Received: 21 September 2022 | Accepted: 9 December 2022
DOI: 10.1111/wre.12564

REVIEW ARTICLE

WEED RESEARCH
An International Journal of Weed Biology, Ecology and Vegetation Management
WILEY

Strategic tillage in Australian conservation agricultural systems to address soil constraints: How does it impact weed management?

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Funding information
Royalties for Regions; Boosting Grains Science Partnerships; Royalties for Regions Western Australia

Subject Editor: Francesco Tei, University of Perugia, Perugia, Italy

Abstract

In the conservation agricultural systems practised in Australia, cultivation is not commonly utilised for the purpose of weed control. However, occasional use of tillage (strategic tillage) is implemented every few years for soil amelioration, to address constraints such as acidity, water repellence or soil compaction. Depending on the tillage method, the soil amelioration process buries or disturbs the topsoil. The act of amelioration also changes the soil physical and chemical properties and affects crop growth. While these strategic tillage practices are not usually applied for weed control, they are likely to have an impact on weed seedbank burial, which will in turn affect seed dormancy and seedbank depletion. Strategic tillage impacts on seed burial and soil characteristics will also affect weed emergence, plant survival, competitive ability of weeds against the crop and efficiency of soil applied pre-emergent herbicides. If growers understand the impacts of soil amelioration on weed demography, they can more effectively plan management strategies to apply following the strategic tillage practice. Weed seed burial resulting from a full soil inversion is understood, but for many soil tillage implements, more data is needed on the extent of soil mixing, burial of topsoil and the weed seedbank, physical control of existing weeds and stimulation of emergence following the tillage event. Within the agronomic system, there is no research on optimal timing for a tillage event within the year. There are multiple studies to indicate that strategic tillage can reduce weed density, but in most studies, the weed density increases in subsequent years. This indicates that more research is required on the interaction of amelioration and weed ecology, and optimal weed management strategies following a strategic tillage event to maintain weeds at low densities. However, this review also highlights that, where the impacts of soil amelioration are understood, existing data on weed ecology can be applied to potentially determine impacts of amelioration on weed growth.

KEYWORDS
soil amelioration, soil renovation, strategic tillage, weed control, weed ecology

1 | INTRODUCTION

Farming systems have witnessed a shift from conventional tillage to conservation agriculture systems (Bellotti & Rochecouste, 2014). Traditionally, conventional tillage involves significant mechanical soil disturbance for crop production, whereas conservation agriculture aims to minimise soil disturbance and is defined as any tillage system used to sow crop (generally to a maximum depth of 10–12 cm), which leaves at least 30% of the soil surface covered with crop residue after planting (Busari et al., 2015; Smith et al., 2021). Crop sowing practices in conservation agriculture range from zero tillage (no-till or direct drilling where soil disturbances are mainly from seeding equipment) to reduced (minimum) tillage, including mulch tillage, ridge tillage and contour tillage (Busari et al., 2015). In the Mediterranean or temperate climate of southern Australia (i.e., coastal areas south of 28°S latitude), the agricultural system is usually winter dominant (rainfed), broad-scale grain crops or grazed pasture. The conservation agricultural system in this area is generally defined as the use of zero tillage (discs), no tillage or minimum tillage (knife point tynes, with or without press wheels) specifically for sowing the crop (Ashworth et al., 2010). There is very rarely any seedbed preparation, or tillage aimed at direct interference of germinating or emerged weeds before or after crop emergence. Crop seeding in this system results in very little mechanical weed control, partly because there is minimal soil disturbance at seeding, and also because ‘dry’ sowing (i.e., sowing before the opening rains) on bare ground is increasingly common (Fletcher et al., 2016).

Advantages of the conservation agriculture system include lower input costs, reduced erosion, better moisture conservation, and improved soil structure (Busari et al., 2015; Smith et al., 2021). However, there are problems with minimal soil disturbance. For example, while conservation agriculture can improve soil structure, soil compaction from machinery or livestock still occurs, and usually needs to be alleviated by deep tillage (Busari et al., 2015). Soil acidification is difficult to address in conservation agriculture as lime applied to the soil surface needs to be incorporated via tillage to change soil pH at depth (Busari et al., 2015; Li et al., 2019). Conservation agriculture can also lead to increased incidence of weeds (Busari et al., 2015; Smith et al., 2021). The conservation agriculture system relies heavily on chemical weed control, but the system also reduces the efficiency of pre-emergent herbicides. Most pre-emergent herbicides require full soil incorporation and the system of minimal soil disturbance results in greater herbicide loss through volatilisation. Non-soluble pre-emergent herbicides also require bare ground for optimal efficiency, and a cover of crop residue intercepts the herbicide and prevents it reaching the soil (Walsh & Powles, 2007). Both these factors ensure that the weeds receive a lower dose of herbicide, and continuous herbicide use combined with a lower dose of herbicide are factors that exacerbate the development of herbicide resistance (Walsh & Powles, 2007). In Australia, the most common weed species include *Lolium rigidum* Gaud. (annual ryegrass), *Raphanus raphanistrum* L. (wild radish), *Avena fatua* L. (wild oats) and species within the *Bromus* genus (brome grass) (with agronomic weed species listed by area, economic impact and cost of control in Llewellyn et al., 2016).

For multiple soil types in Australia, the soil constraints necessitate the introduction of soil amelioration using strategically timed, occasional tillage (strategic tillage), into conservation agriculture systems (Conyers, Van Der Rijt, et al., 2019; Dang et al., 2015; Isbell, 2016). These strategic tillage practices are not performed to sow the crop and aim for greater disturbance of the topsoil or disturbance to a greater depth than that achieved by crop sowing implements in the conservation agricultural system. Strategic tillage in this system may be used to address:

- Soil acidity by incorporating lime deeper in the profile (Azam & Gazey, 2021).
- Water repellence by mixing/spreading clay or inverting the soil profile whereby water-repellent topsoil is buried at depth. Inverting the soil profile is also recognised as a useful weed control technique, but is not usually applied solely for weed management (Roper et al., 2015).
- Soil compaction by deep ripping (Batey, 2009).
- Nutrient and organic matter destratification by deep spading (Tonkin et al., 2012).

From a weed management perspective, strategic tillage in conservation agriculture farming systems offers mixed challenges to growers due to multiple impacts on the weeds life cycle and subsequent management (Figure 1; Bajwa, 2014; Davies et al., 2019). Physically mixing the soil is likely to kill at least a portion of existing weeds and bury weed seeds. Shallower tillage can stimulate weed emergence and growth and deeper seed burial can prevent emergence (Chauhan et al., 2006b; Roper et al., 2015). The physical disturbance and altered soil properties may potentially influence weed seed germination, emergence time and growth (Chauhan et al., 2006b; Davies et al., 2019). Likewise, altered soil properties and levels of surface crop residue may impact pre-seeding soil applied herbicide performance (Chauhan et al., 2006b). These changes are likely to modify the weed-crop competitive interaction.

