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Influence of Management on Long-Term Seedbank Dynamics of Rigid Ryegrass (*Lolium rigidum*) in Cropping Systems of Southern Australia

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A field study was undertaken to investigate the influence of different management strategies on rigid ryegrass plant density and seedbank dynamics over 4 yr. Even though weed seedbank declined by 86% after oaten hay in year 1, the residual seedbank enabled rigid ryegrass to reinfest field peas the next year, and the population rebounded sharply when weed control relied solely on PPI trifluralin. However, use of POST clethodim followed by crop-topping for seed-set prevention of rigid ryegrass in field pea was highly effective and caused a further decline in the weed seedbank. Integration of effective management tactics over 3 yr significantly reduced rigid ryegrass weed and spike density (90 and 81%) in the final year of the 4-yr cropping sequence. Use of oaten hay in year 1, followed by effective weed control in field pea and wheat crops, depleted the high initial seedbank (4,820 seeds m^{-2}) to moderate levels (< 200 seeds m^{-2}) within 3 yr. Effective weed-management treatments depleted the rigid ryegrass seedbank, reduced in-crop weed infestation, and returned higher grain yields and profitability. The results of this study clearly show that large rigid ryegrass populations can be managed effectively without reducing crop productivity and profitability provided multiyear weed-management programs are implemented effectively.

Nomenclature: Clethodim; trifluralin; rigid ryegrass, *Lolium rigidum* Gaudin LOLRI; field pea; *Pisum sativum* L.; oat; *Avena sativa* L.; wheat; *Triticum aestivum* L.

Key words: Rigid ryegrass, seedbank, weed management.

Rigid ryegrass is a major winter annual weed of the southern Australian wheat-belt, which naturalized after its introduction as a pasture species (Gallagher et al. 2004; Gill 1996; Powles and Bowran 2000). The widespread distribution of this well-adapted species in southern Australia has been attributed to its high level of genetic variability (Gill 1996). If not managed effectively, rigid ryegrass can significantly reduce the yield of winter-annual crops, including wheat (Poole and Gill 1987; Smith and Levick 1974), barley (Hordeum vulgare L.) (Lemerle et al. 1995), field peas (McDonald 2003), and canola (Brassica napus L.) (Lemerle et al. 1995; Lemerle et al. 2010). In wheat, rigid ryegrass can be extremely competitive, reducing the yields of certain cultivars by as much as 80% (Lemerle et al. 1996). Rigid ryegrass is a prolific seed producer (Rerkasem et al. 1980), which enables plants that survive weed control to readily replenish the seedbank and reinfest subsequent crops. Combined effects of rigid ryegrass on crop-yield loss and weed-control expenditure make it one of the most important weeds of agriculture in southern Australia (Jones et al. 2005).

Control of rigid ryegrass in crops with selective herbicides has become increasingly difficult because of herbicide resistance (Boutsalis et al. 2012; Broster et al. 2011; Leys et al. 1988). Rigid ryegrass has evolved resistance to nine major herbicide mode-of-action groups (Peltzer et al. 2009), with resistance to the acetyl-coenzyme A carboxylase (ACCase)–inhibiting herbicides (graminicides) being one of the first cases reported (Heap and Knight 1986). Today, ACCase-resistant rigid ryegrass infests thousands of hectares across the southern Australian cropping zone (Boutsalis et al. 2012; Owen et al. 2007). Despite this, some ACCase-inhibiting herbicides, including clethodim (Select®, Sumitomo Chemical Australia, Epping, NSW, Australia), can provide control of many otherwise ACCase-resistant rigid ryegrass populations (Yu et al. 2007). In many situations, clethodim can still be used in break crops, such as pulses and canola, to control rigid ryegrass. Use of clethodim in break crops can provide an ideal opportunity to control rigid ryegrass because it can be followed by crop-topping with glyphosate or paraquat to prevent weed-seed production. However, a recent survey has shown that 61% of the farm populations of rigid ryegrass in southeastern Australia are now resistant to this herbicide (Boutsalis et al. 2012). Overreliance on clethodim to control rigid ryegrass in pulse and canola crops has contributed to the rapid increase in resistance to this herbicide.

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Resistance development in rigid ryegrass to most mode-of-action groups has been of major concern to growers and has resulted in some reexamination of weed management practices used in crops. More consideration is now being given to the selection of crop type and weed control options available. Several studies have shown that changes in crop rotations and weed management can greatly influence weed populations (Ball 1992; Schreiber 1992). However, only a few reports have characterized the effects of crop rotation and management on weed seedbank dynamics. Ball (1992) showed that crop rotation was the most important factor influencing the composition of the weed seedbank, and this was due, in part, to the effect of herbicide use on weed density and fecundity in each cropping sequence. Although seedbanks and the resulting weed populations can comprise many weed species, the seedbank is mostly composed of only a few dominant species (Buhler 1999). Effective management of these dominant species depends on prevention of seed production and on exhausting the seedbank, which can be influenced by the persistence of weed seeds in the soil. Only 7 to 14% of rigid ryegrass seed persists from one season to the next (Chauhan et al. 2006). This feature suggests that the seedbank could be exhausted within a few years when effective weed control can be consistently achieved in the crop sequence. Despite the importance of rigid ryegrass as a weed in Australia, there is limited information available on its long-term seedbank dynamics in cropping systems. Such information could contribute to the development of cropping systems and weed-management practices that not only achieve high productivity but also maintain weed populations at a low level.

