Weed Technology 2011 25:30–37

The Potential for Pyroxasulfone to Selectively Control Resistant and Susceptible Rigid Ryegrass (*Lolium rigidum*) Biotypes in Australian Grain Crop Production Systems

Michael J. Walsh, Tarnya M. Fowler, Bronwyn Crowe, Toshihiro Ambe, and Stephen B. Powles*

The widespread evolution of resistance in rigid ryegrass populations to the highly effective, in-crop, selective herbicides used within southern Australian grain-crop production systems has severely diminished the available herbicide resource. A new PRE grass-selective herbicide, pyroxasulfone, may offer Australian grain producers a new option for rigid ryegrass control in wheat crops. The efficacy and level of selectivity of rigid ryegrass control with pyroxasulfone was investigated for a range of annual crop species in potted-plant, dose–response studies. In comparison with other currently available PRE herbicides, pyroxasulfone provided effective control of both resistant and susceptible rigid ryegrass populations. Additionally, control of these populations was achieved at rates that had little or no effect on the growth and survival of wheat. This crop was also the most tolerant of cereal species, with triticale, barley, and oat being more injured at higher pyroxasulfone rates than wheat was. In general though, pulse-crop species were found to be more tolerant of high pyroxasulfone rates than cereal-crop species. There were subtle effects of soil type on the efficacy of pyroxasulfone, where higher rates were required to achieve effective control on soils with higher clay or organic matter contents. The ability of pyroxasulfone to selectively control resistant and susceptible rigid ryegrass populations as identified in these studies clearly indicate the potential for widespread use and success of this herbicide in Australian cropping systems.

Nomenclature: Pyroxasulfone (proposed common name), 3-[5-(difluoromethoxy)-1-methyl-3-(trifluoromethyl)pyrazol-4-ylmethylsulfonyl]-4,5-dihydro-5,5-dimethyl-1,2-oxazole (formerly KIH-485, now BAY-191); rigid ryegrass, *Lolium rigidum* Gaudin LOLRI; common barley, *Hordeum vulgare* L. HORVX; oat, *Avena sativa* L. AVESA; triticale, ×*Triticosecale rimpaui* Wittm. TTLSS; common wheat, *Triticum aestivum* L. TRZAX.

Key words: Crop selectivity, herbicide efficacy, herbicide resistance, trifluralin, soil activity, weed control.

La evolución generalizada de resistencia en poblaciones de *Lolium rigidum* a los herbicidas selectivos y altamente efectivos, aplicados al cultivo y utilizados en los sistemas de producción de grano del sur de Australia, ha disminuido severamente los recursos disponibles de herbicidas. El pyroxasulfone es un nuevo herbicida PRE selectivo para gramíneas, que puede ofrecer a los productores de grano australianos una nueva opción para el control de *Lolium rigidum* en el cultivo del trigo. Se investigó la eficacia y el nivel de selectividad de control de *Lolium rigidum* con pyroxasulfone para diversas especies de cultivos anuales, con estudios dosis-respuesta llevados a cabo con plantas en macetas. En comparación con otros herbicidas PRE actualmente disponibles, el pyroxasulfone proporcionó control efectivo a poblaciones resistentes y susceptibles de *Lolium rigidum.* Adicionalmente, se logró el control de estas poblaciones a dosis que tuvieron poco o ningún efecto en el crecimiento y supervivencia del trigo. Este cultivo fue también el más tolerante de los cereales, con triticale, cebada y avena sufriendo mayor daño a dosis mayores de pyroxasulfone que el trigo. En general, los cultivos de leguminosas resultaron ser más tolerantes a altas dosis de pyroxasulfone que los cereales. Hubo leves efectos en cuanto al tipo de suelo en la eficacia de pyroxasulfone, donde se requirieron dosis más altas para lograr el control efectivo en suelos con más alto contenido de arcilla o materia orgánica. La habilidad de pyroxasulfone para controlar selectivamente poblaciones resistentes y susceptibles de *Lolium rigidum* como se identificó en este estudio, claramente indica que hay potencial para el uso generalizado y el éxito de este herbicida en sistemas de cultivos en Australia.

Rigid ryegrass, introduced to Australia as a pasture species, was once the staple of the grazing livestock production industry with its potential to produce large amounts of quality forage in the Mediterranean climates of southern Australia (Kloot 1983). However, during the past 40 yr, diminishing livestock production has seen the areas previously devoted to grazing now used for intensive crop production. Consequently, rigid ryegrass has become a major crop weed across vast areas of Australian grain production regions.

Australian grain production is dominated by wheat. To sustain grain production in the Mediterranean type climate on the fragile soils of the moisture-limited, dryland-cropping regions, farmers have almost universally adopted reduced-tillage and stubble-retention technologies (D'Emden and Llewellyn 2006; D'Emden et al. 2008). During the past two decades, the extensive adoption of these technologies has assisted in retaining soil moisture and improving soil structure, leading to sustained yield improvements. However, these technologies eliminate alternative weed-control practices, such as stubble burning and cultivation, leading to greater reliance on herbicides for weed control within these crop production systems.

DOI: 10.1614/WT-D-10-00091.1

* First, second, and fifth authors: Research Associate Professor, Undergraduate Student, and Professor, Australian Herbicide Resistance Initiative, School of Plant Biology, Institute of Agriculture, University of Western Australia, Crawley, WA 6009, Australia; third author: Graduate Student, School of Agricultural and Resource Economics, Faculty of Natural and Agricultural Sciences, University of Western Australia, Crawley, WA 6009, Australia; fourth author: Kumiai Chemical Industry, 4-26 Ikenohata 1-chome, Taitoh, Tokyo, 110-8782, Japan. Corresponding author's E-mail: michael.walsh@uwa.edu.au

Table 1. Physical and chemical properties of soils used in herbicide-screening studies.

Site	Texture	Clay content	Organic matter	pH ($CaCl_2$)
		—% —		
Gingin	Loam	20	2.3	6.1
Buntine	Loam	20	1.7	5.2
Meckering	Loamy sand	5	1.9	5.7
Mingenew	Loamy sand	5	1.9	5.9

The combination of wheat-dominated cropping rotations and the extensive use of in-crop selective herbicides has resulted in the widespread evolution of herbicide resistance in rigid ryegrass populations. There are currently very high frequencies of resistance to most of the herbicides used to selectively control rigid ryegrass in southern Australian dryland-cropping systems (Boutsalis et al. 2008; Broster and Pratley 2006; Owen et al. 2007). The consequence of continuing widespread evolution of herbicide resistance is that effective herbicides are a diminishing resource. The productivity of the current southern Australian, dryland grain-production system is highly dependant on effective herbicidal weed control, and the ever-increasing frequency of herbicide-resistant rigid ryegrass populations is a major threat to the future of these systems. Thus, there is a demand for new herbicides able to control resistant populations.