There are multiple reviews on the effect of strategic tillage on soils and crops, reviews on weed ecology or management and soil quality, and reviews on seedbank decline of seeds on the soil surface or at depth. Gallandt et al. (1999) discussed the impact of improving soil quality on weed management via organic amendments, fertility management, cover crops or green manures. They discuss tillage in terms of the response of weed seed to altered soil physical properties on the surface soil or altered the surface soil environment created by removal of crop residues found in a conservation tillage system. Gamble and Price (2021) discuss occasional use of full soil inversion in a conservation tillage system including cover crops for weed control. Kremer and Li (2003) and Smith et al. (2021) review soil quality and weed management in terms of soil microbial activity and soil quality (mainly related to soil carbon sequestration). Long et al. (2015) review seed degradation and seedbank decline in terms of physical and physiological characteristics of seeds, in relation to the biotic and abiotic

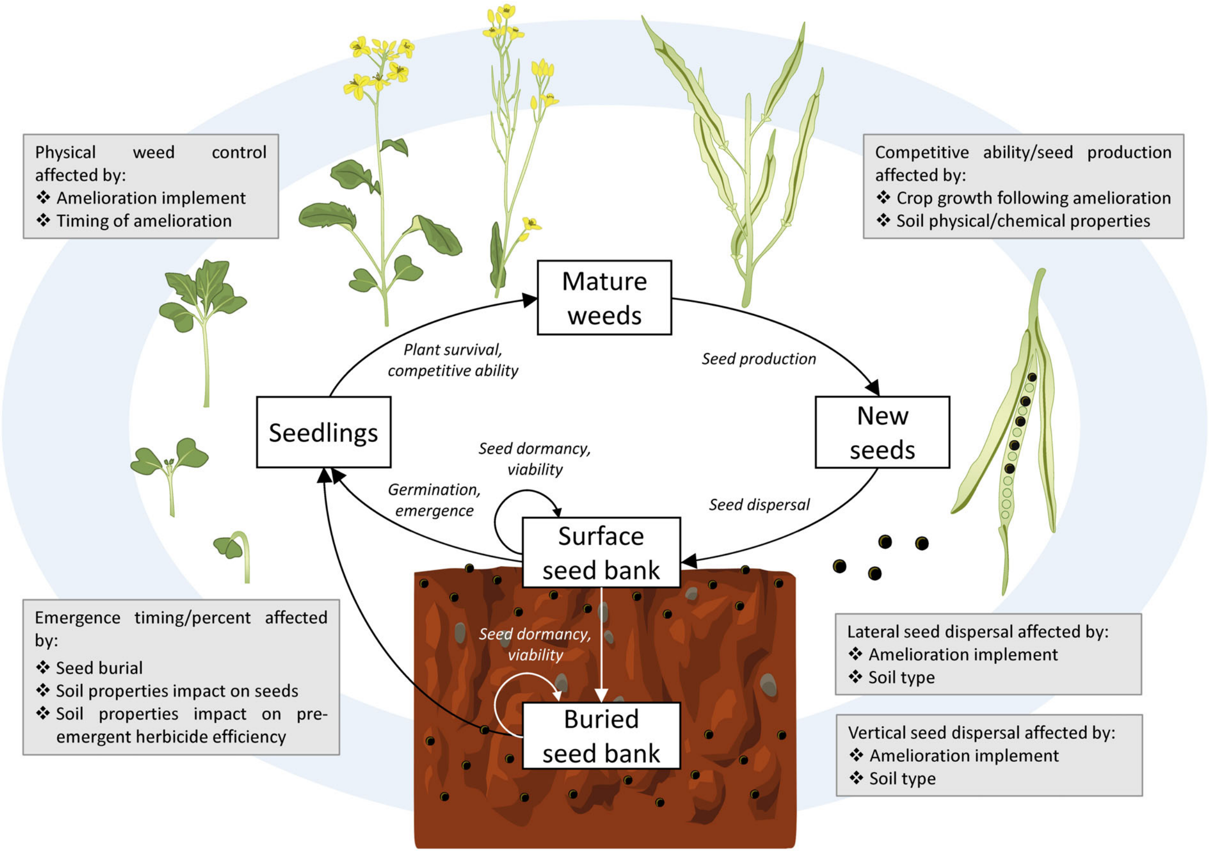

FIGURE 1 A simplified weed lifecycle of *Sinapis arvensis* L. (wild mustard) showing the life stages (white text boxes) and the processes that occur as weeds transition from one life stage to the next (text in italics). The impacts of soil amelioration on these transitions (grey text boxes) are indicated at the point of the lifecycle they affect

environment. There are few studies on strategic tillage to address soil constraints like acidity, compaction, water repellence and the resulting impact on weed ecology. However, there are unrelated studies on weed ecology that can be collated to extrapolate how weeds will respond to changes resulting from soil amelioration. Understanding how soil amelioration via strategic tillage alters weed dynamics in the conservation agriculture system is pivotal to planning an effective integrated weed management strategy to follow the amelioration event. The current study explored this question as it related to the Australian agronomic system, by summarising the existing research on soil amelioration and weeds, extrapolating the impact of soil amelioration on weeds from existing weed ecology studies where research directly relating to soil amelioration is not available, identifying the knowledge gaps, and suggesting future research requirements. Where possible, the research in each topic related to the most common weed species in the southern Australian cropping system discussed above. However, these weeds have international distribution, and lessons from southern Australian are also likely to apply to agronomic systems requiring soil amelioration in other countries. Those topics covered by earlier reviews of soil quality and weed management (i.e., soil nutrient status, microbial activity, cover cropping), and weed seedbank decline were outside the scope of the current review.

2 | TILLAGE METHOD AND DEPTHS USED IN STRATEGIC TILLAGE AND THEIR IMPACT ON WEED ECOLOGY AND BURIAL

In conservation agriculture systems, most weed seeds accumulate near the soil surface (0–2 cm) (Chauhan et al., 2006a). Seeds near the soil surface generally lose viability through germination or mortality more rapidly than seed buried at depth (Mohler, 1993; Nichols et al., 2015). In contrast to the conservation agriculture system, strategic tillage operations vertically redistribute seeds throughout the soil profile; burying surface seed at depth and potentially inducing secondary dormancy, but also returning seeds to the soil surface that were buried at depth by earlier tillage events (Chauhan et al., 2006a; Colbach et al., 2000; Cousens & Moss, 1990; Mohler, 1993; Mohler et al., 2006; Roger-Estrade et al., 2001). In a strategic tillage conservation system, the tillage practice is a one-off event, that is, every 4–8 years as modelled by Renton and Flower (2015). Therefore, only the seeds of species with long term dormancy would be returned to the surface. Weed responses to various tillage operations depend on the type of tillage applied, implements used, depth of penetration, per cent of soil mixing, soil type, soil condition at the time of tillage and on-site weed species (Table 1).

TABLE 1 Tillage implements (and working depth), purpose (crop sowing via conservation tillage or soil amelioration via strategic tillage) and impact on topsoil, modified from Davies et al. (2019), burial of weed seeds on the soil surface, with data taken from the Weed Seed Wizard (1) or SeedChaser model (2) (Agriculture and Food Western Australia, 2020; Spokas et al., 2007) and impact on weeds

