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Corresponding author:
Catherine P. D. Borger;
Email: Catherine.borger@dpird.wa.gov.au

Burial and subsequent growth of rigid ryegrass (*Lolium rigidum*) and ripgut brome (*Bromus diandrus*) following strategic deep tillage

Catherine P. D. Borger[1], George Mwenda[2], Sarah J. Collins[3], Stephen L. Davies[4], Arslan Masood Peerzada[2] and Andrew van Burgel[5]

[1]Discipline Leader Weed Science, Department of Primary Industries and Regional Development, Northam, WA, Australia; [2]Research Scientist, Department of Primary Industries and Regional Development, Northam, WA, Australia; [3]Senior Nematologist, Department of Primary Industries and Regional Development, South Perth, WA, Australia; [4]Principal Research Scientist, Department of Primary Industries and Regional Development, Geraldton, WA, Australia and [5]Applied Statistician, Department of Primary Industries and Regional Development, Albany, WA, Australia

Abstract

Soil amelioration via strategic deep tillage is occasionally utilized within conservation tillage systems to alleviate soil constraints, but its impact on weed seed burial and subsequent growth within the agronomic system is poorly understood. This study assessed the effects of different strategic deep-tillage practices, including soil loosening (deep ripping), soil mixing (rotary spading), or soil inversion (moldboard plow), on weed seed burial and subsequent weed growth, compared with a no-till control. The tillage practices were applied in 2019 at Yerecoin and Darkan, WA, and data on weed seed burial and growth were collected during the following 3-yr winter crop rotation (2019 to 2021). Soil inversion buried 89% of rigid ryegrass (*Lolium rigidum* Gaudin) and ripgut brome (*Bromus diandrus* Roth) seeds to a depth of 10 to 20 cm at both sites, while soil loosening and mixing left between 31% and 91% of the seeds in the top 0 to 10 cm of soil, with broad variation between sites. Few seeds were buried beyond 20 cm despite tillage working depths exceeding 30 cm at both sites. Soil inversion reduced the density of *L. rigidum* to <1 plant m^{-2} for 3 yr after strategic tillage. *Bromus diandrus* density was initially reduced to 0 to 1 plant m^{-2} by soil inversion, but increased to 4 plants m^{-2} at Yerecoin in 2020 and 147 plants at Darkan in 2021. Soil loosening or mixing did not consistently decrease weed density. The field data were used to parameterize a model that predicted weed density following strategic tillage with greater accuracy for soil inversion than for loosening or mixing. The findings provide important insights into the effects of strategic deep tillage on weed management in conservational agricultural systems and demonstrate the potential of models for optimizing weed management strategies.

Introduction

The advantages of a conservation tillage system (no-till farming) with stubble retention include cost-effectiveness, improved water infiltration, reduced erosion, improved soil health and quality, and reduced greenhouse gas emissions (Kassam et al. 2019; Llewellyn et al. 2012). In conservation agricultural systems in southern Australia, the crop is sown using narrow-point or disk openers in a single pass for minimal soil and residue disturbance. There is rarely cultivation for seedbed preparation or cultivation before or after crop emergence for direct interference with germinating or emerged weeds (Mia et al. 2023). Crop seeding in this system results in very little mechanical weed control, partly because there is minimal soil disturbance at seeding and because "dry" sowing on the bare ground before the season-opening rains is common (Fletcher et al. 2016). A major disadvantage of the conservation agricultural system is that weed seeds are left on the soil surface, and weeds are not physically controlled, leading to overreliance on herbicides and increased risk of resistance development (Llewellyn et al. 2012).

For some soil types, soil constraints (i.e., soil compaction, acidity, water repellence) can be addressed using strategically timed deep-tillage operations for soil amelioration (Davies et al. 2019). These tillage operations aim to disturb the soil to a greater depth or extent than that achieved by crop sowing in the conservation agricultural system (Davies et al. 2019). For example, compacted soil may be loosened with a deep ripper (i.e., soil loosening) working 30- to 70-cm deep. This practice causes minimal incorporation and buries 5% to 10% of the topsoil below 10 cm (Scanlan and Davies 2019). To combat soil acidification, surface spread amendments like lime may be incorporated with a rotary spader (i.e., soil mixing) to a depth of 20 to 30 cm, burying 10% to 15% of topsoil below 10 cm (Scanlan and Davies 2019). To alleviate water repellence, a moldboard plow (i.e., full soil inversion) working to a 30- to 40-cm depth

Table 1. Strategic deep-tillage implements used for each treatment at an operating speed of 4 km h^{-1}.

Treatment	Implements
Control	No strategic deep tillage, only minimum tillage crop sowing
Soil loosening	2-m-wide Agroplow deep ripper (model AP11, 2 Castle Street, Molong NSW 2866, Australia) with five narrow-shank tines at 40-cm tine spacing and a maximum operating depth of 35–45 cm
Soil mixing	In Yerecoin, an Imants 3-m-wide, three-point linkage rotary spader (model 40SX_KH, Turnhoutseweg, 29 5541 NV Reusel, Netherlands) with power harrows was used at an operating speed of 4 km h^{-1}, while in Darkan, a combination of Agroplow deep ripping with topsoil inclusion plates and shallow plowing with Kverneland moldboard plow (Plogfabrikkvegen 1, N-4353 Klepp Stasjon, Norway) to 20 cm was used
Soil inversion	Kverneland moldboard plow with three (number 9) plow boards, in-furrow plow with skimmers

buries 60% of topsoil below 10 cm (Scanlan and Davies 2019). When employed to achieve soil amelioration, these tillage events will impact weed ecology due to the burial of the topsoil (Renton and Flower 2015; Scanlan and Davies 2019).

