Weed Technology 2014 28:323–331

Influence of Seeding System Disturbance on Preplant Incorporated Herbicide Control of Rigid Ryegrass (*Lolium rigidum*) in Wheat in Southern Australia

Samuel G. L. Kleemann, Christopher Preston, and Gurjeet S. Gill*

Field experiments were conducted in 2008, 2011, and 2012 to investigate the interaction between seeding system disturbance and PPI herbicides on rigid ryegrass control in wheat. Of the herbicides examined, prosulfocarb + *S*-metolachlor, and pyroxasulfone provided ≥ 70% control of rigid ryegrass, irrespective of seeding system. In contrast, trifluralin was the least-effective herbicide against rigid ryegrass and was particularly ineffective when used with single disc (10% control) relative to the triple-disc seeding system (80%) in 2012. Trifluralin consistently reduced wheat density when incorporated using single discs (46 to 59%) but not do so with the triple disc or double-shoot knife-point systems. Although there were large differences in crop establishment because of herbicide phytotoxicity, that did not always translate into large differences in yield because wheat was able to recover from reductions in plant density by increasing the spike number per plant. Pyroxasulfone caused no damage to wheat and appeared to be the most suitable PPI herbicide for use with single-disc seeding systems.

Nomenclature: Prosulfocarb; pyroxasulfone; *S*-metolachlor; trifluralin; rigid ryegrass, *Lolium rigidum* Gaudin LOLRI; wheat, *Triticum aestivum* L.

Key words: Seeding systems, preplant incorporated herbicides, weed control.

En 2008, 2011 y 2012, se realizaron experimentos de campo para investigar la interacción entre la perturbación causada por el sistema de siembra y el herbicida PPI en el control de *Lolium rigidum* en trigo. De los herbicidas examinados, prosulfocarb + *S*-metolachlor, y pyroxasulfone brindaron ≥70% de control de *L. rigidum*, independientemente del sistema de siembra. En contraste, trifluralin fue el herbicida menos efectivo contra *L. rigidum*, y fue particularmente inefectivo cuando se usó con el disco sencillo (10% de control) en relación con el sistema de triple-disco (80%) en 2012. Trifluralin redujo consistentemente la densidad del trigo cuando se incorporó usando discos sencillos (46 a 59%), pero esto no ocurrió con el triple-disco o con sistemas de doble cuchilla. Aunque hubo grandes diferencias en el establecimiento del cultivo debido a la fitotoxicidad de los herbicidas, esto no siempre se tradujo en grandes diferencias en rendimiento porque el trigo fue capaz de recuperarse de las reducciones en densidad de plantas al incrementar el número de espigas por planta. Pyroxasulfone no causó daño al trigo y pareció ser el herbicida PPI más adecuado para uso con sistemas de siembra de disco sencillo.

Rigid ryegrass is a major winter annual grass 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). If not managed effectively, rigid ryegrass can cause large reductions in wheat grain yield (Poole and Gill 1987; Smith and Levick 1974). As rigid ryegrass is a prolific seed producer (Rerkasem et al. 1980), only a few plants are required to survive weed control to replenish the seedbank and ensure weed infestation in subsequent crops. In the past, rigid ryegrass was effectively controlled in crops with selective grass herbicides (Leys et al. 1988); however, many populations have since evolved resistance to those herbicides, making POST control difficult (Boutsalis et al. 2012; Broster et al. 2011). Consequently, growers now rely heavily on PPI herbicides, such as trifluralin, to provide rigid ryegrass control.

During the past two decades, reliance on nonselective herbicides (i.e., glyphosate, diquat, and paraquat) for weed control before sowing has increased dramatically because many growers across southern Australia have phased out cultivation and have adopted no-till cropping. Rapid adoption of no-tillage and stubble retention by growers has been driven by the need to protect the soil from erosion and to achieve timely planting of crops (D'Emden

DOI: 10.1614/WT-D-13-00065.1

* Research Officer, Associate Professor, and Associate Professor, School of Agriculture, Food and Wine, University of Adelaide, PMB1, Waite Campus, Glen Osmond, South Australia 5064, Australia. Corresponding author's E-mail: samuel.kleemann@adelaide.edu.au

and Llewellyn 2004). The most commonly used no-tillage planters are fitted with knife-point tine openers, which displace soil from the crop row and create a wide furrow for crop seed placement (D'Emden et al. 2008). PPI herbicides can be used safely in these no-tillage systems because the amount of herbicide present in the crop row is reduced by the sowing operation (Chauhan et al. 2006a).

