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Control of Rigid Ryegrass in Australian Wheat Production with Pyroxasulfone

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In Australia, most wheat is sown in a no-till system without prior cultivation where herbicides are applied prior to sowing and incorporated by the planter. Trifluralin has been the most widely used PRE herbicide to control rigid ryegrass. The objective of this research was to determine crop safety and efficacy of alternative mechanism of action PRE herbicides for rigid ryegrass control in no-till wheat production. Pyroxasulfone achieved 98% control with PRE applications. The alternative PRE herbicides tested alone and in mixtures occasionally resulted in a significant reduction in wheat emergence but not crop yield. Trifluralin treatments failed at sites having trifluralin-resistant rigid ryegrass. Pyroxasulfone and prosulfocarb plus *S*-metolachlor were effective for control of rigid ryegrass across all trials with control ranging from 64 to 94%. This research demonstrated that PRE applications of herbicides other than trifluralin such as pyroxasulfone and prosulfocarb plus *S*-metolachlor can be safely and effectively used to control rigid ryegrass in no-till wheat.

Nomenclature: Cinmethylin, *S*-metolachlor; prosulfocarb; pyroxasulfone; trifluralin; rigid ryegrass, *Lolium rigidum* Gaudin LOLRI; wheat, *Triticum aestivum* L. 'Frame', 'Pugsley', 'Young', 'Yitpi'.

Key words: Crop selectivity, herbicide efficacy, herbicide resistance, PRE, preplant-incorporated.

En Australia, la mayoría del trigo se siembra en un sistema de labranza cero sin cultivo previo donde los herbicidas son aplicados antes de la siembra e incorporados con la sembradora. Trifluralin ha sido el herbicida PRE más ampliamente usado para el control de *Lolium rigidum*. El objetivo de esta investigación fue determinar la seguridad para el cultivo y la eficacia de herbicidas PRE con mecanismos de acción alternativos para el control de *L. rigidum* en producción de trigo en labranza cero. Pyroxasulfone alcanzó 98% de control con aplicaciones PRE. Los herbicidas PRE alternativos evaluados solos y en mezclas ocasionalmente resultaron en una reducción significativa en la emergencia del trigo pero no del rendimiento del cultivo. Los tratamientos de trifluralin fallaron en sitios que tenían *L. rigidum* resistente a trifluralin. Pyroxasulfone y prosulfocarb más *S*-metolachlor fueron efectivos para controlar *L. rigidum* en todos los ensayos con un control que fluctuó entre 64 y 94%. Esta investigación demostró que aplicaciones PRE de herbicidas diferentes a trifluralin, tales como pyroxasulfone y prosulfocarb más *S*-metolachlor pueden ser usados en forma segura y efectiva para el control de *L. rigidum* en trigo en labranza cero.

Resistance to herbicides is of major concern in the grain-growing regions of southern Australia where there are 36 weed species confirmed resistant to one or more herbicides (Heap 2013). The most troublesome weed species in Australian cereal production is rigid ryegrass. Random surveys conducted across all four southern Australian states (Boutsalis et al. 2012; Broster et al. 2011; Owen et al. 2007) have revealed an alarming proportion of fields contain herbicide-resistant rigid ryegrass with resistance to acetyl-CoA carboxylase (ACCase)- and acetolactate-synthase (ALS)-inhibiting herbicides being the most common. Resistance to ALS-inhibiting herbicides is the most common form of resistance, with at least half of the fields surveyed in south-eastern Australia containing biotypes expressing resistance to this group (Boutsalis et al. 2012). Similar levels of ALS-inhibiting herbicide resistance have also been identified in New South Wales and Western Australia (Broster et al. 2011; Owen et al. 2007). The incidence of resistance to ACCase-inhibiting herbicides ranged between 30 and 60% of cropping fields depending on the region, with higher frequencies of resistant populations occurring in more intensively cropped regions (Boutsalis et al. 2012).

Over the last 20 yr, the majority of Australian grain growers have adopted no-till farming systems where stubble is retained and seed planted without prior cultivation of the soil (D'Emden et al. 2006,

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Table 1. Details of PRE herbicide efficacy field trials in no-till wheat from 2005 to 2008.

