Chapter

Strategic Tillage for Sustaining the Productivity of Broadacre Cropping in the Arid and Semi-Arid Regions of Southern Australia

Gaus Azam, Md. Shahinur Rahman
and Kanch Wickramarachchi

Abstract

Conventional tillage, usually practised before every cropping cycle, was proven damaging and unsustainable and was replaced by conservation agriculture (CA) using no-till systems following the 'dustbowls' incident in the USA. However, the continuous practice of CA has brought new soil and agronomic challenges, such as soil water repellence, soil pH and nutrient stratification, subsoil acidity, compaction and herbicide resistance, threatening the sustainability of broadacre cropping again. In recent years, one-off deep strategic tillage (ST) has brought attention and shown promise in overcoming the challenges imposed by CA and improving the sustainability of broadacre cropping. Deep ST approaches are now available for applying and incorporating soil amendments such as agricultural lime to a targeted depth while treating soil water repellence and loosening the compacted subsoil. Some ST practices have also been proven to manage weed seed banks and decrease the demand for herbicide applications. Many farmers in southern Australia have adopted ST to address the above-mentioned soil and agronomic challenges. When ST is practised, care should be taken in selecting the right timing, soil conditions and depth of tillage for successful outcomes. Once ST is implemented, reestablishing CA would ensure the longevity of the benefits of ST.

Keywords: strategic deep tillage, water-repellent surface soil, subsurface soil acidity, soil compaction, soil penetrometer resistance, nutrient redistribution, soil re-engineering

1. Introduction

Conventional tillage (CT, usually practised in every cropping cycle) in agriculture involves intentional soil manipulation using mechanical means for increasing water infiltration and storage of soil moisture to improve seed germination and root growth, suppressing weed population and mixing crop residues and organic materials.

However, the disadvantages of CT practices include the breaking of soil structure, which might lead to an increase in soil dispersion [1], wind and water erosion [2, 3], loss of conserved soil moisture [3, 4] and reducing soil organic carbon content [5] depending on the depth of tillage.

To reduce soil erosion, moisture loss, preserve soil organic matter, promote good soil structure and better nutrient cycling and plant nutrition, the Food and Agricultural Organisation (FAO) proposed three principles of conservation agricultural (CA) or no-tillage (NT) system. They are: (i) practising minimum soil disturbance for seed and fertiliser placement, (ii) permanently covering at least 30% of the soil surface with organic matter, i.e., crop residue or cover crop, and (iii) diversifying crop species [6]. CA is not a new concept, and it was first conceptualised to protect the soil by the farming community and scientists in the 1930s after the 'dustbowls' incident during a drought in the mid-west of the USA due to extensive cultivation. However, the CA only became more popular with the development of the improved seeding machinery in the late 1940s [5] and the widespread use of herbicides in 1960s in USA [7]. Currently, 12.5% of agricultural lands under the CA practices around the globe, and Australia has adopted CA practices at a wider scale than any other country [8–10]. The Australian grain grower survey in 2016 reported that around 80–90% of the strategically tilled soil does not receive any pre-sowing cultivation [11].

In current agricultural practices, many agronomic and soil constraints such as water-repellent surface soils [12, 13], soil pH and lime stratification have arisen [14], increase in subsurface soil acidity [15–17], nutrient stratification [18], some soil-borne pests and diseases such as slugs [19] or nematodes [20], and herbicide-resistant weeds [21, 22] due to the long-term NT practices. To manage these soil and agronomic constraints, occasional tillage (known as strategic tillage, ST) might be one of the ways, but there is a fear of reversing the benefits of long-term NT practices on soil physical, chemical and biological properties. While the benefits of CA or NT are overarching, the complete elimination of tillage from the agricultural system and its effect on sustaining the productivity of the broadacre cropping system still need to be investigated [23–33]. This book chapter postulates that ST would remain a key element for sustaining the productivity of broadacre cropping, especially in the arid and semi-arid regions of southern Australia.

2. Strategic tillage: pros and cons

To avoid the conventional tillage (CT) practice, a needs-based occasional, usually every 3–10 years, deep tillage approach [34, 35] is gaining popularity, known as strategic tillage (ST). The occasional soil disturbance in a conservation agriculture (CA) or no-till (NT) system could minimise the risk of CT and amend the soil and agronomic constraints. Besides, ST can increase crop yield significantly over a period which might subsidise the cost of tillage operations and make the cropping system more sustainable and profitable than an NT system. However, there is fear that the practice of ST in a CA or NT system might affect the benefit of the long-term CA by affecting soil properties such as soil erosion and runoff, wind erosion, loss of soil aggregate, infiltration of soil water and soil organic carbon.

The impact of ST on soil properties, in a CA or NT system, needs to be more consistent, and still, there are opportunities to conduct more research and explore further. For instance, soil erosion and runoff may be accelerated by ST in an NT system. Usually, soil erosion and runoff depend on soil hydraulic conductivity and other water infiltration properties [36]. Occasional tillage with a Mouldboard plough did not show any difference in soil hydraulic conductivity in a 35-year NT practice system [37]. Usitalo et al. [38] reported that the loss of dissolved phosphorus by runoff was 67% less in a CT system than in an NT system due to reduced runoff and improve infiltration in tilled soil. A recent review [36] reported that ST increased runoff in two out of five studies while decreased runoff in two studies and had no effect in one. Therefore, the ST in an NT system has a mixed effect on soil erosion and runoff and might also depend on other soil properties, such as soil texture and structure.

NT is very effective in wind-prone and semiarid areas in decreasing wind erosion by crop residue [39, 40]. The tillage buried the crop residue and enhanced wind erosion by increasing the emission of particulate matter in the soil (<2.5 to 10 um) [41, 42]. Considering dry soil aggregate stability, an important factor for soil erosion, no immediate effect of tillage was observed after 1 to 3 years on a 10-year NT system in loam, silt clay loam and clay loam soils [27].

The ST might impact soil aggregation, infiltration and soil water content. A review by Blanco-Canqui and Wortmann [36] reported that ST did not affect the wet and dry stability of soil aggregates in two out of three studies and decreased in one study. It has been reported that soil aggregates might decrease immediately after tillage but would reaggregate soon, within 7 to 12 months, if no further soil disturbance occurs immediately [43].

The impact of ST on soil hydraulic conductivity, soil infiltration and water retention are also mixed. ST might not have any effect [44], inconsistent effect [3, 45], or decrease [46], or increase [47] the soil water infiltration rate. It has been reported that frequent tillage impact more negatively than ST in long-term NT soil [48]. ST reduces soil cover, and it is often thought to decrease plant available water in soil through enhanced evaporation due to exposure to the sun and an increase in soil temperature [4]. It has been reported that soil temperature does not vary significantly between NT and ST [27]. Soil water content might decrease immediately after tillage [3], but it would recover quickly after rain. Therefore, the timing of the ST needed to be considered to minimise water loss.

The tillage operation usually impacts soil organic carbon (OC), where an NT will build soil OC on the surface [49]. ST would assist in removing OC stratification from the topsoil and a uniform distribution along the soil profile [14, 50]. Quincke et al. [51] reported an increase in soil OC in 0.10–0.30 m following an event of mouldboard plough in an NT soil. One of the major concerns is that the tillage might break soil aggregates and expose the protected soil OC to microbial decomposition. The effect of ST on soil OC on top 0.10 m was reviewed in 11 studies with 28 soils; out of which 22 soils showed no effect and 6 soils decreased the level of OC [36]. These results might indicate a limited effect of ST on soil OC content. However, even if soil OC decreases near the surface it has been reported that OC would build up below the surface due to the inversion or mixing of topsoil containing high OC with the subsoil that has low OC [14, 30, 46, 47, 51] as well as through enhanced plant root growth. Where a decrease in OC is reported due to the use of ST, an increase in soil nutrient status was also reported which attributed to the mineralisation of nutrients from the incorporated soil OC and improving crop growth and yield following an event of ST [36].

Another concern of the ST is its effect on the soil microbiological community. The review by Blanco-Canqui and Wortmann [36] reported a small or no effect of ST on soil microbial community in four studies. Dang et al. [3] reported no effect of ST within a few months of using a chisel plough on soil microbial activity or biomass in Australia. In contrast, Wortmann et al. [30, 52] reported a persistent reduction in soil microbial activity in 5 years in Nebraska, USA. However, the decrease in soil microbial activity did not affect the crop yield which might indicate that ST did not have any effect or minimal effect on the broader soil ecosystem [30]. Furthermore, Garcia et al. [53] reported that ST reduced root colonisation by arbuscular mycorrhizae but did not decrease the phosphorus uptake by plant roots.

3. Role of strategic tillage in southern Australian agriculture

In this section we focus on the role of ST in removing soil and agronomic constraints and providing additional benefits toward maintaining sustainable productivity in a broadacre cropping system. A cause-and-effect relationship between multiple interacting soil constraints (soil water repellence, compaction, acidity and sodicity) arises due to long-term farming practices with NT adoption by farmers and the reasons for generating a yield gap are presented in **Figure 1**. The role of ST in amelioration of these constraints such as water repellence, soil acidity and compaction will be discussed further in this chapter.