The stubble-handling ability of no-tillage (tine) systems can be compromised under high loads of crop stubble from the previous season. Zero-tillage disc planters possess superior stubble-handling capacity, and that attribute has been the main driver for their adoption by Australian growers (Ashworth et al. 2010). Zero-tillage disc systems provide lower soil disturbance than knife-point systems do and allow faster sowing and, if set up appropriately, provide more-uniform crop establishment (J Desbiolles, personal communication). However, most PPI herbicides are not recommended for use with disc planters in Australia. The situation is complicated further by the wide range of disc configurations available on the market, which can differ enormously in the level of soil-disturbance created at planting (Desbiolles and Kleemann 2003).

Movement of herbicide-treated soil and herbicide incorporation can vary greatly between high soil-disturbance tine planters and low soil-disturbance disc planters, which can also affect the persistence and efficacy of PPI herbicides, such as trifluralin and pendimethalin (Chauhan et al. 2007). Those volatile herbicides require soil incorporation at planting to reduce losses by photodecomposition and volatilization (Chauhan et al. 2007; Grover et al. 1997; Savage and Barrentine 1969). Trifluralin is also known to bind tightly to organic matter (Kenaga 1980) and is often intercepted by crop residues on the soil surface, reducing its effectiveness under no-tillage systems (Chauhan et al. 2006c). Previous researchers discovered the persistence of trifluralin can be reduced significantly under low soil-disturbance disc systems, which can lead to inadequate weed control (Chauhan et al. 2006c). Although trifluralin use declined in Australia after the introduction of POST herbicides in the mid 1980s, it has become one of the most widely used herbicides for the control of rigid ryegrass under no-tillage cropping systems in southern Australia (Chauhan et al. 2006c). The resurgence in trifluralin use on Australian farms could be attributed to greater crop safety under no-tillage systems than conventional tillage systems, as well as the rapid development of rigid ryegrass resistance to most POST herbicides. However, many populations of rigid ryegrass across southern Australia have now evolved resistance to trifluralin, reducing its effectiveness (Boutsalis et al. 2012). Fortunately two new PPI herbicides prosulfocarb + *S*-metolachlor (Boxer Gold, Syngenta Crop Protection, North Ryde, NSW, Australia) and pyroxasulfone (Sakura, Bayer CropScience, Hawthorn, East VIC, Australia) were recently released in Australia to control several weed species in wheat. These new herbicides effectively control rigid ryegrass (Walsh et al. 2011), including populations with evolved resistance to trifluralin, and they are far less volatile and are more stable in soil than trifluralin (APVMA 2007, 2011). Furthermore, compared with trifluralin, the high stability on the soil surface and greater soil mobility of these herbicides could be responsible for their consistent control of rigid ryegrass under no-tillage systems (P Boutsalis, personal communication). However, there has been little research undertaken in Australia to evaluate the performance of these PPI herbicides under low soil-disturbance disc systems (zero-tillage). Availability of such information may enhance the adoption of disc-seeding systems by Australian growers.

Given the limited information in Australia on the performance of PPI herbicides under disc-seeding systems and the increase in area planted under zero-tillage cropping, research is needed to investigate the performance of different PPI herbicides under zero-tillage systems. The objective of this study was to determine the effect of zero-tillage systems on the activity of PPI herbicides on rigid ryegrass and the risk of wheat phytotoxicity.

Materials and Methods

Field experiments were conducted in different fields over the growing seasons of 2008, 2011, and 2012 at Roseworthy, located in the lower North region of South Australia (–34.51°, 138.68° 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 at the soil surface. The long-term

https://doi.org/10.1614/WT-D-13-00065.1 Published online by Cambridge University Press

Table 1. Summary of rainfall, cropping history, residue levels, planting dates and wheat cultivars at experimental sites in 2008, 2011, and 2012.

Year	Rainfall		Previous crop	Crop residue[c]	Planting date	Wheat cultivar
	Annual	GSR[a,b]				
	mm			t ha^{-1}		
2008	329	255	Faba bean	< 2	June 4 to 5	'Correll'
2011	419	239	Lentil	< 2	May 31 to Jun 1	'Gladius'
2012	307	225	Lentil	< 2	June 26 to 27	'Mace'

[a] Abbreviation: GSR, growing season rainfall.

[b] Growing season rainfall for site year from April to October.