Currently a new herbicide, pyroxasulfone, an inhibitor of very long chain fatty acid synthesis (Tanetani et al. 2009) is being evaluated for potential use in crop production systems. Field research in the United States and Japan has determined that pyroxasulfone, applied as a PRE herbicide, is active on many grass weed species, including rigid ryegrass, as well as some dicot weed species. Pyroxasulfone has excellent selectivity in several major agronomic crops, including wheat, corn (*Zea mays* L.), and soybean [*Glycine max* (L.) Merr.] crops (Geier et al. 2009; Porpiglia et al. 2005; Ritter et al. 2006). Pyroxasulfone is currently being investigated as a PRE herbicide for the selective control of rigid ryegrass and other weeds in Australian cereal-crop production systems. Therefore, the aims of this research were to (1) compare the efficacy of pyroxasulfone with other PRE herbicides on resistant and susceptible rigid ryegrass populations, (2) establish pyroxasulfone selectivity for a range of crop species, and (3) evaluate the influence of cropping soil types on the efficacy of pyroxasulfone.

Materials and Methods

Establishment and Management of Experiments in Pots. The following are general procedures used in the establishment and management of experiments in pots. Specific treatment details and variations in these procedures are described in more detail in subsequent sections. Seeds of crop and weed species were planted into trays or pots filled with Gingin soil : sand (50 : 50 v/v) (Table 1). A highly characterized herbicide-susceptible (S) rigid ryegrass biotype (VLR 1) served as the control population in all studies, and the well-characterized, multiple herbicide-resistant (R) rigid ryegrass biotype (SLR 31) (Christopher et al. 1991, 1992; McAlister et al. 1995; Preston and Powles 1998; Tardif and Powles 1999) was used throughout these studies. The crop species used are described in the relevant experiments below. In each experiment, herbicide treatments were applied to crop and weed seed placed on the soil surface, ensuring that germinating seeds were directly exposed to herbicide treatment. Treatments were applied using a cabinet sprayer equipped with twin flat-fan nozzles (XR 11001)[1] delivering a water rate of 106 L ha^{-1} (210 kPa and 3.6 km h^{-1}). Following herbicide treatment, seeds were immediately covered with an additional 2-cm soil layer. Trays were maintained in the outside growth facility (unshaded) at the Nedlands Campus, University of Western Australia during the initial stages (April to June) of the 2005 to 2007 growing seasons, where average maximum/minimum temperatures for April to May were 24/14 C (2005), 23/12 C (2006), and 22/13 C (2007) (BOM 2010). Fertilizer was applied to the trays on a weekly basis as a complete liquid fertilizer (N 19% [NH_2 15%, NH_4 1.9%, NO_3 2.1%], P 8%, K 16%, Mg 1.2%, S 3.8%, Fe 400 mg kg^{-1}, Mn 200 mg kg^{-1}, Zn 200 mg kg^{-1}, Cu 100 mg kg^{-1}, B 10 mg kg^{-1}, Mo 10 mg kg^{-1}). Trays were irrigated as required (field water capacity) to supplement rainfall throughout the duration of the experiment. Pyroxasulfone efficacy was determined 21 d after treatment by counting emerged seedlings. These seedlings were then harvested by cutting at ground level before oven-drying at 70 C for 2 d and weighing for biomass determination.

Table 2. Herbicide treatments used in the herbicide comparison study.

Herbicide	Application rates
	g ai ha^{-1}
Pyroxasulfone	25, 50, 100, 200, 400
Propyzamide	62.5, 125, 250, 500, 1,000
Diuron	112.5, 225, 450, 900, 1,800
Trifluralin	120, 240, 480, 960, 1,920
Cinmethylin	90, 180, 360, 720, 1,440
Prosulfocarb + *s*-metolachlor	200 + 30, 400 + 60, 800 + 120, 1,600 + 240, 3,200 + 480

Comparison of PRE Herbicides. Six herbicides (pyroxasulfone, propyzamide [proposed common name; 3,5-dichloro-*N*-(1,1-dimethylprop-2-ynl)benazamide], diuron, trifluralin, cinmethylin, and prosulfocarb + *s*-metolachlor)[2] were compared in a dose–response experiment for their efficacy in controlling R and S rigid ryegrass populations (Table 2). Herbicide application rates were 0, 0.125, 0.25, 0.5, 1, and 2 times the proposed or recommended field rate (propyzamide, cinmethylin, and prosulfocarb + *s*-metolachlor) or 0.25, 0.5, 1, 2, and 4 times the proposed or recommended rate (diuron, pyroxasulfone, and trifluralin) for rigid ryegrass control. Seeds (n = 50) of either S or R rigid ryegrass populations were planted (May 27, 2005), with planting, spraying, and maintenance procedures used in these experiments as described previously.

Pyroxasulfone Crop Tolerance. Dose–response experiments were conducted to evaluate the effects of increasing rates of pyroxasulfone (0, 50, 100, 200, 400, and 800 g ha^{-1}) on the survival and biomass of wheat ('Wyalkatchem'), barley ('Sterling'), oat ('Carrolup'), triticale ('Tahara'), canola

(*Brassica napus* L. 'Tribune'), narrowleaf lupins (*Lupinus angustifolius* L. 'Tanjil'), chickpea (*Cicer arietinum* L. 'Sona'), field pea (*Pisum sativum* L. 'Kaspa'), faba bean (*Vicia faba* L. 'Farah'), and lentil (*Lens culinaris* Medik, 'Nipper'). Crop seed were placed on the surface of plastic trays filled with Gingin soil (April 30, 2006) using a planting density of 20 seeds per tray for the cereals and pulse species and 40 seeds per tray for canola. Seeds were covered with an additional 2 cm of soil immediately after herbicide treatment. Spraying, maintenance procedures, and data collection activities used in these experiments were the same as those described above.

Pyroxasulfone Crop Selectivity. The growth and survival of R and S ryegrass biotypes, wheat (cv. Wyalkatchem), lupins (cv. Tanjil), and canola (cv. Tribune) were evaluated in a dose–response study for their tolerance to pyroxasulfone. Crop species and ryegrass seeds were planted (May 30, 2007) into foam boxes (45 cm by 30 cm by 12 cm deep) containing a 10-cm layer of Gingin soil over a 2- to 3-cm layer of gravel. Rigid ryegrass and canola at a density of 100 seeds per box and wheat and lupins at a density of 40 seeds per box were placed on the soil surface before the application of pyroxasulfone at six rates (0, 10, 21, 42, 84, and 168 g ha^{-1}). Treated seeds were then covered with a 2-cm layer of soil. Herbicide treatments, experiment maintenance, and data collection procedures used in this experiment were the same as those described above.

