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Herbicide Application Strategies for the Control of Rigid Ryegrass (*Lolium rigidum*) in Wide-Row Faba Bean (*Vicia faba*) in Southern Australia

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Two field experiments were undertaken at Roseworthy, South Australia from 2006 to 2007 to evaluate the performance of herbicide application strategies for the control of herbicide-resistant rigid ryegrass in faba bean grown in wide rows (WR). The standard farmer practice of applying postsowing PRE (PSPE) simazine followed by POST clethodim to faba bean grown in WR provided consistent and high levels of rigid ryegrass control ($\geq$ 96%) and caused a large reduction ($P < 0.05$) in spike production ($\leq$ 20 spikes m^{-2}) as compared with nontreated control (560 to 722 spikes m^{-2}). Furthermore, this herbicide combination resulted in greatest yield benefits for WR faba bean (723 to 1,046 kg ha^{-1}). Although PSPE propyzamide used in combination with shielded interrow applications of glyphosate or paraquat provided high levels of rigid ryegrass control ($\geq$ 93%), these treatments were unable to reduce ryegrass spike density within the crop row (20 to 54 spikes m^{-2}) to levels acceptable for continued cropping. Furthermore, a yield reduction (13 to 29%) was observed for faba bean in treatments with shielded application of nonselective herbicides and could be related to spray drift onto lower leaves. These findings highlight that shielded interrow spraying in WR faba bean could play an important role in the management of rigid ryegrass in southern Australia. However, timing of shielded interrow applications on weed control, crop safety, and issues concerning integration with more effective early-season control strategies require attention.

Nomenclature: Clethodim; glyphosate; paraquat; propyzamide; simazine; rigid ryegrass, *Lolium rigidum* Gaud LORI; faba bean, *Vicia faba* (L.).

Key words: Rigid ryegrass, herbicide strategies, wide rows, faba bean, weed control.

De 2006 a 2007, dos experimentos de campo fueron realizados en Roseworthy, al sur de Australia, para evaluar el desempeño de estrategias de aplicación de herbicidas en el control de *Lolium rigidum* resistente a herbicidas en frijol faba, cultivado en surcos anchos (WR). La práctica estándar de los agricultores de aplicar simazine después de la siembra PRE emergente (PSPE) seguido por clethodim POS emergente (POST) al frijol faba cultivado en WR, proporcionó niveles altos y consistentes de control de *L. rigidum* ($\geq$96%) y causó una gran reducción (P<0.05) en producción de espigas ($\leq$20 espigas m^{-2}), cuando se comparó con el testigo no tratado (de 560 a 722 espigas m^{-2}). Además, esta combinación de herbicidas proporcionó mayores beneficios en el rendimiento del frijol WR (de 723 a 1046 kg ha^{-1}). Aunque cuando propyzamide PSPE usada en combinación con aplicaciones con pantalla entre surcos de glifosato o paraquat proporcionó altos niveles de control de *L. rigidum* ($\geq$93%), estos tratamientos no pudieron reducir la densidad de espigas de *L. rigidum* dentro del surco del cultivo (de 20 a 54 espigas m^{-2}) a niveles aceptables para la producción continua de cultivos. Además, una reducción del rendimiento de13 a 29% se observó en este cultivo en tratamientos con aplicación con pantalla de herbicidas no selectivos, la cual podría estar relacionada a la aspersión no intencional de las hojas inferiores. Estos resultados resaltan que la aspersión con pantalla entre surcos en frijol faba WR podría jugar un papel importante en el manejo de *L. rigidum* al sur de Australia. Sin embargo, se debe prestar atención al tiempo de las aplicaciones con pantalla entre surcos en el control de malezas, la seguridad del cultivo y los asuntos concernientes a la integración de estrategias de control más eficaz temprano durante el ciclo productivo.

Rigid ryegrass is a major winter annual weed of the southern Australian wheat belt that 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). In the 1980s rigid ryegrass was effectively controlled in crops with selective grass herbicides (Leys et al. 1988); however, this weed species has evolved resistance to nine major herbicide mode-of-action groups in Australia (Peltzer et al. 2009) and has the greatest number of herbicide resistance populations of any species (Preston et al. 1999). In crops and pastures this competitive weed can significantly reduce productivity (Lemerle et al. 1995; Poole and Gill 1987). Rigid ryegrass is a prolific seed producer (Rerkasem et al. 1980), which enables plants surviving weed control to readily replenish the seedbank and make management in following crops more difficult.