The findings of a 4-year field study that examined the effect of weed-management strategies on seedbank dynamics of rigid ryegrass in a cropping sequence widely used in the low to medium rainfall zones of southern Australia is discussed. The effectiveness of integrating several weed-management tactics to deplete the rigid ryegrass seedbank over 4 yr was evaluated. We explored the economic impact of practicing effective weed-management tactics aimed at depleting weed seedbanks in each phase of the cropping sequence.

Materials and Methods

Study Site. A field experiment was established at Roseworthy, in the lower mid-north region of South Australia (34.53°S, 138.75°E at 68 m above sea level) from 2009 to 2013. Soil at the experimental site was Calcarosol (McKenzie et al. (2001)) with sandy loam over medium calcareous clay subsoil. The organic matter content of the field soil in the 0- to 10-cm surface layer varied from 2 to 2.5%, with a pH (water) of 7 to 7.5. The long-term average annual rainfall at Roseworthy was 434 mm, and the average rainfall during the growing season (April to October) is 321 mm; rainfall received at the site from 2009 to 2012 is shown in Table 1 (Australian Bureau of Meteorology 2014). The site had been under no-till production for 10 yr before initiation of the study. Plots were 15 m by 20 m in 2009 and 2010, and 5 m by 20 m in 2011 and 2012. Plots were sown using a John Shearer no-till trash drill (John Shearer Machinery Pty. Ltd, Kilkenny, South Australia) fitted with knife-point openers (16 mm) and press wheels, configured to deep-band fertilizer below the seeding depth at a row spacing of 18 cm. Planting and fertilizer rates were similar to standard local practice with oats (‘Marloo’), wheat (‘Axe’), and barley (‘Scope’) sown at 110, 90, and 75 kg ha^{-1}, respectively, and field pea (‘Kaspa’) at 110 kg ha^{-1} with diammonium phosphate fertilizer banded below the seed at 100 kg ha^{-1}. The crops were sown on May 11 and 13 in 2009 and 2010 and June 15 and June 8 in 2011 and 2012, respectively. Preplant weed control involved applications of glyphosate (900 g ai ha^{-1}) and oxyfluorfen (22 g ai ha^{-1}). Fungicide mancozeb (750 g ai ha^{-1}) was applied to field pea as per farmer practice. All herbicide treatments were applied with a 5-m-wide boom mounted on a quad-motorbike at a spray volume of 100 L ha^{-1}.

Table 1. Monthly rainfall for 2009 to 2012 and monthly mean long-term rainfall (1908 to 2007) at Roseworthy, South Australia.

	Rainfall				
Month	2009	2010	2011	2012	Long-term mean[a]
	mm				
January	1	12	15	9	20
February	0	0	35	15	21
March	9	19	81	35	20
April	48	30	9	15	32
May	25	53	37	47	48
June	50	33	30	60	50
July	59	33	29	25	49
August	47	46	44	34	51
September	19	81	47	30	48
October	21	30	43	14	43
November	21	15	21	11	28
December	2	61	28	12	24
Total	302	413	419	307	434

[a] Rainfall details averaged from 1908 to 2007 (Australian Bureau of Meteorology).

Table 2. Management strategies (MSs) investigated for the control of rigid ryegrass in each phase of a 4-yr cropping rotation. All herbicides were applied at recommended label rates and timings.[a]

	Year[a]				
	2009	2010	2011		2012
MS	Oaten hay	Field pea	Wheat		Barley
1	Early hay cut, glyphosate	Trifluralin (PPI)	1.1	Prosulfocarb + *S*-metolachlor (PPI)	Trifluralin (PPI)
			1.2	Pyroxasulfone (PPI) Prosulfocarb + *S*-metolachlor (one-leaf)	
			1.3	Prosulfocarb + *S*-metolachlor (PPI) Glyphosate (soft dough)	
2	Early hay cut, glyphosate	Trifluralin (PPI) Clethodim (four-leaf)	2.1	Prosulfocarb + *S*-metolachlor (PPI)	Trifluralin (PPI)
			2.2	Pyroxasulfone (PPI) Prosulfocarb + *S*-metolachlor (one-leaf)	
			2.3	Prosulfocarb + *S*-metolachlor (PPI) Glyphosate (soft dough)	
3	Early hay cut Glyphosate	Trifluralin (PPI) Clethodim (four-leaf) Glyphosate (milk to soft dough)	3.1	Prosulfocarb + *S*-metolachlor (PPI)	Trifluralin (PPI)
			3.2	Pyroxasulfone (PPI) Prosulfocarb + *S*-metolachlor (one-leaf)	
			3.3	Prosulfocarb + *S*-metolachlor (PPI) Glyphosate (soft dough)	

[a] Growth stage of rigid ryegrass at herbicide application.

The grain yield of field pea, wheat, and barley was determined using a small-plot harvester after the crop had reached physiological maturity.

