soil strength below 20 cm depth were also recorded (Armstrong et al. 2007b). On soils with dense clay subsoils in high rainfall environments, where excess water can be a problem, raised beds are typically used to improve drainage and crop production. The process of bed forming loosens the topsoil and appeared to reduce the responses to deep ripping. One might question whether the feed-forward mechanism described earlier would be apparent in systems disturbed in this way.

New precision agriculture techniques may provide opportunities for examining the long term effect of management at field scale. For example, Lester et al. (2022) found that two years after deep ripping a compacted Sodosol to 40 cm, use of a Real Time Kinematic GPS at sowing found that the surface level of the plots which had an application of elemental sulphur (to produce gypsum in situ through dissolving of naturally occurring subsoil lime) were 3-5 cm higher than plots deep ripped without sulphur, providing evidence of persistent improvement of soil structure, two years after imposition of the amelioration treatments. In this case the canola yield improvement two years after ripping was 30%.

Deep ripping of a compacted clay soil at soil water contents close to field capacity often creates undesirable consequences. This was evident from mesomorphological imagery of a soil profile that showed how soil compression was induced by the ripping tyne, making conditions for root growth less favourable (Fig. 6 and Koppi et al. 1994). The same deep ripping operation in a soil with profile water contents drier than the 'plastic limit' would have shattered and loosened the soil, rather than smearing it. The moulding of a moist clay soil often makes it more prone to dispersion. This problem often occurs in the north-east grain cropping region where "legacy compaction" has been observed following conversion from uncontrolled to controlled traffic farming on clay soils. These soil voids are observed between the main

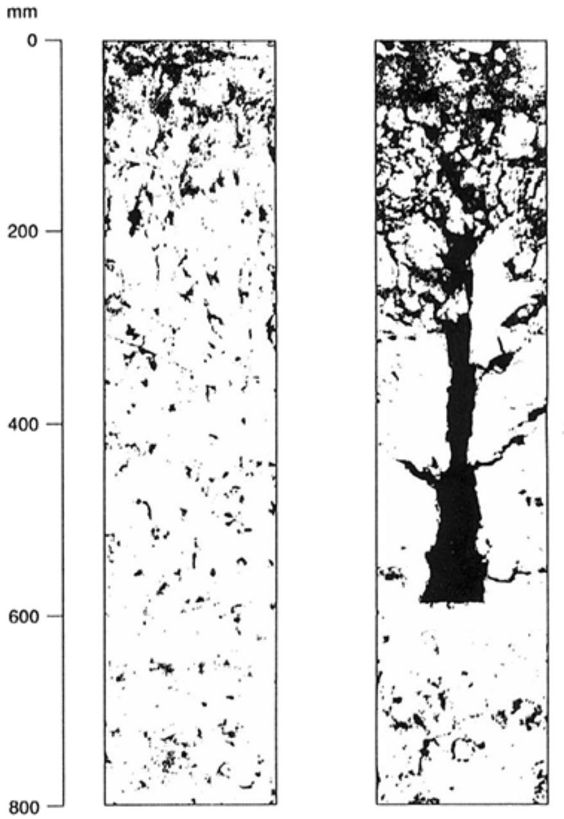

Fig. 6 Binary images from Trangie NSW of Red Chromosol monoliths (170 mm wide, 800 mm long), before (left) and after (right) deep tillage (ca. 600 mm) under moist soil conditions, showing the creation of large soil voids (black areas, from Koppi et al. 1994)

Table 3 Grain yield and yield components for barley or wheat following annual tillage to 30 cm on a deep sand (Calcarosol) at Ouyen in Victoria (from Unkovich et al. 2023)

		Control	30 cm annual tillage	($P < 0.05$)
2017 Barley	Grain Yield (t/ha)	1.99	2.84	*
	Heads (n/m^2)	343	449	*
	Grains/head	17	17	
	Grain size (mg)	36	36	
	Harvest index	0.54	0.53	
2018 Wheat	Grain Yield (t/ha)	1.09	1.61	*
	Heads (n/m^2)	137	157	*
	Grains/head	23	27	
	Grain size (mg)	33	37	*
	Harvest index	0.45	0.47	
2019 Barley	Grain Yield (t/ha)	1.45	2.30	*
	Heads (n/m^2)	266	368	*
	Grains/head	13	15	
	Grain size (mg)	40	40	
	Harvest index	0.54	0.51	

Significant differences between tillage treatments (within a year) are indicated (*)

wheel tracks following ripping when the soil is too moist for deep tillage. Deep tillage, when shown to be needed, *via* soil pit observations and soil strength measurements, is best done when the soil water content is most likely to be well below the ‘plastic limit’, and the soil should shatter well if sensibly designed tillage equipment is used (Godwin and Spoor 2015).