[c] Residue levels were calculated from visual estimates.

average, annual rainfall at Roseworthy is 434 mm, and the average growing season rainfall (April to October) is 321 mm (Table 1; Australian Bureau of Meteorology 2013). Before the start of the experiment, field sites were sprayed with glyphosate (900 g ae ha^{-1}) and oxyfluorfen (22 g ai ha^{-1}) for preplant weed control. All zero-tillage and no-tillage systems were direct planted (without preplant cultivation) and comprised low soil-disturbance Austil (MT3500 series) single disc system in 2008 (Austil Equipment, Dalby, Qld, Australia); a John Deere (JD90 series) single-disc system in 2011 and 2012 (John Deere Ltd., Crestmead, Qld, Australia); an intermediate to high soil-disturbance K-Hart triple-disc system with a Yetter coulter in 2008, 2011, and 2012 (K-Hart Industries, Elrose, SK, Canada); and a high soil-disturbance double-shoot (DS) knife-point and press wheel system in 2008 and 2011 (Primary Sales Australia, Midvale, WA, Australia). Although the Austil single disc was used only in 2008 and was replaced thereafter by the JD90 single disc (2011 and 2012), both of those disc openers are similar and cause very low soil disturbance. All seeding systems were operated according to manufacturer's specifications and planting speeds. The herbicides used were trifluralin (720 g ai ha^{-1}), prosulfocarb (2,000 g ai ha^{-1}) plus *S*-metolachlor (300 g ai ha^{-1}), and pyroxasulfone (100 g ai ha^{-1}). A nontreated weedy treatment was included as a control. The herbicides were applied within 24 h before planting of wheat (PPI) from an all-terrain vehicle fitted with a spray boom delivering 100 L ha^{-1} water volume at a pressure of 200 kPa. In this system, herbicide incorporation occurred because of soil-disturbance caused by the planting operation. Cropping history, residue levels, planting dates, and wheat cultivars at the experimental sites are presented in Table 1. The depth of planting was targeted at 3 cm, with crop rows spaced 25 cm apart, and wheat was planted at 90 kg ha^{-1}. Diammonium phosphate required to supply 18 kg N ha^{-1} and 20 kg P ha^{-1} was banded with the wheat seed at planting.

Wheat density was assessed at the two-leaf growth stage (GS12; Zadoks et al. 1974) by counting the number of plants along a 0.5-m length of two adjacent crop rows at three random locations in each plot. At the same growth stage (GS12), depth of wheat seed placement was assessed by sampling 25 plants in the nontreated plots and measuring the distance between the seed and the point of color change of the seedling (indicator of soil surface). At grain maturity, wheat spikes were assessed by counting the number of spikes along a 1.0-m length of two adjacent crop rows at three random locations in each plot and converted to wheat spike density (spikes m^{-2}). Wheat yield was determined using a small-plot harvester when the grain had reached a moisture content of $\leq$ 12%.

The efficacy of herbicides on rigid ryegrass was evaluated at 30 d after crop planting (DAP) in 2008, 2011, and 2012. Rigid ryegrass density was determined in three quadrats (0.3 m by 0.3 m, 2008; 0.25 m by 0.45 m, 2011; 0.27 m by 0.90 m, 2012) placed at random locations within each plot. Rigid ryegrass plants within quadrats were counted, and the efficacy of the herbicides was expressed as a percentage of the nontreated plots (% control). The same sampling method was used each year to assess rigid ryegrass spikes at maturity, which is a good indicator of its seed production.

Experiments were established in a split-plot design with four replicates; seeding systems were assigned to main plots, and herbicides were assigned

Table 2. Effect of herbicide treatments on rigid ryegrass density at 30 d after planting (DAP) in 2008 and 2011. Values in parenthesis represent herbicide control of rigid ryegrass expressed as a percentage (%) of the nontreated control.

Herbicide	Rate	Rigid ryegrass 2008		Rigid ryegrass 2011	
	g ai ha^{-1}	plants m^{-2}			
Nontreated	—	235		1183	
Trifluralin	720	56	(76)	812	(31)
Prosulfocarb + *S*-metolachlor	2,000 + 300	49	(79)	104	(91)
Pyroxasulfone	100	48	(80)	343	(71)
LSD (P = 0.05)		NS		228	
Seeding system × herbicide		NS		NS	

to subplots. Weed control (plant and spike density) and crop data (wheat plant and spike density, as well as grain yield) were analyzed with ANOVA (Genstat Version 10.0, VSN International, Hemel Hempstead, U.K.; VSN 2007). Because treatment by year interactions for weed control and crop data were significant, data were not combined and are presented separately for each year. Transformation of data did not improve homogeneity of variance; thus, analysis was performed on nontransformed weed control and crop data. Data on variance were visually inspected by plotting residuals to confirm the homogeneity of variance before statistical analysis. Means were separated with the use of Fisher's protected LSD test at $P = 0.05$.