Management Strategies. This field study investigated three different management strategies (MSs) for controlling rigid ryegrass within a typical cropping rotation in the low- to mid-rainfall zone in southern Australia (Table 2). The 4-yr cropping rotation of oaten hay–field pea–wheat–barley was representative of the district practice. In year 1 of the study (2009), the entire experimental site was planted to oaten hay and managed according to grower practice with an early hay cut followed by glyphosate to prevent recovery of rigid ryegrass and to minimize its seed production. This was followed in year 2 by field pea (2010), where trifluralin was applied either alone as a PPI treatment (MS1), or followed by a POST application of clethodim (MS2) or by POST clethodim plus crop-topping with glyphosate in October to prevent seed production of weeds that escaped earlier treatments (MS3). Wheat was grown in year 3 (2011); however, plots of each MS (1 to 3) were split into 3 herbicide subplots (H1.1 to H3.3) of (1) PPI herbicide prosulfocarb plus *S*-metolachlor (Boxer Gold); (2) PPI pyroxasulfone (Sakura), followed by an early POST application of prosulfocarb plus *S*-metolachlor; and (3) PPI prosulfocarb plus *S*-metolachlor followed by crop-topping with glyphosate. The early maturing wheat cultivar Axe was chosen to enable late crop-top application of glyphosate when the wheat crop was at the soft to hard dough development stage (GS85 to GS87; Zadoks et al. 1974). In the final cropping phase (2012) of the 4-yr rotation, barley was grown and all MSs (1 to 3) were treated with PPI trifluralin. It was anticipated that MS1 would only provide effective rigid ryegrass control in year 1, when oaten hay was grown, whereas MS2 would give good weed control in years 1 and 2. MS3, on the other hand, was expected to provide 3 consecutive yr of effective control with crop-topping with glyphosate in spring (October) to prevent weed seed production.

Seedbank Sampling. In March 2009, before the start of the study, the baseline seedbank of the site was estimated by taking 84 soil samples (10 cm in diameter by 10 cm deep) from each block (total = 252 soil samples). These samples were taken every 2 m along two diagonal transects of each block and then combined for each block. In subsequent years, the soil seedbank was estimated in autumn (before seedling emergence of rigid ryegrass) by taking 28 soil samples from each plot (15 m by 20 m) in 2010 and 2011, and 10 soil samples from each plot (5 m by 20 m) in 2012 and 2013. Soil samples from each plot were combined, and the entire sample was used to determine rigid ryegrass seedbank by placing the sample in shallow seedling trays that had been partially filled with the University of California (Davis, CA) potting mix. The soil samples from the field were placed in those trays in a 2-cm-thick layer, watered, and placed outside from March to July each year. Germinated seedlings were recorded and removed at regular intervals. Census for rigid ryegrass plants ceased in late July when no new seedlings emerged over a 3-wk period. The number of seedlings to germinate in each tray represented the germinable seedbank each year and was converted to seeds per square meter for each plot.

Rigid Ryegrass Assessment. Rigid ryegrass density was determined once each year, at 8 to 10 wk after planting, by counting the number of plants in six quadrats (0.6 m by 0.6 m, 2010; 0.4 m by 0.4 m in 2011 and 2012) placed at random in each plot. All plots were assessed in the spring using the same method to determine rigid ryegrass spike density.

Statistical Analyses. The experiment was established in a split-plot design with three replicates; MSs were assigned to the main plots and herbicides to the subplots. Weed control (plant and spike data) and crop grain yield data were analyzed by ANOVA (GenStat Version 14.0, VSN International, Hemel Hempstead, United Kingdom) (VSN 2011). Because herbicide treatment effect on grain yield of wheat (2011) and barley (2012) was not significant, data were combined over herbicide treatments and presented as the mean of MS1 to MS3. Transformation of data did not improve homogeneity of variance; thus, ANOVA was performed on nontransformed weed control and grain yield data. Data variance was visually inspected by plotting residuals to confirm homogeneity of variance before statistical analysis. Mean values were separated using Fisher's Protected LSD test at the $P = 0.05$ level.

Results and Discussion

Rigid Ryegrass Control and Seedbank Changes in Response to Management. In year 1 of the study (2009), oaten hay provided complete control of rigid ryegrass and resulted in a significant reduction (86%) in the soil seedbank (Figure 1). Because oaten hay was cut early, when rigid ryegrass was flowering, and with subsequent regrowth controlled with glyphosate, there was no viable seed set to contribute to the weed seedbank. The effectiveness of oaten hay for the management of herbicide-resistant rigid ryegrass has been established in previous studies, with this practice being widely adopted by many growers in South Australia (P Hooper, personal communication). Even though rigid ryegrass was unable to set seed in year 1, there was still moderate weed infestation (~98 plants m^{-2}) in field peas the following year (2010), presumably from the persistent fraction of the seedbank. Previous studies have shown 10 to 15% of the seedbank can persist (Peltzer and Matson 2002; Chauhan et al. 2006), which is consistent with the carryover reported here (~14%).