Effect of Soil Type on Pyroxasulfone Activity. The effect of soil type on the efficacy of increasing rates of pyroxasulfone (0, 10, 21, 42, 84, and 168 g ha^{-1}) was evaluated in a dose–response study using four soil types with differing physical and chemical properties. Topsoil (0–5 cm) was collected from three cropping fields located at Mingenew (29°12′S, 115°26′E), Meckering (31°38′S, 117°00′E), and Buntine (29°59′S, 116°34′E), Australia, because these sites represent soils typical of the Western Australian cropping region. Gingin soil was included to allow comparison with results from previous experiments. After collection, soils were air-dried and sieved (2-mm-diam screen) before storing in waterproof bunkers until used in the pot experiments; the analysis of each soil sample was conducted by the CSBP soil testing service[3] (Table 1).

Gravel (2–3 cm) was placed in the bottom of 17-cm-diam pots to improve drainage; these pots were then filled with one of the four soil types. Twelve rigid ryegrass (S) seeds were placed on the soil surface of each pot (April 21, 2006) before herbicide treatment and subsequently covered with an additional 2 cm of soil. Pyroxasulfone application, experiment management, and data collection procedures were the same as those described above.

Design and Analysis of Pyroxasulfone-Screening Experiments. All experiments were arranged and analyzed using randomized block designs with four replicates. Plant survival and biomass data were analyzed using nonlinear regression and the open-source statistical software R 2.3.03 with the drc package (Knezevic et al. 2007) (R, Version 2.7.2). These analyses were used to (1) compare PRE herbicide efficacy on R and S rigid ryegrass biotypes, (2) determine pyroxasulfone tolerance for selected crop species, (3) determine selectivity between selected crop species and rigid ryegrass biotypes, and (4) determine the influence of soil type on pyroxasulfone efficacy. In each instance, a three-parameter, sigmoidal log-logistic function (Equation 1), as adapted from Seefeldt et al. (1995), was used:

$$Y = \left[(A/X - 1) \times (\mathrm{LD}_{50})^{B}\right]^{1/B} \qquad [1]$$

where X represents the herbicide dose, Y represents plant survival or shoot biomass compared with the nontreated control, A represents the maximum value of Y, LD_{50} is the application rate required to produce a 50% reduction in plant survival (alternatively, shoot biomass, ED_{50}), and B is the slope at LD_{50} or ED_{50}. Differences in R and S survival to PRE herbicides were determined using the δ method ($P = 0.05$) (van der Vaart 1998) to compare LD_{50} and LD_{90} values, respectively. This method was also used to determine differences in survival and biomass from the effects of soil type on pyroxasulfone activity; the Fisher's Protected LSD test at $P = 0.05$ was used to compare ED and LD values among soil types. In the crop tolerance and crop selectivity studies, where the pyroxasulfone rates used did not allow accurate estimations of LD_{50} and ED_{50}, standard errors were included on regression plots to indicate treatment differences.

Results and Discussion

Comparison of PRE Herbicides. Because multiple resistance to POST herbicides in rigid ryegrass is common throughout Australia's cropping regions (Boutsalis et al. 2008; Broster and Pratley 2006; Owen et al. 2007), PRE herbicides have been widely used to control this weed. In particular, there is high reliance on trifluralin because of its efficacy when incorporated by seeding in no-till stubble retention systems (Chauhan et al. 2007). However, overreliance has already led to widespread occurrence of trifluralin-resistant rigid ryegrass populations (Boutsalis et al. 2008; Owen et al. 2007). Comparison of a range of PRE herbicides with activity on rigid ryegrass identified three herbicides (pyroxasulfone, cinmethylin, and propyzamide) that effectively controlled both R and S rigid ryegrass biotypes (Figure 1; Table 3). Each of these herbicides controlled (> 90%) both biotypes at the proposed rigid ryegrass control rates (pyroxasulfone, cinmethylin, and propyzamide). The current, most widely used, PRE herbicide, trifluralin, controlled the S population but not the R population (48%) at the field-recommended rate (480 g ha^{-1}), as previously observed (McAlister et al. 1995; Tardif and Powles 1999). Effective trifluralin control of the R population required 1,920 g ha^{-1}, or four times the recommended rate. Cinmethylin at 180 g ha^{-1} and higher, or propyzamide at 250 g ha^{-1} and higher, controlled (> 95%) both R and S populations. However, because both these herbicides are equally effective on wheat (Dear et al. 2006; Vaughn and Gayland 1993, 1996; Young et al. 1984), they are not registered for selective control of rigid ryegrass in Australian wheat-production systems. Diuron provided good ryegrass control (> 90%) at the highest rate (1,800 g ha^{-1}); however, at the recommended field application rate (450 g ha^{-1}), control was inadequate. Diuron is registered