Resistance development in rigid ryegrass to most mode-of-action groups has been of major concern to growers and there have been some changes to its management in crops. One approach being explored, particularly by growers practicing precision agriculture, involves cultivation of pulse crops on wide rows (WR) to allow directed spraying of weeds between the crop rows with nonselective herbicides (Hashem et al. 2008, 2011; Peltzer et al. 2009). Traditionally this practice was confined to summer crops such as cotton, sorghum, and maize, which are grown in northern Australia on rows $\geq$ 0.5 m wide. However, WR cropping has been adopted by some lupin growers in Western Australia (Collins and Roche 2002; Hashem et al. 2008, 2011). Crops such as lupins,

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chickpeas, and faba beans appear to be well suited to cultivation on WR as they can maintain yield through their capacity to branch and fill the interrow space (Felton et al. 1996). French and Harries (2006) showed that there is little yield penalty in lupin grown in WR (54 to 74 cm) as compared with the conventional row spacing (25 cm). Similarly, no yield penalty was shown for faba bean grown in WR (36 and 54 cm), with increased pod density contributing to maintenance of yield (Kleemann and Gill 2008).

Precision agriculture and increased row spacing of pulse crops provides an opportunity to safely apply nonselective herbicides such as glyphosate or paraquat with spray shields between the rows (interrow) to prevent weed seed set. However, there are some potential disadvantages associated with the WR system; these include reduced competition with weeds, and increased reliance on nonselective herbicides for weed control (Peltzer et al. 2009).

The most common nonselective herbicide used between crop rows is glyphosate, to which some rigid ryegrass populations have already evolved resistance (Australian Glyphosate Sustainability Working Group 2011; Powles and Preston 2006). Intensive use of glyphosate in WR systems, particularly in the absence of herbicides with alternate modes of action, is likely to accelerate the incidence of weeds developing resistance to this important herbicide. At present information on the use of spray shields for the application of nonselective herbicides in WR cropping systems in southern Australia is limited. However, the potential of this technology for weed management has been acknowledged by other researchers (e.g., Peltzer et al. 2009). To address this knowledge gap, field experiments were conducted to evaluate the performance of shielded application of glyphosate and paraquat for the control of rigid ryegrass in WR faba bean.

Materials and Methods

Two field experiments were conducted over the growing seasons of 2006 and 2007 at Roseworthy located in the Lower North region of South Australia (34°30′36″S, 138°40′48″E at 68 m above sea level). The soil at the field sites was a sandy loam over medium calcareous clay with organic matter content of 2 to 2.5% and a pH (water) of 7 to 7.5. The long-term average annual rainfall at the site is 434 mm and average growing-season rainfall (April to October) 321 mm; rainfall received at the site in 2006 and 2007 is shown in Table 1 (source: Australian Bureau of Meteorology). Before the start of the experiment, the field was sprayed with glyphosate (900 g ai ha^{-1}) and oxyfluorfen (22 g ai ha^{-1}) for presowing weed control. Herbicide treatments of postsowing PRE(PSPE) simazine (1,350 g ai ha^{-1}) followed by POST clethodim (60 g ai ha^{-1}) were applied to faba bean sown on conventional (18 cm) and WR (54 cm) spacing. Application of PSPE simazine followed by POST clethodim to faba bean grown on 18-cm row spacing is considered standard farmer practice for the district. Additional herbicide treatments applied to WR faba bean were PSPE propyzamide (1,000 g ai ha^{-1}) and PSPE propyzamide (1,000 g ai ha^{-1}) followed by shielded application of POST glyphosate (810 g ai ha^{-1}) or paraquat (500 g ai ha^{-1}). A nontreated weedy treatment was also included as a control in both years.

Faba beans (cv Fiesta) were sown at 150 kg ha^{-1} (target 20 plants m^{-2}) on May 21, 2006 and June 5, 2007 using a John Shearer no-till trash drill fitted with knife-point openers (16 mm) and press wheels. Plots were 10-m long and contained 21 and 8 rows per plot respectively for 18- and 54-cm row spacing treatments; the outer crop rows in each plot were not sampled to avoid edge effects. Fertilizer rate was consistent with grower practice of 100 kg ha^{-1} of monoammonium phosphate (11 kg N and 52 kg P ha^{-1}) drilled at sowing.