To deplete the weed seedbank further in year 2, field peas were planted in 2010. In field peas, trifluralin was either applied alone (MS1), followed by clethodim (MS2), or followed by clethodim and crop-topping with glyphosate (MS3) in spring. When trifluralin was used alone (MS1), rigid ryegrass control was poor with plant and spike density sevenfold to eightfold greater than in MS2 and MS3 (Table 3). The subsequent seedbank in MS1 increased from 765 seeds m^{-2} to 8,316 seeds m^{-2} after field peas (Figure 1a). Poor control of rigid ryegrass with trifluralin in the no-till system used in this study was a result of trifluralin resistance in this population. This is also consistent with the survey results of Boutsalis et al. (2012), who found trifluralin resistance in 50% of rigid ryegrass populations in this region of South Australia. Furthermore, the combination of poor competition from field peas (McDonald 2003) coupled with the above average rainfall received in spring of 2010 (Table 1) and the poor control with trifluralin in MS1 caused rigid ryegrass to flourish (~272 spikes m^{-2}), resulting in significant seed production. Rigid ryegrass is well known for its ability to exploit favorable conditions during reproductive development and to set a large amount of seed (Rerkasem et al. 1980). Application of clethodim in MS2 and MS3 reduced rigid ryegrass plant and spike density by 85% compared with MS1 (Table 3). Even with 85% reduction in rigid ryegrass spike density in MS2, the seedbank remained unchanged from 2010 (733 seeds m^{-2}) to 2011 (786 seeds m^{-2}), when clethodim followed PPI trifluralin used in field peas (Figure 1b). Stability of the seedbank in MS2 over 2 yr most likely indicates that replenishment of new rigid ryegrass seed was very similar to the depletion of the old seed (e.g., decay and germination). This population of rigid ryegrass had been previously treated with ACCase-inhibiting herbicides, and low levels of clethodim resistance were known to occur on this farm.

Crop-topping field peas with glyphosate (MS3) caused a further decline in rigid ryegrass seedbank (~500 seeds m^{-2}) (Figure 1c). Previous research

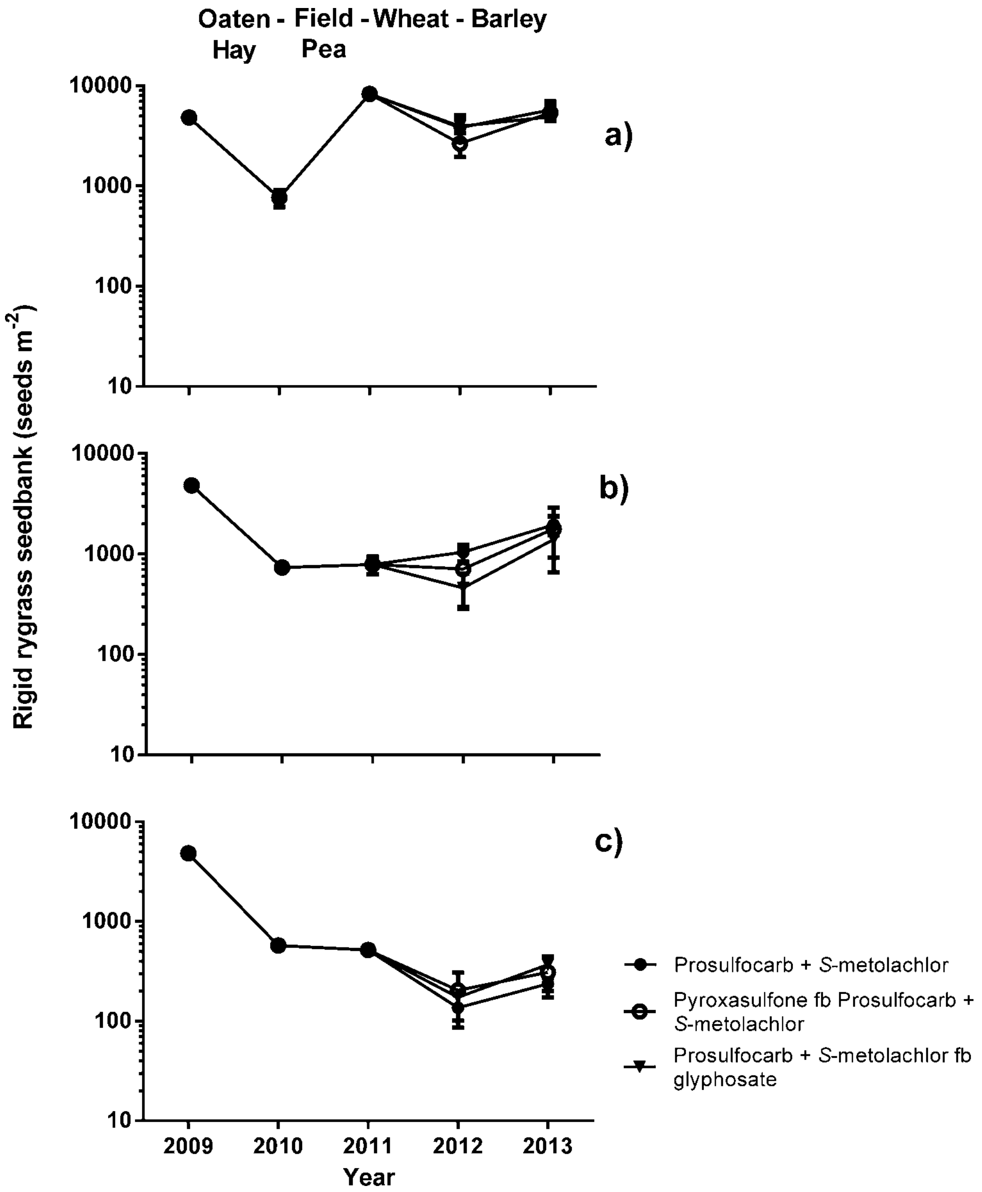

Figure 1. Changes in mean rigid ryegrass seedbank in response to weed management strategy in (a) MS1, (b) MS2, and (c) MS3. Detailed description of management strategies and herbicides are in Table 2. Vertical bars represent standard errors.