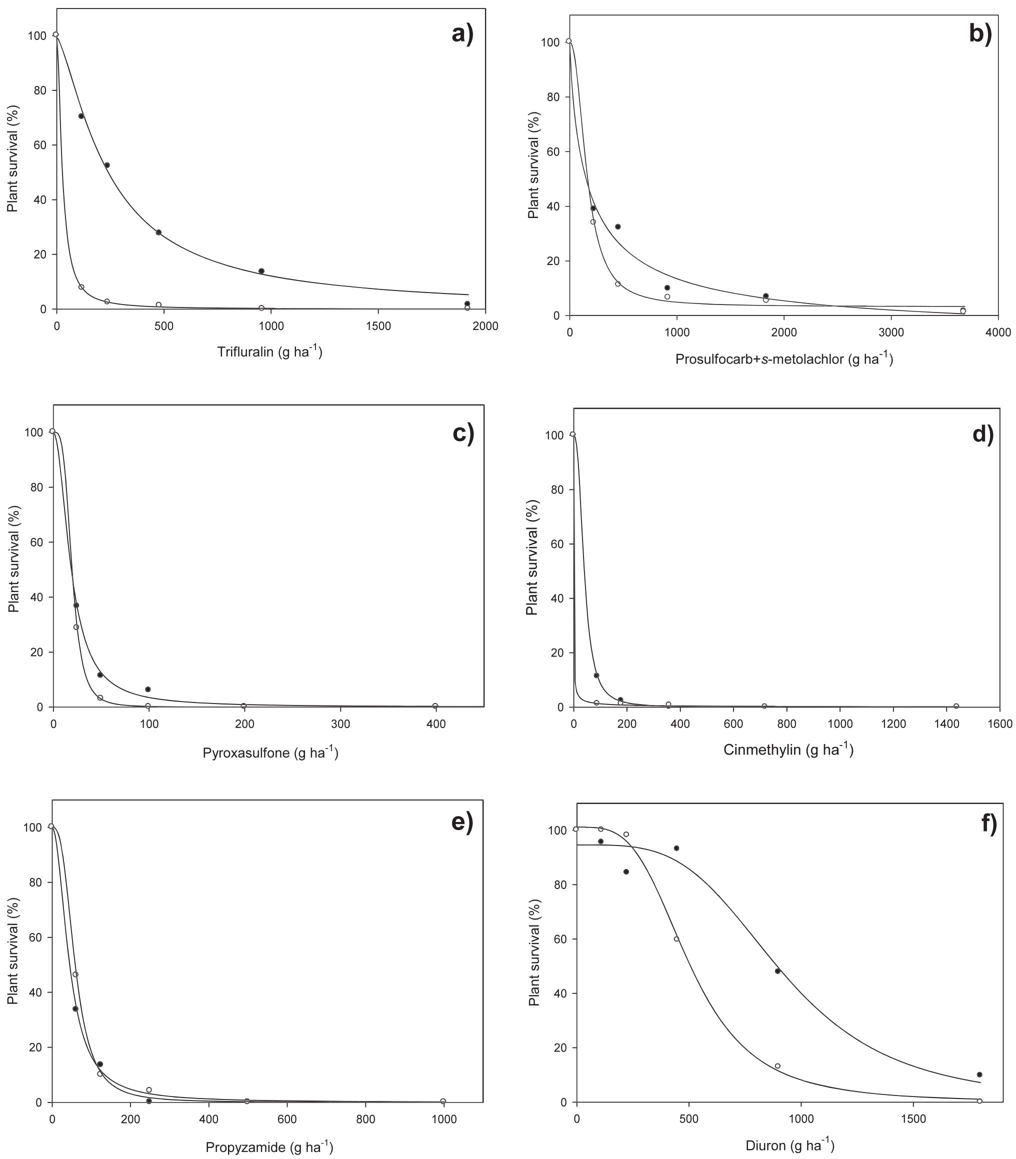

Figure 1. Survival (percentage of nontreated control) of resistant (solid circle) and susceptible (open circle) rigid ryegrass biotypes in response to the application of increasing rates of six PRE herbicides (a) trifluralin, (b) prosulfocarb + *s*-metolachlor, (c) pyroxasulfone, (d) cinmethylin, (e) propyzamide, and (f) diuron. Regression parameters are presented in Table 3.

for suppression only of rigid ryegrass in Australian wheat-production systems. The higher diuron LD_{50} for the R than S population indicates that this R biotype is resistant to this herbicide. The prosulfocarb + *s*-metolachlor combination provided acceptable control (90%) at the 1,600 + 240 g ha^{-1} rate and is registered for rigid ryegrass control in wheat at an application rate of 2,000 + 300 g ha^{-1}. However, the LD_{90} value for the R biotype was greater than that of the S biotype, indicting that this herbicide may not effectively control multiresistant rigid ryegrass populations.

Crop Species Tolerance to Pyroxasulfone. Wheat, along with several grain legume crop species (chickpea, lupins, faba bean, lentil), exhibited high levels of tolerance to pyroxasulfone. At the proposed field application rate, these crop species all exhibited >95% survival, with survival remaining high at twice that rate at >90% survival for all grain legume species and 85% survival for wheat (Figure 2; Table 4). The high tolerance of legume crop species is evident in the high (>65%) survival levels at the highest application rate of 800 g ha^{-1} of pyroxasulfone (Figure 2a). That rate also identified field pea (96% survival) and faba bean (93% survival) as the most pyroxasulfone-tolerant of the grain legume species screened. In fact, the rates used in this study were not high enough to allow differentiation between grain legume-crop species survival because of pyroxasulfone tolerance (Table 4). The pyroxasulfone tolerance observed here does not apply to all grain legumes. In North American field trials, dry bean (*Phaseolus vulgaris* L.) (Sikkema et al. 2007, 2008) and adzuki bean [*Vigna angularis* (Willd.) Ohwi &

Table 3. Regression parameters (see Equation 1) describing the relationships between PRE herbicide application rate and plant survival of resistant (R) and susceptible (S) rigid ryegrass biotypes. PRE herbicide rates (g ha^{-1}) required to reduce plant survival by 50 and 90% are LD_{50} and LD_{90}, respectively. Values in parentheses are standard errors showing variation around the mean of four replicates.

Herbicide	Biotype	*A*	*B*	LD_{50}	P value for LD_{50}	P value for LD_{90}
			%			
Trifluralin	R	100 (3)	1.4 (0.1)	504 (35)	< 0.001	> 1920 (280)*
	S	100 (3)	1.7 (1.4)	56 (76)	NS[a]	208 (66)
Prosulfocarb + *s*-metolachlor	R	99.8 (3)	1.1 (0.1)	169 (20.1)	< 0.001	1,288 (188)*
	S	100 (3)	1.6 (0.3)	148 (20)	< 0.001	578 (85)
Pyroxasulfone	R	100 (6)	2.0 (0.7)	19 (3.8)	< 0.001	57 (16)
	S	100 (6)	3.8 (2.9)	20 (4.2)	< 0.001	35.2 (10)
Cinmethylin	R	100 (1)	2.6 (0.8)	40 (10.1)	< 0.001	94.6 (4)
	S	100 (1)	0.7 (0.9)	0.2 (1.8)	NS	5 (20)
Propyzamide	R	100 (6)	2.0 (0.7)	45 (9)	< 0.001	134 (32)
	S	100 (6)	2.8 (0.9)	59 (6)	< 0.001	129 (27)
Diuron	R	95.3 (3)	4.4 (1.6)	1,020 (59)*	< 0.001	1,676 (346)
	S	103 (4)	3.5 (0.7)	554 (36)	< 0.001	1,040 (150)

[a] Abbreviations: NS, not significant at P = 0.05; *A*, the maximum value of plant survival compared with the nontreated control; *B*, the slope at LD_{50} or ED_{50}.

* Indicates LD_{50} or LD_{90} values of the R biotype that are significantly (P < 0.05) greater than those of the S biotype.