3.1 Role of ST for amelioration of soil and agronomic constraints

3.1.1 ST for treating water-repellent surface soils

Water repellence is one of the major soil constraints in southern Australia. It is estimated that around 10.2 Mha of arable land in the south-west of Western Australia is at risk of water repellence with 3.3 Mha marked as at high risk and another 6.9 Mha at moderate risk [58]. The main reason for water repellence is due to an increased OC content (hydrophobic carbon compounds such as plant waxes and other products from natural processes of plant biodegradation) in the surface soil [59–62], especially

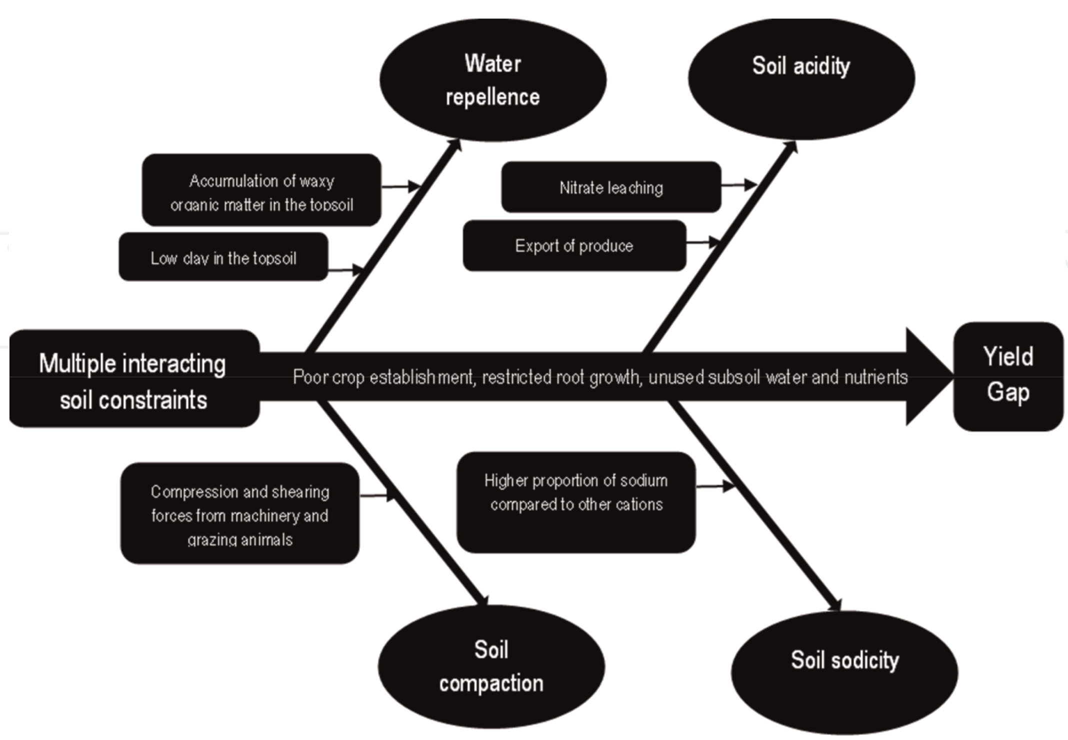

Figure 1.
Cause and effect relationship of multiple interacting soil constraints. For further information on soil constraints' cause and effects, see soil quality: Ebook series [54–57].

in soils with low clay content, i.e., soil with a low particle surface area [60, 63]. The CA or NT practice has exacerbated the scenario by concentrating organic matter and its wax component in the top 0.05 m of the soil [55].

A set of agronomic practices such as furrow or on-row seeding, and repeated application of wetting agents can temporarily treat soil water repellence. Using ST such as mouldboard ploughing, spading, etc. can be a medium-to-long-term solution for treating soil water repellence, albeit at a moderate to high cost. As soil water repellence mainly occurs in sandy topsoil with less than 5% clay [55], the addition of clay followed by incorporation using an ST is a longer-term solution. Claying can be expensive; however, this cost can be cheaper if the clay source is within the same paddock, especially where texture contrast soils (e.g. Planosol and Solonetz in the World Reference Base for Soil Resources) are available. When clay is applied to treat soil water repellence, it is essential to ensure the total amount of clay (applied plus original clay in soil matrix) is around $7 \pm 2\%$. Any less than this amount could treat soil water repellence inefficiently. In contrast, a higher amount might enhance surface crusting and decrease plant available water in the surface soil, especially during plant emergence [55].

One-off deep cultivation, ST, aimed to mix topsoil with subsoil, was found effective in decreasing soil water repellence [64]. However, if the surface soil is extremely repellent, i.e., soil with a molarity of ethanol droplet (MED) value of >3 [55], there is a risk of making whole soil profile water repellence due to soil mixing as proposed by Steenhuis et al. [65]. Mouldboard ploughing has been reported to effectively decrease soil water repellence by burying the repellent topsoil and bringing wettable subsoil to the surface [66, 67]. Davies et al. [68] found rotary spading also effectively decreased soil water repellence in 12 field trial sites in Western Australia. A study by Davies et al. [69] compared different ST implements for mixing soil and treating water repellence and found that benefits from different implements varied in the order of offset disc < deep ripped < rotary hoe < rotary spade < mouldboard plough (**Figure 2**). However, a risk of mouldboard ploughing, or rotary spading is wind erosion which can be minimised by ploughing during a wet season and immediately seeding with a vigorous cereal or cover crop [68]. The duration of the benefits of ameliorating soil water repellence using ST varies between different ST implements. For example, the longevity of the soil inversion with a mouldboard plough has been reported up to more than 10 years [34] and about 3–7 years for the rotary spading [35].

3.1.2 ST for treating subsoil compaction

Approximately 12 million hectares of the south-western agricultural region of WA (75% of arable land) is affected by or susceptible to compaction (**Figure 3**). The annual associated loss of crop yield caused by compaction in WA has been estimated about $AU883 million or $AU36–87 per hectare per year [56]. One of the main objectives of ST is to remove soil compaction allowing plant root growing in the subsoil and accessing soil water and nutrients from the subsoil. Soil penetrometer resistance (also known as soil strength) and bulk density are widely used to measure soil compaction. A soil strength of 2.5 MPa is considered a critical value above which plant root growth is severely arrested [14].

According to Blanco-Canqui and Ruis [70], bulk density and penetrometer resistance did not generally differ between long-term NT and ST systems. However, it is important to note that the lack of soil penetrometer data availability and inconsistency with the measurement was mentioned as a cause of not having a distinct impact of ST

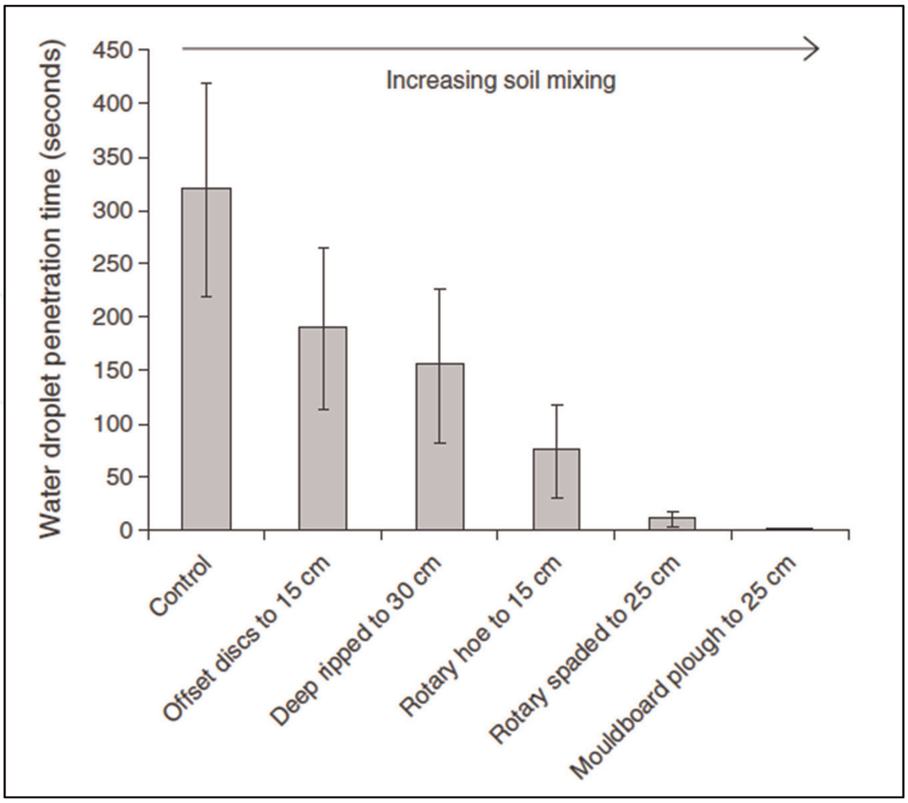

Figure 2.
Impact of one-off cultivation of different intensities on soil water repellence of a Tenosol at Badgingarra as measured in the laboratory using the water-droplet penetration time. Capped lines are standard errors of the mean (n = 4). Adapted from Davies et al. [69].

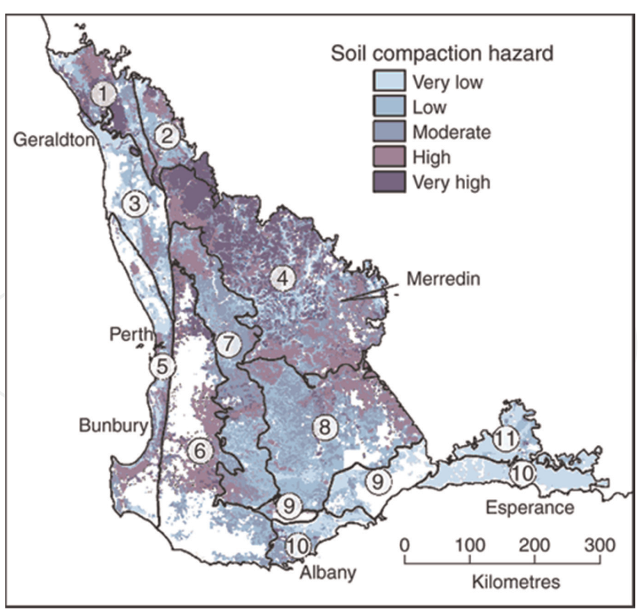

Figure 3.
Status of soil compaction in Western Australia. Source: Parker et al. [56].

on soil compaction [36]. Moreover, the study by Blanco-Canqui and Wortmann [36] used ST implement that addressed only the top 0.20 m of soil which might not alleviate compaction in deeper soil, therefore, deeper tillage was recommended. Azam and Gazey [14] conducted deep tillage (excavation and filling back) in a highly