showed that if crop-topping is undertaken at the correct stage of weed development, > 90% reduction of rigid ryegrass seed set can be achieved (Gill and Holmes 1997; Newman 2003). Performance of crop-topping can, however, be quite variable, both in terms of rigid ryegrass seed-set control and crop safety (Lines et al. 2012). To avoid excessive yield loss in this study, crop-topping was delayed until 70% of field pea pods had changed color (turned yellow) and seed moisture content was < 30%, which consequently allowed most rigid ryegrass spikes to develop beyond anthesis, which is the optimal stage for seed-set control (Steadman et al. 2006).

In year 3 of the study (2011), wheat (main) plots of each MS (1 to 3) were split into three subplots for herbicide treatments: (1) PPI prosulfocarb plus *S*-metolachlor (H1); (2) PPI pyroxasulfone, followed by POST prosulfocarb plus *S*-metolachlor (H2); and (3) PPI prosulfocarb plus *S*-metolachlor, followed by crop-topping with glyphosate (H3). Prosulfocarb plus *S*-metolachlor (Boxer Gold) and pyroxasulfone (Sakura) were recently (2006 and 2012) released in Australia because of their excellent activity on rigid ryegrass, including populations resistant to trifluralin. The legacy effect of the field pea phase (MS1 to MS3) was evident in the wheat phase with average rigid ryegrass plant density of ~300 plants m^{-2} in MS1, 40 plants m^{-2} in MS2, and 12 plants m^{-2} in MS3. In the wheat phase, both rigid ryegrass plant and spike density were significantly affected ($P < 0.05$) by the herbicide treatment (H1 to H3) and its interaction with its MS (Table 3). The response to herbicide was due to reduction in rigid

Table 3. Changes to rigid ryegrass weed and spike density in response to weed management strategy (MS1 to MS3).[a]

		Rigid ryegrass					
		Weed density			Spike density		
MS[b]	Herbicide[b]	2010 Field pea	2011 Wheat	2012 Barley	2010 Field pea	2011 Wheat	2012 Barley
		plants m^{-2}			spikes m^{-2}		
1	1.1		349	320	272	213	331
	1.2	98	181	351		125	301
	1.3		389	284		299	355
	Mean[c]		306	319		212	329
2	2.1		42	116	41	75	173
	2.2	12	29	108		40	140
	2.3		48	91		87	144
	Mean[c]		40	105		67	152
3	3.1		17	30	35	9	73
	3.2	13	4	35		5	63
	3.3		16	32		8	51
	Mean[c]		12	32		7	62
LSD ($P = 0.05$) MS		17	47	50	36	49	148
Herbicide (H)			***	NS		***	NS
MS × H			**	NS		***	NS

[a] Abbreviation: NS, nonsignificant.

[b] Detailed description of weed MSs and herbicides in Table 2.

[c] Represents the means of MS1 to MS3.

** $P \leq 0.01$; *** $P \leq 0.001$.

ryegrass in the treatment where PPI pyroxasulfone was followed by POST prosulfocarb plus *S*-metolachlor (H1.2, H2.2, and H3.2; Table 3). The combination of PPI pyroxasulfone followed by POST prosulfocarb plus *S*-metolachlor reduced weed density by 31 to 76%, relative to the wheat plots treated with PPI prosulfocarb plus *S*-metolachlor only, and this trend was also reflected in rigid ryegrass spike density (Table 3). Pyroxasulfone followed by POST prosulfocarb plus *S*-metolachlor is likely to have longer persistence in the soil than prosulfocarb plus *S*-metolachlor, which could be responsible for the observed improvement in weed control.

Even though there were clear differences in weed control between herbicide treatments within each MS (1 to 3) in the wheat phase, there was little difference in the seedbank of rigid ryegrass within each MS the next season (Figure 1). These seedbank data are supported by rigid ryegrass plant density in barley in 2012, which showed no differences among treatments within each MS (Table 3). Only in MS2 was there a difference in the seedbank between the previous year's herbicide treatments applied in wheat (Figure 1b). In MS2, weed seedbank increased in the PPI prosulfocarb plus *S*-metolachlor treatment; remained stable for PPI pyroxasulfone, followed by POST prosulfocarb plus *S*-metolachlor; and declined when PPI prosulfocarb plus *S*-metolachlor was followed by crop-topping with glyphosate. In contrast, the seedbank showed similar decline for each of the herbicide treatments under MS1 and MS3 (Figures 1a and 1c). However, where effective control was obtained at lower weed-infestation rates under MS3 (4 to 17 plants m^{-2}), the seedbank declined for the third consecutive year to < 200 seeds m^{-2} (Figure 1c). Although the seedbank declined significantly in MS1 from 2011 (8,316 seeds m^{-2}) to 2012 (2,606 to 3,944 seeds m^{-2}) following herbicide treatments in wheat, the level of decline was not sufficient to prevent an increase in rigid ryegrass plant and spike density in the next barley crop.