Tillage implements (and working depth)	Purpose	Impact on topsoil	Weed seed burial	Impact on weeds
Conservation tillage methods[a]				
No-till; knife-point tyne and press wheel based seeding, Figure 2. (9–12 cm)	Displaces soil from the crop row and creates a wide furrow for crop seed placement (Ashworth et al., 2010; Kleemann et al., 2017). Not suitable for seeding with high stubble load. Little soil delving or mixing.	Dependant on row spacing and soil throw.	1. 10% at 0 cm, 80% at 1 cm and 10% at 1–5 cm. 2. 85.4% at 0 cm, 9.6% at 1 cm and 5% at 1–5 cm.	No data—may stimulate emergence of weed seed. Potentially promotes more weed emergence than a disc opener (Solhjou et al., 2012).
Zero-till; disc-based seeding using a single disk. (9–12 cm)	Less soil disturbance and lateral soil throw than knife-point systems when creating a furrow for crop seed placement (Ashworth et al., 2010; Kleemann et al., 2017). Suitable for seeding with high stubble load. Little soil delving or mixing.	Less than 10% of topsoil disturbed.	1. 95% at 0 cm, 2% at 0–1 cm and 3% at 1–5 cm.	Reduced germination of weed seeds due to low disturbance during seeding (Chauhan et al., 2006b). Little burial of weed seeds (Chauhan et al., 2006b). Poor performance of pre-emergent herbicides requiring soil incorporation (Ashworth et al., 2010; Zeng et al., 2021).
Strategic deep tillage[a]				
Deep ripping; using a tyne and press wheel, Figure 2. (30–70 cm)	Creates discrete vertical lines in the soil profile. Minimal incorporation of soil and amendments, depending on ripper type. Backfill to 15 cm.	Buries 5%–10% topsoil below 10 cm.	No data.	No data—may stimulate weed emergence.
Deep ripping with topsoil slotting; inclusion plates are attached to the rear of tyne to allow topsoil to fall into the furrow. (30–70 cm)	As for deep ripping above, but topsoil slots from surface to a depth of 35–40 cm. Partially incorporates surface spread amendments.	Buries 10%–15% of topsoil below 10 cm.	No data.	No data—may stimulate weed emergence.
Subsoil clay delving with incorporation; using a range of specially designed equipment, depending on soil conditions. (60–120 cm)	No data on clay delving impact on soil disturbance. Subsequent incorporation of clay or other amendments will mix soils to 15–45 cm.	No data. Depends on method of subsequent incorporation.	No data.	More even weed emergence, and improved crop competition (Roper et al., 2015).
Soil mixing with large offset discs; using two lines of discs in a front and rear configuration. (20–30 cm)	Offsets throw soil one way then back again. Mixing of topsoil and surface spread amendments typically occurs between 15 and 25 cm.	Buries 10%–15% topsoil below 10 cm (Scanlan & Davies, 2019).	1. 2% at 0 cm, 8% at 1 cm, 40% at 1–5 cm and 50% at 5–10 cm. 2. 10% at 0 cm, 5% at 1 cm, 52% at 1–5 cm, 30% at 5–10 cm and 4% at 10–20 cm.	No data—may stimulate weed emergence.
Soil mixing with rotary spader; using rotating spading blades, Figure 2 (35–40 cm) (Ucgul et al., 2018)	Mixes soil to incorporate a range of surface spread amendments (Ucgul et al., 2018).	Buries 50%–60% topsoil below 10 cm (Scanlan & Davies, 2019).	1. 1.9% at 0 cm, 2% at 1 cm, 16% at 1–5 cm, 31% at 5–10 cm and 49% at 10–20 cm.	Some control of selected weed species (Roper et al., 2015).

(Continues)

TABLE 1 (Continued)

Tillage implements (and working depth)	Purpose	Impact on topsoil	Weed seed burial	Impact on weeds
Soil inversion with mouldboard plough, Figure 2 (35–45 cm)	Buries a layer of topsoil typically between 15–40 cm to incorporate surface applied amendments at depth and place subsoil on the surface.	Buries 80%–90% topsoil below 10 cm (Scanlan & Davies, 2019).	1. 1% at 0 cm, 1% at 0–1 cm, 1% at 1–5 cm, 1% at 5–10 cm and 96% at 10–20 cm. 2. 1% at 0 cm, 0.4% at 1 cm, 3% at 1–5 cm, 19% at 5–10 cm and 76% at 10–20 cm.	50%–99% weed seed burial efficiency and can kill up to 99% of emerged weeds on site (Colbach et al., 2000; Douglas & Peltzer, 2004; Mohler et al., 2006; Roger-Estrade et al., 2001; Roper et al., 2015).
Soil inversion with modified one-way disc plough, Figure 2 (30–40 cm)	Buries topsoil or surface applied amendments in an arc from surface down to a depth of 25–35 cm.	Buries 60% topsoil below 10 cm (Scanlan & Davies, 2019).	1. Similar to mouldboard plough.	Can kill up to 90% of weeds (Agriculture and Food Western Australia, 2020).

[a]Following strategic deep tillage, in a conservation agricultural system, crop sowing may be performed with either knife points or discs.

Weed seed burial by varying implements has been investigated and modelled by prior studies. For example, the model created by Mohler (1993) compares burial depth by no tillage, rotary tillage and mouldboard plough tillage (soil inversion), although the model is mainly applicable to small seeded species. The research concluded that no-tillage will have more seedlings than tillage systems that bury a proportion of seed beyond emergence depth, in the year following the addition of seed to the soil surface. A major conclusion was that in years of substantial, uncontrolled weed growth, a full soil inversion could be used to bury the seeds to achieve optimal weed control. Then in subsequent years, no tillage seeding systems should be used to avoid returning buried seed to the surface. This weed management option was later modelled for Western Australia by Renton and Flower (2015), with a similar conclusion. Likewise, the SeedChaser model considered burial of seeds (plastic beads) by 18 different tillage implements (Spokas et al., 2007). The strength of this model was that burial was assessed in 1 cm implements, and the weakness was that only one soil type was used, a sandy loam. Prior research has suggested that seed burial in the sandy soils common to Australia will be different to that of finer textured soils (Isbell, 2016; Spokas et al., 2007). The Weed Seed Wizard model considered seed burial by 12 different implements (Agriculture and Food Western Australia, 2020; Borger et al., 2021). Unlike the SeedChaser, this model considered seed movement in larger increments (0, 0–1, 1–5, 5–10, and 10–20 cm). However, it has the advantage of letting the user add tillage implements or modify seed movement by existing implements, to account for varying soil type. All models allow multiple tillage events within a year (i.e., deeper soil tillage followed by crop seeding operations) and indicate the return of buried seed to the soil surface.

Studies of seed burial in field conditions have highlighted that the impact of a specific type of tillage operation may vary widely between soil types, specific implement model and operation. For example, a complete soil inversion with a mouldboard plough has 50%–99% seed burial efficiency, depending on soil type and inversion practices, although a few studies have also resulted in all seeds left near the soil surface, or evenly distributed through the top 75% of the disturbed profile (Figure 2, Table 1; reviewed by Mohler, 1993). In a system where only 50% of weed seeds are buried, it is also likely that a proportion of the germinated or emerged plants may be left intact on the surface (Table 1). Colbach et al. (2000) found a ploughing depth of 33–37 cm at Dijon, France or 25 cm at Grignon, France, using the same three-bottom mouldboard plough without a skim-coulter at each site. Roger-Estrade et al. (2001) used a three-bottom mouldboard plough with a skim coulter and reached a depth of 25 cm in a soil type with high bulk density in Dijon, France (i.e., a site that had been rolled prior to ploughing) and a depth of 27–32 cm at an adjoining site that had lower bulk density. In both studies, weed seed distribution (simulated by use of plastic beads) was described by a model, and varied due to the method of soil inversion. Roger-Estrade et al. (2001) demonstrated that after mouldboard ploughing using a skim-coulter, weed seeds (beads) that were on or near the surface (i.e., at 0–5 cm) would have a distribution of 7% of seeds at a depth of 0–5 cm, 23% at 5–10 cm, 27% at 10–15 cm, and 43% at 15–20 cm. By comparison, Colbach et al. (2000) demonstrated that burial of seeds near the surface following use of a mouldboard without a skim-coulter would be 22% of seeds at 0–5 cm, 28% at 5–10 cm, 29% at 10–15 cm, and 21% at 15–20 cm. Godwin et al. (2007) tested a mouldboard plough at speeds of 4–18 km h^{-1}, but at 14.4 km h^{-1} the depth of ploughing was shallower than planned. Ploughing speed was also reduced in relation to the depth of ploughing and number of plough bodies (Godwin et al., 2007). Weed seed burial, depth of ploughing and degree of soil disturbance can vary widely between studies. Unfortunately, some research refers to generic mouldboard ploughing, without specifying the implement or depth (Cousens & Moss, 1990; Roper et al., 2015).