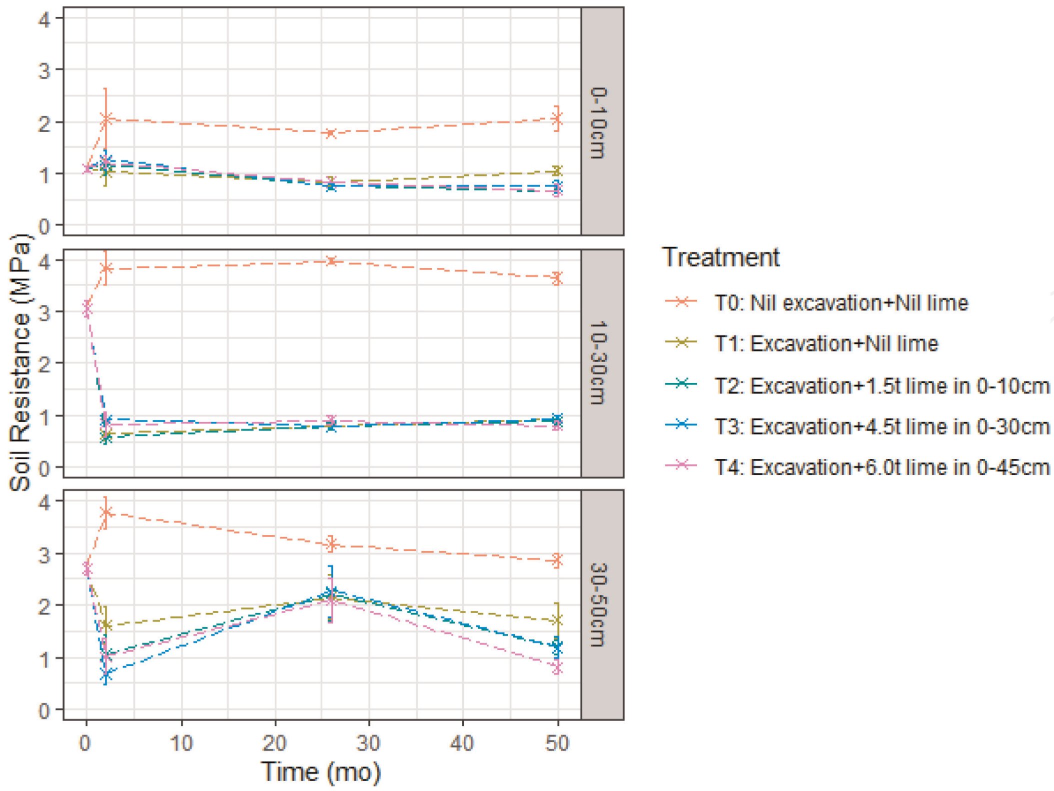

Figure 4.
Effect of strategic tillage (excavation and filling back) on long-term soil resistance. Adapted from Azam and Gazey [14].

compacted soil (a soil strength of 3–4 MPa) in a low rainfall region of Kalannie, WA (35°42'S, 117°29′E) in 2018. They reported deep tillage significantly decreased soil strength (measured at field capacity) and the effect persisted for at least five cropping years (**Figure 4**). Davies et al. [33] reported that deep ripping was the most studied ST practice in southern Australia. Deep ripped soil maintained significantly lower soil strength than the unripped soil for 3–7 years depending on the soil type and rainfall region. Soil with less clay content was naturally recompacted faster than soil with more clay content [33, 56].

3.1.3 ST for treating subsurface soil acidity

In Western Australia (WA), around 50% of the subsoil (0.10–0.30 m) are acidic and have a soil pH (1:5 soil to 0.01 M $CaCl_2$ extract) below the minimum target pH of 4.8 in the subsoil (**Figure 5**). Subsoil acidity is less widely distributed and shallower depths in other southern regions of Australia, but still remains as one of the main soil challenges for the farmers [16]. At low soil pH, the increase in the concentration of toxic forms of aluminium (Al) significantly limits root growth and crop yield [71]. Importantly, soil acidity also often occurs with other soil constraints such as compaction and topsoil water repellence [72].

Several soil amelioration approaches are available for Australian growers to manage subsoil acidity and compaction, the two most widely occurring soil constraints. *Approach 1*: the traditional approach whereby agricultural lime is applied (often multiple applications) on the soil surface. This approach takes many years to increase subsoil pH significantly and does not treat subsoil compaction [14, 16]. *Approach 2*: a

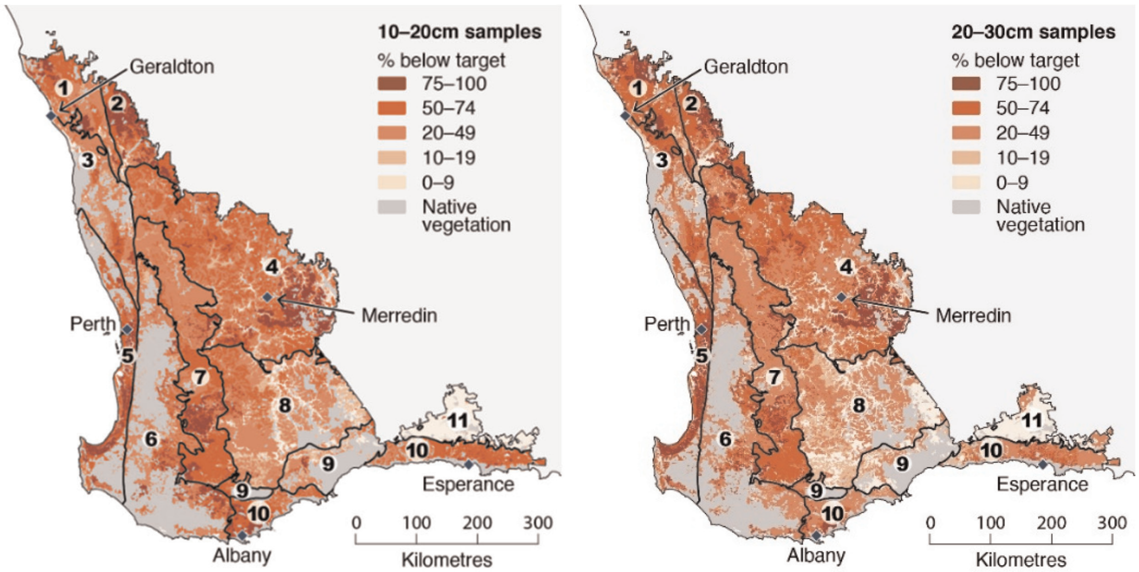

Figure 5.
Status of subsurface soil acidity in Western Australia. Source: Gazey et al. [17].

more recent and increasingly adopted approach that involves the use of ST operations, whereby lime is spread and incorporated at deeper soil depths while loosening compacted soil by a deep ripper or overcoming water-repellent soils by inversion ploughing or rotary spading [33]. Literature suggests that physical tillage operations to treat compaction and non-wetting soils can opportunistically be used to incorporate lime [67]. However, such soil amelioration practices are found to remediate soil acidity only partially, hence yield responses can be variable as observed from various long-term field trials [34]. Scanlan et al. [73] suggested that if a tillage operation incorporates lime to the depths where the soil pH constraint occurs, an immediate payback on lime and cultivation might be possible.

From a long-term (25 years) field experiment with multiple rates (0–8.5 t/ha) and applications of lime, with or without ST, in Wongan Hills, WA (30.°85'S, 116°74′E), soil samples were collected in 2019 and pH was measured [74]. The result showed that the strategic deep tillage was effective in increasing the subsoil pH to the minimum target pH level of 4.8 (in 0.10–0.20 m and 0.20–0.30 m soil depths) within 3 months of applying ST compared to the NT practices, especially where higher rates of lime was applied (**Figure 6**). However, the ST did not show any significant negative effect in changing soil pH of the topsoil (0–0.10 m) compared to the NT [74].

The amelioration of soil acidity will consequently decrease the toxic form Al concentration. In fact, when soil pH (measured in 0.01 M $CaCl_2$) increases to >4.5 pH units, the toxic form of Al almost disappears. An experiment by Azam and Gazey [75] in Kalannie, WA (35°42'S, 117°29′E) reported that lime incorporation increased soil pH to the recommended pH level of 5.5 in the surface and 4.8 in lime-incorporated subsoil horizons (**Figure 7**). Liming also decreased extractable Al concentration from very toxic range (≥30 mg/kg) to below the critical level for wheat (≤5 mg/kg). Loosening by excavation alone also decreased Al concentration, especially at 0.10–0.20 m depth (**Figure 7**).

The longevity of the effect of the lime application on soil acidity may depend on many factors (such as soil texture, rainfall, and moisture content) which might lure more research on that matter. Based on Australian data for ST, Conyers et al. [76] reported that the effect of the addition and incorporation of 2 to 3 t/ha lime should last for at least 10 years.

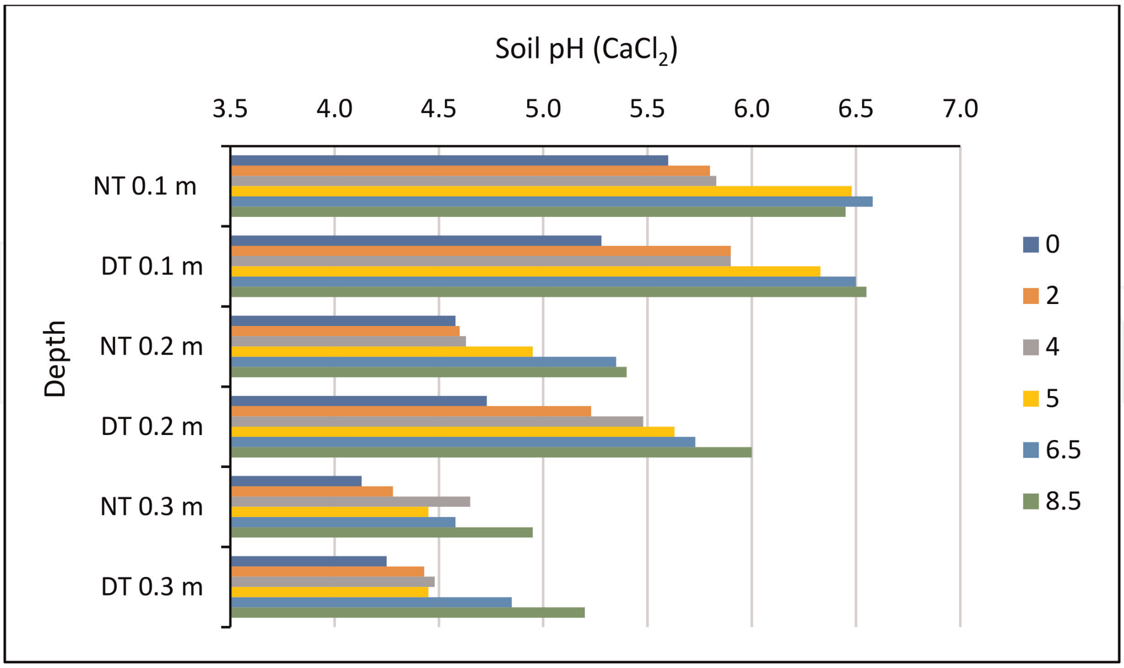

Figure 6.
Soil pH under different liming strategies and tillage treatments in autumn 2019 in loamy sand at Wongan Hills, WA. The NT and DT indicate no-tillage and deep tillage, respectively. Different colours of the Bar indicate lime rates (0–8.5 t/ha). Statistics: The least significant differences (5%) for deep tillage x lime rates at 0–0.10 m depth = 0.36, 0.10–0.20 m depth = 0.60 and 0.20–0.30 m depth = 0.45. Adapted from Azam et al. [74].