Year	Location	Rainfall[a]	Soil classification[b]	Variety	Seeding rate	Planting system	Trifluralin-resistance status[c]
		mm			kg ha^{-1}		
2005	Mintaro	444	Chromosol	Frame	100	Plot	Susceptible
2005	Hart	334	Calcarosol	Frame	100	Plot	Susceptible
2005	Roseworthy	402	Calcarosol	Pugsley	100	Commercial	Susceptible
2006	Cummins	179	Chromosol	Young	100	Plot	Resistant
2008	Berriwillock	130	Calcarosol	Yitpi	70	Commercial	Resistant

[a] Growing season rainfall April to October.

[b] From McKenzie et al. (2001).

[c] Trifluralin resistance determined by pot testing as described in Boutsalis et al. (2012).

2008; Rainbow and Derpsch 2011). Without the use of POST herbicides in wheat due to resistant weeds, there has been a strong reliance on trifluralin to control rigid ryegrass in no-till farming systems. Increased use of trifluralin to control ACCase- and ALS-resistant rigid ryegrass has increased the frequency of resistance to this herbicide in South Australia (SA) (Boutsalis et al. 2012). More recently, a mixture of trifluralin plus triallate has been used by growers in attempts to control trifluralin-resistant rigid ryegrass. Trifluralin plus triallate controls rigid ryegrass populations that are not resistant or are only weakly resistant to trifluralin. However, where strong resistance to trifluralin exists, trifluralin plus triallate fails to control rigid ryegrass.

Trifluralin is typically applied prior to planting the crop in this system and is incorporated by the seeding operation (IBS) (Rainbow and Derpsch 2011). In this system, a narrow (17 mm) knife-point opener or tyne is commonly used to sow the seed. The opener removes herbicide-treated soil from the seed row and distributes it on the interrow. Removal of the herbicide from the furrow improves crop safety and coverage of herbicide in the interrow (Chauhan et al. 2006a, 2007). With more trifluralin-resistant rigid ryegrass populations being detected (Boutsalis et al. 2012), it is important that new mechanism of action herbicides be identified and developed to manage this species in no-till systems.

Until recently, trifluralin, ACCase-inhibitors, and ALS-inhibitors were the primary herbicides available to control rigid ryegrass in wheat. A series of field trials were conducted in SA and Victoria from 2005 to 2008 to evaluate PRE herbicides (cinmethylin, prosulfocarb, and pyroxasulfone) for the control of rigid ryegrass. These herbicides have different mechanisms of action that would complement the existing herbicides currently available for ryegrass control in wheat. Pyroxasulfone and *S*-metolachlor have been reported to inhibit very long chain fatty acids (WSSA Group 15 and HRAC group K3) (Schmalfuss et al. 2000; Tanetani et al. 2009). Prosulfocarb is a thiocarbamate herbicide (WSSA Group 8, 26 and HRAC group N), which inhibits lipid synthesis (Abulnaja and Harwood 1991). The mechanism of action for cinmethylin is unknown, and therefore it has been placed in WSSA Groups 17, 25 and HRAC group Z (El-Deek and Hess 1986). Additionally, the selectivity of these diverse herbicides in no-till wheat in southeastern Australia is unknown. Therefore, the objective of this research was to investigate herbicides with an alternative mechanism of action on rigid ryegrass control and crop safety in no-till wheat production systems.

Materials and Methods

Pyroxasulfone Application Timing for Rigid Ryegrass Control. Two field trials were conducted in 2005 in the midnorth region of SA (Table 1) at Hart (average annual rainfall 407 mm) and Mintaro (average annual rainfall 632 mm). Wheat cultivar 'Frame' was sown with a knife-point opener and press-wheel closer small-plot seeder at the seed rate of 60 kg ha^{-1} with seed depth ranging between 20 and 30 mm. Additionally, 12 kg phosphorous ha^{-1} was applied as 60 kg ha^{-1} diammonium phosphate fertilizer in the same operation. An application of urea was spread during the growing season at both sites; 100 kg ha^{-1} at Mintaro and 70 kg ha^{-1} at Hart. The Hart trial was planted into oat (*Avena sativa* L.) stubble; whereas the Mintaro trial was

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planted into faba bean (*Vicia faba* L.) stubble. Plots were 2 m wide by 10 m long. The trial had three replications.