Strategic deep tillage changes the vertical distribution of weed seeds in the soil profile, altering emergence patterns. Prior research indicated that both rigid ryegrass (*Lolium rigidum* Gaudin) and ripgut brome (*Bromus diandrus* Roth) had increased emergence following shallow burial (2 cm) compared with seed on the soil surface (Chauhan et al. 2006; Harradine 1986). Deep burial (10 cm) prevented the emergence of *L. rigidum* and reduced the emergence of *B. diandrus*. However, weed seed burial following strategic tillage has only been extensively researched for soil inversion (Mia et al. 2023), with a full soil inversion shown to bury 50% to 99% of weed seed beyond a depth of 10 cm and to kill up to 99% of existing weeds (Mohler et al. 2006; Roger-Estrade et al. 2001). Soil mixing with rotary spaders has little research available on weed seed burial. However, seed burial by soil mixing with large offset disks has been investigated, with the SeedChaser model by Spokas et al. (2007) indicating that more than 95% of seed would be left in the top 0 to 10 cm. Subsoilers (similar to deep rippers) increase weed density in the following season or leave density unaffected compared with direct seeding (Davies et al. 2019; Mia et al. 2023; Yalcin and Cakir 2006). However, most studies were conducted in loam soils, and the researchers acknowledged that the response will likely vary in sandy soils (Spokas et al. 2007; Yalcin and Cakir 2006).

While seed burial by tillage implements has been investigated, weed density in the agronomic rotation following strategic tillage has not often been investigated in Mediterranean systems, particularly in sandy soils. Understanding how strategic tillage implementation impacts weed growth is crucial for planning effective weed management programs following amelioration. Based on data generated for sandy loam soils, seed burial and emergence data can be used to parameterize and validate decision support tools for weed management, as was done with the SeedChaser model (Spokas et al. 2007). The Weed Seed Wizard model is designed to assess weed growth in varying agronomic systems and accounts for a range of soil types, including sands (Borger et al. 2021a). However, evidence is required to support its effectiveness in estimating the impact of strategic tillage on weed ecology in the agronomic system (Borger et al. 2021a).

This research investigated the proportion of weed seeds buried at depths greater than 10 cm by soil loosening, mixing, and soil inversion strategic tillage techniques in two soil types. We hypothesized that seed burial will be greatest with soil inversion, followed by mixing, and then loosening. Further, we investigated weed density and seed production following strategic tillage in a standard agronomic system and hypothesized that tillage operations like soil inversion would reduce density due to the burial of the weed seeds and that loosening or mixing would increase density, as these practices stimulate emergence due to shallow burial of seeds. Finally, the field data were used to validate the simulation of weed density within the agronomic system following varying strategic tillage techniques within an existing decision support tool, the Weed Seed Wizard model.

Materials and Methods

Experimental Sites and Design

The impact of four strategic deep soil tillage treatments (Table 1) on weed density and growth was assessed at two sites in Yerecoin and Darkan (Table 2). The tillage treatments were implemented once only in 2019, before seeding. The experiments were arranged in a randomized block design with six replications, with strategic tillage as the factor.

Field Operations

Experiments were established in May/June 2019, after the opening rains of the winter annual grain-cropping season, with plots measuring 20 m by 4 m. The crop was sown using knifepoints and press wheels with a 22-cm row spacing (7 rows of the crop over 1.54 m, twice in each 4-m-wide plot). Regionally appropriate fertilizer and pesticides (where necessary) were applied each year, and herbicides were used to control weeds (Table 2). Herbicides were bulk sprayed with a 10-m boom, 1 m off the ground, with a 50-cm nozzle spacing. Nozzle type, water rate, and spray pressure were adjusted for each herbicide according to label recommendations, and adjuvants were added where instructed by the label.

Data Collection

This paper does not provide a comprehensive analysis of the agronomic details of the experiments, including the impacts of deep tillage on crop yield, soil characteristics, and soil pathogen or nematode pest levels; these data will be presented in other publications. For the current study, the sites were assessed for soil type and particle-size analysis (Table 2), total weed density, panicle production, seed production, and seed burial in 2019, 2020, and 2021. This paper focuses on the most common weed species found at each site, *B. diandrus* and *L. rigidum*. The herbicides did not fully control these species due to staggered cohort emergence and seasonal conditions. Information on the agronomic management of the sites, yield, and initial impact on soil properties and soil pathogens can be found in Collins et al. (2021).

Assessment of Weed Seed Burial

Following strategic tillage, soil cores were collected in 2019 to assess the number of weed seeds at each depth in the seedbank. At both sites, a total of six cores per plot were collected from four soil

Table 2. Description of locations, including GPS, soil type and particle-size analysis (%sand–%silt–%clay) at 0- to 40-cm depths, strategic tillage date and working depth, crop sowing details, herbicides applied to control grass weeds, and crop harvest date.

Yerecoin		Darkan
	GPS	
30.9268°S, 116.3927°E		33.3345°S, 116.7331°E
	Soil type[a] and particle-size analysis	
Yellow orthic Tenosol		Bleached-ferric dystrophic Yellow Chromosol, 40% subrounded ferruginous ironstone gravel and 10% subrounded ferruginous ironstone stone at 0–20 cm
0–10 cm: 93.5%–1.5%–5%		0–10 cm: 87.7%–4.2%–8.2%
10–20 cm: 89.8%–1.2%–9%		10–20 cm: 91.8%–3.1%–5.1%
20–30 cm: 87.8%–0.5%–11.8%		20–30 cm: 92%–4%–4%
30–40 cm: 87.9%–0.8%–11.3%		30–40 cm: 87.9%–5.1%–7.1%
	Strategic tillage date and average working depth cm	
June 14, 2019: 35–37		May 19, 2019: 25–32
	2019: Crop seeding rate kg ha^{-1}	
June 19, 2019: Barley (*Hordeum vulgare* L.) 'La Trobe'; 80		June 19, 2019: Barley 'La Trobe'; 80
	2019: Herbicide[b] g ai ha^{-1}	
June 18, 2019: paraquat/diquat 270/230 (SpraySeed®, 135/115 g L^{-1}, L, Syngenta), prosulfocarb/*S*-metolachlor 1,400/210 (Boxer Gold® 800/120 g L^{-1}, EC, Syngenta Australia) June 19, 2019: prosulfocarb/*S*-metolachlor 600/90		June 19, 2019: paraquat/diquat 270/230, prosulfocarb/*S*-metolachlor 1,400/210 June 21, 2019: prosulfocarb/*S*-metolachlor 600/90
	2019: Harvest date	
November 18, 2019		November 28, 2019
	2020: Crop seeding rate kg ha^{-1}	
May 28, 2020: Wheat 'Ninja'; 90		May 27, 2020: Wheat 'Ninja'; 90
	2020: Herbicide g ai ha^{-1}	
May 28, 2020: paraquat/diquat 270/230, pyroxasulfone 100 (Sakura® 850 g kg^{-1}, WG, Bayer Crop Science), trifluralin 960 (TriflurX® 480 g L^{-1}, EC, Nufarm) June 16, 2020: prosulfocarb/*S*-metolachlor 2000/300 – June 24, 2020: mesosulfuron-methyl 10 (Atlantis® 30 g L^{-1}, OD, Bayer Crop Science)		May 27, 2020: paraquat/diquat 270/230, pyroxasulfone 100, trifluralin 960 July 10, 2020: bromoxynil/pyrasulfotole 168/30 (Velocity® 210/37.5 g L^{-1}, EC, Bayer Crop Science) July 21, 2020: trakkoxydim 150 g (Achieve® 400 g kg^{-1}, WG, Nufarm)
	2020: Harvest date	
November 17, 2020		December 8, 2020
	2021: Crop seeding rate kg ha^{-1}	
April 28, 2021: Canola 'Hyola 410XX'; 4.6		April 28, 2021: Canola 'Hyola 410XX'; 4.6
	2021: Herbicide g ai ha^{-1}	
April 28, 2021: paraquat/diquat 270/230, trifluralin 720 May 19, 2021: glyphosate 620 (Roundup Ready® Plantshield® (690 g kg^{-1}, SG, Bayer Crop Science) June 16, 2021: glyphosate 620 July 6, 2021: glyphosate 620		April 28, 2021: paraquat/diquat 270/230, trifluralin 720 August 3, 2021: MCPB/MCPA 187.5/12.5 (Select® 375/25 g L^{-1}, SC, Dow AgroSciences) August 30, 2021: glyphosate 3,000 (Crucial® 600 g L^{-1}, SL, Nufarm)
	2021: Harvest date	
November 16, 2021		December 3, 2021