Although comparative studies on sandy and clay soils have shown that crop responses to deep tillage tend to be greater on sands (e.g. Hamza and Anderson 2008), this might be due to constraints other than high soil strength in dense clays (see e.g. Nuttall et al. 2003a, b). Some subsoils containing toxic compounds such as boron, or those with a high $CaCO_3$ content, which can tie up phosphorus or other nutrients, should only be ripped with full knowledge of the consequences of soil chemistry changes (Unkovich et al. 2020). On dense sodic clay subsoils deep ripping must be accompanied by gypsum application to the soil surface to obtain a useful and ongoing response (Hamza and Anderson 2002; McBeath et al. 2010), although it can also be achieved with slotting alone (Jayawardane and Blackwell 1986). On texture contrast soils with sub-surface acidity, deep ripping following surface lime addition has been successful (Davies et al. 2019; Ellington 1986).

Recent field research with wheat and barley (Unkovich et al. 2023) has highlighted that grain yield increases following 30 cm tillage were primarily sponsored by an increase in tiller number (grain density) and not primarily through increases in grain size or harvest index (Table 3) or increased water use. One would anticipate that if access to deep soil water was important then the primary effect would be on grain size and harvest index, but this was not the case. The principal problem with reduced tillering/branching in high strength soils is thus inefficient use of the available soil water because reduced leaf area results in reduced radiation interception and therefore increased bare soil evaporation and poor water use efficiency. It is noted that rainfall during the period of the study was very low (88–123 mm in-crop) and that there was unlikely to be any significant deep soil water storage. However, the point remains that there was a significant grain yield response to 30 cm tillage without an increase in total evapotranspiration. Sadras et al. (2005) also found that responses to deep ripping on two Mallee sands were not related to increased water use nor to plant density, but that increased shoot biomass accounted for 96% and 69% of the increase in grain yield following ripping, while at a third site they found all of the yield increase could be attributed to increased total water use. It is likely that increased tillering was responsible for the yield increases at two of the three sites (tiller or head numbers were not reported) as a reduction in bare soil evaporation was observed following deep ripping. Similar responses have been observed in several earlier experiments, but the significance of the observations appears to have been missed.

In field experiments in Western Australia it was noted that wheat responses to deep ripping were due to an increase in head density rather than grain weight or harvest index (all relatively high) and that effects of ripping were manifest early in the life of the crop (Wilson 1986). In other experiments in Western Australia, wheat tiller number increased with depth of tillage from 4 to 30 cm and yield increases from tillage were not associated with increased grain size (Schmidt et al. 1994). No difference in ultimate rooting depth was observed but the deep tilled plots had greater water extraction late in the growing season. Henderson (1986) found that as compaction was increased from 1.5 to 3.5 MPa, wheat became less responsive to N fertiliser, a practice normally associated with increased tillering. In another study comparing species response to increasing compaction (Henderson ibid.), there was a significant decrease in grain density (grains/m^2) for wheat, barley, oat, triticale and field pea in response to compaction. In these experiments grain density decreases were able to account for all the decrease in grain yield but there were no significant changes in grain size. It was concluded that significant effects must have occurred before anthesis. In other field experiments examining depth of tillage in Western Australia, Schmidt and Belford (1994) observed increasing tiller and head density and grains/head in wheat with increasing depth of tillage, but no increase in late season water use. An average increase in grain yield of 32/kg/ha/cm depth of tillage below 4 cm was observed. Such increases in yield with these small increases in ripping depth are unlikely to be achieved from crop access to deeper water alone.

These observations fit with an hypothesis for increased tillering/branching (and crop transpiration) as being the primary response to soil loosening from deep tillage. Direct effects of high soil strength (tillering/branching) on crop growth which are not associated with reduced access to soil water might be more likely to manifest earlier in the life of a crop, while late season effects such as reduced rooting depth and reduced water availability might result in reduced grain size. Importantly both tiller number (Kebrom et al. 2012) and grains/head (Dolferus et al. 2011) are set early in the life of the wheat crop, before anthesis, and perhaps before significant water stress has occurred in many instances. An absence of an increase in grain size does not preclude an increase in late season water use because if there has been an increase in tiller and grain density then there are more grains to fill, however, if the primary effect is an increase in late season water use, then the over-riding response in cereals should be observed as an increase in grain size.

