Weed Science

www.cambridge.org/wsc

Ameliorating soil acidity–reduced growth of rigid ryegrass (*Lolium rigidum*) in wheat

Catherine P. D. Borger[1], Gaus Azam[1], Chris Gazey[2], Andrew van Burgel[3] and Craig A. Scanlan[1]

[1]Research Scientist, Department of Primary Industries and Regional Development, Northam, Western Australia, Australia; [2]Portfolio Manager, Department of Primary Industries and Regional Development, Northam, Western Australia, Australia; and [3]Biometrician, Department of Primary Industries and Regional Development, Albany, Western Australia, Australia

Research Article

Cite this article: Borger CPD, Azam G, Gazey C, van Burgel A, Scanlan CA (2020) Ameliorating soil acidity–reduced growth of rigid ryegrass (*Lolium rigidum*) in wheat. Weed Sci. **68**: 426–433. doi: 10.1017/wsc.2020.38

Received: 18 December 2019
Revised: 9 April 2020
Accepted: 3 May 2020
First published online: 12 May 2020

Associate Editor:
Bhagirath Chauhan, The University of Queensland

Keywords:
Amelioration; annual ryegrass; crop competition; incorporation; lime; soil renovation; weed

Author for correspondence:
Catherine Borger, Department of Primary Industries and Regional Development,
P.O. Box 483, Northam, WA 6401, Australia.
(Email: catherine.borger@dpird.wa.gov.au)

Abstract

Estimates indicate that 30% of land surface globally is affected by soil acidity, influencing agricultural production. Application of lime increases soil pH and improves crop growth. We tested the hypothesis that liming will reduce rigid ryegrass (*Lolium rigidum* Gaudin) growth by improving the competitive ability of the crop. Experiments at Merredin and Wongan Hills in Western Australia indicated that application of lime in previous years reduced *L. rigidum* density, biomass, and seed production in wheat (*Triticum aestivum* L.) crops in 2018. At Merredin, *L. rigidum* seed production in 2018 was reduced from 9,390 to 2,820 seeds m^{-2}, and wheat tiller number and yield was increased, following lime application of 0 to 6,000 kg ha^{-1} in 2016. At Wongan Hills, lime application of 4,000 kg ha^{-1} in 1994 reduced seed production in the 2018 wheat crop from 4,708 to 1,610 seeds m^{-2}, and application of 3,000 kg ha^{-1} of lime in 2014 reduced seed production from 3,959 to 921 seeds m^{-2} in 2018. Again, lime increased wheat tiller number, but not yield. A screen house experiment (in controlled conditions) indicated that lime application increased the initial growth of both *L. rigidum* and wheat seedlings. This supports the conclusion that reduced *L. rigidum* growth and seed production in the field resulted from increased competitive ability of the crop, rather than any direct and detrimental impact of lime on *L. rigidum* growth. Incorporation of lime reduced initial emergence of *L. rigidum* in controlled conditions, with *L. rigidum* seeds at a uniform depth, and in the field experiments in situations of high weed density, with seeds buried by the incorporation process. Nationally, the revenue loss from residual *L. rigidum* in crop is A$93 million per year. The current research confirms that application of lime will increase the competitive ability of crops growing in regions with acidic soils.

Introduction

Use of synthetic nitrogenous fertilizers has improved crop yield but has also resulted in soil acidification, that is, reduced soil pH below 5.5 in the surface horizons of 0 to 20 cm (Li et al. 2019). Estimates suggest that 30% of global land surface is affected by acidity (Dai et al. 2017). Soil acidity reduces plant growth by increasing the availability of toxic mineral elements, including aluminum and ferric iron, and decreasing availability of essential elements like calcium, magnesium, phosphorus, sulfur, molybdenum, and nitrogen (Li et al. 2019; Moore 2001; Sumner and Noble 2003). Application of lime is the most commonly used management practice to increase soil pH and improve crop production in acidic soils (Li et al. 2019; Moore 2001). Increasing pH can significantly increase yield of most crops grown in Western Australia, including wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), canola (*Brassica napus* L.), legume species, and pasture legume species (Li et al. 2019; Moore 2001). The prevalence of soil acidity and interaction of soil amelioration with other aspects of agronomic management is a significant issue for grain production. The interactions between soil pH and nutrient supply are relatively well understood (Slattery et al. 1999). There has also been research into the relationship of liming and herbicide application (Aladesanwa and Akinbobola 2008; Hashem and Borger 2018). However there has been limited investigation into the interactions of pH, soil amelioration (such as lime application or incorporation), and weed management.

The most prominent weed in Australia is rigid ryegrass (*Lolium rigidum* Gaudin) (D'Emden and Llewellyn 2006; Llewellyn et al. 2016). Growth of this species is favored by widespread herbicide resistance and adoption of conservation tillage (D'Emden and Llewellyn 2006). Conservation tillage has less soil disturbance, reducing physical weed control and the effectiveness of PRE herbicides that require soil incorporation (D'Emden and Llewellyn 2006). Liming may influence the growth of this weed, although the soil pH preference of *L. rigidum* is unknown. Application of lime to acidic soils increased the dry biomass production of other

Table 1. The pH and aluminum (Al) of the A1 and B1 horizon in the non-incorporated pots and in the single horizon in the incorporated pots, as well as dry biomass of the wheat and *Lolium rigidum* shoots and roots, and plant density, averaged over the incorporated and non-incorporated treatments, at varying rates of lime (0 to 2,000 kg ha^{-1}).[a]