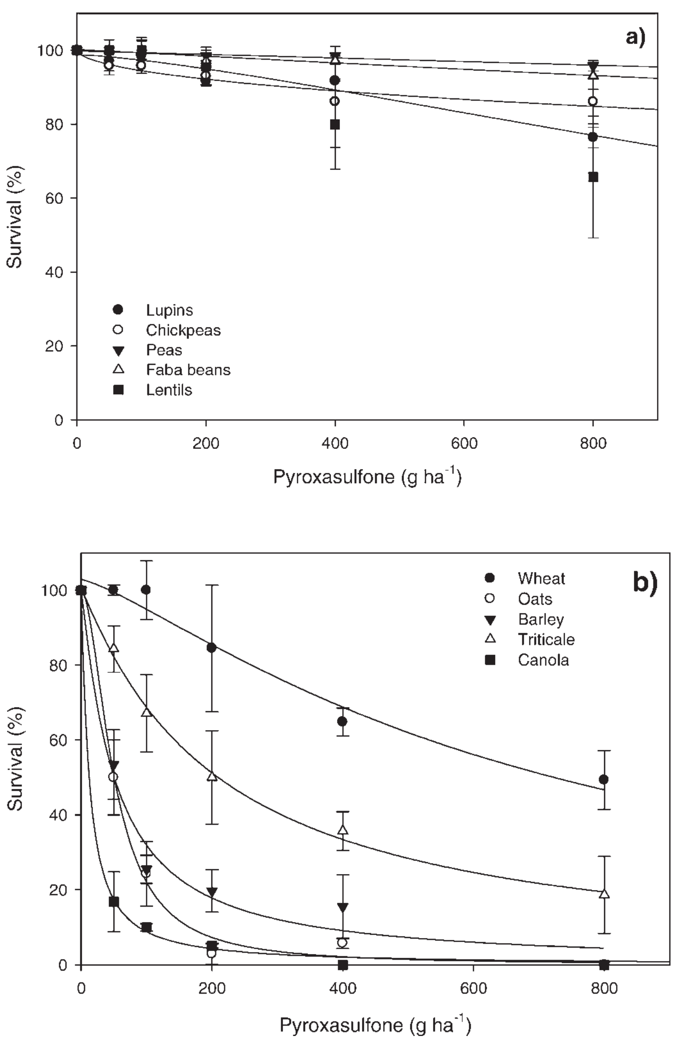

Figure 2. Survival (percentage of nontreated control) of (a) grain legumes and (b) cereal and canola crop species in response to increasing application rates of pyroxasulfone. Bars represent standard error values around the mean of four replicates. Regression parameters are presented in Table 4.

Ohash](Stewart et al. 2010) have been identified as being sensitive to pyroxasulfone at rates used here. Of the cereal species, wheat and triticale were clearly more tolerant to pyroxasulfone treatment than oat and barley (Figure 2b). Only wheat (49% survival) and triticale (19% survival) plants survived the highest pyroxasulfone application rate, with oat, barley, and canola being killed.

Crop species biomass levels confirmed the high pyroxasulfone tolerance of grain legumes and wheat crop species above that of other cereal and canola crop species. Additionally, the biomass results identified field pea as the most tolerant of the grain legume crop species evaluated (Figure 3a; Table 5) and confirmed wheat as the most tolerant of the cereal species. Although survival was not reduced at the proposed field application rate of 100 g ha^{-1} pyroxasulfone, the 10% biomass reduction in chickpea and lentil indicates that these species were affected at this rate. Apart from chickpea (72%) and lentil (64%), the 200 g ha^{-1} pyroxasulfone rate did not reduce plant biomass of the grain legume species by 10%. At the highest pyroxasulfone rate (800 g ha^{-1}), despite high plant survival levels, marked

Table 4. Regression parameters (see Equation 1) and pyroxasulfone (g ha^{-1}) rate that provided 50% reduction in plant survival (LD_{50}) of 10 crop species following the PRE application of increasing pyroxasulfone rates. Values in parentheses are standard errors showing variation around the mean of four replicates.

Crop	*A*	*B*	LD_{50}	P value for LD_{50}
Wheat	103 (5.5)	1.3 (0.3)	693	< 0.001
Oat	100 (7.2)	1.9 (0.5)	51 (9)	< 0.001
Barley	100 (7.2)	2.8 (2.9)	51 (7)	< 0.001
Triticale	102 (6.8)	1.0 (0.2)	192 (42)	< 0.001
Canola	100 (3.1)	1.6 (1.4)	10 (15)	NS[a]
Lupins	96 (2.1)	13 (6)	> 800	NS
Chickpea	100 (4.5)	52 (38)	> 800	NS
Field pea	99 (3.3)	1.0 (2.0)	> 800	NS
Faba bean	99 (2.1)	5.4 (0.2)	> 800	NS
Lentil	102 (3.3)	1.4 (0.4)	> 800	< 0.001

[a] Abbreviations: NS, not significant at P = 0.05; *A*, the maximum value of plant survival compared with the nontreated control; *B*, the slope at LD_{50}.

Table 5. Regression parameters (see Equation 1) and pyroxasulfone (g ha^{-1}) rate that provided 50% plant biomass reduction (ED_{50}) of 10 crop species following the PRE application of increasing pyroxasulfone rates. Values in parentheses are standard errors showing variation around the mean of four replicates.

Crop	*A*	*B*	ED_{50}	P value for ED_{50}
Wheat	102 (8)	1.1 (0.2)	226 (55)	< 0.001
Oat	100 (8)	1.1 (0.8)	14 (17)	NS[a]
Barley	100 (8)	1.3 (0.5)	40 (13)	0.004
Triticale	101 (8)	0.9 (0.3)	60 (19)	0.002
Canola	100 (8)	6.2 (16)	40 (22)	NS
Lupins	105 (6)	1.5 (0.4)	> 800	< 0.001
Chickpea	106 (7)	1.4 (0.3)	333 (63)	< 0.001
Field pea	101 (5)	2.7 (6)	> 800	NS
Faba bean	107 (6)	1.5 (0.4)	617 (116)	< 0.001
Lentil	102 (8)	1.0 (0.3)	455 (123)	< 0.001

[a] Abbreviations: NS, not significant at P = 0.05; *A*, the maximum value of shoot biomass compared with the nontreated control; *B*, the slope at ED_{50}.