Pyroxasulfone was applied IBS, postsowing, preemergent (PSPE), or POST at 30, 60, and 120 g ai ha^{-1} with a single nontreated check in each replication. Treatments were applied with a gas-operated field plot sprayer equipped with a 2-m boom with four 015 minidrift nozzles (Hardi Australia Pty., Ltd). The sprayer was calibrated to deliver 110 L ha^{-1} at 250 kPa. The IBS treatments were applied immediately prior to planting and PSPE treatments 2d following planting. The POST treatments were applied at the Z11 to Z12 growth stage (Zadoks et al. 1974) of wheat. Crop establishment (quantified as density in plants m^{-2}) was determined by counting the number of wheat plants along 1 m of row in each of three parallel crop rows in each plot at 3 wk after treatment (WAT) of the POST herbicide. Grain yield was measured by harvesting the entire plot with a plot harvester. Rigid ryegrass plant numbers were assessed 3 WAT by counting plants within four 40- by 40-cm quadrats randomly placed in each plot.

Efficacy of PRE Herbicides for the Control of Rigid Ryegrass in Cereals. Field trials in wheat were conducted between 2005 and 2008 in SA and Victoria using either commercial or plot seeders. Classification of soil types at the experimental sites has been described in Table 1. Planting was completed using a drill outfitted with a knifepoint opener and press-wheel closer system with depth ranging between 20 and 30 mm. This no-till planting technique is the most common practice in cereal farming in Australia (D'Emden et al. 2008; Rainbow and Derpsch 2011). Individual plot dimensions were 2 m by 10 m. Herbicide application occurred 24 h before to planting to minimize herbicide degradation on the soil surface or volatilization. Herbicides included in the field trials were cinmethylin, *S*-metolachlor, prosulfocarb, pyroxasulfone, and trifluralin. Herbicides were applied using the same gas-operated field plot sprayer described previously. Additional information on each trial, including the location, year, and trifluralin-resistant status of the rigid ryegrass is presented in Table 1. The trial at Roseworthy was IBS into faba bean stubble, that at Cummins into canola (*Brassica napus* L.) stubble, and that at Berriwillock into wheat stubble. Assessment of wheat yield and wheat and rigid ryegrass plant density was made using the same methodology as described previously. Rigid ryegrass spike density was assessed by counting the number of spikes present within five 40- by 40-cm quadrats per plot. Because one of the sites was located on a commercial farm where trifluralin-resistant rigid ryegrass was present, grain yield could not be determined because the crop was sprayed with glyphosate at flowering to prevent weed seedset.

Statistical Analyses. Each field trial was established as a randomized complete block design consisting of three replications. For the Hart and Mintaro trials in 2005, a two-way ANOVA was conducted. Transformation of data did not improve homogeneity of variance; thus, analysis was performed on nontransformed weed control and crop stand and yield data. There was no effect of site or interaction between treatment and site for wheat emergence, so data were pooled for this measurement. There was no interaction between treatment and site for grain yield, but a significant effect of site ($P < 0.0001$) was present, so data from the two sites were analyzed separately. There was a significant interaction between treatment and site for rigid ryegrass numbers ($P < 0.0001$), so sites were analyzed separately. Rigid ryegrass density in the pyroxasulfone dose-response experiment was analyzed by logistic analysis (Seefeldt et al. 1995). The resulting predicted dose-response curves were compared with an *F* test.

In all other trials, an ANOVA was conducted for each measurement in each trial. Transforming rigid ryegrass plant numbers in the Roseworthy trial improved the homogeneity of variance so the ANOVA was performed on the transformed data. Transformation of the remaining data did not improve homogeneity of variance; thus, analysis was performed on nontransformed weed control and crop data. Data on variance was visually inspected by plotting residuals to confirm homogeneity of variance before statistical analysis. Means were separated with the use of Fisher's protected LSD at $P = 0.05$.

Results and Discussion

Pyroxasulfone Application Timing for Rigid Ryegrass Control. Rigid ryegrass control with pyroxasulfone varied significantly with application