Incorporation treatment or species	Measurement	Lime					SEM	LSD	P
		0	500	1,000	1,500	2,000			
		kg ha^{-1}							
No incorporation	pH_{CaCl2}: A1	5.0	6.5	6.8	7.1	7.0	0.1	0.2	<0.001
	pH_{CaCl2}: B1	3.9	3.9	3.9	3.9	3.9	0.02	0.05	0.517
	Al (mg kg^{-1}): A1	0.8	0.4	0.2	0.3	0.5	0.1	0.3	0.018
	Al (mg kg^{-1}): B1	19.5	18.4	16.6	18.4	19.9	1.1	2.6	0.784
Incorporation	pH_{CaCl2}	4.2	4.8	5.2	5.8	6.6	0.2	0.5	<0.001
	Al (mg kg^{-1})	4.6	0.7	0.6	0.4	0.2	0.2	0.5	<0.001
Wheat	Shoot weight (g)	0.405	0.393	0.473	0.672	0.623	0.06	0.17	<0.001
	Root weight (g)	0.444	0.479	0.633	0.739	0.733	0.06	0.19	<0.001
	Density (plants pot^{-1})	5.0	4.8	4.8	4.8	5.0	0.13	0.38	0.736
L. rigidum	Shoot weight (g)	0.012	0.008	0.018	0.019	0.017	0.003	0.009	0.039
	Root weight (g)	0.010	0.009	0.018	0.019	0.019	0.003	0.008	0.004
	Density (plants pot^{-1})	3.5	3.3	3.7	3.5	3.0	0.507	1.507	0.907

[a] The P-values indicate the significance of the linear contrast of the lime treatment, or the significance of the lime treatment in the case of plant density, with standard error of the mean (SEM) and LSD.

Lolium species, including Italian ryegrass [*Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot 'Aristocrat') and perennial *L. perenne* (Bolland et al. 2001; Meharg and Killham 1990). By comparison, applying lime to a subterranean clover (*Trifolium subterraneum* L.) and *L. rigidum* pasture on acidic soil did not increase *L. rigidum* biomass (Hochman et al. 1990). However, increasing soil pH increases wheat growth, and a competitive crop is a highly effective weed control tactic (Lemerle et al. 1995; Li et al. 2019). *Lolium rigidum* has been shown to be highly sensitive to crop competition (Borger et al. 2016a, 2016b). Preliminary research indicated that lime application and subsequent increase in soil pH would reduce weed growth (Gazey and Andrew 2010; Hashem and Borger 2018).

Incorporation of lime may also affect weed growth. An international review of liming experiments indicated that the application method of lime (surface, plow, subsoiling) did not affect the change in soil pH achieved through liming, although the review did not specifically consider varying soil depths (Li et al. 2019). Rainfall can be low in Australian agricultural areas, and both field and pot studies indicate that in weathered soils, lime will not move farther than 2.5 cm through the soil profile without incorporation (Nunes et al. 2019). Lime incorporation through cultivation will bury weed seed, changing the emergence patterns of the weed in subsequent seasons (Chauhan et al. 2006a). While the impact of changes to the vertical distribution of weed seed in the soil are not well understood, seedling recruitment is usually increased if seed is buried near the soil surface and decreased where seed is buried at depth (Chauhan et al. 2006a). Soil amelioration to incorporate lime is done with a wide range of implements, but aims to disrupt soil to a depth of at least 10 to 20 cm and up to 60 to 70 cm depending on soil type (Pluske et al. 2017). It is likely that cultivation to depth to incorporate lime will bury a proportion of weed seed too deeply for emergence, reducing seedling recruitment in subsequent years.

There is little research on soil acidity and crop–weed competition or the impact of incorporation of lime (through cultivation) on *L. rigidum* growth. We tested the hypotheses that (1) application of lime would increase the initial growth of *L. rigidum* and wheat (before the impact of crop weed competition), (2) application of lime to acidic soils would reduce biomass and seed production of *L. rigidum* within a wheat crop due to improved competitive ability of the crop, and (3) incorporation of lime would not affect recruitment of *L. rigidum* seeds in a pot experiment at a uniform depth but would reduce seedling recruitment in the field. These hypotheses were tested through field experiments examining the long-term impact of lime application and incorporation on *L. rigidum* density, biomass, and seed production in wheat crops, and a pot experiment under controlled conditions that examined the impact of lime application and incorporation on early growth of *L. rigidum* seedlings in a wheat crop.

Materials and Methods

Screen House Experiment

A pot experiment was established with treatments of lime at 0, 500, 1,000, 1,500, and 2,000 kg ha^{-1}, on the surface of the soil or fully incorporated, in a randomized block design with three replications. Lime rates were low compared with rates used in the field, because meta-analysis indicated that the overall effect of liming on soil pH was 36% greater in pot conditions than in the field (Li et al. 2019). Soil for the experiment (Yellow orthic acidic Tenosol soil, naturally acidic to a depth of over 1 m; Isbell 2016), was obtained from the Department of Primary Industries and Regional Development Merredin Research Station (31.482°S, 118.215°E). Soil was collected on August 31, 2018, from the A1 horizon (0 to 10 cm; see Table 1 for soil properties) and B1 horizon (20 to 40 cm). The A2 horizon (10 to 20 cm) was removed, because it is very thin in this soil type and could not be collected in bulk without significant contamination from the other soil horizons. On September 3, 2018, soil was sieved to 4 mm to remove crop residue and rocks while retaining soil microaggregates (Augé et al. 2001) For the non-incorporated treatment, pots of 2.5-kg capacity (20-cm height) were lined with paper towel and filled with 2 kg of soil from the B1 horizon and 0.5 kg of soil from A1 layered on top to artificially create the separate horizons. Lime (neutralizing value of 94.9%, 99.2% particles <0.5mm) was manually spread on the surface. For the incorporated treatments, soil from the A1 and B1 horizon and lime at the various rates were mixed in a rotary mixer and 2.5 kg of the resulting soil was placed in each pot. All pots were packed to a bulk density of 1.5 g cm^{-3}, as this was the average bulk density of the soil in the Merredin experiment discussed later. The soil was allowed to absorb water through capillary action (to avoid soil compaction resulting from overhead watering), by placing pots in trays containing 4 cm of water for 3 h. Fifteen holes of 3-mm width were punched in the soil of each pot. Five seeds of wheat (‘Mace’) were sown at 2-cm depth (i.e., 60 kg ha^{-1} of wheat), five seeds of *L. rigidum* at 0.5-cm depth (i.e., 200 plants m^{-2}), and fertilizer (80 kg ha^{-1} K-Start10 Trace, 12.0 N:13.1 P:10.0 K:3.0 S:0.1 Cu:0.2 Zn w/w%, bulk density 1.1, Landmark, 16 Yilgarn Avenue, Northam, WA 6401, Australia) was placed in the final five holes at 4-cm depth. Pots were maintained on benches in a screen house and natural rainfall was supplemented with 6 mm of irrigated water every 3 d.