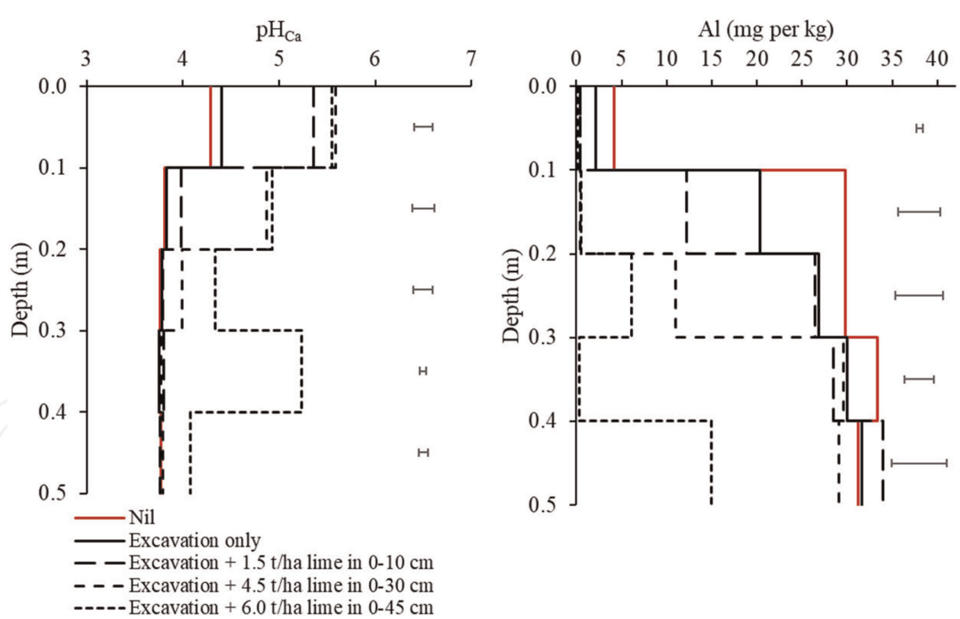

Figure 7.
Effect of lime incorporation on soil pH (left) and extractable Al concentration (right). Horizontal error bars represent the least significant difference at P ≤ 0.05. Adapted from Azam and Gazey [75].

3.1.4 ST for nutrient redistribution

One of the downsides of conservation agriculture is nutrient stratification along the soil profile. It is a problem for mobile and non-mobile plant nutrients [77]. Broadcasting of immobile nutrients like phosphorus (P) with no or incomplete mixing by tillage will increase nutrient concentration in the surface soil and will pose a greater risk of nutrient loss through runoff and will be greatly responsible for nutrient eutrophication. The leaching of soluble nutrients is another cause of nutrient stratification in the subsurface layers. Soil mixing through tillage may reduce the risk of nutrient loss from topsoil layers [78]. Many studies also reported similar findings of an increase in subsoil nutrient concentration after tillage with a low concentration of nutrients [77–82] due to mixing of top and subsoil [83]. However, the benefit of tillage on nutrient redistribution will disappear over time through improved acquisition by plant roots [84]. McLaughlin et al. [85] rotary hoed a 250 kg/ha superphosphate at the top 0.10 m of soil under an annual pasture and the effect lasted for 7 years.

3.1.5 ST for herbicide-resistant weeds

One of the main factors that accelerated the adoption of conservation agriculture (CA) was the development of herbicides. The long-term practice of CA resulted in the development of resistance against herbicides by many weed species [86, 87]. The advantage of ST is the physical mixing of soil which is likely to decrease weed emergence and bury weed seeds. The emergence and growth of weeds can be stimulated by shallow tillage, but deep tillage can potentially prevent weed emergence [35, 88]. A recent review by Mia et al. [89] reported that soil inversion with mouldboard plough (0.35–0.45 m operating depth) can decrease weed emergence by 50–99% [35, 90–93]. Soil inversion with a modified one-way disc plough, (0.30–0.40 m operating depth) decreased weed population by up to 90% [94]. However, in a recent study by Edwards et al. [95] reported an increase in the activity of some herbicides and an increase in phytotoxicity following ST due to decreased organic matter. Therefore, when ST is adopted, herbicides and their doses should be carefully selected.

3.2 Effect of ST on plant growth and crop yield

3.2.1 Effect of ST on plant root growth

In the Wheatbelt region of WA, many paddocks have multiple soil constraints such as compaction, water repellence and subsurface soil acidity, resulting in limited and confined root growth within 0.20–0.30 m of the surface [96]. The amelioration of soil constraints such as soil acidity and compaction would have many benefits for plant growth for accessing subsoil moisture and nutrients [72]. Azam and Gazey, 2021 showed that amelioration of compaction and acidity in a 25-year NT paddock in Kalannie, WA (35°42'S, 117°29′E) by ST and incorporation of lime significantly enhanced root growth up to 0.70 m soil depth compared to control treatment (where root reached 0.30 m below the soil surface, **Figure 8**).

3.2.2 Effect of ST on crop yield

The amelioration of soil compaction, acidity, and other soil and agronomic constraints using ST and agricultural lime is expected to increase crop yield. The level of yield response from the adoption of ST will depend on whether a single or multiple constraints are addressed in a single intervention. Azam et al. [74] demonstrated using a Mouldboard (MBP) plough only for amelioration water repellent soil generated significant yield response for 7 years. However, incorporation of 2 t/ha lime using a MBP to a depth of 0.25–0.30 m significantly increased yield after 7 years and has continued to have a yield advantage over the next 7 years, compared to the MBP-alone and the

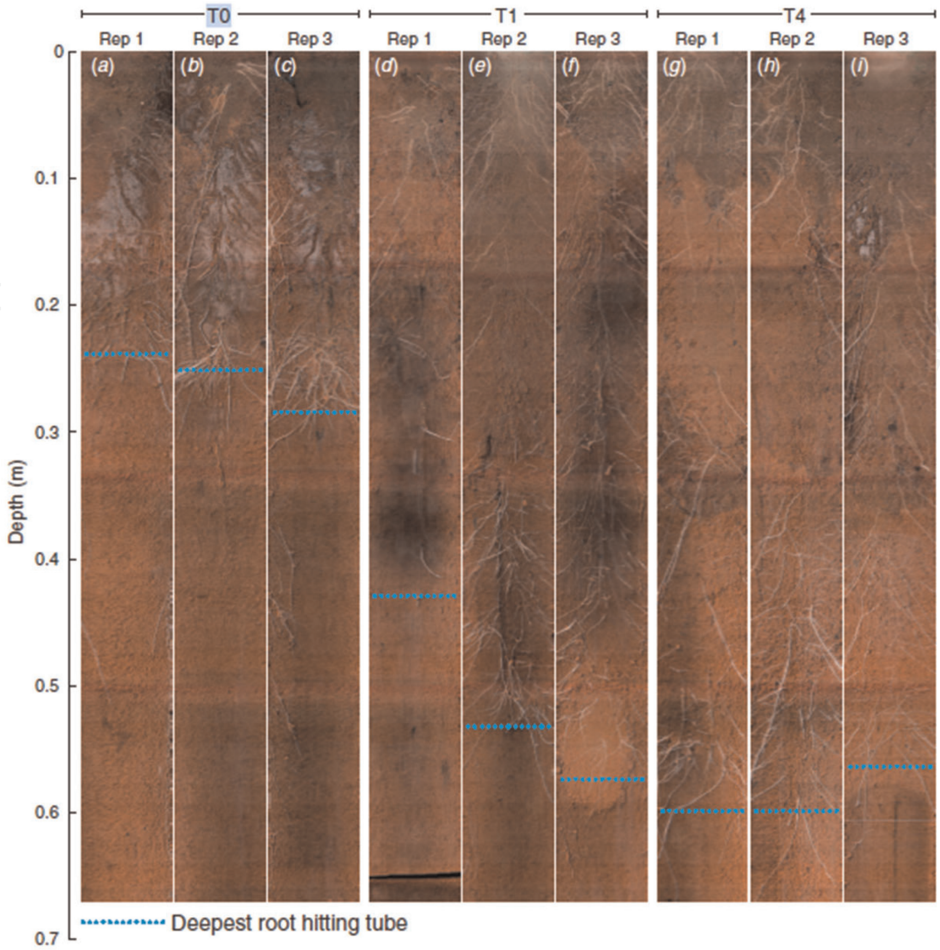

Figure 8.
*Wheat (*Triticum aestivum *L.) rooting depth and architecture in deep loamy sand at Kalannie, WA, 56 days after sowing under control (T0; a–c), removal of compaction only (T1; d–f) and compaction plus deep incorporation of lime (T4; g–i). Wheat root architecture for T0, T1 and T4 was imaged repeatedly in situ using a 360° scanner (CI-600, CID bio-science, camas, WA, USA) inserted in clear glass tubes (Rhizotron tubes, ICT international, Armidale, NSW). Photo adapted from Azam and Gazey [14].*

control [74]. Yield response will also depend on the severity and depth of soil constraints as well as the depth of ST. Davies et al. [33] 2019 reported an increasing yield response with increasing depth of deep ripping (**Figure 9**). However, a recent review of the effect of ST on crop yield by Blanco-Canqui and Wortmann [36] reported that about 80% of the studies (12 studies including 31 soils across different regions of Australia and worldwide) showed no effect, 15% of cases increased the yield. In comparison, there was a yield penalty in 5% of cases. The reason for such variable results was speculated as the variability of site-crop-year-management-specific. Another reason could be the use of shallow tillage activity (only the top 0.20 m of the soil), which does not ameliorate deeper subsoil compaction and acidity and allow plant root to explore further. Such shallow tillage operation might damage to the soil structure and increase the loss of soil water through enhanced evaporation rates [4].