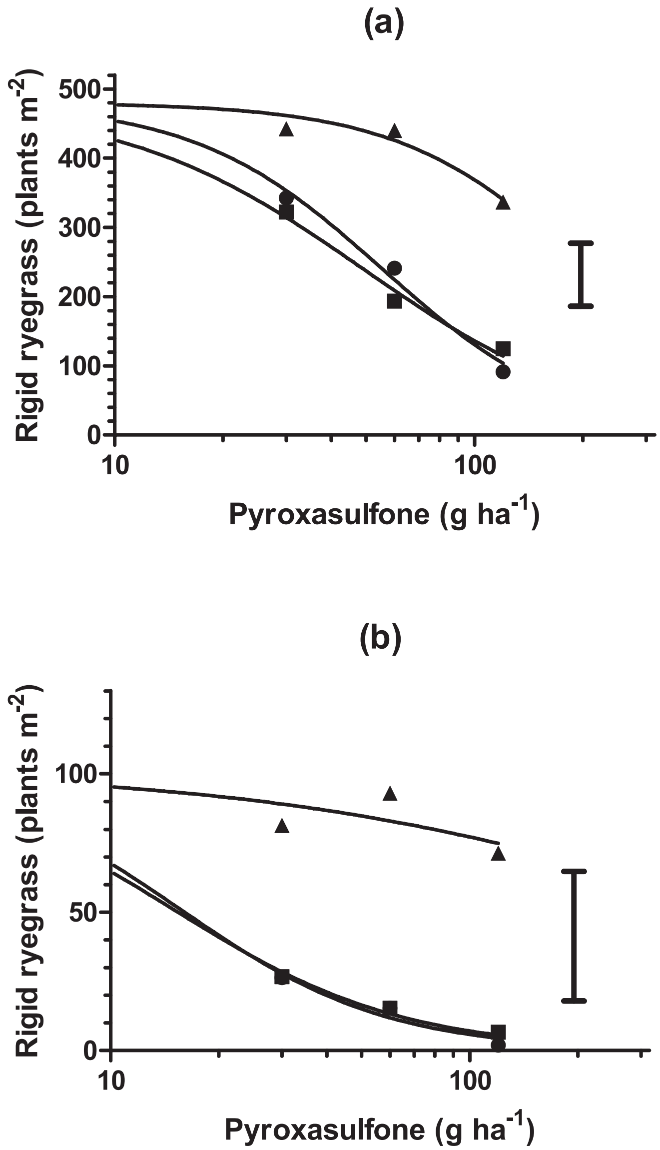

Figure 1. Effect of pyroxasulfone dose applied/incorporated by the seeding operation (IBS) (●), postsowing, preemergent (PSPE) (■), and POST (▲) applications on rigid ryegrass density in field experiments at (a) Mintaro and (b) Hart. The predicted dose-response curves are for Mintaro: $Y = 480/\{1 + e^{[(55.5 - \text{dose}) \times -3.841]}\}$, $Y = 480/\{1 + e^{[(49.1 - \text{dose}) \times -3.0]}\}$, and $Y = 480/\{1 + e^{[(203 - \text{dose}) \times -3.882]}\}$ for IBS, PSPE, and POST treatments, respectively; and for Hart: $Y = 102/\{1 + e^{[(15.7 - \text{dose}) \times -3.48]}\}$, $Y = 102/\{1 + e^{[(15.0 - \text{dose}) \times -3.29]}\}$, and $Y = 102/\{1 + e^{[(557 - \text{dose}) \times -1.523]}\}$ for IBS, PSPE, and POST treatments, respectively. The bar represents the LSD.

timing. Control of rigid ryegrass by pyroxasulfone was significantly greater at both sites for PRE IBS or PSPE applications than for POST applications (Figure 1). Rigid ryegrass control was similar between PRE IBS and PSPE treatments, but there was a difference between these two application timings and pyroxasulfone applied POST at both sites ($P < 0.0001$ at Mintaro; $P = 0.002$ at Hart). For the PRE IBS and PSPE treatments, all herbicide rates reduced rigid ryegrass density compared with the nontreated control. The Hart site had a considerably lower rigid ryegrass density compared with the Mintaro site (102 compared with 480 plants m^{-2}), which resulted in better overall control with PRE IBS and PSPE applications of pyroxasulfone.

Table 2. Effect of different dose and timing of pyroxasulfone on wheat plant density and grain yield at Mintaro and Hart locations.[a]

Timing	Rate	Wheat	Grain yield: Mintaro	Grain yield: Hart
	g ha^{-1}	plants m^{-2}	kg ha^{-1}	kg ha^{-1}
Nontreated check	0	164	1,930	1,850
PRE[b]	30	173	2,060	2,110
	60	163	2,190	2,230
	120	161	2,460	2,300
PSPE[c]	30	175	2,050	2,000
	60	173	2,250	2,190
	120	158	2,470	2,250
POST[d]	30	154	1,900	1,880
	60	155	2,080	1,820
	120	170	2,200	2,080
$LSD_{(0.05)}$		NS	310	310

[a] Abbreviations: PSPE, postsowing, preemergent; IBS, incorporated by the seeding operation.
[b] Applied IBS immediately prior to sowing.
[c] PSPE treatment 2 d after the PRE treatment.
[d] POST treatments applied at one- to two-leaf stage of crop.