Plant density was assessed on October 4, 2018, when plants reached the 2- to 4-leaf stage. A single soil sample was taken from the pots with incorporated soil and two soil samples (from the A1 and B2 horizon) were taken from the pots with no incorporation. Soil samples were used to assess pH_{CaCl2} and extractable aluminum (Bromfield 1987; Rayment and Lyons 2011). Bulk root and shoot biomass of wheat and *L. rigidum* were harvested from each pot by washing away the remaining soil. The plant material was dried at 60 C for 3 d and weighed to determine dry biomass.

An exponential model was fit to the pH-extractable aluminum concentration data using Genstat (VSN International 2019). A linear model was used to compare wheat root or shoot dry biomass with that of *L. rigidum*. An ANOVA was used to assess lime rate, incorporation, and the interaction between these treatment factors on pH, aluminum, plant density, and dry root and shoot biomass. Residual plots indicated the data were normally distributed. A linear contrast was applied to the lime factor, and means are presented with standard errors of the means (SEMs). Fisher’s protected LSD was used to compare means (with significance at 0.05).

Merredin Experiment

A field experiment was conducted from 2016 to 2018 at the Merredin Research Station. The site was adjacent to the area used to collect soil for the screen house experiment, with the same soil type. The experiment was a split-split-plot design with four replicates and a plot size of 20 m by 1.54 m. The main plot factor was crop rotation; continuous wheat (2016 to 2018) or wheat–chemical fallow rotation (i.e., wheat in 2016, chemical fallow in 2017, and wheat in 2018). The subplot factor was cultivation (before seeding in 2016) to incorporate lime with offset disks to a depth of 15 cm; with soil testing to confirm that cultivation reached 15 cm. The lime (neutralizing value of 90.0%, 99.0% particles <0.6mm) at 0, 2,000, 4,000, or 6,000 kg ha^{-1} was sub-subplot factor, applied directly before cultivation in 2016.

In each year wheat (Mace) was sown at 60 kg ha^{-1}, with 22-cm row spacing, at a depth of 3 cm, using a no-tillage seeding system (knife points and press wheels), with 60 kg ha^{-1} of fertilizer (Agras, 16.1:9.1:14.3:0.5:0.06% N:P:S:Ca:Zn, CSBP, Goldfields Rd, Merredin, WA 6415, Australia) banded 4 cm below the seed. The fallow was maintained by spraying a nonselective, nonresidual herbicide (paraquat/diquat, 270/230 g ai ha^{-1}, Spray. Seed®, 135/115 g ai L^{-1}, SL, Syngenta, North Ryde, NSW, Australia) as required to ensure no weed growth. In 2018, sowing was on June 1, 2018, directly after application of paraquat/diquat (270/230 g ai ha^{-1}), pyroxasulfone (102 g ai ha^{-1}; Sakura® 850WG, 850 g ai kg^{-1}, WG, Bayer Crop Science, Bentley, WA, Australia), and trifluralin (480 g ai ha^{-1}; Trifluralin, 480 g ai L^{-1}, EC, Nufarm, Kwinana Beach, WA, Australia). Nitrogen fertilizer (Flexi-N, 32% N, CSBP) was applied at 50 L ha^{-1} on July 27, 2018 and harvest occurred on December 3, 2018.

Lolium rigidum and wheat density were assessed on July 12, 2018, from two 50 by 50 cm quadrats per plot (i.e., two 50-cm rows of wheat per quadrat). On October 10, 2018, wheat tillers were counted in two quadrats of 50 by 50 cm, and then *L. rigidum* biomass was harvested from the same quadrats by cutting plants off at ground level. Biomass samples were dried at 60 C for 3 d and weighed, and the entire sample was threshed. A subsample of approximately 5 g was taken from each sample to count *L. rigidum* seeds, and seed number per subsample was used to determine seed production per meter. Wheat grain yield was assessed by harvesting the entire plot. A subsample was taken from each plot and used to assess clean yield (with 2-mm sieves used to remove chaff and screenings).

The continuous wheat and wheat–fallow rotations were analyzed separately because of an order of magnitude difference in mean and variability of *L. rigidum* density, biomass, and seed production. Differences between rotations were examined based on whole-plot results and analyzed by *t*-test allowing for unequal variances (VSN International 2019). For wheat density, tillers, and yield, a paired *t*-test was used, as the variances were similar between rotations. The ANOVA applied to the separate crop rotation data sets used incorporation as the main plot factor and lime as the subplot factor. The variates included *L. rigidum* density, biomass, seed production, and crop density, tiller number, and yield. A linear contrast was applied to the lime factor. All means are presented with SEMs, and LSDs (0.05) are presented to separate the means. Residual plots indicated that the *L. rigidum* density, biomass, and seed production variates were not normally distributed, and a square- or cube-root transformation was performed, with data presented as back-transformed means. A complication of back-transforming is that the LSD values on the original scale vary depending on which treatments are being compared, and so in situations of more than two treatment factors, an LSD range was calculated. The LSD from the ANOVA was subtracted from the largest mean ($x_1 - \text{LSD} = a$) and added to the smallest mean ($x_2 + \text{LSD} = b$) before transformation. Following back-transformation of these two values (a and b) and the means (x_1 and x_2), the difference between the largest mean and value a or the smallest mean and value b are presented as the maximum and minimum LSD values. To apply this LSD range, the minimum LSD value is relevant for comparisons to the smallest means and the maximum LSD for comparisons to the largest means. In a similar way the SEM from the ANOVA was added and subtracted to each mean before transformation, and then the SEM was calculated as the average of the lower and upper SEMs. While the SEM from the ANOVA is a single pooled estimate, the back-transformation process results in different SEM values for the various factor levels of each treatment.