Results and Discussion

Effect of Seeding Systems and Herbicides on Rigid Ryegrass. In 2008, regardless of the seeding system, all herbicides provided similar levels of weed control, and values of rigid ryegrass density reduction ranged from 76 to 80% of the nontreated control (Table 2). However, in 2011, there were large differences between the three herbicides in their efficacy on rigid ryegrass. Because there was no interaction between the herbicide treatments and the seeding systems ($P > 0.05$), data for herbicides were pooled across seeding systems. Rigid ryegrass control at 30 DAP in 2011 ranged from as low as 31% for trifluralin to 71 and 91% for pyroxasulfone and prosulfocarb + *S*-metolachlor, respectively (Table 2). Even though rigid ryegrass emerged for a longer period because of the wetter conditions in 2011, control, even after 60 DAP, remained greater than 80% for both prosulfocarb + *S*-metolachlor and pyroxasulfone, whereas trifluralin efficacy diminished from 32 to 11% (data not presented). Pyroxasulfone can persist in the soil longer than trifluralin (P Boutsalis, personal communication), and that persistence could be responsible for the consistent weed control. Inability of trifluralin to provide effective control of rigid ryegrass at the 2011 field site, even under knife-point (no-tillage) system, could have been due to herbicide resistance rather than poor incorporation. Previous research (Chauhan et al. 2007) indicated that trifluralin applied under knife-points can provide $\geq$ 90% control of rigid ryegrass. Furthermore, trifluralin-resistant rigid ryegrass is now quite common in the lower north region of South Australia. A recent, random survey of the lower North region of South Australia found that 44% of rigid ryegrass populations were resistant to trifluralin (Boutsalis et al. 2012).

In 2012 only, rigid ryegrass density was significantly affected ($P < 0.05$) by the interaction between seeding system and herbicide (Table 3). The response to seeding system was likely due to stimulation of rigid ryegrass establishment in the absence of herbicide treatment under the triple disc (379 plants m^{-2}) relative to the single disc (152 plants m^{-2}) seeding system. Increased soil disturbance by the triple-disc seeding system could have provided shallow burial and more favorable germination environment than the single-disc system, where seeds remained exposed to rapid wetting and drying cycles on the soil surface. Large differences in rigid ryegrass recruitment because of variations in soil disturbance between tillage systems have been reported previously (Chauhan et al. 2006b). In spite of greater rigid ryegrass density in the triple-disc seeding system than in the single-disc seeding system (379 vs. 152 plants m^{-2} nontreated plots),

https://doi.org/10.1614/WT-D-13-00065.1 Published online by Cambridge University Press

Table 3. Effect of seeding systems and herbicides on rigid ryegrass density at 30 d after planting (DAP) in 2012. Values in parenthesis represent herbicide control of rigid ryegrass expressed as a percentage (%) of the nontreated control.

Seeding system	Herbicide: Nontreated	Trifluralin		Prosulfocarb + *S*-metolachlor		Pyroxasulfone	
	plants m^{-2}						
JD90 single disc	152	137	(10)	45	(70)	25	(83)
K-Hart triple disc	379	77	(80)	52	(86)	65	(83)
LSD (P = 0.05)[a]	123						

[a] Represents the significance (P < 0.05) of the interaction between seeding system and herbicide.

weed control with trifluralin was greater with the triple-disc seeding system (80%) than it was with the single-disc seeding system (10%). Prosulfocarb + *S*-metolachlor and pyroxasulfone controlled rigid ryegrass in both disc systems (70 to 86%). Lack of trifluralin efficacy on the 2012 rigid ryegrass population in low soil disturbance, single-disc incorporation treatments (10%), relative to the higher disturbance, triple-disc incorporation (80%), was most likely due to inadequate herbicide activation rather than herbicide resistance. Previous research indicated that, when incorporated using single discs, most of the applied trifluralin remains on the soil surface even after planting, where it is susceptible to losses through volatilization and photodecomposition (Chauhan et al. 2006c). Consistent performance of prosulfocarb + *S*-metolachlor and pyroxasulfone using both disc systems could be related to their much lower volatility than trifluralin. Moderate water solubility in prosulfocarb + *S*-metolachlor and pyroxasulfone (Mueller and Steckel 2011) would allow some herbicide movement into surface soil, where most of rigid ryegrass seed bank is concentrated under zero-tillage systems (Chauhan et al. 2006b).