[a]Australian soil classification from Isbell (2016).
[b]All herbicides were purchased from Nutrien Ag Solutions®, Northam, WA 6401, Australia, https://www.nutrienagsolutions.com.au.

depths (0 to 10, 10 to 20, 20 to 30, and 30 to 40 cm) in three of the six treatment replications, using a 4-cm-diameter auger, and were then bulked by soil depth for each plot. A bulked subsample from each bulked treatment and soil depth in each replication was used for particle-size analysis. Trays measuring 30 cm by 30 cm by 10 cm in height were filled with potting mix to a depth of approximately 8 cm. A 2-cm layer of the field soil was spread over the potting mix (approximately 2.5 kg dry bulked soil per tray). The trays were kept in a screen house at the Department of Primary Industries and Regional Development, Northam, WA. Overhead sprinklers delivered 13 mm of water d^{-1} where natural rainfall was insufficient to maintain the soil moisture at optimal levels to trigger emergence. For 18 mo, emerged seedlings (*L. rigidum* and *B. diandrus*) were counted every 3 d and removed. The observations ended at this time because no emergence had been noted over the final 3 mo. In conditions favorable to dormancy release (i.e., field-based afterripening) and germination (shallow burial), both *L. rigidum* and *B. diandrus* have 90% to 100% of seeds germinate in the year following seed production (Borger et al. 2021b; Chauhan et al. 2006).

An ANOVA was applied for each site, where tillage was the treatment factor, replicate was the block factor, and total percent weed emergence at each depth was the variate. The total percent weed emergence was assessed, because emergence was low from some depths due to the displacement of seeds, so the total weed emergence data set had a better distribution of residuals than data for each species. Weed emergence from depths below 20 cm was too low to allow valid analysis. Strategic tillage treatments were considered different based on the LSD using a 5% significance level ($P < 0.05$). All analysis was done in Genstat (https://vsni.co.uk/software/genstat).

Assessment of Weed Density and Seed Production

Weed density at each site was determined using 50 cm by 50 cm quadrats, two per plot at Yerecoin and four per plot at Darkan, due to lower initial weed density, approximately 6 wk after seeding or after weeds had adequate time to die following in-crop selective herbicide application. Note that this method would not assess total weed emergence but aimed to assess final weed density in the agronomic system (i.e., those plants contributing to the future soil seedbank). At maturity, the number of panicles for each species was assessed from two (Yerecoin) or four (Darkan) quadrats each year (before shedding of *B. diandrus* seed). Quadrat locations were different for assessing weed density and number of panicles, using the method of Kleemann et al. (2016) and Kleemann and Gill (2009) for similar studies of *L. rigidum* and rigid brome (*Bromus rigidus* Roth). In 2020 and 2021, 20 panicles were removed for each weed species per plot and dried at 60 C for 3 d. Samples were weighed, threshed, and processed (STJL-2 stainless steel fine aggregate sample splitter, Anditech. PO Box 759, Macleod, Vic 3085, Australia) to obtain a subsample of <4 g. Subsamples of seeds were counted manually, and the total seeds on 20 panicles and average seeds per panicle were calculated using the initial sample weight. Total seeds per square meter in 2020 and 2021 were calculated based on seeds per panicle and the number of panicles per square meter.

Data were analyzed using an ANOVA, with strategic tillage as the treatment factor and replicate as the block factor. Variates included *L. rigidum* and *B. diandrus* density, panicle number and seed number per square meter, and seed number per panicle. Residual plots were used to check data distribution, and a square-root or cube-root transformation was applied where residuals were not normally distributed. Tillage treatments were considered different based on the LSD using a 5% significance level. All analysis was done in GenStat.

Use of the Weed Seed Wizard Model

An open-access decision support tool, the Weed Seed Wizard model (Borger et al. 2018), simulates weed population dynamics in response to agronomic decisions and environmental parameters under various climates and soil types. This program is available from Agriculture and Food Western Australia (2020) and includes an input interface, data lists, data editors, an event queue, and an output interface. A complete list of model parameters can be extracted by downloading the model and selecting Model and Save a Parameter Set. Further, each parameter is defined when users click the adjoining "?" in the user interface.