There are several examples of crop grain yields increasing with tillage depth. For example, Dzoma et al. (2019) reported on a field trial on a texture contrast soil in South Australia where soil was ripped at a range of depths up to 70 cm, either at 30 or 60 cm tyne spacing. Their data showed a linear relationship between ripping depth and dry matter or grain yield (Fig. 7). There were no significant differences in grain yields between the 30 and 60 cm tyne spacing.

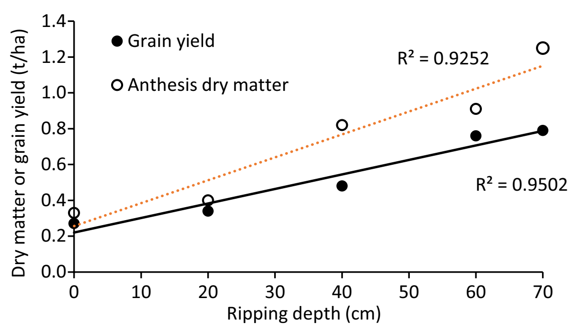

Fig. 7 Relationships between anthesis dry matter or grain yield and ripping depth of barley on a texture contrast soil in South Australia (plotted from the data of Dzoma et al. 2019)

In another experiment on a deep sand in Western Australia (Hall et al. 2010), following ripping to 50 cm in 2005, there was a positive grain yield response in barley (2005) and canola (2007), but not in narrow-leaf lupin in the intervening year (2006). In Australia, narrow-leaf lupin seems to be much less responsive to deep ripping compared to other grain crops (Moodie et al. 2022; Tennant 1986). While there are many examples of wheat and barley being grown after ripping, we have not been able to identify any Australian field studies where there are direct comparisons between these two cereals in their response to ripping, and hence, we are unable to assess the relative responses of wheat and barley to deep tillage. There are very few reports of the response of canola to deep ripping, perhaps because it is difficult to have the fine control of seeding depth needed for small seeds in the first year after ripping. However, Parker and Isbister (2020) report good yield increases in canola yield immediately following ripping to 55 cm on a loamy yellow sand in Western Australia (especially in conjunction with topsoil slotting or inclusion).

At present it remains unclear why the effects of deep ripping are long lived in some cases and not in other situations, with anecdotal evidence of benefits lasting up to a decade (Hall et al. 2010; Parker et al. 2021). Sandy soils very often recompact within three years, due to vehicular traffic or natural resettling, but a range of response lengths have been observed. Whether this is due to the implementation or not of controlled traffic systems or to other factors is not yet clear, although controlled traffic systems will obviously reduce the rate of recompaction by machinery (McHugh et al. 2009). Recent research on a range of soils in Western Australia (Parker and Isbister 2020) has shown that when ripping under a controlled traffic system, a 30 cm tillage was sufficient to achieve substantive grain yield increases in three out of eight sites in the first year, and five out of eight with deeper ripping at > 40 cm. While responses to ripping were observed up to the third year (1/6, 30 cm) or fourth year (1/7, > 40 cm) post ripping, the study showed that even with controlled traffic systems the effects of deep ripping do not generally appear to be long lived. Correlations between cumulative rainfall over time and increasing penetration resistance following ripping of sandy loams has led some to conclude that rainfall effects soil movement, repacking and increases soil strength (Busscher et al. 2002). What the relative importance of this is compared to other factors is unclear. There is the possibility that where responses to deep ripping are long lived there may be other factors at play, such as amelioration of water repellency (Roper et al. 2015; Unkovich et al. 2020) or other changes in the soil which contribute to ongoing yield increases.

One of the interesting observations from reading the literature is that interactions between tillage and fertiliser or ameliorant treatments in field experiments are rare (see Armstrong et al. 2015; Bowden 1986; Hall et al. 2020; Hamza and Anderson 2003; Jarvis 1986; Radford et al. 2001), although examples from laboratory experiments are emerging (Wang et al. 2021). Generally, the effects of ripping appear to be additive to those from fertiliser or ameliorants. In tillage experiments in Western Australia, the application of high rates of N did not appear to be able to overcome the effects of soil strength (Bowden 1986) and there appeared to be no interaction between N application and deep ripping in wheat, excepting for negative interactions at high N rates which exacerbated haying off effects. Radford et al. (2001) found no interactions between tillage/compaction, irrigation and fertiliser applications in a long term trial in Queensland.