Rigid ryegrass spike number was influenced by the interaction between seeding system and herbicides in all 3 yr of the study (Figure 1). In the nontreated plots, rigid ryegrass spike densities were similar between single- and triple-disc seeding systems in 2011 (456 vs. 506 spikes m^{-2}). Even in 2012, a similar spike density was recorded in nontreated plots between the single- and triple-disc seeding systems (359 vs. 400 spikes m^{-2}), even though there were large differences in rigid ryegrass establishment between the two systems (152 vs. 379 plants m^{-2}; Table 3). Greater spikes per plant recorded when herbicides were incorporated using the single-disc seeding system could be due to lower early vigor of wheat than found when using the triple-disc seeding system. In contrast, rigid ryegrass spike density in 2008 was greater in nontreated plots of the single-disc (198 spikes m^{-2}) than the triple-disc (126 spikes m^{-2}) system and DS knife-point seeding systems (114 spikes m^{-2}). In 2008, lower crop population was recorded in the single-disc (132 plants m^{-2}),

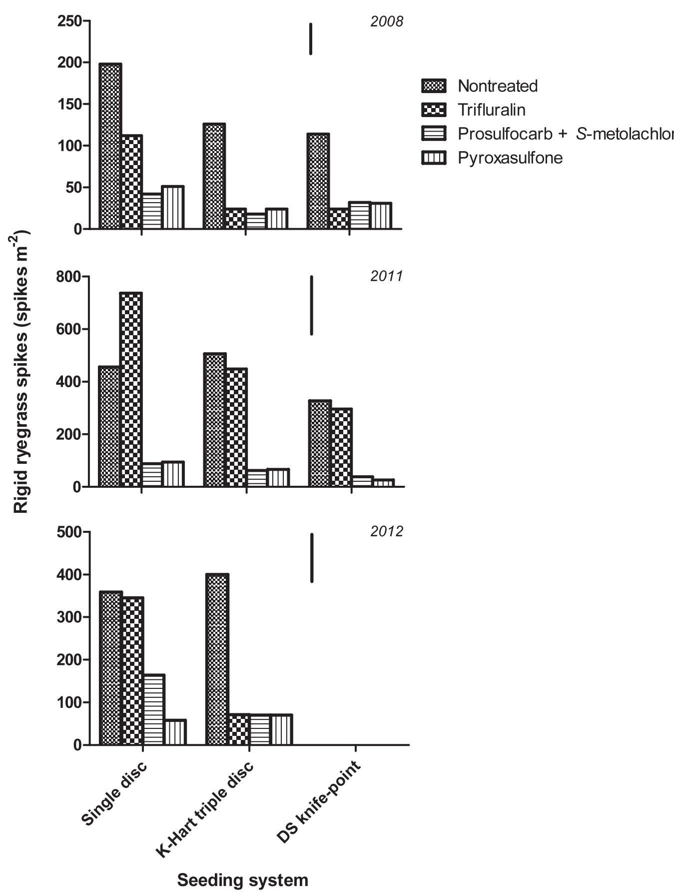

Figure 1. Effect of seeding systems and herbicides on rigid ryegrass spike number in 2008, 2011, and 2012. Single disc was Austil in 2008 and JD90 in 2011 and 2012. Vertical lines represent the Fisher's protected LSD (P = 0.05) test for the interaction between seeding system and herbicide.

https://doi.org/10.1614/WT-D-13-00065.1 Published online by Cambridge University Press

Table 4. Effect of seeding systems and herbicides on wheat plant density in 2008, 2011, and 2012. Values in parentheses represent the percentage reduction in wheat emergence for herbicides relative to the nontreated control.

	Herbicide						
Seeding system	Nontreated	Trifluralin		Prosulfocarb + *S*-metolachlor		Pyroxasulfone	
	plants m^{-2}						
2008							
Austil single disc	132	71	(46)	142	(0)	146	(0)
K-Hart triple disc	177	160	(10)	177	(0)	170	(4)
DS knife-point	181	182	(0)	176	(3)	171	(5)
LSD (P = 0.05)[b]	29						
2011							
JD90 single disc	176	87	(51)	132	(25)	163	(7)
K-Hart triple disc	187	193	(0)	170	(9)	203	(0)
DS knife-point	212	188	(11)	189	(11)	207	(2)
LSD (P = 0.05)[b]	26						
2012							
JD90 single disc	211	87	(59)	90	(57)	202	(4)
K-Hart triple disc	213	192	(10)	209	(2)	208	(2)
LSD (P = 0.05)[b]	33						

[a] Abbreviation: DS, double-shoot.