As a consequence of the high level of resistance to POST herbicides, Australian growers are becoming increasingly reliant on PPI herbicides to control rigid ryegrass. Barley usually follows wheat in the cropping sequence in southern Australia. The results of this study clearly indicate that to prevent rigid ryegrass build-up in barley, trifluralin is unlikely to be a suitable option. Use of crop-topping of wheat with glyphosate according to the current herbicide label was relatively ineffective in preventing seed set of rigid ryegrass. At present, glyphosate is only recommended for use as a harvest-aid when wheat grain is at 28% moisture content. Applying glyphosate earlier is likely to improve weed seed set control. However, this advantage could be offset by a large reduction in crop yield.

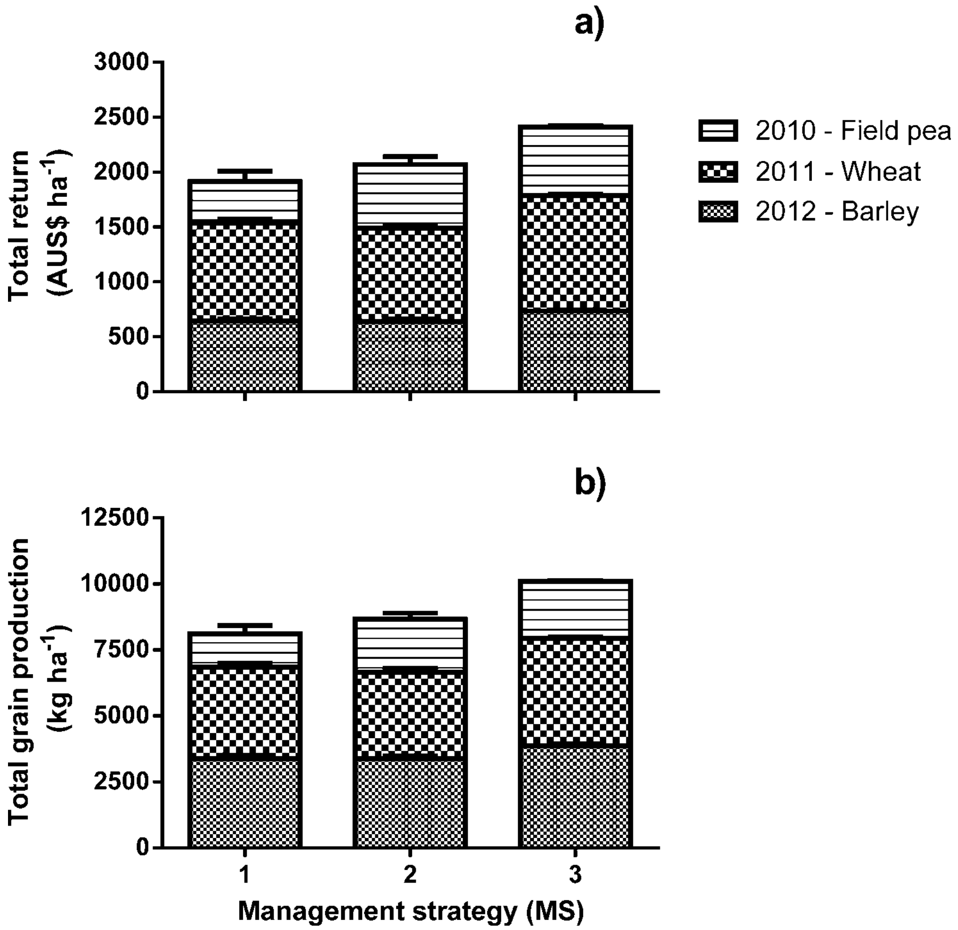

Figure 2. (a) Total economic return and (b) grain production for weed-management strategies (MS1 to MS3). Because herbicide effect on grain yield of wheat (2011) and barley (2012) was not significant, data were combined over herbicide treatment and are presented as the mean of MS1 to MS3. Economic return estimates are based on crop yield, farm costs, and historical commodity prices averaged from 2009 to 2013 (source: Rural Solutions SA 2013). Vertical bars represent standard errors.

In the final year of the study (year 4), trifluralin treatment in barley was quite ineffective and resulted in a large increase in rigid ryegrass plant and spike density (Table 3). From the wheat to barley phase, rigid ryegrass spike density increased by 1.5-fold in MS1, 2.3-fold in MS2, and 8.9-fold in MS3. These results highlight the ability of rigid ryegrass to rapidly build-up infestations from low levels, which is related to its high fecundity (Rerkasem et al. 1980). Even though barley is well known for its strong ability to compete with weeds (Lemerle et al. 1995), it was not enough to prevent this rebound in rigid ryegrass density (Table 3, Figure 1). Ineffectiveness of barley to contain or reduce weed seedbank was most likely related to the poor control with trifluralin because of resistance. Despite the increase in rigid ryegrass seedbank in barley in the final year, the seedbank had been depleted by 59 to 71% in MS2 and 92 to 95% in MS3 over the 4-yr duration. In contrast, in MS1, in which rigid ryegrass control was initially poor in field peas, subsequent management tactics failed to narrow the gap with MS2 and MS3, and the seedbank at the end of the 4-yr cropping cycle was even greater (4,913 to 5,735 seeds m^{-2}) than it was in the initial seedbank (4,820 seeds m^{-2}).