For this study, a scenario was constructed in the model for each site, with the time frame and weed species reflecting the field sites (Table 2). Within Event Management, the seeding rate in each Sow Event was specified (in kg ha^{-1}) and taken from the field data (Tables 2 and 3). At sowing, the tillage type was Knifepoint Seeding to reflect the annual sowing method at the sites after deep soil tillage treatments were imposed. To generate the soil inversion within the scenarios, Till event and Full Inversion were selected on the appropriate date. Soil mixing (rotary spader) and loosening (deep ripper) were not included in the model, but a soil mixing and loosening event was added by selecting Model, Edit Till Types, and Add. The Spading seed burial was set to 50% of seed at 0 to 10 cm (specifically 1% on the soil surface, 9% at 0 to 1 cm, 20% at 1 to 5 cm, 20% at 5 to 10 cm) with 50% of seed at 10 to 20 cm, based on Scanlan and Davies' (2019) measurements that a rotary spader buries 50% to 60% of topsoil (containing the weed seeds) below 10 cm. Deep Ripping seed burial was set to 90% of seed at 0 to 10 cm (specifically 60% at the surface, 10% at 0 to 1 cm, 10% at 1 to 5 cm, 10% at 5 to 10 cm) and 10% of seed at 10 to 20 cm, based on Davies et al.'s (2019) indication that deep ripping buries 5% to 10% of the topsoil below 10 cm, leaving most of the topsoil undisturbed. At each Harvest Event, we selected "Yield . . . based on average season".

The model's data output included estimated plant density and seed production. In the model output, plant density was matched to the date density was assessed in the field (i.e., after herbicide application). To estimate seed production from a single harvest event within the model, two assessments of the seedbank were undertaken: the day before and the day after harvest. By subtracting the before- from the after-harvest measurement, we were left with an estimate of the total seed added at harvest. Any seeds in the seedbank before harvest were dormant seeds from prior years. The data for plant density and seed production in the field were compared with the values from the model output each year. At Yerecoin, seed production data were only taken in 2020 and 2021. Therefore, the estimated total seed production in 2019 was determined from each species' seed number per panicle in 2020 and 2021. To compare observed (field experiment) values with predicted means from the model, the mean absolute error (MAE) was used (Chai and Draxler 2014). MAE is the average of the absolute errors of the predicted (y_i) and actual (x_i) values (Equation 1).

$$\mathrm{MAE} = \frac{\sum_{i=1}^{n}(y_i - x_i)}{n} \qquad [1]$$

Results and Discussion

Weed Seed Burial

Strategic tillage techniques altered the number of seeds at 0 to 10 cm and 10 to 20 cm at each site (Table 4). At Yerecoin and Darkan, the soil inversion plots had fewer seeds in the top 0 to 10 cm than the control. Conversely, at 10 to 20 cm, the soil inversion plot had more seeds than the control. At Yerecoin, soil loosening seed burial was similar to that of the control at both depths, but Darkan soil loosening had fewer seeds at 0 to 10 cm than the control. The number of seeds buried by the soil mixing was similar to that of the control at both sites. The control and

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Table 3. The location of each site, time frame set in the model, initial weed seedbank, soil type, weather records, and the exported Event List.

Yerecoin		Darkan
	Time frame	
December 1, 2018–December 30, 2021		December 1, 2018–December 30, 2021
	Initial seedbank seeds m^{-2}	
Lolium rigidum; 5,000 *Bromus diandrus*; 2,000		*L. rigidum*; 2,000 *B. diandrus*; 1,000
	Soil type	
Southern region: sand		Southern region: loam
	Weather records[a]	
WA Wongan Hills		Darkan Post Office weather station 10524
	Event List[b]	
June 18, 2019 Spray: SpraySeed® June 18, 2019 Spray: Boxer Gold® June 19, 2019 Sow: Barley, knifepoint seeding November 18, 2019 Harvest: barley harvested, all chaff spread/ normal harvest used May 28, 2020 Spray: SpraySeed®/Trifluralin May 28, 2020 Spray: Sakura® May 28, 2020 Sow: Wheat, Knifepoint Seeding June 16, 2020 Spray: Boxer Gold® June 24, 2020 Spray: Atlantis® November 17, 2020 Harvest: Wheat harvested, all chaff spread/ normal harvest used April 28, 2021 Spray: SpraySeed®/Trifluralin April 28, 2021 Sow: RR Canola, Knifepoint Seeding May 19, 2021 Spray: Glyphosate 450 June 16, 2021 Spray: Glyphosate 450 July 6, 2021 Spray: Glyphosate 450 November 16, 2021 Harvest: RR Canola harvested, chaff spread/ normal harvest used		June 19, 2019 Spray: SpraySeed® June 19, 2019 Spray: Boxer Gold® June 19, 2019 Sow: Barley, knifepoint seeding November 28, 2019 Harvest: barley harvested, all chaff spread/normal harvest used May 27, 2020 Spray: SpraySeed®/Trifluralin May 27, 2020 Spray: Sakura® May 27, 2020 Sow: Wheat, Knifepoint Seeding July 21, 2020 Spray: Achieve® (tralkoxydim) December 8, 2020 Harvest: Wheat harvested, all chaff spread/normal harvest used April 28, 2021 Spray: SpraySeed®/Trifluralin April 28, 2021 Sow: RR Canola, Knifepoint Seeding August 3, 2021 Spray: Select® August 30, 2021 Spray: Glyphosate 450 December 3, 2021 Harvest: RR Canola harvested, chaff spread/normal harvest used

[a]WA_Wongan Hills was selected in the model as the closest weather station to Yerecoin. A weather record for Darkan was added to the model, using data (maximum and minimum temperature, daily rainfall, and evaporation) downloaded from the Darkan Post Office weather station (Department of Science Information Technology and Innovation 2019). Note that a weather station was located at each experimental site, but the model was used with publicly available data.
[b]Herbicide names are listed as they appear in the list of selectable model parameters (i.e., not by active ingredient as for a herbicide applied in the field).

Table 4. The total percent weed seed burial (*Lolium rigidum* and *Bromus diandrus*) from soil cores at 0–10 cm and 10–20 cm at each site following strategic tillage in 2019, and the P-value from the analysis applied to each depth.