Wongan Hills Experiment

The Wongan Hills experiment was established in 1994, also on a Yellow orthic acidic Tenosol soil (30.854°S, 116.741°E) (Isbell 2016). Soil pH_{CaCl} was 5.0 at 0 to 10 cm and 4.2 at 10 to 30 cm. At the same depths, aluminum concentration was <1.0 mg kg^{-1} and 7 mg kg^{-1}. This soil is not naturally acidic like the Merredin soil. Low pH values resulting from agricultural practices extend to a depth of 40 cm; the B2 horizon beyond 40 cm is not acidic. In 1994, the experiment was a completely randomized block design with four replications (paired plots of 1.8 m by 30 m), arranged in two banks of two blocks each. The treatment factor was lime (neutralizing value of 94.9%, 99.2% particles <0.5mm)

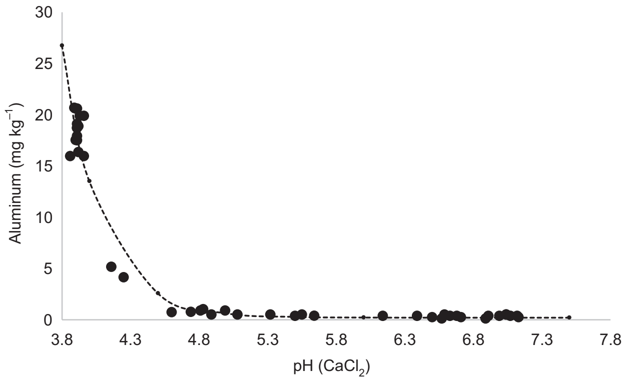

Figure 1. The pH and aluminum concentration in each pot. The dotted line indicates the exponential regression. $Al = 0.210 + 13004017e^{-3.448 * pH}$ ($R^2 = 97.1$, $P < 0.001$).

applied at 0, 500, 1,000, 2,000, and 4,000 kg ha^{-1}. In 1998, the design was changed to a split-plot design with four replications (single plots of 1.8 m by 30 m) by the addition of 0 or 1,500 kg ha^{-1} of lime to one of each pair of plots. In 2014, the design changed to a split-split-plot design with four replications (plots of 1.8 m by 15 m) by the addition of 0 or 3,000 kg ha^{-1} of lime to each plot. In 2018, each plot was split into three (plots of 1.8 m by 5 m) when a rotary hoe was run perpendicular to the original plots to incorporate lime to a depth of 0, 15, or 25 cm before seeding.

On May 29, 2018, wheat (Mace) was sown at 80 kg ha^{-1}, with 22-cm row spacing, at a depth of 3 cm, using a zero-tillage seeding system (coulters, knife points, and press wheels), with 80 kg ha^{-1} of fertilizer (Macro Pro Extra, 9.7:11.2:11.2:10.2:0.1:0.2% N:P:K:S:Cu:Zn, CSBP) banded 4 cm below the seed. Weeds were controlled over summer (i.e., in February), but no herbicide was applied at seeding due to dry conditions. Nitrogen fertilizer (Flexi-N, 32% N, CSBP) was applied at 50 L ha^{-1} on July 18, 2018, and harvest occurred on November 29, 2018. On June 29, 2018, crop density was assessed in two 50 by 50 cm quadrats per plot (i.e., two 50-cm lines of wheat per quadrat). Initial *L. rigidum* density was low (0 to 5 plants m^{-2}), but more *L. rigidum* cohorts emerged as the growing season progressed. On October 19, 2018, *L. rigidum* density and tillers were recorded in two 50 by 50 cm quadrats per plot, before harvesting *L. rigidum* biomass from the same quadrats. Note that crop and *L. rigidum* were not assessed in every plot; treatments of interest were those plots that had 0, 2,000, or 4,000 kg ha^{-1} of lime in 1994. *Lolium rigidum* samples were processed, and clean yield was determined as described for the Merredin field experiment. An additional 25% of the data were excluded from the analysis of crop yield because plots were impacted by wheel tracks. The single wheel track evident on some plots appeared after measurements of wheat and *L. rigidum* density were performed. The track only affected one row of wheat, and so wheat tillers and *L. rigidum* biomass measurements could still be taken from those plots. The 25% of affected plots were evenly spaced though the trial.

ANOVA was used to assess *L. rigidum* density, biomass, seed production, and crop yield variates with blocking and treatment structures used that matched the design (VSN International 2019). The main effect of tillage was assessed separately to account for the strips going across the experiment. Residual plots indicated that the *L. rigidum* plant density, biomass, and seed production data were not normally distributed, and a cube-root transformation was performed to improve the distribution. Back-transformed means, SEM, and LSD were determined using the process described for the Merredin field experiment.

Results and Discussion

Lime and Soil Incorporation in Controlled Conditions

Lime rates of 0 to 2,000 kg ha^{-1} increased soil pH from 4.2 to 6.6 in pots with full incorporation (Table 1). Pots with no incorporation had pH values of 5.0 to 7.0 in the A1 horizon, and a consistent pH of 3.9 in the B1 horizon. Extractable aluminum concentration increased rapidly once pH was below 4.3 (Table 1; Figure 1). As a result, aluminum concentration was only high in the B1 horizon of the non-incorporated pots, where pH remained consistently low (Table 1). These results supports the findings of Nunes et al. (2019) that incorporation is required to change soil pH at depth. Australian soils can be highly acidic to depths of 40 to 100 cm, naturally or due to agronomic practices (Isbell 2016). It is likely that tillage is required to change the pH at a depth beyond 0 to 20 cm, following application of lime (Nunes et al. 2019).

Increasing rates of lime increased the above- and belowground dry biomass of wheat and *L. rigidum*, with the biomass of *L. rigidum* roots or shoots increasing in those pots where biomass of wheat increased, but did not affect plant density (Table 1; Figure 2). This finding supports the hypothesis that the growth of *L. rigidum*, like that of wheat and *L. perenne*, is favored by increased soil pH (Bolland et al. 2001; Meharg and Killham 1990). In the current study, *L. rigidum* plants were deliberately grown in a simulated cropping system (to create an environment similar to that in the field) and then harvested at the seedling stage when the plants were too young for biomass to be affected by inter- or intraspecies competition. However, further research on plants grown to maturity is required to determine optimal pH requirements for *L. rigidum* and other common weeds. If optimal soil pH for weed species is not identical to that of crops, there may be scope to manipulate soil pH to reduce weed competitive ability.