If soil inversion is practised repeatedly, it is likely that weed seeds would be placed at depth, and then returned to the surface. As stated, existing models can be used to determine the proportion of seed returned to the surface (Agriculture and Food Western Australia, 2020; Mohler, 1993; Spokas et al., 2007). For mouldboard ploughing, Colbach et al. (2000) demonstrated that weed seed (plastic beads) at depth could be returned to the surface, and then used the model to demonstrate the value of shallow soil inversion if there are a large proportion of viable seeds at depth. In the Australian strategic tillage system (where tillage is a one-off event every few years), weed

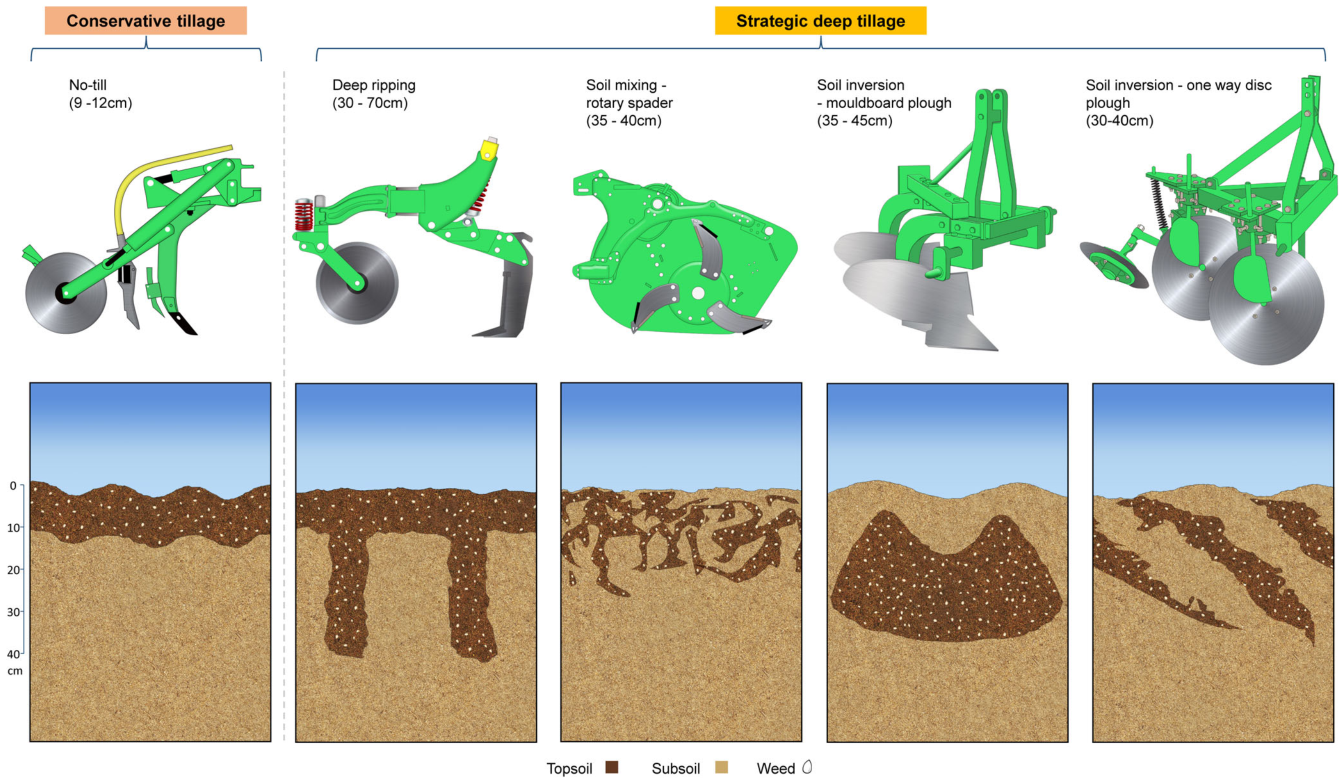

FIGURE 2 Graphical representation of some of the conventional implements used to achieve strategic tillage (with individual tillage techniques clarified in Table 1), tillage depth, and resulting placement of topsoil (containing the weed seeds) and subsoil. Note that this image is an approximation; actual depth and level of soil disturbance will vary due to soil properties, implement model or speed of application

seeds are left at depth for several years in between amelioration events, with only the crop sowing process to bury seeds throughout the top 7–12 cm of soil. A recent study of 24 weed species in Australia highlighted that while the seeds of grass species like *C. truncata* R.Br. (windmill grass), *Bromus diandrus* Roth. (ripgut brome) or *Hordeum leporinum* L. (barley grass) generally degrade in 1–4 years, broad leaf weed species like *Citrullus amarus* Schrad. (Afghan melon), *Rumex hypogaeus* T.M.Schust. & Reveal (doublegee) or *Polygonum aviculare* L. (wireweed) produce seed that last over 4 years at a depth of 2 or 10 cm (Gill et al., 2021). Therefore, in a system with a soil inversion every 4 years, as proposed by Renton and Flower (2015), return of dormant seed to the soil surface may be a management issue for growers to consider. If a soil inversion occurs every 8 years, it is likely that most seed previously buried would have degraded, although some seed may last up to 30 years at depth (Gill et al., 2021; Spokas et al., 2007).

A recent review of implements used for soil amelioration in the Australian strategic tillage system highlighted a range of different tillage implements are used in varying soil types to achieve different soil amelioration goals (Table 1). Deep ripping produces discrete vertical lines in the soil profile, a rotary spader mixes soil and soil inversion attempts to bury the topsoil at depth (Table 1, Figure 2). Although the depth of soil disturbance under different strategic tillage implements is generally well understood, the per cent of topsoil (containing the weed seeds in a conservation agricultural system) buried below 10 cm is highly variable (Table 1, Davies et al., 2019). Soil inversion using a mouldboard plough, one-way disc plough or soil mixing with a rotary spader will likely cause the greatest reduction in weed emergence (Table 1). A full soil inversion by mouldboard plough has the advantage of being comprehensively researched and modelled, in terms of soil disturbance and weed seed burial in different scenarios or soil types. For some tillage operations like subsoil clay delving or soil mixing with one pass, the exact patterns of soil disturbance and topsoil burial have not been investigated (Table 1). There are also tillage operations like clay delving or deep ripping where there is little data on weed seed burial. Future research needs to investigate soil disturbance and seed burial for some tillage operations.

2.1 | Weed emergence from depth

Weed seed burial depth affects the number of emerging weeds and the timing of emergence. Most species have increased emergence at shallow burial, compared to seeds on the soil surface, but deep burial inhibits emergence. For example, Chauhan et al. (2006a) reported *L. rigidum* emergence of 16% from seeds on the surface, 49% for seeds buried at 1 cm, 44% from 2 cm, 10% from 5 cm and 0% from 10 cm. Therefore, the mouldboard ploughing using a skim-coulter practiced by Roger-Estrade et al. (2001), *L. rigidum* seeds on the soil surface (as occurs in a conservation agricultural system) would have high emergence from the 7% of seeds at a depth of 0–5 cm, very low (<10%) emergence of the 23% of seed at 5–10 cm, and zero emergence of the 70% of seed at 10–20 cm. Similarly, Harradine (1986) found that *B. diandrus* had increased emergence when seeds were buried within 2–5 cm (97%), but emergence reduced with increasing depth until it was <1% if seed were buried ≥15 cm. In contrast, Dastgheib and Poole (2010) reported no difference in ripgut brome germination due to seed burial depth from 0 to 20 cm; although seedlings from depth had reduced establishment and vigour. Therefore, following mouldboard ploughing using a skim-coulter, 70% of seed would have either low emergence or reduced vigour from 10 to 20 cm (Roger-Estrade et al., 2001). Seed burial by soil inversion substantially reduced density of resistant *Amaranthus palmeri* S. Wats (careless weed) in the United States or *L. rigidum* in Western Australia in conservation tillage systems at multiple sites (Douglas & Peltzer, 2004; Price et al., 2016). Tillage that results in shallow burial may increase emergence, allowing successful chemical control (Chauhan et al., 2006a). However, tillage that partially mixes soil, placing seeds at varying depths and leaving some on the surface, may create staggered weed cohorts that are difficult to manage. There is generally existing research on weed seed germination and emergence at depth for major agronomic weeds. Once we have data on exactly how each tillage method mixes the soil (as for the existing data for soil inversion), we will be able to determine weed emergence and formulate appropriate weed management plans.