	Weed seed burial[a]			
	Yerecoin		Darkan	
Strategic tillage	0–10 cm	10–20 cm	0–10 cm	10–20 cm
	%			
Control	77.8bc	22.2a	75.4a	24.6a
Inversion	11.1a	88.9b	10.7b	89.3b
Loosening	91.1c	6.7a	36.1bc	29.2a
Mixing	30.6ab	58.3ab	66.6ac	22.4a
P	0.032	0.035	0.010	0.002

[a]Within each column, means sharing a common letter differ at $P < 0.05$.

inversion treatments at both sites had no seed below 20 cm. Soil loosening had low seed density below 20 cm at Yerecoin and 33% of seeds below 20 cm at Darkan, but as stated, the 20 to 30 cm data set had emergence too low to allow valid analysis.

Supporting the hypothesis, soil inversion buried more weed seeds than soil loosening or mixing. At both sites, approximately 90% of weed seed was buried beyond 10 cm. By comparison, the seed burial rate for loosening and mixing was inconsistent between sites. Interestingly, despite all soil inversion reaching a depth of 35 cm, the seed burial data revealed that most seeds were placed at 0 to 10 cm and 10 to 20 cm, with no seeds found below 20 cm following soil inversion at either site. Seed burial depth following inversion in the literature is variable, with previous research reporting weed seed placement near the furrow bottom, at the center of the plowed layer, or uniformly distributed through the profile (reviewed by Mohler 1993; Roger-Estrade et al. 2001). It was suggested that if seeds were placed in the middle of the plowed layer by a soil inversion reaching a depth of 25 cm (with an 18-cm-wide and 10-cm-deep skim coulter), this likely occurred because the seeds were initially concentrated at the lower limit of the furrow slice (Roger-Estrade et al. 2001). In the current study, the control treatments demonstrated that weed seeds were mainly in the top 10 cm of soil, not the base of the furrow slice. However, variation in burial occurs due to initial seed distribution, soil type, soil conditions, plow characteristics, soil throw, and speed of operation, which are not fully described in prior papers reviewed by Roger-Estrade et al. (2001). Ucgul et al. (2017, 2018) utilized a validated discrete element method (DEM) to model soil particle movement in response to tillage tools and assess the impact of operating speed and depth to quantify the topsoil burial performance of moldboard plows and rotary spaders. Increased operating speed reduced the topsoil burial performance of both implements. For example, the DEM modeling showed a moldboard plow with skimmers operating at 5 km h^{-1} buried 39% of topsoil in the 20 to 30 cm

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layer, but this was reduced to 24% with an operating speed of 7.5 km h^{-1} (Ucgul et al. 2017). In these field experiments, we used a low operating speed of 4 km h^{-1} for both implements, and this should have aided the optimal burial of topsoil and associated weed seeds. Depth of operation is another critical factor, with greater depths promoting deeper burial of topsoil, though even for moldboard plow modeled operating depths of 20, 25, 30, and 35 cm, the largest proportion of buried topsoil can still be found in the 10- to 20-cm layer (Ucgul et al. 2017), consistent with our weed seed burial depths. In the present study, there is limited potential to speculate why the current system consistently buried weed seeds to half the working depth, with none found in the deeper 20- to 30-cm layer. Seed size was likely not a factor in burial, even though *B. diandrus* seed is much larger than *L. rigidum* seed (Borger et al. 2020), as seeds of both species were not found beyond 20 cm. There are no data in the literature on seed burial or subsequent emergence by soil loosening via deep ripping and little data on weed emergence following the use of subsoilers (Mia et al. 2023). The current study highlighted that it was the only technique to place seeds beyond a depth of 20 cm reliably, resulting in a considerable proportion of seeds that are unlikely to emerge in subsequent years. It would be highly beneficial to consider whether a deep ripping device itself (i.e., the inclusion plates attached to the rear of the tine to allow more topsoil to fall into the furrow) or operation parameters (speed, soil characteristics, etc.) could be modified to bury a higher proportion of seed beyond 20 cm (Mia et al. 2023).

Weed Density and Seed Production in the Field

In both sites, soil inversion reduced *L. rigidum* density and panicles to 0 to 1 m^{-2} from 2019 to 2021 (Table 5). Seed production in 2019 was not assessed at Yerecoin. At Darkan, seed production following inversion was similar to that of the control. In 2020, soil inversion reduced seeds per panicle and seeds per square meter at both sites compared with the control. In 2021, at both sites, seeds per panicle and seeds per square meter were zero (at Darkan, no treatments contained *L. rigidum* due to comprehensive weed control in the glyphosate-tolerant canola [*Brassica napus* L.] crop).

Soil loosening and mixing treatments had little impact on weed growth. Soil loosening at Yerecoin had higher *L. rigidum* density than the control in 2019, although panicle and seed numbers were similar. In 2020 and 2021, weed density, panicle, and seed number were similar to those of the control. Loosening at Darkan did not affect *L. rigidum*. Soil mixing at Yerecoin initially reduced weed density, although there was no difference in panicle or seed number. In 2020 and 2021, weed density after mixing was similar to that of the control, but in the 2021 canola crop, seed number per panicle was reduced compared with the control. There was no impact from mixing at Darkan, except for the increased seed number per square meter and seed number per panicle in 2019.

Soil inversion reduced *B. diandrus* density and panicle production at Yerecoin from 2019 to 2021 (Table 6). The number of seeds per square meter decreased in 2020 but not seeds per panicle. In 2021, seeds per panicle and seeds per square meter were universally low, again due to the use of a glyphosate-tolerant canola crop. Likewise, at Darkan, weed density in 2019 was low in all treatments. In 2020 and 2021, the soil inversion treatments reduced plant and panicle density and seeds per square meter. The number of seeds per panicle at Yerecoin was not affected by treatment each year. At Darkan, seeds per panicle after soil inversion were not affected in 2019, increased in 2020, and were reduced in 2021.

Soil loosening had no impact on *B. diandrus*. Soil mixing in 2019 reduced plant and panicle density at Yerecoin compared with the control, but there was no difference in 2020 and 2021. In Darkan 2020, soil mixing increased seed production per panicle; in 2021, soil mixing plots had increased plant density compared with the control.

The second hypothesis was partially supported, as soil inversion reduced weed emergence due to seed burial compared with other treatments. However, soil loosening or mixing did not stimulate emergence due to shallow burial. These strategic tillage implements had small and inconsistent impacts on weed density and seed production at both sites, even in 2019, when the treatments were applied. Strategic tillage was performed before seeding at both sites, with the knifepoint seeding system causing additional soil disturbance. If the soil loosening or mixing event occurred in spring or over the summer fallow (i.e., in a system where strategic tillage is not followed by sowing of winter grain crops), this may have stimulated weed emergence due to soil disturbance (Roberts and Potter 1980). However, seed burial and soil movement are related to soil conditions and moisture, which are likely different over the summer fallow (Mia et al. 2023).