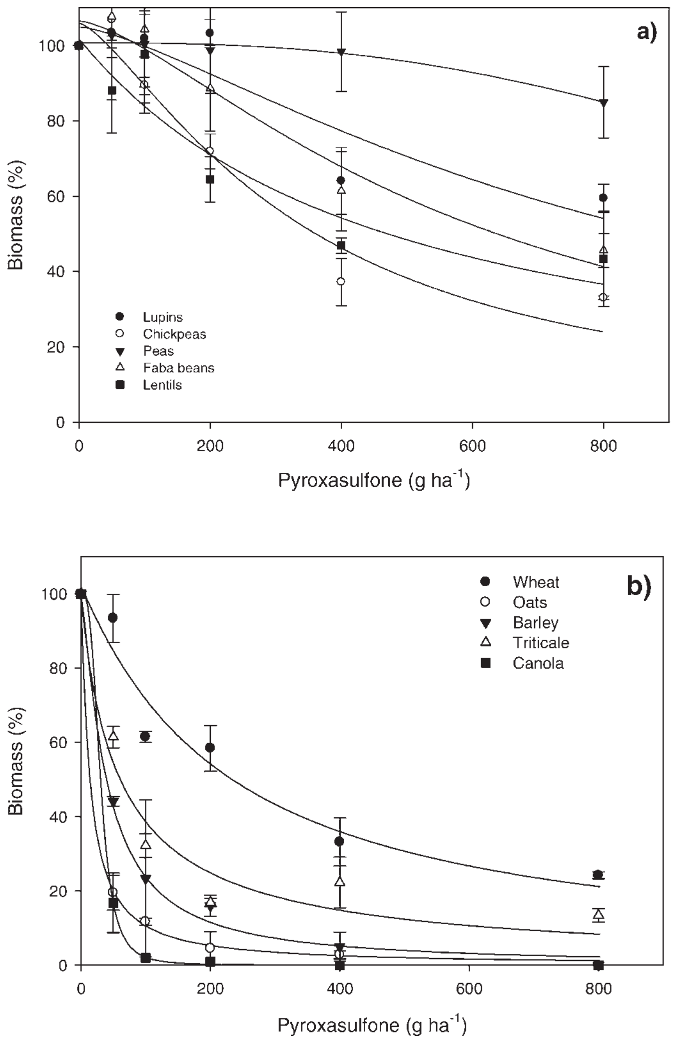

Figure 3. Biomass (percentage of nontreated control) of (a) grain legumes and (b) cereal and canola crop species in response to increasing application rates of pyroxasulfone. Bars represent standard error values around the mean of four replicates. Regression parameters are presented in Table 5.

reductions in plant biomass were recorded for lupins (41%), chickpea (67%), faba bean (54%), and lentil (57%), with field pea (15%) the least effected. Although wheat plant biomass was the least affected, all cereal crop species in general experienced large reductions in the growth of surviving plants (Figure 3b; Table 5). At the proposed field application rate of 100 g ha^{-1}, there were substantial reductions in plant biomass for wheat (39%), triticale (68%), barley (77%), and oat (88%).

Crop Selectivity. The ability of pyroxasulfone to selectively control rigid ryegrass populations in Australian cropping systems was evident in the differential response between R and S rigid ryegrass biotypes and different crop species to increasing rates of pyroxasulfone (Figure 4; Table 6). Pyroxasulfone rates that provided effective control of R and S rigid ryegrass biotypes did not affect the survival and biomass production of wheat or lupin plants. Specifically, at 42 g ha^{-1} pyroxasulfone, R and S rigid ryegrass populations were

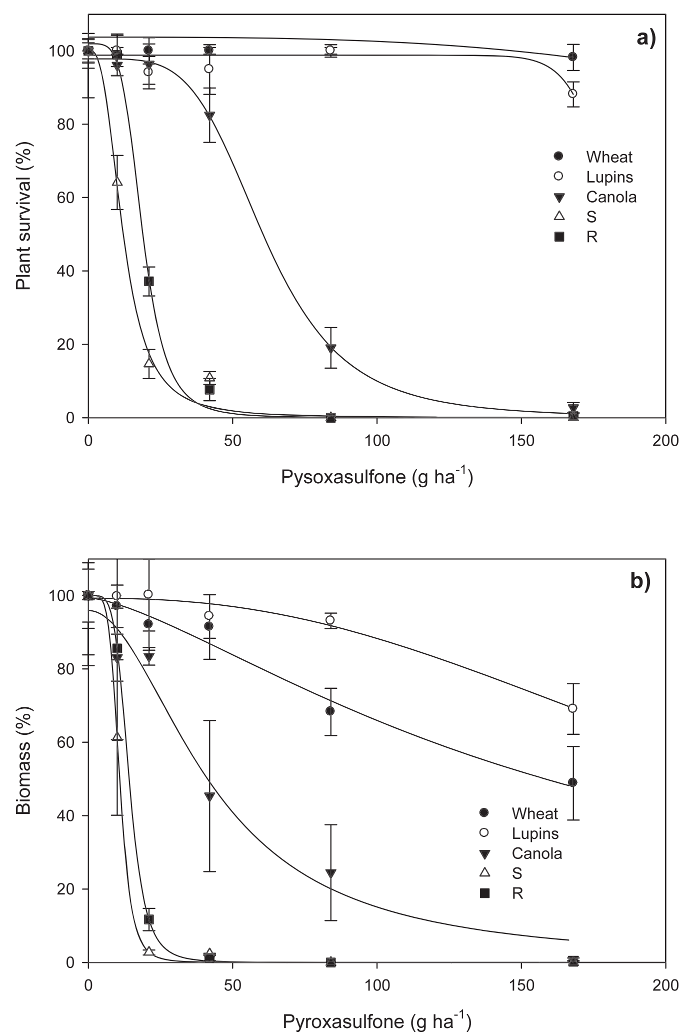

Figure 4. (a) Survival and (b) plant biomass responses (percentage of nontreated control) of wheat, lupins, canola, and susceptible (S) and resistant (R) rigid ryegrass plants following PRE application of increasing rates of pyroxasulfone. Bars represent standard error values around the mean of four replicates. Regression parameters are presented in Table 6.

Table 6. Regression parameters (see Equation 1) and pyroxasulfone (g ha^{-1}) rates that provided 50% reduction in plant survival (LD_{50}) and biomass (ED_{50}), derived from the relationship between seedling survival and plant biomass, respectively, of wheat, lupins, canola, and resistant (R) and susceptible (S) rigid ryegrass biotypes following the PRE application of increasing pyroxasulfone rates. Values in parentheses are standard errors showing variation around the mean of four replicates.

	Plant survival			
	%			
Species	*A*	*B*	LD_{50}	P value for LD_{50}
Wheat	99.2 (1.5)	3.6 (8.8)	> 168 (1,297)	NS[a]
Lupins	98.8 (1.94)	6.8 (9.3)	> 168 (115)	0.02
Caola	96.7 (2.0)	4.5 (0.5)	62 (2)	< 0.001
S	100 (3.2)	2.8 (0.4)	12 (1)	< 0.001
R	100 (3.0)	4.1 (0.8)	19 (1)	< 0.001
	Plant biomass			
	%			
	A	*B*	ED_{50}	P value for ED_{50}
Wheat	99.4 (6.8)	1.5 (0.6)	160 (75)	< 0.001
Lupins	99.3 (5.4)	2.4 (2.5)	> 168 (102)	0.02
Canola	95.9 (7.8)	2.0 (0.6)	43 (6)	< 0.001
S	100 (9.1)	5.4 (4.6)	11 (1)	< 0.001
R	100 (9.1)	5.1 (1.7)	14 (2)	< 0.001

[a] Abbreviations: NS, not significant at P = 0.05; *A*, the maximum value of plant survival or shoot biomass compared with the nontreated control; *B*, the slope at LD_{50} or ED_{50}.

controlled (< 10% survival) with little or no effect ($P < 0.05$) on wheat and lupin plant survival or biomass. When this rate was doubled to 84 g ha^{-1}, wheat and lupin plants survived, but wheat biomass was reduced by 32%. When the application rate was further increased to 168 g ha^{-1}, wheat and lupin plant survival remained unaffected, but plant biomass levels for both species were reduced by 51 and 30%, respectively. There appears to be little or no opportunity for pyroxasulfone to be used to selectively control rigid ryegrass in canola crops, with rates of 84 g ha^{-1} and above causing large reductions in canola plant survival and biomass.