There was no effect of pyroxasulfone at any rate or timing of application on wheat establishment at either Mintaro or Hart in 2005 (Table 2). A significant effect of herbicide application on wheat yield was identified at both sites. At both sites, the nontreated check had the lowest crop yield. At Mintaro, there was a significant increase in crop yield over the nontreated check for pyroxasulfone rates of 120 g ha^{-1} applied PRE IBS and 60 or 120 g ha^{-1} applied PSPE; however, the POST application of pyroxasulfone did not increase grain yield (Table 2). Likewise at Hart, there was a significant increase in grain yield over the nontreated check for pyroxasulfone rates of 60 and 120 g ha^{-1} for the PRE IBS and PSPE treatments, but not for the POST treatment.

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Table 3. Effect of PRE herbicides applied/incorporated by the seeding operation (IBS) on wheat variety 'Pugsley' yield and rigid ryegrass control at Roseworthy, South Australia in 2005.

Herbicide[a]	Rate	Grain yield	Rigid ryegrass	
	g ha^{-1}	kg ha^{-1}	plants m^{-2}	% of nontreated
Nontreated	0	3,620	168	—
Trifluralin	480	3,950	76	53
Trifluralin	960	3,830	69	58
Pyroxasulfone	60	3,980	40	76
Pyroxasulfone	120	3,770	41	75
Cinmethylin	200	3,960	117	29
Prosulfocarb	1,600	3,960	58	65
Prosulfocarb	3,200	3,990	80	52
Prosulfocarb + *S*-metolachlor	1,600 + 288	3,930	40	76
Prosulfocarb + *S*-metolachlor	3,200 + 288	4,120	47	72
$LSD_{(0.05)}$		350	19	

[a] Herbicides used: cinmethylin, Cinch, 735g L^{-1}, BASF Crop Protection, Limburgerhof, http://www.agro.basf.com/agr/AP; *S*-metolachlor, Dual Gold, 960g L^{-1}, Syngenta, Basel, Switzerland, www.syngenta.com; prosulfocarb, Defy, 800g L^{-1}, Syngenta, Fulbourn, Cambridge, www.syngenta-crop.co.uk; pyroxasulfone, Sakura, 850g kg^{-1}), Kumiai Chemical Industry, Taito-Ku, Tokyo, www.kumiai-chem.co.jp; and trifluralin, Triflur X, 480g L^{-1}, Nufarm, Laverton, Victoria, www.nufarm.com.

Pyroxasulfone was safe on wheat at the rates and timings used while providing acceptable rigid ryegrass control at rates of 60 and 120 g ha^{-1}. Greater wheat yields in the pyroxasulfone treatments were likely due to reduction in competition from rigid ryegrass. The trial also demonstrated POST application of pyroxasulfone had lower efficacy than PRE IBS or PSPE applications.

Efficacy of PRE Herbicides for the Control of Rigid Ryegrass in Cereals. The effect of PRE herbicides applied IBS on rigid ryegrass control in wheat was investigated in three field trials conducted in different cropping regions (each 500 to 600 km apart) across southern Australia in 2005 (Roseworthy, SA), 2006 (Cummins, SA), and 2008 (Berriwillock, Victoria). Both SA sites are in intermediate rainfall areas, whereas the Berriwillock site is in a low-intermediate rainfall area (Table 1). A feature of no-till fields in southern Australia is the shallow placement of weed seed near to the soil surface (Chauhan et al. 2006b). Such vertical distribution of the weed seed bank is ideal for the efficacy of PRE herbicides applied IBS, because the herbicide is applied directly onto the weed seed and soil and then covered with a small amount of soil.

At Roseworthy in 2005, all herbicide treatments resulted in significant reductions in rigid ryegrass relative to the nontreated check, with significant differences between herbicide treatments (Table 3). The most effective treatments for reducing rigid ryegrass density were both rates of pyroxasulfone (60 and 120 g ha^{-1}) and prosulfocarb plus *S*-metholachlor at 1,600 + 288 g ha^{-1} which resulted in a 72 to 78% rigid ryegrass density reduction (Table 3). These treatments were significantly better than cinmethylin (29% density reduction).