The incorporation treatment significantly reduced *L. rigidum* density compared with the non-incorporated treatment (2.73 and 4.07 seedlings per pot, $P = 0.009$, $LSD = 0.95$), and also reduced dry weight of *L. rigidum* roots (0.0069g for incorporated and 0.0231 g for non-incorporated, $P < 0.001$, $LSD = 0.0051$) and shoots (0.0053 g for incorporated and 0.0245 g for non-incorporated, $P \leq 0.001$, $LSD = 0.0056$). By comparison, incorporation had no significant effect on wheat density compared with the non-incorporation treatment (average of 4.9 wheat seedlings per pot), but still reduced the dry weight of wheat roots (0.487g for incorporated and 0.724 g for non-incorporated, $P \leq 0.001$, $LSD = 0.121$) and shoots (0.442 g for incorporated and 0.584 g for non-incorporated, $P \leq 0.012$, $LSD = 0.106$). There were no significant interactions between lime and incorporation for plant density or biomass. The reduced biomass of *L. rigidum* shoots and roots may have resulted from reduced plant number or a combination of reduced plant number and reduced plant growth, as observed for the wheat seedlings. Because reduced growth of wheat and reduced emergence of *L. rigidum* were apparent in both the limed and unlimed pots, and there was no herbicide used in the screen house, the change to early wheat growth and *L. rigidum* emergence was potentially related to altered soil properties following incorporation. For example, the mixing (incorporation) process may have reduced soil aggregate size, which can influence emergence and root growth of some species (Braunack and Dexter 1989). We do not fully understand the interaction of incorporation and lime on weed emergence and early plant growth. Because plants were harvested early in this study, and *L. rigidum* seeds that failed to emerge were not retrieved and tested for viability, we did not determine whether seeds germinated and failed to

Table 2. The *Lolium rigidum* density, biomass, and seed production and wheat tillers and yield for the continuous wheat rotation compared with the wheat–fallow rotation at Merredin in 2018.[a]

Measurement	Continuous wheat	Wheat–fallow	P
L. rigidum density (plants m^{-2})	32.0 (9.1)	3.4 (0.8)	0.052
L. rigidum biomass (g m^{-2})	61.0 (13.5)	9.6 (1.3)	0.031
L. rigidum seeds (m^{-2})	6,901 (1,719)	1,393 (275)	0.047
Wheat tillers (m^{-2})	322	319	0.729
Wheat yield (kg ha^{-1})	2,820	3,160	0.039

[a] Means (and standard errors of the means [SEMs]) are based on the raw data. Significance is indicated by the P-values.

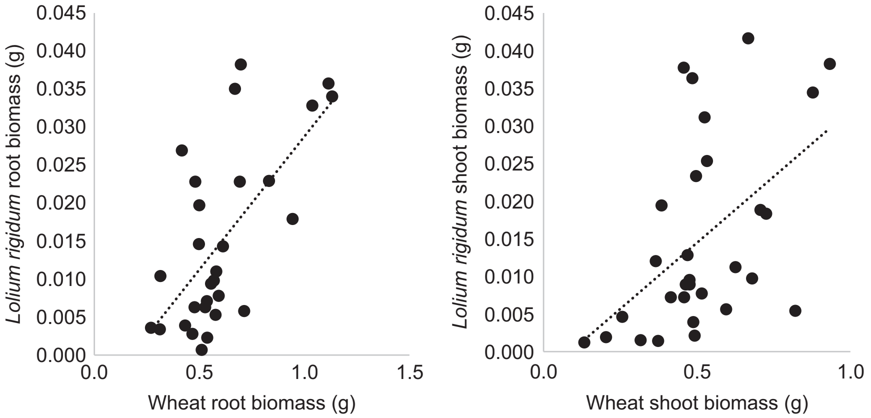

Figure 2. The dry biomass of *Lolium rigidum* roots compared with that of wheat roots (left, where the line indicates the relationship $y = 0.0351x - 0.0063$, $R^2 = 41.8$, $P < 0.001$) and the dry biomass of *Lolium rigidum* shoots compared with that of wheat shoots (right, where the line indicates the relationship $y = 0.0352x - 0.0031$, $R^2 = 23.2$, $P = 0.004$).

emerge, or whether incorporation induced short- or long-term seed dormancy. If weeds germinated and failed to emerge, this would improve weed control. However, if dormancy was induced, seeds are likely to emerge later in the season or in subsequent years. If seedling recruitment is delayed by incorporation, the late seedlings will escape exposure to nonselective or PRE herbicides (Storrie 2014). Delayed recruitment of *L. rigidum* seedlings following incorporation may reduce their competitive ability in the crop (Pannell et al. 2004). However, this would not be an advantage if early growth of the crop (and subsequent competitive ability of the crop) is also reduced by incorporation. The current experiment was conducted in controlled conditions, and the incorporation achieved in the pots was not equivalent to field conditions. Even the non-incorporated soil in the pots experienced considerable disturbance being transferred from the field to pots. It is clear that we need more research on plant germination, emergence, and growth following soil incorporation in field conditions to determine whether reduced emergence is a consistent result of soil incorporation.

Wheat–Fallow Compared with Continuous Wheat at Merredin

At Merredin, *L. rigidum* density, biomass, and seed production were lower in the wheat–fallow rotation compared with the continuous wheat rotation (Table 2). Within the wheat–fallow rotation there were no effects of lime rate or incorporation on each *L. rigidum* variate, due to uniformly low weed density. Wheat density and tiller number were not affect by rotation, although the fallow rotation increased wheat yield. While a fallow is a highly effective weed control technique, it is not economically beneficial, except where weed density is exceptionally high (Monjardino et al. 2004). However, fallow has additional benefits, such as stored soil moisture and increased nitrogen mineralization, and may be a profitable rotation choice for a low-rainfall area like Merredin (Oliver and Sands 2013).

Lime and Incorporation at Merredin and Wongan Hills

Within the continuous wheat rotation at Merredin, increasing rates of lime were linearly correlated to reduced density, biomass, and seed production of *L. rigidum* and increased wheat tiller number and yield (Table 3). For each variate, the deviations from the linear relationship were not significant. Incorporation of lime in the continuous wheat rotation reduced *L. rigidum* density, but the reduction to biomass and seed production was not significant (Table 4). Incorporation also did not affect wheat tiller number or yield. Wheat density averaged 109 plants m^{-2} and was not affected by treatments (data not shown).