[b] Represents the significance (P < 0.05) of the interaction between seeding system and herbicide.

relative to the triple disc (177 plants m^{-2}) and DS knife-point seeding (188 plants m^{-2}), systems. Reduced crop density likely reduced the competitive ability of wheat and allowed rigid ryegrass to proliferate under the single-disc system. In all 3 yr, and regardless of the seeding system, the greatest reduction in rigid ryegrass spike density, when compared with the nontreated control, was recorded in prosulfocarb + *S*-metolachlor (54 to 88%) and pyroxasulfone (73 to 92%) treatments. Similar to the trend for weed control, trifluralin was ineffective in reducing rigid ryegrass spike number (0 to 43%) relative to the nontreated control under single-disc systems (Austil and JD90). In trifluralin treatment under the single disc in 2011, where weed control failed because of herbicide resistance and crop density declined because of phytotoxicity, rigid ryegrass spike density (737 spikes m^{-2}) was even higher than it was in the nontreated control (420 spikes m^{-2}). In that same year, trifluralin failed to reduce rigid ryegrass spike numbers relative to the nontreated control even in the triple disc (506 vs. 448 spikes m^{-2}) and DS knife-point seeding (327 vs. 296 spikes m^{-2}) systems. Rigid ryegrass is known to be a prolific seed producer (Rerkasem et al. 1980), and each spike can produce around 20 to 30 viable seeds (SGL Kleemann and GS Gill, unpublished data). Such a high level of spike density is likely to lead to massive seed production and buildup in the seed bank, which could have serious effects on the productivity of subsequent crops in the rotation. However, in 2008 and 2012, treatments of trifluralin incorporated by the triple-disc and DS knife-point seeding systems had rigid ryegrass spike densities similar to that of prosulfocarb + *S*-metolachlor and pyroxasulfone.

Effect of Seeding Systems and Herbicides on Plant Density and Grain Yield of Wheat. Wheat plant density was significantly affected by the interaction between herbicides and seeding systems (Table 4). In all 3 yr, trifluralin significantly (P < 0.05) reduced wheat emergence when incorporated using the single-disc seeding system (46 to 59%) but caused no significant reduction in wheat density under the triple-disc or DS knife-point seeding systems (< 11%). Prosulfocarb + *S*-metolachlor also reduced wheat establishment in 2011 (25%) and 2012 (57%) when incorporated using the JD90 single-disc seeding system, and that effect was associated with postplanting rainfall. Such rainfall events after planting could cause movement of this moderately water soluble herbicide into the furrow. In contrast to trifluralin and prosulfocarb + *S*-metolachlor, no crop damage was observed with pyroxasulfone, which appears to be the safest PPI

https://doi.org/10.1614/WT-D-13-00065.1 Published online by Cambridge University Press

Table 5. Effect of seeding systems and herbicides on wheat grain yield in 2008, 2011, and 2012.

Seeding system[a]	Herbicide: Nontreated	Trifluralin	Prosulfocarb + *S*-metolachlor	Pyroxasulfone
		kg ha^{-1}		
2008				
Austil single disc	2,800	2,430	2,710	2,770
K-Hart triple disc	2,930	2,780	2,840	2,800
DS knife-point	2,930	2,850	2,890	2,300
LSD (P = 0.05)		NS		
2011				
JD90 single disc	3,400	2,590	4,030	4,070
K-Hart triple disc	3,400	3,500	3,980	3,960
DS knife-point	3,300	3,400	4,040	3,970
LSD (P = 0.05)[b]		420		
2012				
JD90 single disc	3,420	3,260	4,130	4,360
K-Hart triple disc	3,340	3,880	4,290	4,220
LSD (P = 0.05)[b]		390		

[a] Abbreviations: DS, double-shoot.

[b] Represents the significance ($P < 0.05$) of the interaction between seeding system and herbicide.

herbicide option for use in wheat sown with low soil disturbance, single-disc seeding systems. The greater soil disturbance that occurred with the K-Hart triple-disc and DS knife-point seeding systems appears to create adequate movement of herbicide-treated soil out of the furrow, whereas the single-disc openers (Austil and JD90) appear to leave herbicide-treated soil in the furrow where it is in close proximity to the germinating crop seed. In this study, the greater herbicide phytotoxicity observed under the single-disc treatments was not caused by shallower seed placement because the wheat seed had been placed at a similar depth in all three seeding systems (data not shown). Movement of herbicide-treated soil into the furrow slot by either the single disc or closing furrow wheel could have contributed to crop damage in the single-disc seeding system (J Desbiolles, personal communication) and warrants further research.