At Cummins in 2006, application of a PRE herbicide, regardless of active ingredient, resulted in a significant reduction of rigid ryegrass density compared to the nontreated check (Table 4). Pyroxasulfone at 150 g ha^{-1} provided the greatest level of reduction in rigid ryegrass density (79%), which was significantly different to trifluralin at 480 g ha^{-1} and cinmethylin at 200 g ha^{-1}. There were no significant differences between the other herbicide treatments. The lack of control with trifluralin in this trial was attributed to trifluralin-resistant rigid ryegrass being present in the population (Table 1).

At Berriwillock in 2008, all PRE herbicides reduced rigid ryegrass density compared with the nontreated check. Trifluralin at 960 g ha^{-1} provided the least reduction in rigid ryegrass density (60%) and that density reduction was significantly less than all other herbicide treatments. Resistance to trifluralin was confirmed in this population (data not shown) and is likely to have contributed to the reduced efficacy of this herbicide. Control of rigid ryegrass 4 WAT for other PRE herbicide treatments ranged between 85 to 94% reduction of rigid ryegrass density, and were similar (Table 5). The

Table 4. Effect of PRE herbicides applied/incorporated by the seeding operation (IBS) on wheat variety 'Young' establishment, grain yield and control of trifluralin-resistant rigid ryegrass at Cummins, South Australia in 2006.

Treatment	Rate	Wheat	Grain yield	Rigid ryegrass	
	g ha^{-1}	plants m^{-2}	kg ha^{-1}	plants m^{-2}	% of nontreated
Nontreated	0	217	1,680	236	—
Trifluralin	480	160	1,770	154	32
Cinmethylin	200	174	1,710	142	37
Pyroxasulfone	100	200	2,490	82	64
Pyroxasulfone	150	155	2,700	47	79
Prosulfocarb + *S*-metolachlor + trifluralin	1,200 + 180 + 720	160	2,080	120	47
Prosulfocarb + *S*-metolachlor	2,000 + 300	221	2,500	75	67
$LSD_{(0.05)}$		60	560	81	

reduction in rigid ryegrass density 4 WAT with pyroxasulfone and prosulfocarb plus *S*-metholachlor resulted in reduced rigid ryegrass spikes compared to trifluralin (data not shown). This has important implications for reducing seed bank replenishment.

Selectivity of PRE Herbicides in Wheat. In each of the field trials at Roseworthy, Cummins, and Berriwillock the effect of PRE herbicides applied IBS on wheat was investigated. At Roseworthy in 2005, grain yield only was measured. There was no reduction in grain yield with PRE herbicides applied IBS in this trial (Table 3), suggesting the alternative herbicides pyroxasulfone, cinmethylin, and prosulfocarb can be used safely in wheat if applied IBS.

At Cummins in 2006, wheat emergence and grain yield were measured. A significant reduction in crop emergence was observed with trifluralin, prosulfocarb plus *S*-metholachlor plus trifluralin, and pyroxasulfone at 150 g ha^{-1} compared with the nontreated check (Table 4). Despite these reductions in wheat establishment, several of the herbicides and mixtures significantly improved wheat yield compared to the nontreated check. Wheat yield with trifluralin, cinmethylin, and prosulfocarb plus *S*-metolachlor plus trifluralin was not significantly different to the nontreated check, but all other treatments resulted in an increase in wheat yield. Application of pyroxasulfone at 150 g ha^{-1} resulted in the highest wheat yield, even though this herbicide application resulted in a significant reduction in wheat establishment. This was likely a result of the effective rigid ryegrass control provided by this treatment and has been reported previously (Hulting et al. 2012).

At Berriwillock in 2008, wheat emergence only was measured because the trial was prematurely destroyed to prevent resistant weed seed entering the seedbank. In this trial, pyroxasulfone at 100 and 150 g ha^{-1} and prosulfocarb plus *S*-metholachlor at 2,000 + 300 g ha^{-1} did not reduce wheat establishment compared with the nontreated check.

Table 5. Effect of PRE herbicides applied/incorporated by the seeding operation (IBS) on wheat variety 'Yitpi' establishment and control of trifluralin-resistant rigid ryegrass at Berriwillock, Victoria in 2008.