Reductions in weed density following soil inversion varied between species. *Lolium rigidum* had a density of less than 1 plant m^{-2} at 3 yr after soil inversion at both sites. This species has limited emergence beyond a depth of 5 cm (Chauhan et al. 2006). By comparison, *B. diandrus* seeds can emerge from depths of 10 to 20 cm, with the greatest emergence at 2 to 5 cm (Harradine 1986). While *B. diandrus* density was reduced by soil inversion in 2019, emergence in subsequent years was greater than that of *L. rigidum* (4 *B. diandrus* plants m^{-2} in Yerecoin 2020 and 147 m^{-2} in Darkan 2021).

Inversion also caused a reduction in *L. rigidum* seed number per panicle compared with the control treatment. Conversely, the seed number per panicle for *B. diandrus* plants in the soil inversion plots was similar to that of the control, except in Darkan 2021. There are multiple potential reasons for *L. rigidum* to have reduced seed number per panicle following an inversion. First, a seed at depth likely uses more resources in the preemergence growth phase to reach the soil surface than a seed near the soil surface. Therefore, it is possible that seedlings of *L. rigidum* incurred a fitness penalty when they emerged from depth in the soil inversion plots, which did not affect the larger *B. diandrus* seedlings to the same extent. Arnott (1969) noted that the weight of perennial ryegrass (*Lolium perenne* L.) seedlings and leaf and tiller production rate decreased in direct response to an increased seeding depth from 1.25 cm to 7.5 cm. Dastgheib and Poole (2010) found that growth of *B. diandrus* and soft brome (*Bromus hordeaceus* L.) seedlings emerging from 1 to 5 cm was comparable, while seedlings emerging from 10 cm were less vigorous. This implies that *Bromus* spp. may be less affected by emergence depth compared with *Lolium* spp., potentially due to differences in seed size (Arnott 1969). Second, the crop in the soil inversion plots was more competitive (higher yielding) than the control treatments (Collins et al. 2021). *Lolium rigidum* seed production per panicle may have been reduced by the increased crop competitiveness, as this species is more susceptible to crop competition than *B. diandrus* (Borger et al. 2021b; Lemerle et al. 1995). Thirdly, strategic deep-tillage practices, particularly inversion and mixing, modify the soil environment. This can impact the efficacy of soil-applied

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Table 5. *Lolium rigidum* plant density, panicle density, seed number per square meter, and seed number per panicle at each site, in response to varying methods of strategic deep tillage.[a]

Site	Strategic tillage	Plant density			Panicle number			Seed number					
		2019	2020	2021	2019	2020	2021[b]	2019[c]	2020	2021[b]	2019[c]	2020	2021[b]
		m^{-2}									panicle^{-1}		
Yerecoin	Control	54 (7.3)	27 (5.2)	45 (6.8)	88 (9.4)	46	2 (1.3)	—	3685	5 (2.3)	—	85	5
	Inversion	0 (0.0)	0 (0.7)	0 (0.4)	1 (1.1)	0	0 (0.0)	—	0	0 (0.0)	—	11	0
	Loosening	86 (9.3)	41 (6.4)	40 (6.4)	131 (11.4)	59	4 (1.9)	—	4833	13 (3.7)	—	83	4
	Mixing	27 (5.2)	15 (3.9)	44 (6.6)	88 (9.4)	30	2 (1.2)	—	2984	0 (0.6)	—	91	2
P		<0.001	<0.001	0.003	<0.001	0.008	0.043	—	0.02	0.037	—	<0.001	0.011
LSD		1.8	2.0	3.4	2.1	31.7	1.3	—	2939.0	2.6	—	26.2	2.8
Data transformation		Square root	Square root	Square root	Square root	None	Square root	—	None	Square root	—	None	None
Darkan	Control	4	5 (2.2)	14 (3.8)	3	14 (3.7)	0	66	1529 (39.1)	0	12	113	0
	Inversion	0	0 (0.7)	0 (0.9)	0	0 (0.5)	0	0	18 (4.2)	0	0	52	0
	Loosening	5	4 (2.1)	26 (5.1)	3	22 (4.7)	0	86	2621 (51.2)	0	22	116	0
	Mixing	6	7 (2.6)	26 (5.1)	4	20 (4.4)	0	264	2246 (47.4)	0	35	106	0
P		0.003	0.01	0.014	0.003	0.001	0	0.03	0.002	0	0.005	<0.001	0
LSD		2.9	1.1	2.7	1.9	1.9	—	171.8	22.5	—	17.7	24.5	—
Data transformation		None	Square root	Square root	None	Square root	—	None	Square root	—	None	None	—

[a]P-values and LSD are included for the separation of means. Where a data transformation was performed, means were back-transformed, but transformed means are presented in parentheses, and these transformed means should be considered in relation to the LSD value.
[b]At Darkan in 2021, the panicle and seed numbers were zero in all treatments.
[c]At Yerecoin in 2019, the seed number was not assessed.

Table 6. *Bromus diandrus* plant density, panicle density, seed number per square meter, and seed number per panicle at each site, subjected to varying methods of strategic tillage.[a]