Farming system effects

Australia's march toward no-till and stubble retention in grain production systems has been rapid (Llewelyn and Ozman 2019), driven by a need to sow large areas early, quickly and cheaply, along with a desire for reduced soil erosion risk. The challenges of increasing economies of scale in Australia, and elsewhere, have resulted in substantial increases in size and axle load of farm machinery over the last two decades (Rainbow and Derpsch 2011). Current weights well in excess of 20 tonnes present a particular challenge for harvesting on wet soils with high clay contents. To prevent such compaction vehicle masses of < 6t, along with controlled traffic, are required (McPhee et al. 2020). It should be noted that not all compaction near the surface is caused by traffic, some of it can be cause by natural slumping or settling (Mullins et al. 1990). On a Vertosol in Queensland vehicular compaction was repaired within a cropping season due to the shrink swell nature of the Vertosol soil (Radford et al. 2001) and compaction by heavy machinery could be avoided provided the soil water content was less than 22%. In some cases the repair might require more wetting and drying cycles, and is thus, slower (Anon 2021; McHugh et al. 2009).

In addition to the adoption of no-till, another significant change in farming systems in recent decades has been a substantial shift away from the use of long (≥ 9 month) fallows in much of the grain cropping region. For example 48% of the wheat cropping area in the SE Australian mallee was sown on to long fallow at the turn of the century (Latta 2002) compared to only 6% today (Umbers 2021). This may have significant implications for the soil strength encountered by crops roots. For example, in field studies in NSW (Kirkegaard and Lilley 2007), rooting depth of wheat at one site was 40 cm deeper after fallow than after canola while at a second site there was no difference in rooting depth of wheat whether following canola or lucerne (Table 4). Since few roots were observed in soils with < 45% of plant available water capacity, presumably the deeper rooting following the fallow was due to increased soil water storage. A similar observation was made by Mead and Chan (1985) who examined the effect of fallow removal and tillage to 20 cm on soil water, soil strength and soil biology on a hard setting red-brown earth. They found fallow to be more effective in increasing yield because the additional water storage decreased soil strength. Such an effect will of course be season dependent and perhaps more important on the east coast of Australia where soils are finer-textured, rainfall is equiseasonal, and crops rely more on stored soil water, and less important as one moves west where soils become coarse textured and rainfall strongly winter dominant (Sadras et al. 2016). In some situations, such as on deep Vertosols, soil strength can be reduced more quickly with greater soil water extraction, because this leads to bigger and deeper cracks, greater water infiltration and improved clod formation (Pillai and McGarry 1999). For example, in field studies on a Vertosol (Hulme et al. 1991), soil penetration resistance to 0.35 m depth appeared to be the same following wheat and safflower, and these were both lower than in a fallow. This effect was thought to arise from water extraction by the crops leading to the formation of soil fissures as the soil dried out.

Table 4 Ultimate rooting depth of wheat on Red Kandosols as a function of previous crop (data from Kirkegaard and Lilley 2007)

Site/Year	Previous crop	Wheat root depth (cm)	s.e.
Bethungra/1994	Canola	105	12
	Lucerne	100	3
Gundibindyal/2003	Canola	100	10
	Fallow	140	10

There are thus interactions between crop rotation, fallowing, soil type and soil strength. However, for non-cracking soils reduced water storage is likely to result in increased soil strength. Therefore on non-cracking soils the effects of biopores following say lucerne or other deep rooted perennials may be of limited use until such time as the soil water is recharged (Nuttall et al. 2008).

Shallow tillage for the preparation of land for cropping and for seeding has been an integral part of agriculture for centuries. Perhaps one of the unrecognised benefits of this was to increase the rate of root growth and tillering/branching of crops, and this only becomes apparent with the move toward no-till cropping systems. Problems of slow early root growth and the effects of soil biota on plant thrift in reduced tillage systems have been reported (Watt et al. 2003), however the direct effects of soil strength on shoot growth might have been overlooked in earlier field studies. The combination of less near-surface soil loosening through no-till, greater compaction due to increasing machinery weights and reductions in the use of long fallowing for increasing soil water storage are likely to have resulted in reduced shoot growth (feed forward) and reduced root growth and water uptake (feedback) effects on crop growth and yield in modern no-till grain cropping systems.

Summary, knowledge gaps and future work

All grain cropping soils in Australia are susceptible to high subsoil strength, although self-mulching Vertosols are able to self-repair, these soils are not immune to high soil strength. Sandy soils are more problematic because the depth of compaction is greater and therefore more difficult to ameliorate. Increasing vehicular weights and more frequent cropping exacerbate the problem. While controlled traffic can help mitigate the effects it does not eliminate them in most soils. On dense clay subsoils, crop responses to deep tillage can be similar to those on sands when deep tillage is used in conjunction with ameliorants such as gypsum and possibly organic matter, excepting where waterlogging, salinity or other toxicities remain intransient problems. Transient hard setting subsoil layers may be common, but it is not clear how much they affect crop growth and water extraction.