Although rigid ryegrass shows relatively low levels of seedbank persistence (10 to 15%), it can produce large quantities of seed (Rerkasem et al. 1980) to rapidly replenish the seedbank if control in subsequent years is not maintained. However, as this study has shown, if effective management is implemented to reduce seed set, the seedbank of large infestations of rigid ryegrass can be depleted to low levels within 3 yr.

Influence of Rigid Ryegrass Management on Grain Yield and Profitability. In this study that comprised three crops (field pea, wheat, and barley), rigid ryegrass infestation had a significant effect on grain production and economic returns from the three MSs (Figure 2). In year 2 of the study, when rigid ryegrass was particularly competitive against field pea, the influence of MS on grain production was the greatest (Figure 2b). Even under modest rigid ryegrass infestation (98 plants m^{-2}), field peas under MS1 produced significantly less grain (1,265 kg ha^{-1}) relative to MS2 (1,997 kg ha^{-1}) and MS3 (2,162 kg ha^{-1}). Field peas are known for their high sensitivity to weed interference (McDonald 2003), and even small populations of rigid ryegrass can have a large effect on crop yield. Surprisingly, MS3 had very similar grain yields to MS2 (2,162 kg ha^{-1} vs. 1,997 kg ha^{-1}), despite being crop-topped with glyphosate. Several studies (Mayfield and Presser 1998; Lines et al. 2012) have shown that even slightly earlier than optimal timing of crop-topping in field peas with glyphosate can significantly reduce grain yield. However, the results presented here clearly show that if crops are monitored carefully, it is possible to safely use glyphosate to reduce rigid ryegrass seed production in field peas.

As differences in rigid ryegrass density within MSs were relatively small, herbicide effect on grain yield of wheat (2011) and barley (2012) was nonsignificant, and data were pooled across herbicide treatments within each MS (Figure 2b). However, large differences in rigid ryegrass density (Table 3) between MS1 and MS3 were reflected in wheat and barley grain yield (Figure 2b). As a consequence of reduced competition from rigid ryegrass, MS3 produced 15% more grain yield of wheat and 13% more yield of barley than MS1.

Over the 3-yr cropping sequence in this study (2010 to 2012), superior management of rigid ryegrass in MS3 and MS2 resulted in a 25 and 7% increase in cumulative grain production relative to MS1 (8,106 kg ha^{-1}; Figure 2b). Furthermore, effective management of rigid ryegrass in MS3 and MS2 provided an additional economic return of AUS $498 ha^{-1} and AUS$155 ha^{-1}, as compared with MS1 (AUS$1914 ha^{-1}; Figure 2a). Previous research in Western Australia (Roy 1999; Draper and Bent 2002) also showed that effective management of rigid ryegrass in the first year of the cropping cycle, when weed density was the highest, greatly improved profitability. In our study, additional investment in weed management in field peas and wheat substantially improved overall profitability of the cropping system.

Although rigid ryegrass has relatively short persistence in the seedbank, it is a prolific seed producer and populations can build up rapidly in a single season in response to ineffective weed-management practices. Integration of effective weed-management tactics within and across seasons caused a large decline in the rigid ryegrass seedbank and improved crop productivity and profitability. This study highlights the importance of complete seed-set prevention in situations in which weed populations have increased to extremely high levels because of control failure associated with herbicide resistance. This objective was achieved in this study by incorporating oaten hay in year 1 of the cropping sequence, which reduced rigid ryegrass seedbank by 86%. However, use of moderately effective weed-control tactics next season could lead to a large rebound in weed infestation, as occurred in this study in MS1. Therefore, it is vital to develop a multiyear program that not only provides early season weed control to protect crop yield from weed competition but also prevents seed set by weeds that escape control early in the growing season. Keeping the rigid ryegrass seedbank low could also reduce the risk of herbicide-resistance development to alternative herbicides used in an integrated weed management program. This combination of weed-management tactics is crucial considering the propensity of rigid ryegrass to rapidly evolve resistance to different mode-of-action herbicides across southern Australia (Broster et al. 2011; Boutsalis et al. 2012). The results of this study provide confidence that severe rigid ryegrass infestations can be managed effectively without reducing crop productivity and profitability when multiyear weed-management programs are implemented effectively.