A deep lime incorporation (re-engineering) experiment (see details [74]) was established in Kalannie (30°25'S, 117°17'E) in 2018 using 0, 1.5, 4.5 and 6.0 t/ha lime and monitored for three seasons. Five soil amelioration treatments were included, comprising an untreated control, removal of compaction only and removal of both compaction and acidity (by incorporating lime at 0–0.10, 0–0.30 and 0–0.45 m depths). In this experiment at Kalannie, the combined removal of compaction and

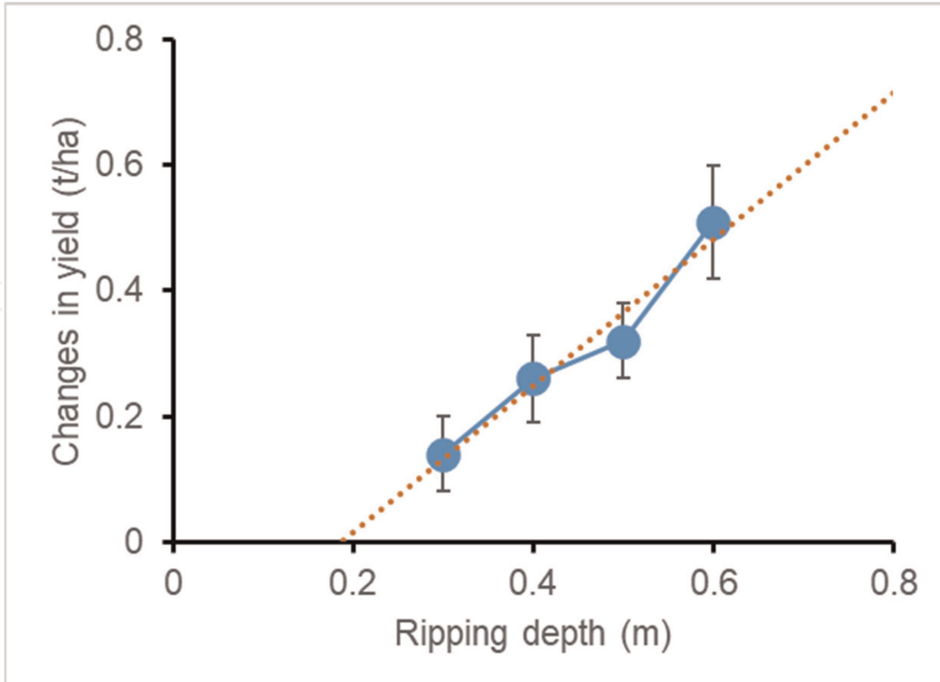

Figure 9.
Relationship between ripping depths and changes in grain yield. The number of data points (comparisons) with 0.30, 0.40, 0.50, and 0.60 m ripping depths are 32, 29, 24, and 14, respectively. Adapted from Davies et al. [33].

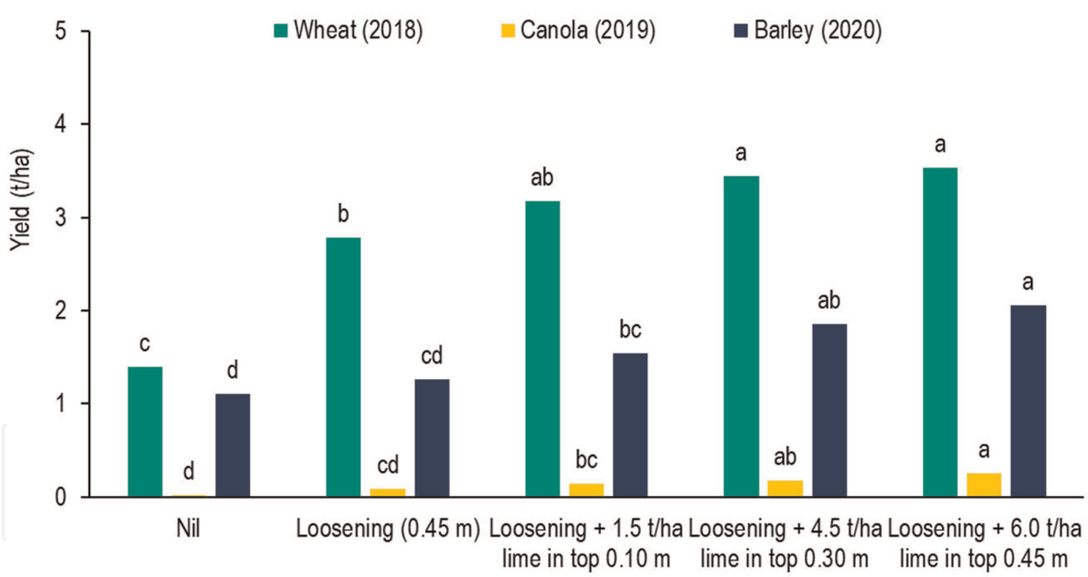

Figure 10.
Grain yield responses due to soil re-engineering in Kalannie. Different letters indicate significant difference in re-engineering experiments at $P \leq 0.05$. Adapted from Azam and Gazey [74].

acidity doubled the grain yield (**Figure 10**). Removal of compaction alone increased the yield of wheat but not of canola or barley. Grain yield exceeded the water-limited potential by 33–56% (as calculated using the French and Schultz equation [97] due to the amelioration of multiple constraints under standard agronomic practice [74]. Deep soil re-engineering allowed plants to produce 0.60–0.65 m deep root systems, while they were only 0.20–0.25 m deep for control [74]. Significant and rapid improvements in root growth and yield were achieved due to the increase in subsoil pH and a uniform and sustained decrease in soil resistance [74, 75].

4. Economic benefits of ST

Currently the occurrence of multiple interacting soil and agronomic constraints is costing Australian farmers millions of dollars due to loss in crop productivity [54–57]. ST can manage these soil and agronomic challenges. However, use of ST always incurs an additional cost. The cost of tillage operation depends on many factors such as type of tillage equipment, type of tillage operation; deep ripping or soil mixing, strategic deep tillage, constraint type; single constraint or multiple constraints [33]. Yield response depends on crop type, soil productivity, rainfall, and other management factors. In calculating the economic benefits of ST, the longevity of operation for specific or multiple interacting constraints needed to be considered.

Among different tillage tools, deep ripping is mostly expensive in southern Australia, ranging from $AU 45 to 1400 and depending on the type of tillage tool and constraints that need to be fixed (**Table 1**). Soil mixing is the cheapest one due to its shallow tillage depth capacity ranging from (0.20–0.40 m). The cost of soil inversion is higher than soil mixing ranging from $AU 40 to 150 but would address more soil constraints.

The existing literature showed that soil mixing or inversion is the cheapest tillage method with maximum yield response and long-lasting benefits compared to the deep ripping method of tillage (**Table 2**). Although deep ripping methods show less economic return in the current literature, it requires more study and time to justify their contribution to yield. Because deep ripping up to 0.70 m is a new concept that requires careful attention to build the necessary equipment to reduce the operation cost at a cheaper rate. Deep ripping using a ‘soil re-engineering’ approach showed a greater yield increase potential in recent years (**Figures 8** and **9**) and require a longer observation before concluding its effect on longevity. Moreover, deep ripping in ST could address multiple soil constraints following the soil re-engineering approach.

Tillage	Tillage tool	Tillage depth (m)	Soil constraints addressed*	Cost (approx) ($AU/ha)
Deep ripping	Ripper	0.3–0.7	1, 2	$45–100
	With topsoil slotting		1, 2, 3, 4	$55–120
	Subsoil placement		1, 2, 3, 5	$300–1400
Soil mixing	Offset discs	0.2–0.3	1, 3, 6	$50–70
	One pass tillage	0.3–0.35	1, 3	$70–100
Soil inversion	Rotary spader	0.35–0.4	1, 3, 5, 6	$120–150
	Mouldboard plough	0.35–0.45	1, 5, 6, 7	$100–150
	Modified one-way disc plough	0.3–0.4	1, 5, 6, 7	$40–60

**Soil constraints included (1) compaction, (2) Hardpans, (3) subsoil acidity (4) subsoil sodicity, (5) subsoil fertility, (6) water repellence, and (7) weeds.*
Adapted from Davies et al. [33].

Table 1.
Cost involvement in selecting tillage techniques and methods to specific/group of soil constraints.

Tillage method	Features	Yield responses	References
Deep ripping	• More effective in sandy soil than clay soil • Benefit last for 3 seasons	*Wheat* NSW: 33% SA: 10–23% VIC: 23–25% WA: 20–47%	[98]
Deep ripping with amendments	• Gypsum, nutrients, wheat straw + nutrient, chicken manure	VIC: 12–16%	[33]
Soil mixing or inversion	• Benefits last for 10 years	*WA: In Cereal* 1st and 2nd year: 56–86% 3rd & after 11–49%	[33]
		SA Field research Yield increase: 200%	[99]

NSW = New South Wales, SA = South Australia, VIC = Victoria, and WA = Western Australia.

Table 2.
Yield response from different tillage methods practised in various regions of southern Australia.