Treatment	Rate	Wheat	Rigid ryegrass		
	g ai ha^{-1}	plants m^{-2a}	plants m^{-2a}	spikes m^{-2b}	% of nontreated
Nontreated	0	225	216	161	—
Trifluralin	960	180	87 (60)[c]	143	11
Pyroxasulfone	100	235	32 (85)	21	87
Pyroxasulfone	150	235	21 (90)	7	96
Prosulfocarb + *S*-metolachlor	2,000 + 300	215	14 (94)	21	87
Prosulfocarb + *S*-metolachlor + trifluralin	1,200 + 144 + 720	180	28 (87)	63	61
$LSD_{(0.05)}$		42	47	37	

[a] 4 wk after treatment.

[b] 22 wk after treatment.

[c] Figures in parentheses are reduction (%) relative to nontreated check.

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In contrast, trifluralin and prosulfocarb plus *S*-metolachlor plus trifluralin significantly reduced wheat plants (Table 5).

This research established that several alternative PRE herbicides, alone or in mixtures, applied IBS could be safely used in wheat to control rigid ryegrass. Certain herbicides performed better than others. Pyroxasulfone provided the most consistent control of rigid ryegrass in all trials. It has been previously reported that pyroxasulfone is effective at controlling rigid ryegrass (Walsh et al. 2011). Prosulfocarb plus *S*-metolachlor was also among the more effective treatments in controlling rigid ryegrass in the three trials. In contrast, performance of trifluralin was variable because it was affected by the presence of resistance in some trials; for example, Cummins in 2006 and Berriwillock in 2008. Cinmethylin performance on rigid ryegrass was poor with 29% and 37% control of rigid ryegrass density at Roseworthy and Cummins, respectively (Tables 3 and 4).

Rigid ryegrass control with PRE herbicides is difficult due to several factors. The presence of organic matter, such as crop residue, on the soil surface can act as a barrier preventing herbicide from contacting weed seeds (Chauhan et al. 2006a). Additionally, certain herbicides such as trifluralin bind strongly to organic matter (Kenaga 1980), although others such as pyroxasulfone are more soluble (Mueller and Steckel 2011) and can be washed off by rainfall. Low soil moisture can also reduce PRE herbicide performance (Jacques and Harvey 1979; Osborne et al. 1995; Walker 1971). Efficacy of some PRE herbicides is influenced by soil parameters such as soil texture, organic matter, clay content, and pH (Ladlie et al. 1976; Lo and Merkle 1984; Moomaw and Martin 1978; Salzman and Renner 1992; Westra 2012). These factors can cause PRE herbicides to be less effective than POST herbicides. Rigid ryegrass control was achieved in these trials with pyroxasulfone and prosulfocarb plus *S*-metholachlor applied IBS. Control was achieved because no-till seeding systems result in weed seeds in close proximity to the soil surface (Chauhan et al. 2006b, 2007) where contact of PRE herbicide with germinating seedlings is more likely. In contrast, in conventional tillage systems weed seed is distributed throughout the soil profile, making it more difficult to contact the seed with the herbicide.

Pyroxasulfone and prosulfocarb plus *S*-metolachlor can be used safely PRE in IBS systems in southeastern Australia. All herbicides, except for prosulfocarb plus *S*-metolachlor, resulted in a reduction of wheat emergence in at least one trial, particularly when used at higher rates. However, these reductions in stand establishment did not result in yield reductions. It is common for reduced stands of wheat to recover where ideal conditions prevail such as reduced weed competition and adequate nutrition and moisture. The IBS system used in these trials is likely to improve crop safety of PRE herbicides by partially removing the herbicides from the crop furrow. Higher rates, high rainfall, and other crop seeding systems might lead to more crop damage with these PRE herbicides in wheat (Rainbow and Derpsch 2011).

PRE herbicides with diverse modes of action applied IBS can provide control of rigid ryegrass in no-till wheat production in Australia. Because Australian no-till farming systems are already using trifluralin PRE (Chauhan et al. 2006c), other PRE herbicides could be effective alternatives for trifluralin using IBS seeding systems. Herbicides, such as pyroxasulfone and prosulfocarb plus *S*-metolachlor, were generally less damaging to wheat than trifluralin when applied IBS and consistently provided improved rigid ryegrass control. These herbicides were also effective where trifluralin-resistant rigid ryegrass was present in the fields.

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