Wheat grain yield was influenced by the interaction between seeding systems and herbicides in 2 yr out of the 3 yr (Table 5). The interaction in 2011 and 2012 was probably due to the low grain yields for the trifluralin treatment with the single-disc seeding system (2,590 and 3,260 kg ha^{-1}), which suffered a 36 and 25% yield loss relative to the highest yielding pyroxasulfone treatment in 2011 (4,070 kg ha^{-1}) and 2012 (4,360 kg ha^{-1}), respectively. Trifluralin incorporated using the single disc in 2011 reduced yield (24%) more than it did in 2008 (13%) or 2012 (5%), when compared with the nontreated control. The yield reduction in 2011 was most probably due to failure to kill herbicide-resistant rigid ryegrass. Although the interaction between the seeding system and herbicide was nonsignificant in 2008, wheat planted with the single-disc system and treated with trifluralin had the lowest grain yield (2,430 kg ha^{-1}) and suffered a 13% yield loss relative to the nontreated control (2,800 kg ha^{-1}). In 2011 and 2012, the highest wheat grain yield ($\geq$ 4,000 kg ha^{-1}) was observed in seeding systems where rigid ryegrass was effectively controlled with prosulfocarb + *S*-metolachlor and pyroxasulfone, with little or no reduction in wheat plant density (Table 5). Despite the effectiveness of all herbicides against rigid ryegrass in 2008 ($\geq$ 75% control), there was little increase in wheat grain yield relative to the nontreated control for all seeding systems. Lower rigid ryegrass density in 2008 (< 250 plants m^{-2}) could have been responsible for small yield gains from rigid ryegrass control. However, competition from larger populations of rigid ryegrass in 2011 (> 1000 plants m^{-2}) and 2012 (> 250 plants m^{-2}) reduced wheat yields by as much as 36% in the nontreated control and the trifluralin-treated plots relative to prosulfocarb + *S*-metolachlor and

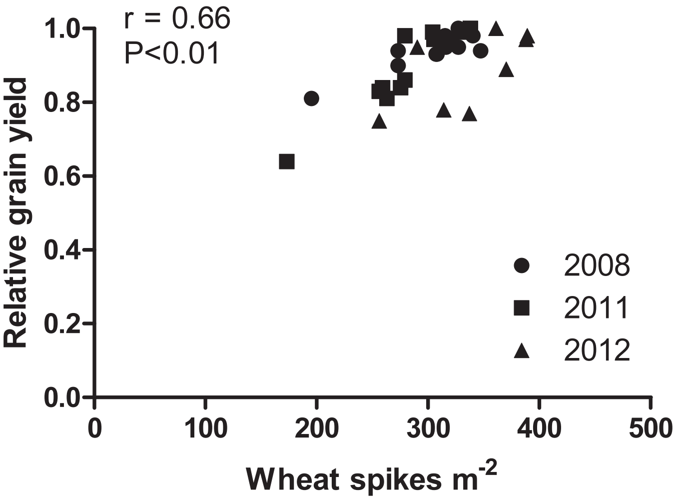

Figure 2. The relationship between mean wheat spike density after treatment with PPI herbicides and grain yield of wheat (relative to the pyroxasulfone treatments in each year) for different seeding systems in 2008, 2011, and 2012. *Relative yield* = (*Treatment*/*Pyroxasulfone*) × 100.

pyroxasulfone. Although reductions in wheat plant density were observed in prosulfocarb + *S*-metolachlor when incorporated using a single-disc seeding system (2011 and 2012), there was still a significant yield increase relative to the nontreated as a result of the effective weed control. In contrast, trifluralin incorporated by the single-disc seeding system in 2012, which caused a large reduction in wheat density but provided little rigid ryegrass control (10%), did not improve yield relative to the nontreated control (3,420 kg ha^{-1}) and was the lowest yielding treatment (3,260 kg ha^{-1}). The results suggest that wheat can compensate for moderate early reduction in plant density, provided weeds are controlled effectively. During the three growing seasons, there was a positive relationship ($r=0.66$, $P < 0.01$) between wheat spike density and grain yield expressed as a percentage of the highest yielding treatment, pyroxasulfone (Figure 2). In all 3 yr, the crops sown with single-disc seeding systems (Austil and JD90) and treated with trifluralin had lower spike density because they were unable to fully compensate for the reduced crop density or because the herbicide failed to adequately control rigid ryegrass. These results are consistent with the findings of Chauhan et al. (2006b), who reported that wheat yield responses between tillage systems and PPI herbicides were positively correlated to spike number rather than to grain number per spike and grain size.