Site	Strategic tillage	Plant density			Panicle number			Seed number					
		2019	2020	2021	2019	2020	2021	2019[b]	2020	2021	2019[b]	2020	2021
		m^{-2}									panicle^{-1}		
Yerecoin	Control	13 (3.6)	60 (7.8)	10 (3.1)	13 (3.6)	64 (8.0)	20 (4.4)	—	901 (9.7)	6 (2.5)	—	23	2
	Inversion	0 (0.0)	4 (1.9)	0 (0.6)	0 (0.2)	4 (2.0)	0 (0.3)	—	61 (3.9)	0 (0.0)	—	20	0
	Loosening	13 (3.7)	120 (11.0)	23 (4.8)	17 (4.1)	116 (10.8)	31 (5.6)	—	1462 (11.4)	12 (3.5)	—	20	2
	Mixing	1 (0.8)	37 (6.1)	3 (1.6)	2 (1.3)	25 (5.0)	8 (2.8)	—	407 (7.4)	8 (2.8)	—	20	2
P		0.016	0.002	0.011	<0.001	0.016	0.015	—	0.012	0.538	—	0.890	0.250
LSD		2.6	3.9	2.4	1.6	5.3	3.1	—	4.3	5.3	—	11.4	2.3
Data transformation		Square root	Square root	Square root	Square root	Square root	Square root	—	Cube root	Square root	—	None	None
Darkan	Control	2 (1.5)	17 (2.6)	492 (22.2)	2 (1.2)	43 (3.5)	5 (2.3)	31 (5.6)	4468 (16.5)	74 (8.6)	22	104	9
	Inversion	1 (1.1)	1 (1.0)	147 (12.1)	1 (0.8)	3 (1.5)	0 (0.6)	9 (2.9)	422 (7.5)	7 (2.6)	21	141	4
	Loosening	2 (1.5)	13 (2.4)	540 (23.2)	1 (1.2)	54 (3.8)	3 (1.6)	33 (5.7)	6179 (18.4)	27 (5.2)	21	116	8
	Mixing	2 (1.5)	22 (2.8)	755 (27.5)	2 (1.3)	73 (4.2)	9 (3.0)	39 (6.3)	8640 (20.3)	149 (12.2)	22	119	13
P		0.703	<0.001	<0.001	0.755	<0.001	0.003	0.553	<0.001	0.014	0.954	0.003	0.019
LSD		0.9	0.7	5.1	1.1	0.8	1.1	5.3	4.0	5.6	5.2	17.2	5.1
Data transformation		Square root	Cube root	Square root	Square root	Cube root	Square root	Square root	Cube root	Square root	None	None	None

[a]P-values and LSD are included for the separation of means. Where a data transformation was performed, means were back-transformed, but transformed means are presented in parentheses, and these transformed means should be considered in relation to the LSD value.
[b]At Yerecoin in 2019, the seed number was not assessed.

Table 7. *Lolium rigidum* plant density in the field or predicted by the model in each year at each site, following varying methods of strategic tillage.

Site	Strategic tillage	Plant density[a]								
		2019			2020			2021		
		Field	Model	Absolute error	Field	Model	Absolute error	Field	Model	Absolute error
		m^{-2}								
Yerecoin	Control	53.9	69.3	15.4	26.9	25.5	1.4	45.5	0.0	45.5
	Inversion	0.0	0.8	0.8	0.5	0.1	0.4	0.2	0.1	0.1
	Loosening	85.8	4.0	81.8	41.4	5.3	36.1	40.5	0.9	39.6
	Mixing	27.0	2.4	24.6	15.3	0.8	14.5	44.0	0.1	43.9
Darkan	Control	4.2	25.8	21.6	5.0	2.5	2.5	14.3	105.5	91.2
	Inversion	0.1	0.4	0.3	0.5	0.0	0.5	0.8	1.7	1.0
	Loosening	4.9	7.2	2.3	4.3	0.5	3.8	26.3	22.0	4.3
	Mixing	6.0	3.2	2.8	6.8	0.2	6.6	25.9	11.6	14.3
MAE				18.7			8.2			30.0

[a]The absolute error between the field and model values and the mean absolute error (MAE) are included for comparison.

herbicides to the extent that they can cause greater crop damage (Edwards et al. 2023). Increased herbicide efficacy could be a factor in ongoing control of weeds on inverted and mixed soils but may also impact weed performance, including panicle size and weed seed production.

Prior studies have indicated that a full soil inversion is effective for *L. rigidum* control but less so for *B. diandrus* control. Douglas and Peltzer (2004) found a 95% reduction in *L. rigidum* density during the two seasons following soil inversion at two sites in southern Western Australia. In Nebraska, USA, Kettler et al. (2000) observed a 97% reduction in cheatgrass (*Bromus tectorum* L.) density in the crop following soil inversion to 15 cm (in a silt loam soil) in the first year, but by the third wheat (*Triticum aestivum* L.) crop after the inversion, the decrease in weed density compared with the conservation tillage control plots had fallen to 41%. The authors assumed that *B. tectorum* seeds were reintroduced to the plots from neighboring plots, potentially by wind or granivorous species. However, as an alternative to seed being reintroduced via dispersal, it is possible that this species can emerge from 15-cm depth, as is known for *B. diandrus* (Dastgheib and Poole 2010; Harradine 1986). Therefore, the buried seeds may have gradually reinfested the soil inversion plots. Our study showed that while soil inversion was effective in controlling *L. rigidum*, it was less successful in controlling *B. diandrus*. Although it is possible that *B. diandrus* seeds from neighboring plots were reintroduced to the inversion plots in the current study, it is unlikely, as *L. rigidum* seeds were not transported between plots during the experiments. Further research is necessary to understand the emergence of *B. diandrus* from various soil types, but this species' ability to emerge from depth probably contributes to its ability to reinfest agricultural systems after soil inversion. Kettler et al. (2000) and our study employed regionally appropriate herbicides to control weeds. Yet the density of the *Bromus* species increased regardless (until the use of a glyphosate-tolerant crop in 2021 reduced plant density at Yerecoin and seed production at both sites). Further investigation is required to optimize and increase the longevity of effective *B. diandrus* control following soil inversion. For example, the current study did not use a time-series analysis; first, because seed production was not assessed at Yerecoin in 2019; second, because the considerable differences between years would obscure differences between means in years with low weed density; and third, because the aim was to examine the agronomic response, that is, weed growth in the presence of herbicides, rather than the maximum weed growth that could be achieved. A long-term assessment of weed recovery in the absence of herbicides can assist in identifying the value of amelioration as a weed control technique.

Weed Density and Seed Production Estimated by the Weed Seed Wizard Model

In the control treatment, the model gave a reasonable approximation of *L. rigidum* density at both sites in 2019 and 2020, although the model predictions of plant density were less accurate in 2021 (absolute error of 45.5 at Yerecoin and 91.2 at Darkan; Table 7). The model underestimated *L. rigidum* seed production in the control at Yerecoin during 2019 and 2020 and Darkan during 2020. At Yerecoin in 2021, the estimation was comparable to the field data but underestimated *L. rigidum* in 2019 and 2020 (Table 8).