5. Future research direction

Continuous practices of conservation agricultural (CA) has created a new generation of soil and agronomic challenges that can be strategically managed using one-off deep tillage (ST) and then returning to CA in a no-till cropping. ST is likely to offer a sustainable solution to the soil and agronomic constraints that arise from long-term CA. However, the longevity of the ST in an NT system after fixing single or multiple soil constraints needed to be explored further.

Soil re-engineering is a new approach that signifies the importance of ST, however, identifying the right soil re-engineering approaches for treating multiple interacting soil constraints needs further research before being ready for adoption at farmer scale.

Developing the next generation soil amelioration machinery for optimum amelioration outcome is required. The deep tillage technique requires heavy machinery which would involve an elevated cost to the farmers for agricultural activities. Therefore, new machinery options must be explored to attain a cheaper investment cost for agricultural activities.

Soil water holding capacity (also known as crop upper limit) is usually determined by soil textural classes and by soil organic matter. Under conservation agriculture, soil texture cannot be readily changed, therefore, soil water holding capacity remains unchanged. Using strategic tillage implements such as deep-ripper or delver in soil amelioration can bring deep subsoil clay (especially in duplex soil) to the upper sandy layers (where most crop roots grow) and improve the soil water holding capacity. In re-engineered soil, a prescribed amount of clay can be added to the sandy layer, significantly increasing water holding capacity while maintaining adequate water infiltration. Plant available water (the amount of water a soil can hold after free drainage minus the amount of water at the crop's lower limit) in ameliorated soil will differ from the constrained soil due to restricted root growth. Therefore, an improved understanding of the relationship between plant available water, plant growth and crop yield responses for strategically tilled soil is necessary.

Acknowledgements

We thank the Government of Western Australia and the Grains Research and Development Corporation for investing in various soil research projects under the Soil Constraints West banner. We are grateful to Chris Gazey and Dr. Stephen Davies for pioneering the management of multiple soil constraints in Western Australian agriculture and the many challenging and productive conversations in this area. We thank Daron Malinowski, Richard Bowles, Hasinur Rahman, Alistair Hall for helping in these research projects and other technical staff from DPIRD's research support operations.

Conflict of interest

The authors declare no conflicts of interest.

Author details

Gaus Azam*, Md. Shahinur Rahman and Kanch Wickramarachchi
Department of Primary Industries and Regional Development, Northam, Western Australia, Australia

*Address all correspondence to: gaus.azam@dpird.wa.gov.au

References

[1] Emerson WW. Inter-particle bonding. In: Soils: An Australian Viewpoint. Div. Of Soils, CSIRO, Melbourne. London, England: Academic Press; 1983. pp. 477-498

[2] Melland AR, Antille DL, Dang YP. Effects of strategic tillage on short-term erosion, nutrient loss in runoff and greenhouse gas emissions. Soil Research. 2016;**55**:201-214. DOI: 10.1071/SR16136

[3] Dang YP, Balzer A, Crawford M, Rincon-Florez V, Liu H, Melland AR, et al. Strategic tillage in conservation agricultural systems of North-Eastern Australia: Why, where, when and how? Environmental Science and Pollution Research. 2018;**25**:1000-1015. DOI: 10.1007/s11356-017-8937-1

[4] Betti G, Azam G. Topsoil Evaporation in Water Repellent Soil Affected by Tillage and Claying: Preliminary Case-study Results. In: Proceedings of Soil Science Australia WA Branch Conference. Perth, Western Australia: University of Western Australia; 2019. Available from: https://library.dpird.wa.gov.au/cgi/viewcontent.cgi?article=1077&context=ssswa_conf

[5] Swaminathan C, Sobhana E, Kannan P, Yassin MM. Principles, positives and limitations of conservation agriculture: A review. Agricultural Reviews. 2022;**43**:410-418. DOI: 10.18805/ag.R-2166

[6] Food and Agriculture Organization. Conservation Agriculture. 2022. Available from: https://www.fao.org/3/cb8350en/cb8350en.pdf [Accessed: June 15, 2023]

[7] Kirkegaard J, Kirkby C, Oates A, van der Rijt V, Poile G, Conyers M. Strategic tillage of a long-term, no-till soil has little impact on soil characteristics or crop growth over five years. Crop and Pasture Science. 2020;**71**:945-958. DOI: 10.1071/CP20334

[8] Fischer RA, Hobbs P. Tillage: global update and prospects. In: Pratley J, Kirkegaard J, editors. Australian agriculture in 2020: from conservation to automation: Graham Centre for Agricultural Innovation. Wagga Wagga, NSW, Australia: Charles Sturt University; 2019. p. 3-19

[9] Kassam A, Friedrich T, Derpsch R. Global spread of conservation agriculture. International Journal of Environmental Studies. 2019;**76**:29-51. DOI: 10.1080/00207233.2018.1494927

[10] Llewellyn R, Ouzman J. Conservation agriculture in Australia: 30 years on. In: Pratley J, Kirkegaard J, editors. Australian agriculture in 2020: from conservation to automation: Graham Centre for Agricultural Innovation. Wagga Wagga, NSW, Australia: Charles Sturt University; 2019. p. 21-31

[11] Umbers A. Farm Practices Survey Report 2016. 2017. Available from: https://grdc.com.au/resources-and-publications/all-publications/publications/2018/farm-practices-survey-report-2016 [Accessed: June 15, 2023]

[12] Chan KY. Development of seasonal water repellency under direct drilling. Soil Science Society of America Journal. 1992;**56**:326-329. DOI: 10.2136/sssaj1992.03615995005600010054x

[13] Hall DJ, Jones HR, Crabtree WL, Daniels TL. Claying and deep ripping can increase crop yields and profits on water repellent sands with marginal fertility in southern Western Australia.

Soil Research. 2010;**48**:178-187. DOI: 10.1071/SR09078

[14] Azam G, Gazey C. Slow movement of alkali from surface-applied lime warrants the introduction of strategic tillage for rapid amelioration of subsurface acidity in South-Western Australia. Soil Research. 2020;**59**:97-106. DOI: 10.1071/SR19329

[15] Conyers MK, Heenan DP, McGhie WJ, Poile GJ. Amelioration of acidity with time by limestone under contrasting tillage. Soil and Tillage Research. 2003a;**72**:85-94. DOI: 10.1016/S0167-1987(03) 00064-3

[16] Li GD, Conyers MK, Helyar KR, Lisle CJ, Poile GJ, Cullis BR. Long-term surface application of lime ameliorates subsurface soil acidity in the mixed farming zone of South-Eastern Australia. Geoderma. 2019;**338**: 236-246. DOI: 10.1016/j.geoderma.2018.12.003

[17] Gazey C, Andrew J, Griffin E. Soil acidity. In: Report Card on Sustainable Natural Resource Use in Agriculture: Department of Primary Industries and Regional Development, Perth, Western Australia; 2013. pp. 26-43. Available from: https://www.agric.wa.gov.au/sites/gateway/files/Report%20card%20on%20sustainable%20natural%20resource%20use%20in%20agriculture%20-%20full%20report%20-%2025MB.pdf

[18] Paul K, Black A, Conyers M. Development of acidic subsurface layers of soil under various management systems. Advances in Agronomy. 2003;**78**:187-214. DOI: 10.1016/S0065-2113(02)78005-X

[19] Glen DM, Symondson WO. Influence of soil tillage on slugs and their natural enemies. In: Eli Titi A, editor. Soil Tillage in Agroecosystems. Boca Raton: CRC Press; 2003. pp. 207-227. DOI: 10.1201./9781420040609.ch8

[20] Rahman L, Chan KY, Heenan DP. Impact of tillage, stubble management and crop rotation on nematode populations in a long-term field experiment. Soil and Tillage Research. 2007;**95**:110-119. DOI: 10.1016/j.still.2006.11.008

[21] Owen MJ, Walsh MJ, Llewellyn RS, Powles SB. Widespread occurrence of multiple herbicide resistance in Western Australian annual ryegrass (Lolium rigidum) populations. Australian Journal of Agricultural Research. 2007;**58**: 711-718. DOI: 10.1071/AR06283

[22] Powles SB, Yu Q. Evolution in action: Plants resistant to herbicides. Annual Review of Plant Biology. 2010;**61**: 317-347. DOI: 10.1146/annurevarplant-042809-112119

[23] Pierce FJ, Fortin MC, Staton MJ. Periodic plowing effects on soil properties in a no-till farming system. Soil Science Society of America Journal. 1994;**58**:1782-1787. DOI: 10.2136/sssaj1994.03615995005800060029x

[24] Kirkegaard JA. A review of trends in wheat yield responses to conservation cropping in Australia. Australian Journal of Experimental Agriculture. 1995;**35**: 835-848. DOI: 10.1071/EA9950835

[25] Dick WA. Tillage system impacts on environmental quality and soil biological parameters. Soil and Tillage Research. 1997;**41**:165-167. DOI: 10.1016/S0167-1987(96)01093-8

[26] Bolliger A, Magi J, Amado TJC, Neto FS, Ribeiro MDD, Calegari A, et al. Taking stock of the Brazilian "zero-till revolution": A review of landmark research and farmers' practice. Advances in Agronomy. 2006;**91**:47-110. DOI: 10.1016/S0065-2113(06)91002-5

[27] Baan CD, Grevers MCJ, Schoenau JJ. Effects of a single cycle of tillage on long-term no-till prairie soils. Canadian Journal of Soil Science. 2009;**89**:521-530. DOI: 10.4141/cjss08041

[28] Giller KE, Witter E, Corbeels M, Tittonell P. Conservation agriculture and smallholder farming in Africa: The heretics' view. Field Crops Research. 2009;**114**:23-34. DOI: 10.1016/j.fcr.2009.06.017

[29] Domínguez A, Bedano JC, Becker AR. Negative effects of no-till on soil macrofauna and litter decomposition in Argentina as compared with natural grasslands. Soil and Tillage Research. 2010;**110**:51-59. DOI: 10.1016/j.still.2010.06.008

[30] Wortmann CS, Drijber RA, Franti TG. One-time tillage of no-till crop land five years post-tillage. Agronomy Journal. 2010;**102**:1302-1307. DOI: 10.2134/agronj2010.0051