At Wongan Hills, *L. rigidum* density, biomass, and seed production in the 2018 crop were reduced with application of lime in 1994 and 2014, but the reduction in *L. rigidum* density and seed production due to the 1998 lime application was not significant (Table 5). Wheat density was not affected by lime, but tiller number increased with increasing rates of lime applied in 1994 and 2014. The slight increase to wheat yield following application of lime was not significant in 1994, 1998, or 2014. Incorporation of lime in 2018 did not affect *L. rigidum* or wheat. However, the interaction between lime application in 2014 and incorporation of lime in 2018 was significant for *L. rigidum*. *Lolium rigidum* density, biomass, and seed production decreased with increasing depth of incorporation in those plots where lime was not applied in 2014 (0 kg ha^{-1}), but was not significantly affected in those plots where 3,000 kg ha^{-1} of lime was applied in 2014 (Table 6).

Table 3. The *Lolium rigidum* density, biomass, and seed production and wheat tillers and yield at lime rates of 0 to 6,000 kg ha^{-1} for the continuous wheat rotation at Merredin in 2018.[a]

Measurement	Lime				LSD or LSD range	P
	0	2,000	4,000	6,000		
	kg ha^{-1}					
L. rigidum density (plants m^{-2})	54.2 (12.0)	28.5 (8.7)	11.7 (5.6)	5.2 (3.7)	16.7–29.5	<0.001
L. rigidum biomass (g m^{-2})	81.4 (16.1)	69.1 (14.9)	37.1 (10.9)	24.9 (8.9)	33.6–40.9	0.002
L. rigidum seeds (m^{-2})	9,390 (1,766)	8,226 (1,653)	3,758 (1,117)	2,820 (967)	3,608–4,513	<0.001
Wheat tillers (m^{-2})	294 (199)	312 (199)	330 (199)	351 (199)	3,826	<0.001
Wheat yield (kg ha^{-1})	2,360 (50)	2,920 (50)	2,940 (50)	3,060 (50)	190	<0.001

[a] The LSD and P-values indicate the significance of the linear contrast of lime rate, with standard errors of the means (SEMs) presented in parentheses. Due to back-transformation of density, biomass, and seed production, SEMs vary between means, and LSD is presented as a range.

Table 4. *Lolium rigidum* density, biomass, and seed production and wheat tillers and yield following initial incorporation or no incorporation of lime in 2016 in a continuous wheat cropping system at Merredin in 2018.[a]

Measurement	Incorporation	No incorporation	LSD	P
L. rigidum density (plants m^{-2})	14.0 (4.3)	29.9 (6.3)	15.6	0.045
L. rigidum biomass (g m^{-2})	40.2 (9.7)	61.9 (12.1)	49.1	0.252
L. rigidum seeds (m^{-2})	4,462 (655)	7,090 (825)	3,331	0.086
Wheat tillers (m^{-2})	333 (21)	311 (21)	70	0.392
Wheat yield (kg ha^{-1})	2,840 (50)	2,800 (50)	220	0.541

[a] The P-values and LSD values indicate the significance of the incorporation treatment and standard errors of the means (SEMs; presented in parentheses) vary between treatment levels of density, biomass, and seed production due to back-transformation.

Table 5. *Lolium rigidum* density, biomass, and seed production and wheat tillers and yield at Wongan Hills in 2018, following application of lime in 1994 (0, 2,000, or 4,000 kg ha^{-1}), 1998 (0 or 1,500 kg ha^{-1}), and 2014 (0 or 3,000 kg ha^{-1}) or incorporation of lime in 2018 to a depth of 0, 15, or 25 cm.[a]

Treatment	Rate	*L. rigidum* density	*L. rigidum* biomass	*L. rigidum* seeds	Wheat tillers	Wheat yield
		plants m^{-2}	g m^{-2}	m^{-2}	m^{-2}	kg ha^{-1}
Lime 1994	0 kg ha^{-1}	24.8 (4.6)	43.8 (9.5)	4,708 (1,144)	288	2,910 (210)
	2,000 kg ha^{-1}	10.7 (2.6)	21.9 (6.0)	2,930 (835)	306	3,610 (240)
	4,000 kg ha^{-1}	10.3 (2.6)	13.0 (4.2)	1,610 (561)	335	3,600 (300)
P		0.045	0.045	0.100	0.018	0.126
LSD (range)		11.8–12.7	20.7–25.3	2,808–2,949	19	790–950
Lime 1998	0 kg ha^{-1}	19.8 (2.6)	46.8 (7.2)	5,124 (784)	288	3,290 (100)
	1,500 kg ha^{-1}	15.9 (2.3)	30.1 (5.4)	3,959 (661)	307	3,390 (100)
P		0.282	0.076	0.267	0.109	0.534
LSD		7.3	18.7	2148	25	380
Lime 2014	0 kg ha^{-1}	15.9 (2.3)	30.1 (5.4)	3,959 (661)	307	3,240 (40)
	3,000 kg ha^{-1}	8.8 (1.5)	7.5 (2.1)	921 (250)	334	3,350 (40)
P		0.016	<0.001	<0.001	0.038	0.093
LSD		5.6	10.8	1307	25	140
Incorporation 2018	0 cm	15.8 (2.8)	23.8 (4.0)	2,980 (465)	302	3,350 (80)
	15 cm	15.7 (2.8)	25.5 (4.2)	3,119 (479)	315	3,170 (80)
	25 cm	11.7 (2.3)	23.2 (3.9)	2,622 (427)	311	3,440 (80)
P		0.466	0.920	0.740	0.486	0.127
LSD (range)		7.4–9.0	11.9–16.4	1,381–1,770	24	270

[a] Significance is indicated by the P-values and LSD values or LSD range. Standard errors of the means (SEMs; presented in parentheses) and LSD values vary between treatment levels due to back-transformation (density, biomass, and seed production data) or unequal replication (yield). For wheat tillers, there was no transformation, and the design was not unbalanced, so the SEMs were consistent, and a single LSD is presented.