2.2 | Weed seedbank persistence

Weed seedbank persistence is affected by seed burial, but this topic has been extensively reviewed by previous studies (Long et al., 2015; Schwartz-Lazaro & Copes, 2019). The impact of burial is species specific. For example, *L. rigidum* seed shed onto the soil surface has an initial after-ripening period, and then the bulk of the seed emerge after the onset of winter rainfall (Bajwa et al., 2021). Burial of *L. rigidum* seeds during the after-ripening process reduced emergence as it prevented seeds from completing after-ripening (due to reduced light and temperature at depth; Bajwa et al., 2021). Chauhan et al. (2006a) noted greater decay of *L. rigidum* seeds on the soil surface than those at depth. *Lolium rigidum* had 48%–60% seed mortality per year in a South Australian no-tillage system where seeds are mainly left on the soil surface. By comparison, two operations of full cultivation before seeding, burying seed to a depth of 1–10 cm, reduced seedbank decline (12%–39% mortality per year) (Chauhan et al., 2006a). Burial of *R. raphanistrum* seed likewise increased seedbank persistence. Reeves et al. (1981) reported that after 24 months of burial, seed viability was 54% for seed at 10 cm and 16% for seed at 1 cm. In contrast to these species, Gleichsner and Appleby (1989) reported that under field conditions, *B. diandrus* seeds on the soil surface retained a viability of 83%, 62% and 23% after 1, 9 and 12 months respectively. Those seeds that persisted over 1 year had a high proportion of enforced dormancy. For seeds buried at 1–30 cm, over 90% germinated in the first month (Gleichsner & Appleby, 1989). There is considerable variation in the seedbank degradation rates among different weed species, but it has been investigated for multiple agronomic weed species (Chee-Sanford et al., 2006; Long et al., 2015; Schwartz-Lazaro & Copes, 2019). It is clear that once we understand how each strategic tillage implement affects seed burial, it will be possible to extrapolate the impact on seed germination and decay using existing reviews.

3 | WEED RESPONSE TO SOIL CONSTRAINTS AND SOIL AMELIORATION

While the physical and chemical soil properties required for optimal crop growth have been researched extensively, the requirements for optimal weed growth and the response of weeds to soil amelioration have not. If we understand how weeds respond to agronomic changes, we can plan integrated weed management strategies following amelioration with more efficiency. There are three possible responses of weed species to soil constraints, illustrated below using the example of soil acidity as the soil constraint. First, weeds may be favoured by the same conditions as the crop. For example, weed species within the *Bromus* genus are closely related to the tribe Triticeae, which includes wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.) and rye (*Secale cereale* L.; Kon & Blacklow, 1989; O'connor, 1990). It follows that if soil amelioration removes a soil constraint to encourage growth of these grain crops, the closely related weeds of the *Bromus* genus are also likely to be favoured by the change. *Bromus arvensis* L., common to wheat fields in China, had 0% germination at pH 4 and over 90% germination at pH values of 5 and above, which is similar to the pH preference of wheat (Li et al., 2015; Scanlan et al., 2015). Growers may need to plan for these weeds to become more competitive following the application of lime to address acidity. Second, weeds may invade an agronomic system because their growth is favoured by soil constraints induced by the cropping system. For example, acidic soils may occur naturally, and species adapted to acidic soils, like *Seteria viridis* (L.) Beauv. (green foxtail), demonstrated increased growth and competitive ability against crops in acidic soils compared to other weed species (Sumner & Noble, 2003; Weaver & Hamill, 1985). Therefore, if growers increase soil pH to the benefit of the crop, they have an added benefit of these weed species becoming less competitive. Third, species may become weeds because they can tolerate a wide range of environmental conditions, and soil constraints will have less impact on weedy species than on the crop species. For example, *Bromus inermis* Leyss. (smooth brome) in Alberta, Canada, was related to soil moisture and organic nitrogen but was not influenced by other environmental conditions like soil pH (Carrigy et al., 2016). Therefore, addition of lime is not likely to affect competitive ability of this species. While the goal of soil amelioration is to maximise crop growth, the weed may or may not have the same response as the crop to the changes in soil properties. Future investigations are required to determine response of common weed species in Australia to soil amelioration, to allow growers to determine if the weeds will be easier to manage or require a more extensive integrated weed management plan following the amelioration event.

3.1 | Soil acidity

Soil acidity can be natural or induced by the cropping system (Sumner & Noble, 2003). While some species are adapted to highly acidic soils, crops prefer soils with a pH ranging from 5 to close to neutral (Brennan & Bruce, 1999). Borger, Azam, et al. (2020a) noted increased initial growth of *L. rigidum* in response to increased soil pH following application of lime, as for wheat (in soils with natural acidity). Weaver and Hamill (1985) noted that above-ground dry biomass of *Amaranthus powellii* S. Wats. (Powell's amaranth) and *Abutilon theophrasti* Medik. (velvetleaf) were lower in acidic soil (pH 4.8 compared to pH 6.0 or 7.3). However, *S. viridis* biomass was greater in acidic soil, and weed competitive ability when growing in mixed stands with corn (*Zea mays* L.) was improved in acidic soil. Buchanan et al. (1975) assessed the growth of 16 weed species in soils with varying pH without crop competition. *Crotalaria spectabilis* Roth (showy rattlebox) and *Digitaria sanguinalis* (L.) Scop. (hairy crabgrass) were highly tolerant to low pH soils. In contrast, species like *Sinapis arvensis* L. ssp. *arvensis*, previously *Brassica kaber* (DC.) L.C. Wheeler var. *pinnatifida* (Stokes) L.C. Wheeler (wild mustard) or *Stellaria media* (L.) Vill (common chickweed) had reduced growth in acidic soils. *Raphanus raphanistrum* growth and development in a pot trial in Western Australia was not affected by soil pH levels greater than 5.5 and less than 7.5 (Willis & Walsh, 2007). However, in the presence of crop, *R. raphanistrum* biomass reduced as increasing pH increased the competitive ability of the crop. This data confirms that soil amelioration to increase soil pH and optimise crop growth will affect the incidence or density of some weed species in crop, and growers should plan management strategies accordingly (Borger, Azam, et al., 2020a).

Optimal soil pH for many common weeds in Australia has not been researched. Naturally acidic soils are common in Australia, and it is possible that native weed species, like *Chloris truncata* R.Br. (Australian fingergrass), are tolerant to acidic conditions (Chauhan et al., 2018; Isbell, 2016). Chauhan et al. (2018) found that *C. truncata* seed germination was high across a broad pH range (74% germination at pH 4, increasing to 82% at pH 6 and reducing to 77% at pH 10). The research concluded that pH was not a limiting factor for *C. truncata* germination. *Dactyloctenium radulans* (R.Br.) P.Beauv. (buttongrass), another native weed, had 70%–90% germination at pH 8, and significantly reduced germination at pH 4 (approximately 30% to 55%), indicating optimal growth following amelioration of acidic soils (Asaduzzaman et al., 2019). While studies on germination of various weed species at different pH levels are common, few studies investigate the subsequent emergence, growth, seed production/seed viability and competitive ability of weeds at varying pH ranges. Further research is required to determine the impact of soil pH and subsequent amelioration via the application of lime on growth and competitive ability of most weed species.