[31] Crawford MH, Rincon-Florez V, Balzer A, Dang YP, Carvalhais LC, Liu H, et al. Changes in the soil quality attributes of continuous no-till farming systems following a strategic tillage. Soil Research. 2015;**53**(3):263-273. DOI: 10.1071/SR14216

[32] Nunes MR, da Silva AP, Denardin JE, Giarola NF, Vaz CM, Van Es HM, et al. Soil chemical management drives structural degradation of Oxisols under a no-till cropping system. Soil Research. 2017;**55**:819-831. DOI: 10.1071/SR17063

[33] Davies S, Armstrong R, Macdonald LM, Condon J, Peterson E. Soil constraints: A role for strategic deep tillage. In: Pratley J, Kirkegaard J, editors. Australian Agriculture in 2020: From Conservation to Automation. Wagga Wagga, NSW, Australia: Agronomy Australia and Charles Stuart University; 2019. p. 117-135. Available from: https://researchoutput.csu.edu.au/ws/portalfiles/portal/35078495/35078149_peer_review.pdf

[34] Davies S, Boyes T, Reynolds C, Petersen L, Walker J, Fulwood T, et al. Understanding the impact of a comprehensive range of deep tillage practices on crop performance and soil properties for two water repellent soil types. In: Proceedings of GRDC Grains Research Updates, 26-27 February 2018. Perth, WA, Australia: Grains Research and Development Corporation; 2018. Available from: https://grdc.com.au/resources-andpublications/grdc-update-papers/tabcontent/grdc-update papers/2018/02/understanding-the-impactof-deep-tillage-practices

[35] Roper MM, Davies SL, Blackwell PS, Hall DJ, Bakker DM, Jongepier R, et al. Management options for water-repellent soils in Australian dryland agriculture. Soil Research. 2015;**53**:786-806. DOI: 10.1071/SR14330

[36] Blanco-Canqui H, Wortmann CS. Does occasional tillage undo the ecosystem services gained with no-till? A review. Soil and Tillage Research. 2020;**198**:104534. DOI: 10.1016/j.still.2019.104534

[37] Blanco-Canqui H, Wienhold BJ, Jin VL, Schmer MR, Kibet LC. Long-term tillage impact on soil hydraulic properties. Soil and Tillage Research. 2017;**170**:38-42. DOI: 10.1016/j.still.2017.03.001

[38] Uusitalo R, Lemola R, Turtola E. Surface and subsurface phosphorus discharge from a clay soil in a nine-year study comparing no-till and plowing. Journal of Environmental Quality. 2018;**47**(6):1478-1486. DOI: 10.2134/jeq2018.06.0242

[39] Rakkar MK, Blanco-Canqui H. Grazing of crop residues: Impacts on soils and crop production. Agriculture, Ecosystems & Environment. 2018;**258**: 71-90. DOI: 10.1016/j.agee.2017.11.018

[40] Blanco-Canqui H, Wortmann CW. Crop residue removal and soil erosion by wind. Journal of Soil and Water Conservation. 2017;**72**:97A-104A. DOI: 10.2489/jswc.72.5.97A

[41] Mendez MJ, Aimar SB, Buschiazzo DE. PM10 emissions from aggregate fractions of an Entic Haplustoll under two contrasting tillage systems. Aeolian Research. 2015;**19**: 195-201. DOI: 10.1016/j.aeolia.2015.01.009

[42] Li H, Tatarko J, Kucharski M, Dong Z. PM2. 5 and PM10 emissions from agricultural soils by wind erosion. Aeolian Research. 2015;**19**:171-182. DOI: 10.1016/j.aeolia.2015.02.003

[43] Nunes MR, Denardin JE, Pauletto EA, Faganello A, Pinto LF. Effect of soil chiseling on soil structure and root growth for a clayey soil under no-tillage. Geoderma. 2015;**259**: 149-155. DOI: 10.1016/j.geoderma.2015.06.003

[44] DeLaune PB, Sij JW. Impact of tillage on runoff in long term no-till wheat systems. Soil and Tillage Research. 2012;**24**:32-35. DOI: 10.1016/j.still.2012.04.009

[45] Quincke JA, Wortmann CS, Mamo M, Franti T, Drijber RA, Garcia JP. One-time tillage of no-till systems: Soil physical properties, phosphorus runoff, and crop yield. Agronomy Journal. 2007a;**99**:1104-1110. DOI: 10.2134/agronj2006.0321

[46] Celik I, Gunal H, Acar M, Acir N, Bereket Barut Z, Budak M. Strategic tillage may sustain the benefits of long-term no-till in a vertisol under Mediterranean climate. Soil Tillage and Research. 2019;**185**:17-28. DOI: 10.1016/j.still.2018.08.015

[47] Kettler TA, Lyon DJ, Doran JW, Powers WL, Stroup WW. Soil quality assessment after weed-control tillage in a no-till wheat–fallow cropping system. Soil Science Society of America Journal. 2000;**64**(1):339-346. DOI: 10.2136/sssaj2000.641339x

[48] Díaz-Zorita M, Grove JH, Murdock L, Herbeck J, Perfect E. Soil structural disturbance effects on crop yields and soil properties in a no-till production system. Agronomy Journal. 2004;**96**(6):1651-1659. DOI: 10.2134/agronj2004.1651

[49] Spargo JT, Alley MM, Follett RF, Wallace JV. Soil carbon sequestration with continuous no-till management of grain cropping systems in the Virginia coastal plain. Soil and Tillage Research. 2008;**100**:133-140. DOI: 10.1016/j.still.2008.05.010

[50] Zhao X, Xue JF, Zhang XQ, Kong FL, Chen F, Lal R, et al. Stratification and storage of soil organic carbon and nitrogen as affected by tillage practices in the North China plain. PLoS One. 2015;**10**:e0128873. DOI: 10.1371/journal.pone.0128873

[51] Quincke JA, Wortmann CS, Mamo M, Franti T, Drijber RA. Occasional tillage of no-till systems: Carbon dioxide flux and changes in total and labile soil organic carbon. Agronomy Journal. 2007;**99**:1158-1168. DOI: 10.2134/agronj2006.0317

[52] Wortmann CS, Quincke JA, Drijber RA, Mamo M, Franti T. Soil microbial community change and

recovery after one-time tillage of continuous no-till. Agronomy Journal. 2008;**100**:1681-1686. DOI: 10.2134/agronj2007.0317

[53] Garcia JP, Wortmann CS, Mamo M, Drijber R, Tarkalson D. One-time tillage of no-till: Effects on nutrients, mycorrhizae, and phosphorus uptake. Agronomy Journal. 2007;**99**:1093-1103. DOI: 10.2134/agronj2006.0261

[54] Barrett-Lennard E, Hall D, Parker W, Munir R. Soil quality 8: Sodic and alkaline soil. In: Hoyle F, Murphy D, Gazey C, Maddern R, Gazey P, editors. The Soil Quality eBooks Series. Perth, WA, Australia: SoilsWest; 2022. p. 53

[55] Davies S, Fisher J, Roper M, Murphy D. Soil quality 7: Soil water repellence. In: Hoyle F, Murphy D, Gazey C, Maddern R, Gazey P, editors. The Soil Quality eBooks Series. Perth, WA, Australia: Soils West; 2022. p. 48

[56] Parker W, Isbister HF, Leopold M. Soil quality 6: Soil compaction. In: Hoyle F, Murphy D, Gazey C, Maddern R, Gazey P, editors. The Soil Quality eBooks Series. Perth, WA, Australia: SoilsWest; 2021. p. 63

[57] Gazey C, Azam G, Clausen J, Rengel Z. Soil quality 4: Soil acidity. In: Murphy D, Hoyle F, Boggs G, Gazey P, editors. The Soil Quality eBooks Series. Perth, WA, Australia: SoilsWest; 2019. p. 48

[58] Van Gool D. Identifying soil constraints that limit wheat yield in South-West Western Australia. In: Resource management technical report 399: Department of Primary Industries and Regional Development, Perth, Western Australia;2016. Available from: https://www.agric.wa.gov.au/managing soils/soil-constraints-limit-wheat-yield-southwest-western-australia [Accessed 2023-06-15]

[59] Bisdom EB, Dekker LN, Schoute JF. Water repellency of sieve fractions from sandy soils and relationships with organic material and soil structure. Geoderma. 1993;**56**:105-118. DOI: 10.1016/0016-7061 (93) 90103-R

[60] Harper RJ, McKissock I, Gilkes RJ, Carter DJ, Blackwell PS. A multivariate framework for interpreting the effects of soil properties, soil management and landuse on water repellency. Journal of Hydrology. 2000;**231**:371-383. DOI: 10.1016/S0022-1694(00)00209-2

[61] Blanco-Canqui H, Lal R. Extent of soil water repellency under longterm no-till soils. Geoderma. 2009;**149**:171-180. DOI: 10.1016/j.geoderma.2008.11.036

[62] Roper MM, Ward PR, Keulen AF, Hill JR. Under no-tillage and stubble retention, soil water content and crop growth are poorly related to soil water repellency. Soil and Tillage Research. 2013;**126**:143-510. DOI: 10.1016/j.still.2012.09.006

[63] Matějková Š, Šimon T. Application of FTIR spectroscopy for evaluation of hydrophobic/hydrophilic organic components in arable soil. Plant, Soil and Environment. 2012;**58**:192-195. DOI: 10.17221/317/2011-PSE

[64] Nadav I, Tarchitzky J, Chen Y. Soil cultivation for enhanced wastewater infiltration in soil aquifer treatment (SAT). Journal of Hydrology. 2012;**470**:75-81. DOI: 10.1016/j.jhydrol.2012.08.013

[65] Steenhuis TS, Hunt AG, Parlange JY, Ewing RP. Assessment of the application of percolation theory to a water repellent soil. Soil Research. 2005;**43**:357-360. DOI: 10.1071/ SR04093