The hypothesis that the addition of lime to acidic soil is correlated to a reduction in the growth and seed production of *L. rigidum* was supported in both field experiments. Because lime application also increased wheat tillers in both field trials and yield at Merredin, and the screen house experiment indicated that initial growth of *L. rigidum* was increased by lime application, the reduction in *L. rigidum* growth is likely due to improved competitive ability of the crop, rather than a direct result of lime application on *L. rigidum* growth. Lime application did not significantly affect yield at Wongan Hills, although tiller number increased from both the 1994 and the 2014 lime applications. However, the most recent lime application at Wongan Hills (i.e., in 2014) was 4 yr before the current assessment of yield or *L. rigidum* growth compared with Merredin, where lime was applied 2 yr before the current assessment (in 2016). In this study the soil pH data in the year of liming and the year of assessment are not presented.

Table 6. *Lolium rigidum* density, biomass, and seed production interaction at Wongan Hills in 2018 between application of lime in 2014 (0 or 3,000 kg ha^{-1}) and incorporation of lime in 2018 to a depth of 0, 15, or 25 cm.[a]

Measurement	Incorporation	Lime 2014	
		0	3,000
		kg ha^{-1}	
L. rigidum density (plants m^{-2})	0 cm	23.0 (3.6)	7.3 (1.7)
	15 cm	17.2 (3.0)	10.1 (2.1)
	25 cm	9.6 (2.0)	9.3 (2.0)
P	0.015		
LSD range	5.7–9.2		
L. rigidum biomass (g m^{-2})	0 cm	36.1 (5.8)	4.5 (1.4)
	15 cm	32.1 (5.3)	7.7 (2.1)
	25 cm	23.0 (4.3)	11.5 (2.7)
P	0.007		
LSD range	4.9–15.4		
L. rigidum seeds (m^{-2})	0 cm	5,151 (754)	582 (177)
	15 cm	4,158 (654)	982 (250)
	25 cm	2,809 (504)	1,295 (301)
P	0.004		
LSD range	612–1988		

[a] The significance of interactions is indicated by the P-values and LSD values. Standard errors of the means (SEMs; presented in parentheses) and LSD values vary between treatment levels due to back-transformation.

However, it is common for soil in Western Australia to reacidify over 4 yr due to annual application of nitrogen fertilizer, and so lime applied in 2014 would have reduced impact on crop yield in 2018 (Mason et al. 1994a, 1994b). These findings support prior work indicating the sensitivity of *L. rigidum* to long-term competition from wheat crops and reduction in *L. rigidum* growth following lime application to crops in acidic soils (Borger et al. 2016b; Gazey and Andrew 2010). At Merredin, lime application may have altered soil chemistry, which can also influence PRE herbicide performance. However, other research found no interaction between liming and efficacy of PRE herbicides like prosulfocarb, pyroxasulfone, or simazine (Hashem and Borger 2018).

As stated, incorporation of lime in the screen house (where seeds were planted at a consistent depth) reduced *L. rigidum* recruitment and increased soil pH at depth. At Merredin, incorporation reduced *L. rigidum* density in the continuous wheat rotation. Weed density in the wheat–fallow rotation was too low to be affected by lime or incorporation. Likewise, at Wongan Hills, incorporation reduced *L. rigidum* density, biomass, and seed production in the plots where lime application was 0 kg ha^{-1} in 2014. There was no significant effect of incorporation in plots where 3,000 kg ha^{-1} of lime was applied in 2014, but weed density at all depths of incorporation was much lower in these limed plots. Reduced weed density following incorporation in the field may have resulted from altered soil properties, as for the screen house experiment, but may also have resulted from burial of the *L. rigidum* seed beyond a depth suitable for emergence (Braunack and Dexter 1989; Chauhan et al. 2006a). At Merredin, reduced weed density may have resulted from increased efficacy of the PRE herbicide (Chauhan et al. 2006b). The efficacy of nonsoluble PRE herbicides is reduced if they bind to crop residue on the soil surface, but incorporation buries a proportion of the crop residue and improves herbicide performance (Chauhan et al. 2006b). However, no PRE herbicide was applied at Wongan Hills. Incorporation did not affect wheat yield in the field experiments, indicating that if wheat growth is initially impacted by altered soil properties (as observed in the screen house), plants can recover during the course of the season. We do not fully understand the impact of incorporation on weed emergence or early crop and weed growth, soil properties, and herbicide performance. It is clear that we need more research on weed recruitment following soil disturbance.

Lolium rigidum growth is reduced by competition from a wide range of cereal crops, but most cereal crops have reduced growth in acidic soils (Lemerle et al. 1995; Paynter and Hills 2009; Slattery et al. 1999). In Australia, the revenue loss from residual *L. rigidum* in-crop is estimated to cost growers A$93 million per year, due to an annual yield loss of 346,618 t of grain (Llewellyn et al. 2016). The current research confirms that application of lime to increase soil pH in regions with acidic soils will increase the competitive ability of crops. Further work is required to determine the competitive advantage to other crop species following lime application in acidic soils.

Acknowledgments. The research was supported by the Grains Research and Development Corporation (Soil Constraints Initiative—Innovative Approaches to Managing Subsoil Acidity, DAW00252). The authors thank staff at the Department of Primary Industries and Regional Development Merredin and Wongan Hills Research stations, Gavin Sarre, Pete Gray, and Nerys Wilkins. The authors have no conflicts of interest to declare.