Currently, in Australia, no herbicides are recommended for use in wheat incorporated using disc planters, and this is impeding the adoption of zero-tillage in southern Australia. The field studies reported here discovered that wheat crops can be seriously damaged by the use of trifluralin when incorporated using single-disc seeding systems. In contrast, the new PPI herbicide pyroxasulfone caused no damage to wheat establishment, even when incorporated using single-disc seeding systems and was highly effective for management of rigid ryegrass. Based on these results, pyroxasulfone appears to be the most suitable PPI herbicide for use in wheat planted using disc systems. Although prosulfocarb + *S*-metolachlor caused a significant reduction in wheat plant density when incorporated using the single disc seeding system in two years out of three, the crop was able to fully recover and did not suffer any yield penalty. Although prosulfocarb + *S*-metolachlor and pyroxasulfone provide effective new options for the selective control of rigid ryegrass under no-tillage and zero-tillage systems in southern Australia, these herbicides need to be used by growers as part of an integrated weed management program to ensure their sustainability.

Acknowledgments

The financial assistance of the Grains Research and Development Corporation (GRDC) is gratefully acknowledged. We also wish to thank Jack Desbiolles and Dean Thiele from the University of South Australia for planting the field experiments and Malinee Thongmee for providing technical assistance.

Literature Cited

APVMA [Australian Pesticides and Veterinary Medicines Authority] (2007) Public Release Summary—On the Evaluation of the New Active Prosulfocarb in the Product Boxer Gold Herbicide. http://www.apvma.gov.au. Accessed: March 4, 2013

APVMA [Australian Pesticides and Veterinary Medicines Authority] (2011) Public Release Summary—On the Evaluation of the New Active Pyroxasulfone in the Product Sakura® 850 WG Herbicide. http://www.apvma.gov.au. Accessed: March 4, 2013

Ashworth M, Desbiolles JMA, Tola E (2010) Disc Seeding in Zero-Till Farming Systems—A Review of Technology and Paddock Issues. Northam, Western Australia: Western Australian No-Tillage Farmer's Association

Australian Bureau of Meteorology (2013) Climate Data Online. http://www.bom.gov.au/climate/data/index.shtml. Accessed: March 12, 2013

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

Chauhan BS, Gill GS, Preston C (2006a) Tillage system effects on weed ecology, herbicide activity and persistence: a review. Aust J Exp Agric 46:1557–1570

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

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

Chauhan BS, Gill GS, Preston C (2007) Effect of seeding systems and dinitroaniline herbicides on emergence and control of rigid ryegrass (*Lolium rigidum*) in wheat. Weed Technol 21:53–58

Desbiolles J, Kleemann S (2003) Seeding system factors influence no-till cropping results. Pages 364–372 *in* Proceedings of the 16th Triennial International Soil Tillage Research Organization ISTRO Conference. Brisbane, Australia: University of Queensland

D'Emden FH, Llewellyn RS (2004) No-till adoption and cropping issues for Australian grain growers. Page 108 *in* T Fischer, ed. 4th International Crop Science Conference. Brisbane, Australia: The Regional Institute

D'Emden FH, Llewellyn RS, Burton MP (2008) Factors influencing the adoption of conservation tillage in Australian cropping regions. Aust J Agric Res Econ 52:169–182

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

Grover R, Wolt JD, Cessna AJ, Schiefer HB (1997) Environmental fate of trifluralin. Rev Environ Contam Toxicol 153:1–16

Kenaga EE (1980) Predicted bioconcentration factors and soil sorption coefficients of pesticides and other chemicals. Ecotoxicol Environ Saf 4:26–38

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

Mueller TC, Steckel LE (2011) Efficacy and dissipation of pyroxasulfone and three chloroacetamides in a Tennessee field soil. Weed Sci 59:574–579

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: RG & FJ 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 31:549–658

Savage K, Barrentine W (1969) Trifluralin persistence as affected by depth of soil incorporation. Weed Sci 17:349–352

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

Walsh MJ, Fowler TM, Crowe B, Ambe T, Powles SB (2011) The potential for pyroxasulfone to selectively control resistant and susceptible rigid ryegrass (*Lolium rigidum*) biotypes in Australian grain crop production systems. Weed Technol 25:30–37

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

Received April 16, 2013, and approved January 20, 2014.