[66] Davenport D, Hughes B, Davies S, Hall D. Spread, delve, clay, invert: A best

practice guide to the addition of clay to sandy soils. WA, Australia: Grains Research and Development Corporation; 2011. Available from: https://cdn.environment.sa.gov.au/landscape/docs/mr/spread-delve-spade-invert-rep.pdf [Accessed: June 15, 2023]

[67] Davies SL, Blackwell PS, Bakker DM, Scanlan CA, Gazey C, Hall DJ, et al. Deep soil cultivation to create improved soil profiles for dryland crop production. In: Proceedings of Society for Engineering in Agriculture (SEAg) Conference: Innovative Agricultural Solutions for a Sustainable Future, 22-25 September 2013. Mandurah, WA, Australia: Engineers Australia, Barton, ACT; 2013. p. 410-420

[68] Davies S, Blackwell P, Bakker D, Scanlan C, Roper M, Ward P. Developing and assessing agronomic strategies for water repellent soils. In: Proceedings of Agribusiness Crop Updates, 28-29 February 2012. Perth, WA, Australia: Grains Research and Development Corporation and Department of Agriculture and Food Western Australia; 2012. p. 71-77

[69] Davies S, Newman P, Best B. Impact of soil inversion, soil dilution and claying on nonwetting sandplain soils. In: Proceedings of Agribusiness Crop Updates, 25 February 2010. Perth, WA, Australia: Western Australian Agriculture Authority; 2012. p. 223-228

[70] Blanco-Canqui H, Ruis S. No-tillage and soil physical environment. Geoderma. 2018;**326**:164-200. DOI: 10.1016/j.geoderma.2018.03.011

[71] Kopittke PM, Moore KL, Lombi E, Gianoncelli A, Ferguson BJ, Blamey FP, et al. Identification of the primary lesion of toxic aluminum in plant roots. Plant Physiology. 2015;**167**:1402-1411. DOI: 10.1104/pp.114.253229

[72] Van Gool D. Identifying soil constraints that limit wheat yield in south-west Western Australia. In: Resource Management Technical Report 399. Perth, Western Australia: Department of Primary Industries and Regional Development; 2016. Available from: https://www.agric.wa.gov.au/managing-soils/soil-constraints-limit-wheat-yield-south-west-western-australia [Accessed: June 15, 2023]

[73] Scanlan C, Brennan R, Sarre G. Shifting investment from nutrients to lime and cultivation on acid soils: Is an immediate payback possible? In: Proceedings of Agribusiness Crop Updates (ABCU' 14). Perth, WA, Australia: ABCU; 2014, 2014. pp. 1-6

[74] Azam G, Gazey C, Davies S, Scanlan C. Mind the depth of soil amelioration to surpass the yield gap in Western Australia. In: Proceedings of the 20th Agronomy Australia Conference; 18-22 September 2022; Toowoomba, Qld, Australia: Australian Society of Agronomy; 2022. Available from: http://agronomyaustraliaproceedings.org/images/sampledata/2022/Soil/ASAazam_g_422s.pdf

[75] Azam G, Gazey C. Re-engineering soil pH protiiles to boost water use efficiency by wheat. In: Proceedings of the Agronomy Australia Conference, 25-29 August 2019. Wagga Wagga, NSW, Australia: Australian Society of Agronomy; 2019. Available from: http://agronomyaustraliaproceedings.org/images/sampledata/2019/2019ASA_Azam_Gaus_351.pdf

[76] Conyers MK, Mullen CL, Scott BJ, Poile GJ, Braysher BD. Long-term benefits of limestone applications to soil properties and to cereal crop yields in

southern and Central New South Wales. Australian Journal of Experimental Agriculture. 2003;**43**(1):71-78. DOI: 10.1071/EA01121

[77] Wolkowski, D. Tillage Effects On Nutrient Stratification and Soil Test Recommendations, New Horizons in Soil Science, Department of Soil Science, University of Wisconsin-Madison. 2006. Available from: https://soilsextension.webhosting.cals.wisc.edu/wp-content/uploads/sites/68/2014/02/2006Soil TestStratification.pdf [Accessed: June 15, 2023]

[78] Vu DT, Tang C, Armstrong RD. Tillage system affects phosphorus form and depth distribution in three contrasting Victorian soils. Soil Research. 2009;**47**:33-45. DOI: 10.1071/SR08108

[79] Bauer PJ, Frederick JR, Busscher WJ. Tillage effect on nutrient stratification in narrow-and wide-row cropping systems. Soil and Tillage Research. 2002;**66**(2): 175-182. DOI: 10.1016/S0167-1987(02) 00025-9

[80] Wright AL, Hons FM, Lemon RG, McFarland ML, Nichols RL. Stratification of nutrients in soil for different tillage regimes and cotton rotations. Soil and Tillage Research. 2007;**96**:19-27. DOI: 10.1016/j.still.2007.02.005

[81] Ryan MH, Tibbett M, Lambers H, Bicknell D, Brookes P, Barrett-Lennard EG, et al. Pronounced surface stratification of soil phosphorus, potassium and sulfur under pastures upstream of a eutrophic wetland and estuarine system. Soil Research. 2017;**55**: 657-669. DOI: 10.1071/SR16144

[82] Obour AK, Holman JD, Simon LM, Schlegel AJ. Strategic tillage effects on crop yields, soil properties, and weeds in dryland no-tillage systems. Agronomy. 2021;**11**:662. DOI: 10.3390/agronomy11040662

[83] Scanlan CA, Davies SL. Soil mixing and redistribution by strategic deep tillage in a sandy soil. Soil and Tillage Research. 2019;**185**:139-145. DOI: 10.1016/j.still.2018.09.008

[84] Nash DM, Watkins M, Heaven MW, Hannah M, Robertson F, McDowell R. Effects of cultivation on soil and soil water under different fertiliser regimes. Soil and Tillage Research. 2015;**145**: 37-46. DOI: 10.1016/j.still.2014.08.006

[85] McLaughlin MJ, Baker TG, James TR, Rundle JA. Distribution and forms of phosphorus and aluminum in acidic topsoils under pastures in South-Eastern Australia. Soil Research. 1990; **28**:371-385. DOI: 10.1071/SR9900371

[86] Busari MA, Kukal SS, Kaur A, Bhatt R, Dulazi AA. Conservation tillage impacts on soil, crop and the environment. International Soil and Water Conservation Research. 2015;**3**: 119-129. DOI: 10.1016/j.iswcr.2015.05.002

[87] Smith RG, Ryan MR, Menalled FD. Direct and indirect impacts of weed management practices on soil quality. In: Hatiield J, Sauer T, editors. Soil Management: Building a Stable Base for Agriculture. WI, USA: American Society of Agronomy, Soil Science Society of America; 2011. p. 275-86. DOI: 10.2136/2011.soilmanagement.c18

[88] Chauhan BS, Gill GS, Preston C. Tillage system effects on weed ecology, herbicide activity and persistence: A review. Australian Journal of Experimental Agriculture. 2006;**46**: 1557-1570. DOI: 10.1071/EA05291

[89] Mia MS, Azam G, Nouraei S, Borger C. Strategic tillage in Australian

conservation agricultural systems to address soil constraints: How does it impact weed management? Weed Research. 2023;**63**:12-26. DOI: 10.1111/wre.12564

[90] Colbach N, Roger-Estrade J, Chauvel B, Caneill L. Modelling vertical and lateral seed bank movements during mouldboard ploughing. European Journal of Agronomy. 2000;**13**:111-124. DOI: 10.1016/S1161-0301(00)00069-1

[91] Douglas A, Peltzer SC. Weed management—Balancing people plant Profit. In: Sindel BM, Johnson SB, editors. Proceedings of the 14th Australian Weed Conference, 6-9 September 2004. NSW, Australia: Weed Society of New South Wales; 2004. p. 300-303

[92] Mohler CL, Frisch JC, McCulloch CE. Vertical movement of weed seed surrogates by tillage implements and natural processes. Soil and Tillage Research. 2006;**86**:110-122. DOI: 10.1016/j.still.2005.02.030

[93] Roger-Estrade J, Colbach N, Leterme P, Richard G, Caneill J. Modelling vertical and lateral weed seed movements during mouldboard ploughing with a skim-coulter. Soil and Tillage Research. 2001;**63**:35-49. DOI: 10.1016/S0167-1987(01)00229-X

[94] Agriculture and Food Western Australia. Weed Seed Wizard. Version 7.1.7. 2020. Available from: https://www.agric.wa.gov.au/weed-seed-wizard-0 [Accessed: April 29, 2020]

[95] Edwards T, Davies S, McDonald M, Hall D, Moore J. Understanding interactions between pre-emergent herbicides and inversion tillage. In: Proceedings of the GRDC Grains Research Updates (GRU'18), 26 February 2018. Perth, Western Australia: Grains Research and Development Corporation; 2018. Available from: https://grdc.com.au/resources-andpublications/grdc-update-papers/tabcontent/grdc-updatepapers/2018/02/interactions-between-preemergent-herbicides-and-inversion-tillage

[96] Reynolds CD, Betti G, Davies SL. Testing options for the management of soil water repellence and subsoil compaction in dry environment. In: Proceedings of National Soil Science Conference (NSSC' 18); 18–23 November 2018. Canberra, ACT, Australia: NSSC; 2018. pp. 490-493

[97] French RJ, Schultz JE. Water use efficiency of wheat in a Mediterranean-type environment. I. the relation between yield, water use and climate. Australian Journal of Agricultural Research. 1984;**35**:743-764. DOI: 10.1071/AR9840765

[98] Armstrong RD, Davies SL, Kirkegaard JA. Deep Ripping Not Appropriate for all Soil Types Deep Ripping Factsheet. WA, Australia: Grains Research and Development Corporation; 2009. Available from: https://grdc.com.au/__data/assets/pdf_file/0028/91738/grdc_fs_deepripping_hr.pdf.pdf [Accessed: July 11, 2023]

[99] Macdonald L, McBeath T, Llewellyn R, Moodie M, Desbiolles J, Saunders C, et al. Underperforming sandy soils—Targeting constraints for cost effective amelioration. In: Proceedings of the GRDC Grains Research Updates (GRU'19); 12–13 February 2019. Adelaide, South Australia: GRU; 2019. pp. 79-84