References

Aladesanwa RD, Akinbobola TN (2008) Effects of lime on the herbicidal efficacy of atrazine and yield response of maize (*Zea mays* L.) under field conditions in southwestern Nigeria. Crop Prot 27:926–931

Augé RM, Stodola AJW, Arnold JET, Saxton M (2001) Moisture retention properties of a mycorrhizal soil. Plant Soil 230:87–97

Bolland MDA, Rengel Z, Paszkudzka-Baizert L, Osborne LD (2001) Responses of subterranean clover and Itailian ryegrass to application of lime. Aust J Exp Agric 41:177–185

Borger C, Hashem A, Powles SB (2016a) Manipulating crop row orientation and crop density to suppress *Lolium rigidum*. Weed Res 56:22–30

Borger CPD, Riethmuller G, D'Antuono M (2016b) Eleven years of integrated weed management: long-term impacts of row spacing and harvest weed seed destruction on *Lolium rigidum* control. Weed Res 56:359–366

Braunack MV, Dexter AR (1989) Soil aggregation in the seedbed: a review. II Effect of aggregate sizes on plant growth. Soil Till Res 14:281–298

Bromfield S (1987) Simple tests for the assessment of aluminium and manganese levels in acid soils. Aust J Exp Agric 27:399–404

Chauhan BS, Gill G, Preston C (2006a) Influence of tillage systems on vertical distribution, seeding recruitment and persistence of rigid ryegrass (*Lolium rigidum*) seed bank. Weed Sci 54:669–676

Chauhan BS, Gill G, Preston C (2006b) Tillage systems affect trifluralin bioavailability in soil. Weed Sci 54:941–947

Dai Z, Zhang X, Tang C, Muhammad N, Wu J, Brookes PC, Xu J (2017) Potential role of biochars in decreasing soil acidification-a critical review. Sci Total Environ 581–582:601–611

D'Emden FHD, Llewellyn RS (2006) No-tillage adoption decisions in southern Australian cropping and the role of weed management. Aust J Exp Agric 46:563–569

Gazey C, Andrew J (2010) Long-term effect of lime application on soil pH, crop yields and annual ryegrass competition. Pages 229–233 *in* Proceedings of the 2010 Agribusiness Crop Updates. Perth, WA, Australia: Grains Research and Development Corporation

Hashem A, Borger C (2018) Lime improves control of wild radish and annual ryegrass in acid soils of Western Australia. Pages 153–156 *in* Proceedings of the Weed Biosecurity—Protecting Our Future. 21st Australasian Weeds Conference. Sydney, NSW, Australia: Weed Society of New South Wales

Hochman Z, Osborne GJ, Taylor PA, Cullis BR (1990) Factors contributing to reduced productivity of subterranean clover (*Trifolium subterraneum* L.) pastures on acidic soils. Aust J Agric Res 41:669–682

Isbell RF (2016) Tenosols [TE]. *In* The Australian Soil Classification. 2nd ed. Clayton South, VIC, Australia: CSIRO Publishing. https://www.clw.csiro.au/aclep/asc_re_on_line_V2/te/tenosols.htm. Accessed: December 16, 2019

Lemerle D, Verbeek B, Coombes N (1995) Losses in grain yield of winter crops from *Lolium rigidum* competition depend on crop species, cultivar and season. Weed Res 35:503–509

Li Y, Cui S, Chang SX, Zhang Q (2019) Liming effects on soil pH and crop yield depend on lime material type, application method and rate, and crop species: a global meta-analysis. J Soil Sediment 19:1393–1406

Llewellyn R, Ronning D, Clarke M, Mayfield A, Walker S, Ouzman J (2016) Impact of weeds on Australian grain production: the cost of weeds to Australian grain growers and the adoption of weed management and tillage practices. Canberra, ACT, Australia: Grains Research and Development Corporation, Commonwealth Scientific and Industrial Research Orgainsation. 112 p

Mason MG, Porter WM, Cox WJ (1994a) Effect of an acidifying nitrogen fertiliser and lime on soil pH and wheat yields. 1. Soil effects. Aust J Exp Agric 34:237–246

Mason MG, Porter WM, Cox WJ (1994b) Effect of an acidifying nitrogen fertiliser and lime on soil pH and wheat yields. 2. Plant response. Aust J Exp Agric 34:247–253

Meharg AA, Killham K (1990) The effect of soil pH on rhizosphere carbon flow of *Lolium perenne*. Plant Soil 123:1–7

Monjardino M, Pannell DJ, Powles SB (2004) The economic value of haying and green manuring in the integrated management of annual ryegrass and wild radish in a Western Australian farming system. Aust J Exp Agric 44:1195–203

Moore GA (2001) Soilguide (Soil Guide): A Handbook for Understanding and Managing Agricultural Soils. Perth, WA, Australia: Department of Agriculture and Food, Western Australia. 381 p

Nunes MR, Denardin JE, Vaz CMP, Karlen DL, Cambardella CA (2019) Lime movement through highly weathered soil profiles. Environ Res Commun 1:1–15

Oliver Y, Sands R (2013) Yield, soil water and economic benefits of long fallow. Pages 1–4 *in* Proceedings of the Grains Research Updates. Perth, WA, Australia: Grains Research and Development Corporation

Pannell DJ, Stewart W, Bennett A, Monjardino M, Schmidt C, Powles SB (2004) RIM: a bioeconomic model for integrated weed management of *Lolium rigidum* in Western Australia. Agric Syst 79:305–25

Paynter HH, Hills AL (2009) Barley and rigid ryegrass (*Lolium rigidum*) competition is influenced by crop cultivar and density. Weed Technol 23:40–48

Pluske W, Boggs G, Leopold M (2017) Integrated Soil Management (Soil Quality 2). Crawley, WA, Australia: SoilsWest, https://books.apple.com/au/book/soil-quality-2-integrated-soil-management/id1350650941. Accessed: May 16, 2020

Rayment G, Lyons D (2011) Soil Chemical Methods: Australasia (Australian Soil and Land Survey Handbooks). Melbourne, VIC, Australia: CSIRO Publishing, https://www.publish.csiro.au/book/6418/. Accessed May 15, 2020

Slattery WJ, Conyers MK, Aitken RL (1999) Soil pH, aluminium, manganese and lime requirement. Pages 103–128 *in* Peverill KI, Sparrow LA, Reuter DJ, eds. Soil Analysis: An Interpretation Manual. Collingwood, VIC, Australia: CSIRO Publishing

Storrie AE, ed (2014) Integrated Weed Management in Australian Cropping Systems. Australia: Grains Research and Development Corporation. 16 p

Sumner ME, Noble AD (2003) Soil acidification: the world story. Pages 1–28 *in* Rengel Z, ed. Handbook of Soil Acidity. New York: Marcel Dekker

VSN International (2019) GenStat for Windows. 19th ed. Hemel, Hempstead, UK: VSN International