Effect of Soil Type on Pyroxasulfone Activity. Pyroxasulfone is likely to be more effective in controlling rigid ryegrass on sandy soils. As indicated by differences in LD_{50} values, higher rates of pyroxasulfone were required to reduce survival by 50% for soils with higher clay content (Gingin and Buntine) than were required on sandier soils (Meckering and Mingenew) (Figure 5a; Table 7). However, there were no differences in LD_{90} values among the four soils, indicating that effective control of rigid ryegrass could be achieved at similar PRE application rates.

Plant biomass responses to pyroxasulfone indicated more clearly the decreased efficacy of pyroxasulfone at lower application rates in Gingin soil, which has both higher clay and organic matter contents (Figure 5b; Table 7). Both the ED_{50} and ED_{90} values were consistently highest for Gingin soil. Corresponding values were lower for Buntine soil, which has a clay content similar to Gingin soil but has lower organic matter content. Similar effects of soil type on pyroxasulfone activity were previously reported by Knezevic et al. (2009). Therefore, pyroxasulfone activity may be reduced in soils with

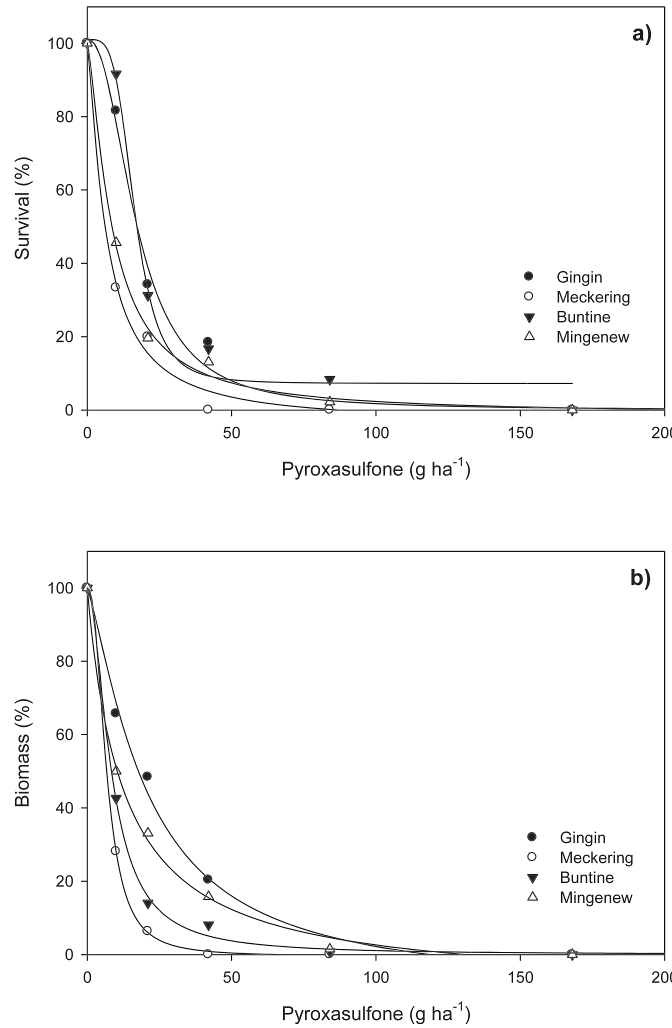

Figure 5. (a) Survival and (b) plant biomass responses (percentage of nontreated control) of susceptible rigid ryegrass grown in four soil types following PRE application of increasing rates of pyroxasulfone. Regression parameters are presented in Table 7.

relatively high clay content, high organic matter content, or both.

In summary, the efficacy of pyroxasulfone in selectively controlling rigid ryegrass suggests this herbicide has the potential to play a major role in the management of the current herbicide-resistance problems in Australian dryland wheat production systems. Herbicide screening determined that pyroxasulfone effectively controlled R and S rigid ryegrass biotypes and that control could be achieved at rates that had little or no effect on wheat. Further, grain legume crop species were found to be generally more tolerant of the herbicide than were cereals, with field pea being the most tolerant crop evaluated. A key aspect in the suitability of pyroxasulfone for Australian conditions is likely to be its flexibility. Results from this and previous studies indicate that activity remains robust on targeted weed species across a range of soil environments and application timings. The attributes of high stability following soil surface application and increased soil mobility (Dyer et al. 2005) allow this herbicide to be effective in both

Table 7. Regression parameters (see Equation 1) describing the relationships between pyroxasulfone application rate and plant survival and plant biomass of susceptible rigid ryegrass grown in four soil types. Pyroxasulfone rates (g ha^{-1}) required to reduce plant survival and biomass by 50 and 90% are the ED_{50} and ED_{90} values, respectively. Values in parentheses are standard errors showing variation around the mean of four replicates.[a]

	Plant survival[b]				
	%			P value for	%
Soil	*A*	*B*	LD_{50}	LD_{50}	LD_{90}
Gingin	100 (5.9)	2.3 (0.5)	17.2 (1.8) a	< 0.001	44 (6) a
Meckering	100 (6.2)	1.6 (0.5)	6.7 (1.7) b	< 0.001	27 (20) a
Buntine	100 (5.8)	3.0 (0.9)	17.4 (1.5) a	< 0.001	36 (5) a
Mingenew	100 (6.2)	1.4 (0.4)	8.7 (1.8) b	< 0.001	40 (12) a
	Plant biomass[b]				
	%			P value for	%
	A	*B*	ED_{50}	ED_{50}	ED_{90}
Gingin	99 (7.3)	1.6 (0.3)	17.8 (2.4) a	< 0.001	69 (85) a
Meckering	100 (7.2)	2.5 (1.6)	6.8 (2.2) b	0.002	17 (3) b
Buntine	100 (7.2)	1.8 (0.7)	8.4 (1.8) b	< 0.001	28 (9) b
Mingenew	100 (7.2)	1.3 (0.3)	10.8 (2.4) b	< 0.001	58 (19) a

[a] Abbreviations: *A*, the maximum value of plant survival or shoot biomass compared with the nontreated control; *B*, the slope at LD_{50} or ED_{50}.