3.2 | Soil compaction

Soil compaction will reduce weed emergence. *Abutilon theophrasti*, *Polygonum convolvulus* L. (black bindweed), and *Portulaca oleracea* L. (little hogweed) had reduced emergence with increasing depth in three soil types, but emergence was also reduced by compaction (Benvenuti & Mazzoncini, 2018). Compaction and the resulting impact on emergence were greater in loam or clay soil (16%–35% clay) compared to sandy soil (2% clay). The small-seeded *P. convolvulus* and *P. oleracea* (seed weight of 0.09–1.45 mg) were affected by burial depth and compaction to a greater extent than the large-seeded *A. theophrasti* (seed weight of 8.85 mg). In the conservation agriculture systems common to Australia, seeds are deposited on the soil surface and buried by the crop seeding process to germinate on or near the soil surface (Ashworth et al., 2010; Kleemann et al., 2017). Germination of such seeds will be less affected by compaction (Benvenuti & Mazzoncini, 2018). Further, sandy soils are common in southern Australian agricultural systems (Isbell, 2016). Therefore, while the impact of soil compaction on weed germination has not been researched widely in Australia, it is likely that in the conservation agriculture systems with sandy soil, the impact on weed emergence will be minimal.

Following emergence, there is little data on weed growth and competition with crops in compact soils. Increasing compaction reduced weed dry biomass and density in a barley crop, and there was some evidence that perennial species suffered less impact than annual species like *Spergula arvensis* L. (corn spurry) and *Tripleurospermum perforatum* (Mérat) M. Lainz, previously *Matricaria inodora* L. (scentless false mayweed) (Reintam & Kuht, 2012). *Fumaria officinalis* L. (drug fumitory) had the greatest density decrease due to compaction, but dry biomass of *Chenopodium album* L. (lambsquarters) as a per cent of total weeds increased with compaction. Likewise, Azam et al. (2014) found that in compacted soil a garden pea (*Pisum sativum* L.) crop produced most of their roots near the soil surface, whereas the roots of perennial species, such as *Acacia salicina* Lindl. (cooba), were more uniformly distributed throughout the depth of the soil column. Place et al. (2008) noted that the two weed species, *Senna obtusifolia* L. Irwin & Barneby (java-bean) and *A. palmeri* had roots that penetrated a compacted soil layer and acquired nitrogen from below it more efficiently than the soybean (*Glycine max* L.) crop. Further, the weeds' overall shoot growth was sustained when root growth beyond the compact layer was restricted, while soybean shoot growth declined. It is likely that soil compaction will change weed species incidence, density and crop-weed competition, but it is also likely that some weed species will be less affected by compaction than the crop species.

3.3 | Water repellent soil

Water repellent soil may delay weed germination, allowing species that would ordinarily emerge at the same time as the crop or with the opening winter rains to instead emerge over multiple weeks as the soil becomes completely wet. The late cohorts would avoid control by pre-seeding, pre-emergent or early in-crop herbicides (Roper et al., 2015). For example, Blake and Peltzer (2002) applied clay to repellent soils at Esperance and Brookton, Western Australia. This amelioration increased grass weed emergence by 64% at the first significant rainfall event of the year (i.e., the time of crop seeding in the winter annual cropping system) compared to the untreated control. Water repellent soil impedes weed control over the fallow, as well as within the cropping season. Panetta (1988) highlighted that the summer fallow species *Chondrilla juncea* L. (rush skeleton weed) would not readily emerge in water repellent soil following less than 10 mm rainfall in Western Australia. When the emergence of weeds during summer fallow is not uniform, non-selective herbicides are less effective as weeds are at different growth stages and older weeds are stressed due to high temperatures. The management strategies for these soils

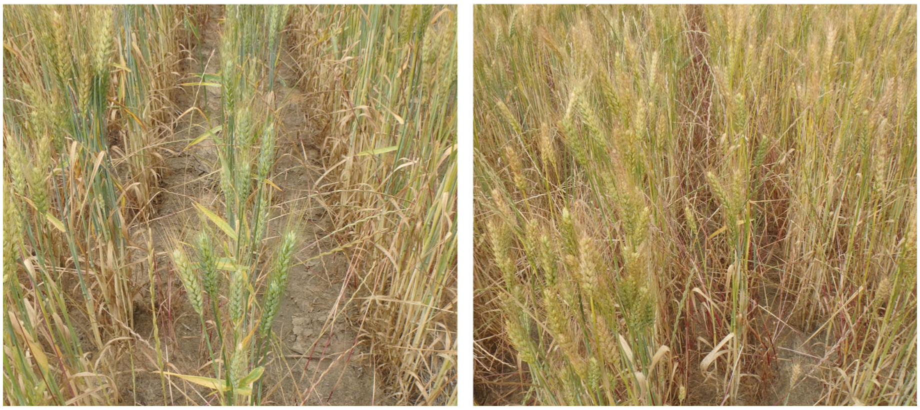

FIGURE 3 *Lolium rigidum* Gaud. in a wheat crop, on a yellow orthic acidic Tenosol soil (Isbell, 2016) at Wongan Hills, Western Australia. Weed density was lower in 2018 in soil that had been ameliorated in 2014 with 3 t ha^{-1} lime (left) compared to control plots that had no lime (right, photo courtesy of Catherine Borger, DPIRD)

include mitigation techniques (i.e., wetting agents, on-row seeding), which can have a small and potentially inconsistent impact, or amelioration techniques (i.e., claying, rotary spading, soil inversion), which are expensive and may have environmental risks (reviewed by Roper et al., 2015). The techniques used can affect weed seed placement in the soil profile (Table 1), pre-emergent herbicide efficiency, crop residue levels and resulting weed emergence patterns, all of which will affect weed management in the year after addressing the water repellence (Roper et al., 2015). While the impact of delayed weed emergence in water repellent soil is well researched, more information is required on the interaction of water repellent soil management strategies and weed ecology.

4 | CROP-WEED COMPETITION FOLLOWING SOIL AMELIORATION

Soil amelioration aims to enhance crop growth by altering soil properties to remove constraints. Regardless of whether the changes enhance the growth of the weeds, multiple studies have shown that a healthy, competitive crop can reduce weed growth. For example, adding lime to acidic soils can increase the pH, improving the competitive ability of crops. Borger, Azam, et al. (2020a) demonstrated in controlled conditions, there was increased growth of *L. rigidum* shoot and root dry biomass following the application of lime to acidic soil. However, a 25-year-old field site at Wongan Hills, Western Australia demonstrated that over the long term, improved crop competition in limed soil reduced weed density. For example, following application of 3 t ha^{-1} lime (Figure 3 left) or 0 t ha^{-1} lime (Figure 3 right) at Wongan Hills in 2014, *L. rigidum* density in 2018 was 8.8 and 15.9 plants m^{-2} respectively. Roper et al. (2015) concluded that weeds can be highly competitive in water repellent soils where crops have staggered emergence or grow less vigorously. Strategic deep tillage to remove the water repellent topsoil ensured better moisture penetration, leading to uniform crop establishment (Figure 4; Roper et al., 2015). However, a long-term field study (4 years) indicated that in a no-tillage system, with high retention of crop residue, water infiltration (through current or prior crop furrows) was greater than in a system where strategic tillage had removed the water repellent soil and crop residue (Roper et al., 2013). The resulting crop was more vigorous due to increased soil moisture retention found in no-tillage systems (Busari et al., 2015). To gain an accurate indication of weed–crop interactions following amelioration, long term studies are needed. This issue was highlighted by Cusser et al. (2020), who compared a no-tillage and conventional agricultural system over 29 years. It took over 15 years before trends in crop yield and soil moisture availability were consistent with those found after 29 years. Of course, field studies are expensive, and agriculture will improve very slowly if it takes over 15 years for trials to identify outcomes of value. Further, no-tillage systems are widely embraced in Australia, on the basis of research trials conducted over periods of less than 15 years (D'emden et al., 2008). Long-term demography of weeds following amelioration in field conditions can be investigated with models. Examples include the PERTH model or the Weed Seed Wizard model, which have the advantage of considering a wide range of different weed species under varying (and easily adjustable) tillage techniques (Agriculture and Food Western Australia, 2020; Borger et al., 2021; Renton & Flower, 2015). However, the finding of Cusser et al. (2020) that studies of over 10 years are required to fully understand the