In the inversion treatment, the model's prediction was close to the actual *L. rigidum* density and seed production at both sites (absolute error of 0 to 1.0 for plant density and 0 to 25 for seed production; Tables 7 and 8). In the loosening and mixing treatments, the model's plant density and seed production predictions were less accurate at Yerecoin across all years (high absolute error). At Darkan, the model results for soil loosening and mixing were comparable to the field density of *L. rigidum*. The model results for seed production were similar to field results, except for the underestimation of seed production in 2020 (Table 8).

In the control treatments at both sites, the model reasonably estimated *B. diandrus* density in all years (a low absolute error; Table 9). However, in 2021, the model slightly overestimated Yerecoin density and underestimated Darkan density. By comparison, the model overestimated *B. diandrus* seed production in 2019 and underestimated it in 2020 at both sites (Table 10). In the inversion treatments, the model gave reasonable estimations of plant density at both sites, although it underestimated *B. diandrus* density at Darkan in 2021. Similarity estimations of seed production were similar to the field values at both sites, except for Darkan 2020.

Estimations of *B. diandrus* plant density by the model following loosening or mixing were more variable than for the soil inversion treatment. At both sites, the model gave reasonable estimations of plant density following loosening or mixing in 2019. However, the model predictions were less accurate for the loosening treatment at Yerecoin in 2020 and both treatments at Darkan in 2021.

Table 8. *Lolium rigidum* seed number in the field or predicted by the model in each year at each site, following varying methods of strategic tillage.

		Seed number[a]								
		2019			2020			2021		
Site	Strategic tillage	Field[b]	Model	Absolute error	Field	Model	Absolute error	Field	Model	Absolute error
		m^{-2}								
Yerecoin	Control	7,878	3,538	4,340	3,685	64	3,622	5	18	13
	Inversion	55	30	25	0	3	3	0	0	0
	Loosening	11,513	139	11,374	4,833	54	4,779	13	0	13
	Mixing	8,495	99	8,396	2,984	24	2,960	0	0	0
Darkan	Control	66	1,631	1,565	1,529	44	1,485	0	219	219
	Inversion	0	19	19	18	0	18	0	8	8
	Loosening	86	234	148	2,621	15	2,606	0	68	68
	Mixing	264	125	139	2,246	6	2,240	0	39	39
MAE				3,251			2,214			45

[a]The absolute error between the field and model values and the mean absolute error (MAE) are included for comparison.
[b]Note that field seed production was not assessed for Yerecoin in 2019, so data for use in the model were estimated from panicle number and 2020–2021 seed production, as discussed in "Materials and Methods."

Table 9. *Bromus diandrus* plant density in the field or predicted by the model in each year at each site, following varying methods of strategic tillage.

		Plant density[a]								
		2019			2020			2021		
Site	Strategic tillage	Field	Model	Absolute error	Field	Model	Absolute error	Field	Model	Absolute error
		m^{-2}								
Yerecoin	Control	12.7	17.5	4.8	60.2	35.6	24.6	10.0	41.6	31.6
	Inversion	0.0	0.9	0.9	3.7	1.0	2.7	0.3	0.3	0.0
	Loosening	13.4	7.7	5.7	120.3	49.1	71.2	23.2	5.4	17.8
	Mixing	0.6	9.6	9.0	37.2	11.0	26.2	2.6	3.2	0.6
Darkan	Control	2.2	8.7	6.5	16.9	28.9	12.0	491.5	183.5	308.0
	Inversion	1.1	0.5	0.6	1.0	0.4	0.6	146.7	5.5	141.2
	Loosening	2.3	5.0	2.8	13.2	5.3	7.9	540.1	82.7	457.4
	Mixing	2.3	5.6	3.4	22.0	4.2	17.8	754.6	61.6	693.0
MAE				4.2			20.4			206.2

[a]The absolute error between the field and model values and the mean absolute error (MAE) are included for comparison.

Table 10. *Bromus diandrus* seed number in the field or predicted by the model in each year at each site, following varying methods of strategic tillage.

		Seed number[a]								
		2019			2020			2021		
Site	Strategic tillage	Field	Model	Absolute error	Field	Model	Absolute error	Field	Model	Absolute error
		m^{-2}								
Yerecoin	Control	462	2,060	1,598	901	36	865	6	3	3
	Inversion	0	57	57	61	35	26	0	0	0
	Loosening	508	366	142	1462	525	937	12	0	12
	Mixing	78	518	440	407	222	185	8	0	8
Darkan	Control	31	1,006	975	4468	661	3,807	74	584	510
	Inversion	9	39	30	422	21	401	7	29	22
	Loosening	33	314	281	6179	306	5,873	27	345	318
	Mixing	39	399	360	8640	241	8,399	149	274	125
MAE				485			2,562			125

[a]The absolute error between the field and model values and the mean absolute error (MAE) are included for comparison.

Similarly, estimates of *B. diandrus* seed production following loosening or mixing were accurate in 2019 and 2021, but seed production was underestimated in 2020 at both sites.

The model demonstrated reasonable accuracy in predicting the impact of soil strategic tillage. The MAE for *B. diandrus* actual and estimated seed production ranged from 125 to 2,562 across years, which was lower than the MAE of *B. diandrus* seed production of 4,250 and 6,551 found in Borger et al. (2021a). This confirms that the model output for this strategic deep-tillage use pattern is more accurate than instances in which the model has considered standard crop rotations (Borger et al. 2021a). For *L. rigidum* seed production, the MAE ranged from 45 to 3,251, often higher than

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the MAE of 47 (root-mean-square error of 68.6) found for *L. rigidum* seed production predicted by Borger et al. (2018). The studies by Borger et al. (2018, 2021a) compared seed production in the field and model but did not compare plant density, as was done here. In the current study, the weed density and seed production estimation after a full soil inversion was the most accurate (lowest MAE), likely due to low weed density and seed set following inversion. Results from the model were more variable for soil loosening and mixing, consistent with the variation observed in the field results after applying these strategic tillage techniques. Our results demonstrate that the Weed Seed Wizard can be valuable in developing integrated weed management strategies for various weed and crop species in the rotations following a strategic tillage event, mainly when using a soil inversion.

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