Experiments were established in a randomized complete block design with four replicates. Herbicide applications (PSPE and POST) were applied using an all-terrain vehicle fitted with a spray boom delivering 100 L ha^{-1} water volume at a pressure of 200 kPa. Commercial TPOS spray shields (TPOS Fabrication Pty. Ltd., Victoria, Australia) applying similar water volume (100 L ha^{-1}) were used for interrow herbicide application 13 wk after sowing (WAS), when rigid ryegrass was at late tillering to stem elongation growth stage and the crop was at the flowering stage. Dates of herbicide application are shown in Table 1.

Rigid ryegrass plant and spike density were assessed in a 0.1-m^2 quadrat placed at three random intra- (on crop row) and interrow locations in each plot for herbicide treatments propyzamide and propyzamide followed by spray-shield glyphosate or paraquat. For all other treatments quadrat (0.1 m^2) assessments were undertaken in the same way; however, they were not specific to either the intra- or interrow locations. Assessments of plant density were taken 6 and 16 WAS before and after POST herbicide application. Spike density was assessed 16 to 18 WAS when all spikes had emerged. Faba bean yield was determined using a small plot harvester when the crop had reached physiological maturity. Harvest dates for each experiment are shown in Table 1. A grain subsample (500 g) was used to determine grain size (g [100 seeds]$^{-1}$).

Weed control (plant and spike density) and crop data (yield and grain size) were analyzed with ANOVA (Genstat 5 Committee, 1993). A square-root variance-stabilizing transformation was used for weed control data before analysis. Original means are reported with mean separation of the transformed data. Means were separated using LSD at $P = 0.05$. A two-tailed t test was used to compare the effect of row spacing (18 and 54 cm) on mean weed establishment 6 WAS, and before application of clethodim herbicide (Table 2).

Results and Discussion

Weed Control. Herbicide treatments applied to faba bean grown on conventional row spacing (18 cm) and WR (54 cm) in 2006 and 2007 resulted in significant ($P \leq 0.05$) reduction in rigid ryegrass density relative to the nontreated control (Table 3). In both years, the standard farmer practice of PSPE simazine (1,350 g ai ha^{-1}) followed by POST clethodim (60 g ai ha^{-1}) to beans grown on conventional row spacing provided 84 and 95% control of rigid ryegrass relative

Table 1. Rainfall, harvest dates, and herbicide management details for the two study sites.

Year	Rainfall		Harvest date	Spray application date		
				Postsowing PRE	POST	
	Annual	GSR[a,b]		Simazine/propyzamide	Clethodim[c]	Glyphosate/paraquat[d]
	mm					
2006	302	158	November 8	May 22	July 19	August 21
2007	363	238	November 27	June 6	August 6	September 04

[a] Abbreviation: GSR, growing season rainfall.

[b] GSR for site year from April to October.

[c] Clethodim was applied POST when weeds were at two- to five-leaf stage of growth.

[d] Spray-shield treatments of glyphosate/paraquat were applied when weeds were at late tillering to stem elongation stage of growth.

to the nontreated control (189 plants m^{-2}, 2006; 111 plants m^{-2}, 2007). PSPE propyzamide by itself provided 79 to 88% reduction in rigid ryegrass density in WR faba bean. Slightly lower weed kill in this treatment than the farmer practice could simply be related to absence of any follow-up POST treatment. In PSPE propyzamide treatment, most of the rigid ryegrass that survived was present within the crop row, 70% in 2006 and 61% in 2007. This was also reflected in the density of rigid ryegrass spikes with 68% in 2006 and 60% in 2007 present within the row (Table 4). This pattern of rigid ryegrass distribution in the crop puts a limit on the level of efficacy that could be achieved from the shielded herbicide treatments without damaging the crop and reducing grain yield.

In spite of the high levels of weed control with the standard practice, surviving ryegrass managed to produce 12 to 125 spikes m^{-2} (Table 4). Herbicide resistance screening of this population revealed low levels of resistance (< 20% survival) to clethodim. The same herbicide combination applied to WR beans also provided high levels of weed control in 2006 (97%) and 2007 (96%); however, spike production was much lower (7 to 20 spikes m^{-2}) than the conventional row spacing treatment (12 to 125 spikes m^{-2}). This difference in spike density of rigid ryegrass between the two row-spacing treatments in both years was associated with lower initial ryegrass establishment under WR (35 to 48 plants m^{-2}) relative to the narrow row-spacing (85 to 139 plants m^{-2}) treatment (Table 2). Increased soil disturbance under narrow row spacing could have provided shallow burial and more favorable germination environment than under the WR system where seeds remain exposed to wetting and drying cycles on the soil surface. Large differences in ryegrass recruitment due to soil disturbance by tillage have been reported in previous research (Chauhan et al. 2006).