FIGURE 4 A oil seed rape crop with reduced emergence and competitive ability in the untreated water repellent sandplain soil (foreground) compared to the highly competitive crop in soil ameliorated with 300 t ha^{-1} of incorporated subsoil clay (background) at Esperance, Western Australia (photo courtesy of David Hall, DPIRD)

interactions of soil properties and plant demography remains valid, and field studies would still be required to validate any hypotheses raised by models.

5 | CHANGES TO CROP RESIDUE FOLLOWING AMELIORATION AND ITS EFFECT ON HERBICIDE EFFICACY

In a conservation agricultural system, at least 30% of the soil surface is covered by crop residue (Alletto et al., 2010). Under strategic tillage systems, crop residues may be buried, with the uniformity, depth, and spatial distribution of the residue within the soil profile largely dependent on the tillage equipment (Table 1, Staricka et al., 1991). For example, Allmaras et al. (1996) found that after mouldboard ploughing, 67%–75% of the incorporated crop residues were localised at a depth of 10–20 cm with a tillage depth of 30 cm, while in chisel ploughing, more than 90% of the incorporated residues stayed in the upper 11 cm. Likewise, Staricka et al. (1991) reported that mouldboard-ploughing incorporated oat residue to a depth of 28 cm while chisel and disk ploughing incorporated the residues to 10 cm. Mairhofer et al. (2019) demonstrated that spatial distribution of barley straw residue was unaffected by the increased tillage depth (10, 20 and 30 cm) in a chernozem soil, as more than 90% of the incorporated straw remained concentrated within the top 10 cm. These studies also reported highly clustered residue arrangement and patchy distribution with many voids without crop residue along with the tilled layer.

Crop residue can play a vital role in determining pre-emergent herbicide efficacy, persistence and degradation. Studies confirm that crop residues could act as a barrier or binding agent and intercept 15%–80% of the applied chemicals, preventing them from reaching the targeted weed (Chauhan et al., 2006b). This problem is most evident for non-soluble chemicals like trifluralin or prosulfocarb (Khalil et al., 2018). In a long-term tillage study in a soybean crop, Locke and Harper (1991) found that pre-emergent herbicides, such as metribuzin, had reduced degradation in a conservation agricultural system with higher crop residue surface density. Likewise, Dao (1995) reported limited movement of metribuzin due to surface and subsurface wheat residue. There was 2–5 times higher metribuzin retention in the near-surface zone where crop residues were concentrated. It is evident that burial of residues will reduce interception of pre-emergent herbicides at the surface but will also impact degradation and movement of individual herbicide products.

6 | TIMING OF AMELIORATION AND CROP ROTATION AS A WEED CONTROL TECHNIQUE

6.1 | Amelioration timing

A key impact of amelioration on weed management is physical disruption of the growth of germinating or emerged weeds. Within conservation agriculture systems, physical weed control via soil disturbance using cultivation and soil inversion (for seedbed preparation, at sowing, after sowing within the crop rows or specifically for control of existing plants) are increasingly rare due to the environmental benefits of reduced tillage systems (Llewellyn et al., 2012). It follows that the timing of soil disturbance events with strategic tillage, where they are utilised to address soil constraints, should maximise physical control of existing weeds where practical. How effectively weeds are killed by tillage and the weed density in subsequent crops is related to the time of year in which tillage occurs, type of amelioration and weed species (Morris et al., 2010).

We have exact data on optimal time of emergence and cohort structure for most major agronomic weed species in Australia, like *L. rigidum* or *B. diandrus*. For example, in the semi-arid, winter annual cropping region of Madrid, Spain, *B. diandrus* had the greatest emergence in early to mid-winter (85% of the total population) in barley crops (Mokhtassi-Bidgoli et al., 2013). Subsequent cohorts through mid or late winter were 4%, 1% and 0.9% of the population. Further, the first cohort had the greatest seeds per plant (24, 11, 2 and 1 seeds per plant for cohort one to four) (Mokhtassi-Bidgoli et al., 2013). Likewise, research in Queensland, Australia, indicated that *L. rigidum* emerging in the week a chickpea (*Cicer arietinum* L.) crop was sown had a biomass of 282–337 g m^{-2} and 89–120 seed heads m^{-2}. By comparison, cohorts emerging 3–6 weeks after the chickpea's seeding had a biomass of 4.7–22.2 g m^{-2} and 5–24 seed heads m^{-2} (Mahajan et al., 2019). In winter annual cropping systems, greatest weed emergence occurs at the beginning of the cropping season, and these weeds have greater competitive ability and seed production when compared to the later cohorts. Therefore, if seeding can be delayed and soil amelioration used to target the first cohort of weeds, highly effective weed control may be achieved. However, this is dependent on initial rainfall. For example, in a cereal rotation in Spain, *B. diandrus* emergence prior to crop seeding (i.e., those plants that could be killed by an early amelioration event) was over 90% in a crop with delayed sowing in 2014/2015. By comparison, the autumn of 2015/2016 was dry, and emergence of *B. diandrus* was less than 10% prior to the date of delayed sowing (Royo-Esnal et al., 2018). Therefore, delayed sowing would not always guarantee high initial weed control from amelioration and will only be suitable in those years with early rainfall. Further, soil amelioration can be very slow, as previously discussed. Godwin et al. (2007) found that a full soil inversion needed to be conducted at less than 14 km h^{-1}, or the depth of ploughing was shallower than planned (in a model and field experiments). Ucgul et al. (2019) noted that ploughing with deep ripping followed by rotary spading had greater uniformity of soil mixing (and improved burial of topsoil) at slower speeds. By comparison, amelioration to disrupt a surface crust or hard pan is a much faster operation (Conyers, Dang, & Kirkegaard, 2019). Delayed seeding directly reduces crop yield potential in southern Australia (Tennant, 2000). Therefore, depending on the type of amelioration, it may not be logistically feasible to achieve soil amelioration prior to crop seeding.