[b] Means within a column followed by the same letter are not significantly different at P = 0.05 according to Fisher's Protected LSD test.

tyned-seeding and disc-seeding systems (Porpiglia et al. 2005; Watanabe et al. 2006). Therefore, the introduction of pyroxasulfone as a new, highly effective herbicide for selective control of rigid ryegrass in Australian wheat production systems is likely to be a milestone for Australian grain producers. However, a new, selective herbicide for rigid ryegrass control presents an imperative for producers to adopt diverse, integrated management strategies to prolong the sustainability of this herbicide.

Sources of Materials

[1] XR11001 TeeJet flat fan spray nozzles. Spraying Systems Co., North Avenue, Wheaton, IL 60189.

[2] Pyroxasulfone sourced from Kumiai Chemical Industry, Taitoh, Tokyo, 110-8782, Japan; propyzamide, diuron, trifluralin, and cinmethylin sourced from Nufarm Australia, Laverton North, Vic. 3026, Australia; prosulfocarb + *s*-metolachlor sourced from Syngenta Crop Protection, Inc., Greensboro, NC 27419.

[3] CSBP Soil Test Facility, Kwinana Beach Rd, Kwinana, WA 6167, Australia.

Literature Cited

[BOM] Bureau of Meteorology. 2010. Weather and Climate Statistics. Available at http://www.bom.gov.au. Accessed: September 2010.

Boutsalis, P., C. Preston, and G. Gill. 2008. Current levels of herbicide resistance in broadacre farming across southern Australia. Page 83 *in* Proceedings of the 16th Australian Weeds Conference. Brisbane, Australia: Weed Society of Queensland.

Broster, J. C. and J. Pratley. 2006. A decade of monitoring herbicide resistance in *Lolium rigidum* in Australia. Aust. J. Exp. Agric. 46:1151–1160.

Chauhan, B. S., G. S. Gill, and C. 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.

Christopher, J. T., S. B. Powles, and J.A.M. Holtum. 1992. Resistance to acetolactate synthase inhibiting herbicides in annual ryegrass (*Lolium rigidum*) involves at least two mechanisms. Plant Physiol. 100:1909–1913.

Christopher, J. T., S. B. Powles, J.A.M. Holtum, and D. R. Liljegren. 1991. Cross-resistance to herbicides in annual ryegrass (*Lolim rigidum*), II: chlorsulfuron resistance involves a wheat-like detoxification system. Plant Physiol. 95:1036–1045.

Dear, B. S., G. A. Sandral, and B.C.D. Wilson. 2006. Tolerance of perennial pasture grass seedlings to PRE- and POST-emergent grass herbicides. Aust. J. Exp. Agric. 46:637–644.

D'Emden, F. H. and R. S. Llewellyn. 2006. No-tillage adoption decisions in southern Australian cropping and the role of weed management. Aust. J. Exp. Agric. 46:563–569.

D'Emden, F. H., R. S. Llewellyn, and M. P. Burton. 2008. Factors influencing adoption of conservation tillage in Australian cropping regions. Aust. J. Agric. Res. Econ. 52:169–182.

Dyer, C. D., T. T. Bauman, and M. D. White. 2005. Determination of the soil persistence of KIH-485, acetochlor, dimethenamid and S-metolachlor. Proc. North Central Weed Sci. Soc. 59:63.

Geier, P. W., P. W. Stahlman, and J. C. Frihauf. 2009. KIH-485 and *s*-metolachlor efficacy comparisons in conventional and no-tillage corn. Weed Technol. 20:622–626.

Kloot, P. 1983. The genus *Lolium* in Australia. Aust. J. Bot. 31:421–435.

Knezevic, S. Z., A. Datta, J. Scott, and P. J. Porpiglia. 2009. Dose response curves of KIH-485 for PRE-emergence weed control in corn. Weed Technol. 23:34–39.

Knezevic, S. Z., J. C. Streibig, and C. Ritz. 2007. Utilizing R software package for dose–response studies: the concept and data analysis. Weed Technol. 21:840–848.

McAlister, F. M., J.A.M. Holtum, and S. B. Powles. 1995. Dintroaniline herbicide resistance in rigid ryegrass (*Lolium rigidum*). Weed Sci. 43:55–62.

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

Porpiglia, P. J., M. Nakatani, and R. Ueno. 2005. KIH-485: a new broad-spectrum herbicide. Weed Sci. Soc. Am. Abstr. 45:314.

Preston, C. and S. B. Powles. 1998. Amitrole inhibits diclofop metabolism and synergises diclofop-methyl in a diclofop-methyl resistant biotype of *Lolium rigidum*. Pestic. Biochem. Physiol. 62:179–189.

Ritter, R. L., H. Membere, and P. J. Porpiglia. 2006. Field investigations with KIH-485 in Maryland. Weed Sci. Soc. Am. Abstr. 46:50.

Seefeldt, S., J. E. Jensen, and E. P. Fuerst. 1995. Log-logistic analysis of herbicide dose–response relationships. Weed Technol. 9:218–227.

Sikkema, P. H., D. E. Robinson, R. E. Nurse, and N. Soltani. 2008. PRE-emergence herbicides for potential use in pinto and small red Mexican bean (*Phaseolus vulgaris*) production. Crop Prot. 27:124–129.

Sikkema, P. H., C. Shropshire, and N. Soltani. 2007. Dry bean response to preemergence-applied KIH-485. Weed Technol. 21:230–234.

Stewart, C. L., R. E. Nurse, C. Gillard, C, and P. H. Sikkema. 2010. Tolerance of adzuki bean to preplant-incorporated, PRE-emergence, and POST-emergence herbicides in Ontario, Canada. Weed Biol. Manag. 10:40–47.

Tanetani, Y., K. Kaku, K. Kawai, T. Fujioka, and T. Shimizu. 2009. Action mechanism of a novel herbicide, pyroxasulfone. Pestic. Biochem. Physiol. 95:47–55.

Tardif, F. J. and S. B. Powles. 1999. Effect of malathion on resistance to soil-applied herbicides in a population of rigid ryegrass (*Lolium rigidum*). Weed Sci. 47:258–261.

van der Vaart, A. W. 1998. Asymptotic Statistics. Cambridge, UK: Cambridge University Press.

Vaughn, S. F. and F. S. Gayland. 1993. Volatile monoterpenes as potential parent structures for new herbicides. Weed Sci. 41:114–119.

Vaughn, S. F. and F. S. Gayland. 1996. Synthesis and herbicidal activity of modified monoterpenes structurally similar to cinmethylin. Weed Sci. 44:7–11.

Watanabe, O., P. J. Porpiglia, Y. Yamaji, and H. Honda. 2006. Residual control with KIH-485. Weed Sci. Soc. Am. Abstr. 46:13.

Young, F. L., D. R. Gealy, and L. A. Morrow. 1984. Effect of herbicides on germination and growth of four grass weeds. Weed Sci. 32:489–493.

Received July 3, 2010, and approved October 12, 2010.