Table 2. Effect of row spacing (18 and 54 cm) on rigid ryegrass establishment (plants m^{-2}) 6 wk after sowing and before application of POST clethodim at Roseworthy in 2006 and 2007.[a] Means were compared using a two-tailed *t* test (P = 0.05).

Row spacing	2006	2007
cm	Plants m^{-2}	
18	139 (19)	85 (12)
54	48 (8)	35 (5)
P = 0.05	< 0.001	< 0.001

[a] Values in parentheses are SE of the mean.

In the absence of any herbicide treatment, rigid ryegrass managed to produce a large number of spikes (560 to 722 spikes m^{-2}). This is not entirely unexpected, as legume crops are known to be less competitive against weeds than cereals (Lemerle et al. 1995). Reduction in the competitive ability of the crop with weeds growing in the interrow space has also been reported in other crop species (e.g., Fischer and Miles 1973; Osten et al. 2006), and is an inherent problem associated with WR cropping systems. In contrast, competition within the crop row may be expected to increase provided seeding rates are maintained, with the number of crop plants in the row increasing as the row space becomes wider. As a consequence, interspecific competition between the crop and weeds within the crop row is expected to increase (Wells 1993), thus reducing the weed impact.

The combination of shielded interrow applications of glyphosate or paraquat with PSPE propyzamide in both 2006 and 2007 resulted in significant improvements in rigid ryegrass control (93 to 97%) and most of the surviving weeds were present within the rows. Application of the shielded treatments virtually eliminated ryegrass spike production between the rows (0 to 4 spikes m^{-2}); however, there was still a sizable spike density present within the rows (20 to 54 spikes m^{-2}). Rigid ryegrass is known to be a prolific seed producer (Rerkasem et al. 1980) and each spike can produce around 20 viable seeds (Kleemann and Gill, unpublished data). Therefore even with the use of spray shields, rigid ryegrass present within rows is likely to replenish the seedbank and ensure future infestations by this weed species.

Crop Grain Yield. Rigid ryegrass was extremely competitive against faba bean and caused large reductions ($P < 0.05$) in grain yield (Table 5). Significant yield penalties due to ryegrass interference have also been reported for other pulse crops (Hashem et al. 2011; Lemerle et al. 1995; McDonald 2003;). Crop yield loss caused by rigid ryegrass in nontreated control relative to simazine followed by clethodim was much greater in 2006 (85%) than in 2007 (36%). Greater sensitivity of faba bean to rigid ryegrass in 2006 could be the result of greater weed density and lower growing-season rainfall, which could have exacerbated competition for soil water. In both years, grain yield was higher in WR plots treated with simazine and clethodim (723 to 1,046 kg ha^{-1}) than the conventional row spacing (577 to 698 kg ha^{-1}),

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Table 3. Effect of herbicide treatments on rigid ryegrass plant density (plants m^{-2}) in faba bean grown in wide-rows at Roseworthy in 2006 and 2007.[a]

Treatment[b]	Dose	Row spacing	Rigid ryegrass plants 2006 Mean	2006 Intrarow	2006 Interrow	2007 Mean	2007 Intrarow	2007 Interrow
	g ai ha^{-1}	cm	Plants m^{-2}	%		Plants m^{-2}	%	
Nontreated	-	54	189 a	-	-	111 a	-	-
Simazine PSPE/clethodim POST	1,350 + 60	18	30 b	-	-	6 c	-	-
Simazine PSPE/clethodim POST	1,350 + 60	54	5 d	-	-	4 c	-	-
Propyzamide PSPE	1,000	54	22 bc	70	30	23 b	61	39
Propyzamide PSPE/interrow glyphosate POST	1,000 + 800	54	6 d	58	42	4 c	100	0
Propyzamide PSPE/interrow paraquat POST	1,000 + 500	54	13 cd	76	24	3 c	100	0

[a] Means within the same column followed by the same letters are not significantly different according to LSD at the $P \leq 0.05$ level. Weed control data were square-root transformed before means comparisons. Nontransformed means are shown in the table.

[b] Abbreviation: PSPE, postsowing PRE.