The consequences of high soil strength vary with season and soil type, but all crop species are likely to be affected, with the possible exception of narrow-leaf lupin, a non-mycorrhizal crop which might have reduced strigolactone sensitivity. Some crop species are able to penetrate more dense layers with little or no change in root morphology, while others have small changes that assist in penetration of soils, and others appear to have no ability to penetrate zones of high soil strength. Such differences highlight the possibilities for finding plants capable of penetrating high strength soils and to create biopores which may be of use in improving growth of other species. Comparative studies of crop responses (both root and shoot) to high soil strength need to be conducted under controlled conditions in the glasshouse and then corroborated in the field to enable better ranking of the important grain crops in terms of root diameter, root thickening and penetration of high strength soils. These can then be related to the current penetrometer benchmarks of 1.5 MPa (reduced root growth) to 2.5 MPa (cessation of root growth) and relevant adjustments made.

Somewhat surprisingly, there is a dearth of data quantifying changes in total crop water use (evapotranspiration) following deep ripping. Increased access to deeper soil water and increased crop water use is frequently assumed but almost never measured. When it has been reported, the additional water use measured is usually insufficient to explain observed increases in crop yields.

A significant number of glasshouse and field studies clearly demonstrate a reduction in tillering or branching on high strength soils. In the field this is likely to lead to substantially reduced radiation interception and consequently decreased crop water use efficiency. On examination of this, we propose a new hypothesis that the primary effect of high soil strength is not on root growth and development but on shoot development and growth. This is the feed-forward mechanism alluded to in other studies (e.g. Sadras et al. 2005) and it appears to be important under Australian conditions. It is now clear that this mechanism operates through strigolactone group hormones and that these probably respond to nutrition as well as increasing soil strength. This hormone pathway provides exciting new avenues for potential selection of genotypes and improvement of crop growth in high strength soils. There nevertheless remains a need to measure changes in soil water and crop water use in high strength and loosened soils to elucidate under what circumstances and in which soils additional soil water extraction is critical to the success of deep tillage practices. Importantly such studies must also include careful measurements of the rate of development and growth of crop shoots, paying particular attention to tillering in cereals and branching in dicots.

It is unclear whether the emergence of conservation or minimum tillage has resulted in less soil loosening to the extent that tillering or branching might be more constrained in contemporary no-tillage systems. There is a need to understand when soil loosening might be useful to increase water use efficiency, as opposed to deep tillage to increase total soil water use. The management responses might be quite different and have different costs, e.g. soil slotting or blade loosening vs. deep ripping. How some of this sits with conservation tillage practices needs to be explored.

Furthermore, since modern wheat cultivars have fewer tillers than older varieties (Siddique et al. 1989), is it possible that the long term effort to breed crops with a higher harvest index has inadvertently selected for fewer tillers through strigolactone (shoots) or ethylene (root) sensitivity to soil strength? These concepts need to be investigated, along with the role of soil fertility and N supply in tillering and how this might interact with soil strength. For example, has the demise of the legume ley pasture system in Australia reduced soil fertility and N availability and played into a scenario of decreased tillering in cereal crops, especially on high strength soils?

The role of biopores formed by lucerne and other crops seems important but how they might be usefully created remains uncertain. While it is clear that biopores are often occupied by roots of crops, the quantitative importance in terms of water and nutrient uptake is not clear. Whether they have an important role in reducing root or and shoot sensitivity to high strength has not yet been investigated. If plants are able to create biopores, then roots of some species must penetrate high strength soils without biopores, contrary to the suggestion by Gao et al. (2016a) that roots can only grow below 50 cm through biopores or deep cracks. Generally, we have a poor understanding of the growth and operation of plant roots at depth. In the earlier literature (pre 1980s), reports of wheat, barley and lupin rooting to 2-3 m deep appear common, but these depths are not evident in contemporary studies. How much this is due to soil compaction, lower soil water contents associated with reduced fallowing or climate change, or to reduced rooting depth of contemporary crop genotypes is not clear. The relative importance of these need to be better understood.

Over time agricultural practices and farming systems change. We are also seeing changes in temperatures and rainfall patterns, especially in southern Australia. With those changes come substantial modifications to the underlying soil fertility, changes in soil physical structure, changes in the crops grown and their frequency, changes in soil chemistry, changes in soil organic matter and its distribution, and changes in soil biota. Together these affect soil strength and many other properties of soils and their suitability for agriculture. Our reassessment of the causes and consequences of high soil strength in the context of current farming practices, grain crop genotypes and environments provides new opportunities for understanding and management of the widespread problem of high soil strength in Australia and globally.

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