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Literature Cited

Australian Bureau of Meteorology (2014) Climate Data Online. http://www.bom.gov.au/climate/data/index.shtml. Accessed March 4, 2014

Ball DA (1992) Weed seedbank response to tillage, herbicides, and crop rotation sequence. Weed Sci 40:654–659

Boutsalis P, Gill GS, Preston C (2012) Incidence of herbicide resistance in rigid ryegrass (*Lolium rigidum*) across southeastern Australia. Weed Technol 26:391–398

Broster JC, Koetz EA, Wu H (2011) Herbicide resistance levels in annual ryegrass (*Lolium rigidum* Gaud.) in southern New South Wales. Plant Prot Q 26:22–28

Buhler DD (1999) Weed population responses to weed control practices,1: seed bank, weed populations, and crop yields. Weed Sci 47:416–422

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

Draper A, Bent MJM (2002) Herbicide resistance in ryegrass: stochastic evaluation of management strategies. No. 7028 *in* Proceedings 13th International Farm Management Congress. Whittlesford, Cambridge, U.K.: International Farm Management Association

Gallagher RS, Steadman KJ, Crawford AD (2004) Alleviation of dormancy in annual ryegrass (*Lolium rigidum*) seeds by hydration and after-ripening. Weed Sci 52:968–975

Gill GS (1996) Why annual ryegrass is a problem in Australian Agriculture. Plant Prot Q 11:193–195

Gill GS, Holmes JE (1997) Efficacy of cultural control methods for combating herbicide resistant *Lolium rigidum*. Pestic Sci 51:352–358

Heap I, Knight R (1986) The occurrence of herbicide cross-resistance in a population of annual ryegrass, *Lolium rigidum*, resistant to diclofop-methyl. Aust J Agric Res 37:149–156

Jones RE, Vere DT, Alemseged Y, Medd RW (2005) Estimating the economic cost of weeds in Australian annual winter crops. Agric Econ 32:253–265

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

Lemerle D, Verbeek B, Cousens RD, Coombes NE (1996) The potential for selecting wheat varieties strongly competitive against weeds. Weed Res 36:505–513

Lemerle D, Lockley P, Luckett D, Wu H (2010) Canola competition for weed suppression. Pages 60–62 *in* Zydenbos SM, ed. Proceedings of the 17th Australasian Weeds Conference. Christchurch, New Zealand: New Zealand Plant Protection Society

Leys AR, Plater B, Cullis B (1988) Response of six temperate annual grasses to six selective herbicides. Plant Prot Q 3: 163–168

Lines M, McMurray L, Brand J (2012) Grain yield implications of crop-topping pulses for late weed control in south-eastern Australia. *In* Yunusa I, ed. Proceedings of 16th Australian Agronomy Conference: Capturing Opportunities and Overcoming Obstacles in Australian Agronomy. Warragul, VIC, Australia: Australian Society of Agronomy

Mayfield A, Presser R (1998) Crop-topping in pulses with paraquat and glyphosate for control of annual ryegrass. Pages 20–21 *in* Agribusiness Crop Updates. Perth, Western Australia: Department of Agriculture

McDonald GK (2003) Competitiveness against grass weeds in field pea genotypes. Weed Res 43:48–58

Newman P (2003) Crop topping Lupins for Ryegrass Control. E-Weed 4(16):67–70

Owen MJ, Walsh MJ, Llewellyn RS, Powles SB (2007) Widespread occurrence of multiple herbicide resistance in Western Australian annual ryegrass (*Lolium rigidum*) populations. Aust J Agric Res 58:711–718

Peltzer SC, Hashem A, Osten VA, Gupta ML, Diggle AJ, Riethmuller GP, Douglas A, Moore JM, Koetz EA (2009) Weed management in wide-row cropping systems: a review of current practices and risks for Australian farming systems. Crop Pasture Sci 60:395–406

Poole ML, Gill GS (1987) Competition between crops and weeds in southern Australia. Plant Prot Q 2:86–89

Powles SB, Bowran DG (2000) Crop weed management systems. Pages 287–306 *in* Sindel BM, ed. Australian Weed Management Systems. Meredith, VIC, Australia: R.G. and F.J. Richardson

Rerkasem K, Stern WR, Goodchild NA (1980) Associated growth of wheat and annual ryegrass, 1: effect of varying total density and proportion in mixtures of wheat and annual ryegrass. Aust J Agric Res 31:649–658

Rural Solutions SA. (2013) Farm Gross Margin and Enterprise Planning Guide Barton, ACT, Australia: Grains Research and Development Corporation

Roy W (1999) A systems approach to the control of herbicide resistant ryegrass. Page 226 *in* Bishop AC, Boersma M, Barnes CD, eds. Proceedings of the 12th Australian Weeds Conference. Hobart, Tasmania, Australia: Tasmanian Weed Society

Schreiber MM (1992) Influence of tillage, crop rotation, and weed management on giant foxtail (*Setaria faberi*) population dynamics and corn yield. Weed Sci 40:645–653

Smith DF, Levick GRT (1974) The effect of infestation by *Lolium rigidum* Gaud. (annual ryegrass) on the yield of wheat. Aust J Agric Res 25:381–393.

Steadman KJ, Eaton DM, Plummer JA, Ferris DG, Powles SB (2006) Late-season non-selective herbicide application reduces *Lolium rigidum* seed numbers, seed viability, and seedling fitness. Aust J Agric Res 57:133–141

VSN International (2011) GenStat for Windows. 14th edn. Hemel, Hempstead, U.K.: VSN International

Yu Q, Callaro A, Zheng M, Owen M, Sattin M, Powles SB (2007) Diversity of acetyl-coenzyme A carboxylase mutations in resistant *Lolium* populations: evaluation using clethodim. Plant Physiol 145:547–558

Zadoks JC, Chang TT, Konzak CF (1974) A decimal code for the growth stages of cereals. Weed Res 14:415–421

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