Table 4. Effect of herbicide treatments on rigid ryegrass spike density (spikes m^{-2}) in faba bean grown in wide rows at Roseworthy in 2006 and 2007.[a]

Treatment[b]	Dose	Row spacing	Rigid ryegrass spikes 2006 Mean	2006 Intrarow	2006 Interrow	2007 Mean	2007 Intrarow	2007 Interrow
	g ai ha^{-1}	cm	Spikes m^{-2}	%		Spikes m^{-2}	%	
Nontreated	-	54	722 a	-	-	560 a	-	-
Simazine PSPE/clethodim POST	1,350 + 60	18	125 c	-	-	12 c	-	-
Simazine PSPE/clethodim POST	1,350 + 60	54	20 e	-	-	7 c	-	-
Propyzamide PSPE	1,000	54	187 b	68	32	122 b	60	40
Propyzamide PSPE/interrow glyphosate POST	1,000 + 800	54	30 e	97	3	20 c	100	0
Propyzamide PSPE/interrow paraquat POST	1,000 + 500	54	54 d	96	4	30 c	100	0

[a] Means within the same column followed by the same letters are not significantly different according to LSD at the $P \leq 0.05$ level. Weed control data were square-root transformed before means comparisons. Nontransformed means are shown in the table.

[b] Abbreviation: PSPE, postsowing PRE.

which received the same herbicide treatment. In previous research (Felton et al. 2004; Kleemann and Gill 2008) yield increases in WR faba bean in comparison with the conventional row spacing have been attributed to increased pod density (Kleemann and Gill 2008). Despite improvements in rigid ryegrass control when propyzamide was followed by shielded glyphosate or paraquat, grain yields in these treatments were lower (502 to 614 kg ha^{-1}) than propyzamide alone (705 to 716 kg ha^{-1}) in 2006 and 2007. This yield reduction (13 to 29%) in treatments with shielded application of nonselective herbicides could be related to spray drift onto lower leaves of the well-developed crop. Earlier use of interrow glyphosate and paraquat in crops with smaller canopies may reduce or prevent crop damage. However, there could be some trade-off in terms of escape of later-emerging weed cohorts if interrow treatment is applied much earlier (Hilgenfeld et al. 2004). Although not examined in this study, timing of shielded applications on weed control and crop safety and issues concerning integration with more effective early-season control strategies require future attention. In contrast to previous studies (Hashem et al. 2008) where interrow glyphosate resulted in greater crop damage and yield

Table 5. Effect of herbicide treatments on grain yield (kg ha^{-1}) and grain size (g [100 seeds]$^{-1}$) of faba bean grown in wide rows at Roseworthy in 2006 and 2007.[a]

Treatment[b]	Dose	Row spacing	Grain yield 2006	Grain yield 2007	Grain size 2006	Grain size 2007
	g ai ha^{-1}	cm	kg ha^{-1}		g [100 seeds]$^{-1}$	
Nontreated	-	54	156 d	462 d	60.6 b	54.5 b
Simazine PSPE/clethodim POST	1,350 + 60	18	698 b	577 bcd	66.1 a	60.1 a
Simazine PSPE/clethodim POST	1,350 + 60	54	1046 a	723 a	65.0 a	59.2 a
Propyzamide PSPE	1,000	54	705 b	716 ab	64.7 a	60.4 a
Propyzamide PSPE/interrow glyphosate POST	1,000 + 800	54	614 bc	562 cd	64.5 a	61.7 a
Propyzamide PSPE/interrow paraquat POST	1,000 + 500	54	502 c	536 cd	64.1 a	61.0 a

[a] Means within the same column followed by the same letters are not significantly different according to LSD at the $P \leq 0.05$ level.

[b] Abbreviation: PSPE, postsowing PRE.

loss (6 to 12%) compared with diquat and paraquat (1%), this study showed no differences in yield between shielded glyphosate and paraquat.

Faba bean grain size was unaffected by the herbicide treatment in 2006 (64.1 to 66.1 g [100 seeds]$^{-1}$) and 2007 (60.4 to 61.7 g [100 seeds]$^{-1}$) (Table 5). However, grain size was reduced significantly in the nontreated control (54.5 to 60.6 g [100 seeds]$^{-1}$) as compared with the herbicide treatments, which is likely to be due to competition between rigid ryegrass and the crop for water during the reproductive phase.

Given the growing number of populations of rigid ryegrass showing resistance to grass-selective herbicides, including clethodim (Boutsalis et al. 2008), shielded interrow spraying could play an important role in the management of resistant rigid ryegrass in southern Australia. However, as this study has shown, poor control of weeds in the crop row is a major limitation of spray shields. This limitation needs to be overcome before shielded spraying can become an effective weed management option for WR cropping systems in southern Australia.

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