Soil amelioration may occur in a spring crop, or winter fallow, which would reduce the chance of tillage resulting in erosion due to a moist soil profile and plant cover (Zachar, 2011). Killing a mature crop in spring through cultivation (green manuring), or haying (application of non-selective herbicide), prior to maturity, is occasionally practised as a weed control tactic in southern Australia (Monjardino et al., 2004). It is likely to be particularly effective to control those weed cohorts that emerge later in the growing season or those species with staggered cohorts throughout the growing season, which may be difficult to kill with a single pre-emergent or selective in-crop herbicide (Borger, Hashem, & Gill, 2020b; Mahajan et al., 2019; Mokhtassi-Bidgoli et al., 2013). However, modelling has indicated that, in spite of excellent weed control, green manuring is not economically viable except in cases of high weed density or high levels of herbicide resistance (Monjardino et al., 2004). Fields may be left fallow over winter, in northern Australia where the cropping system has both summer and winter crops (Agriculture and Food Western Australia, 2020). Winter fallow may occur in southern Australia in low rainfall areas, where the benefits of stored soil moisture and increased nitrogen mineralisation improve the profitability of a fallow as a rotation choice (Oliver & Sands, 2013). Therefore, soil amelioration in a spring crop or winter fallow is viable in some regions, but further economic modelling is required to consider the value of the amelioration itself in removal of the soil constraint, potential weed control, moisture retention and nitrogen for the subsequent crop, compared to the cost of lost crop production.

Over a summer fallow, in a rain-fed Australian agricultural system, the water and nutrients used by the weeds can reduce the yield potential of the following crop (Hunt & Kirkegaard, 2011). Chemical control is often difficult because the dry, stressed plants are less responsive to herbicide (Cameron & Storrie, 2014). Physical weed control in the summer fallow via strategic tillage may be more effective than herbicides, and has the added benefit of reducing reliance on the non-selective herbicides that are increasingly prone to resistance (Duke et al., 2018; Yu et al., 2007). The greatest disadvantage of soil amelioration over the summer fallow is the risk of severe wind erosion, and potential sandblasting of emerging crops (D'emden et al., 2008; Morris et al., 2010). Amelioration over summer is generally performed after a rainfall event, to minimise the risk of erosion.

6.2 | Crop rotation following soil amelioration

As discussed, we do not have complete information about how much a strategic tillage event will stimulate weed emergence for some tillage implements (Table 1). If a soil disturbance event is likely to stimulate weed growth, a carefully developed weed management plan will be required in the subsequent rotation (Roberts & Potter, 1980). However, soil amelioration that controls weeds allows greater flexibility in crop choice in subsequent years. For example, a rotation in Nebraska, USA consisted of a 2-year fallow between wheat crops due to intense competition from *Bromus tectorum* L. (cheatgrass). A soil inversion using a mouldboard plough reduced *B. tectorum* by 97% in the following crop, and wheat yields were 30% higher (Kettler et al., 2000). The low weed density allowed greater flexibility (fewer fallows) in the years following the inversion. In the research by Kettler et al. (2000), weed density in the third wheat crop after the inversion was only reduced 41% compared to the conservation tillage control plots, and so the initial weed control was not well maintained. The authors propose that plots were re-infested via edge effects, but the soil was only inverted to a depth of 15 cm. It is likely that not all seed was placed at a depth of 15 cm, and that *B. tectorum* seed can emerge from depths up to 15 cm, as for *B. diandrus* (Table 1; Dastgheib & Poole, 2010; Harradine, 1986). Therefore, it is possible that the *B. tectorum* population recovered in subsequent years. At multiple sites in eastern Australia, a strategic tillage event (strip tillage, narrow chisel or disc) was introduced to systems with a history of long-term conservation tillage. Researchers concluded that a single cultivation event generally reduced weed density in the following year, although reductions to weed density in subsequent years were not significant (Dang et al., 2018). The computer simulation modelling results by Renton and Flower (2015) indicated that occasional use of a full soil inversion (every 4 or 8 years) improved weed control in a modelled winter-crop/summer-fallow system, but the model results were highly dependent on the efficacy of weed seed burial by the soil inversion process. A range of strategic soil amelioration methods can reduce weed density in the subsequent year, giving greater flexibility in choice of the future rotation. However, without a comprehensive weed management plan, the weeds quickly return.

7 | DISCUSSION

This review highlights that there is considerable variation in the outcome of tillage operations. Factors affecting the outcomes of strategic tillage include soil type, tillage technique/machinery and speed/method of tillage operation, as highlighted earlier using studies on mouldboard ploughs as an example. This variability affects soil mixing and the resultant physical weed control, seed burial, seed emergence and herbicide performance. This review has highlighted that there is extensive research on aspects of weed ecology that are affected by soil disturbance and burial, but we do not have extensive knowledge on extent of soil disturbance from some strategic tillage implements. It is particularly important to understand how much of the topsoil (containing the weed seed bank) is buried below a depth of 10 cm during soil amelioration. Some tillage methods, like soil inversion, have been extensively researched for weed control potential. However, this review has highlighted the variability of seed burial from soil inversion and the importance of effective weed seed burial when using soil inversion as a weed control technique. Therefore, even this technique needs research on how much weed seed is buried in different soil types and how seed burial can be optimised. It is also clear that future publications on amelioration should consider adding data on exact implements used for soil tillage (model etc.), speed of operation, soil type and depth of disturbance, to allow full consideration of the potential impact on weed ecology and soil properties.

Aside from the direct impact on weeds (physical weed control and burial of seed), soil amelioration may impact; (a) emergence, through seed burial or removal of soil constraints/changes to soil properties, (b) pre-emergent soil-applied herbicide performance and

(c) crop-weed competition. These changes may be beneficial. For example, if emergence is increased from a strategic tillage event, weeds can be controlled with herbicide and the weed seed bank will be reduced. However, for growers to take advantage of these changes to the agronomic system, they need to fully understand the impacts of different amelioration strategies in different soil types on subsequent weed growth. Long-term field sites are required to fully understand impacts of altered soil properties on weed growth and crop weed competition.

There are multiple studies highlighting how quickly the weeds can return after a strategic tillage event that offers initial weed control. However, there is no research on optimal time of amelioration for weed control during the year, even though the research suggests that varying timing of amelioration will affect physical weed control. There is likewise no research on the optimal time within a rotation to perform strategic tillage. After the initial strategic tillage event, there is little research to compare different crop rotations and integrated weed management strategies to maintain weeds at low densities in the subsequent crops, while compensating for the potential altered performance of pre-emergent herbicides due to changes in crop residue.

Future research requirements:

1. Long-term field studies (over 10 years) are required to fully understand interactions of altered soil properties, crop growth and weed demography.
2. Impact of select soil amelioration implements (i.e. subsoil clay delving, soil mixing with one pass tillage, deep ripping) on soil properties, topsoil burial, physical weed control or weed seed burial.
3. Stimulation of weed emergence following varying soil amelioration techniques, at varying times in the year/rotation.
4. Aspects of weed ecology for selected weed species, including maximum depth of successful emergence and degradation of buried seed in varying soil types.
5. Impact of amelioration on weed growth/competitive ability and soil applied herbicide performance. Optimal rotation choice and integrated weed management strategy to maintain weeds at low levels.

Research to indicate how strategic tillage can be used to reduce weed density and maintain weeds at low densities in subsequent rotations will be highly beneficial to growers attempting to optimise their costly soil amelioration operations. This review has identified multiple areas of future research, as there is little existing research in this field, but has also highlighted how effectively existing data on weed ecology can be applied to the field of soil amelioration where there is a good understanding of what changes the amelioration technique had on the soil properties.

ACKNOWLEDGEMENTS

This work was funded by Boosting Grains Science Partnerships, Royalties for Regions Western Australia. The authors would like to acknowledge Miranda Slaven, Tom Edwards, and Bowen Zhang (DPIRD) for reviewing the manuscript.

CONFLICT OF INTEREST

The authors have no conflict of interest to declare.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analysed in this study.

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How to cite this article: Mia, M.S., Azam, G., Nouraei, S. & Borger, C. (2023) Strategic tillage in Australian conservation agricultural systems to address soil constraints: How does it impact weed management? *Weed Research*, 63(1), 12–26. Available from: https://doi.org/10.1111/wre.12564