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Weed Management in Conventional- and No-Till Soybean Using Flumioxazin/Pyroxasulfone

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Eleven field experiments were conducted over a 3-yr period (2010, 2011, and 2012) in conventional- and no-till soybean with a flumioxazin and pyroxasulfone premix. PRE and preplant applications were evaluated for soybean injury, weed control, and yield compared to standard herbicides. Early-season soybean injury from flumioxazin/pyroxasulfone ranged from 1 to 19%; however, by harvest, soybean yields were similar across labeled rates (160 and 200 g ai ha^{-1}), standard treatments, and the nontreated control. Flumioxazin/pyroxasulfone provided excellent control (99 to 100%) of velvetleaf, pigweed species (redroot pigweed and smooth pigweed), and common lambsquarters across almost all rates tested (80 to 480 g ai ha^{-1}). Common ragweed, green foxtail, and giant foxtail control increased with flumioxazin/pyroxasulfone rate. The biologically effective rates varied between tillage systems. The flumioxazin/pyroxasulfone rate required to provide 80% control (R_{80}) of pigweed was 3 and 273 g ai ha^{-1} under conventional- and no-till, respectively. For common ragweed, the R_{80} was 158 g ai ha^{-1} under conventional tillage; yet, under no-till, the rate was nonestimable. The results indicate that flumioxazin/pyroxasulfone can provide effective weed control as a setup for subsequent herbicide applications.
Nomenclature: Flumioxazin; pyroxasulfone; common lambsquarters, *Chenopodium album* L.; common ragweed, *Ambrosia artemisiifolia* L.; giant foxtail, *Setaria faberi* Herrm.; green foxtail, *Setaria viridis* (L.) Beauv.; redroot pigweed, *Amaranthus retroflexus* L.; smooth pigweed, *Amaranthus hybridus* L.; velvetleaf, *Abutilon theophrasti* Medik.; soybean, *Glycine max* (L.) Merr.
Key words: Biologically effective rate, preplant herbicides, preemergence herbicides, soybean yield, weed control.

Durante un período de 3 años (2010, 2011, y 2012), se realizaron once experimentos de campo usando pre-mezclas de flumioxazin y pyroxasulfone en soya con labranza convencional y cero labranza. Se evaluó el efecto de aplicaciones PRE y pre-siembra en el daño de la soya, el control de malezas, y el rendimiento en comparación con herbicidas estándar. El daño de la soya, temprano durante la temporada de crecimiento, producto de flumioxazin/pyroxasulfone varió entre 1 y 19%. Sin embargo, al momento de la cosecha, los rendimientos de la soya fueron similares al compararse las dosis de etiqueta (160 y 200 g ai ha^{-1}), los tratamientos estándar, y el testigo sin tratamiento. Flumioxazin/pyroxasulfone brindó excelente control (99 a 100%) de *Abutilon theophrasti*, *Amaranthus retroflexus*, *Amaranthus hybridus*, y *Chenopodium album* en casi todas las dosis evaluadas (80 a 480 g ai ha^{-1}). El control de *Ambrosia artemisiifolia*, *Setaria viridis*, y *Setaria faberi* aumentó con la dosis de flumioxazin/pyroxasulfone. Las dosis biológicamente efectivas fueron diferentes según el sistema de labranza. La dosis de flumioxazin/pyroxasulfone requerida para brindar 80% de control (R_{80}) de *Amaranthus* spp. fue 3 y 273 g ai ha^{-1} en labranza convencional y en labranza cero, respectivamente. Para *A. artemisiifolia*, la R_{80} fue 158 g ai ha^{-1} en labranza convencional, aunque en labranza cero, la dosis no fue estimable. Los resultados indican que flumioxazin/pyroxasulfone puede brindar un control inicial de malezas efectivo que sirva de base para aplicaciones subsecuentes de otros herbicidas.

Use of glyphosate-resistant soybean has steadily increased since it was introduced in 1996, and now glyphosate resistance is the predominate trait found in soybean grown in North and South America (James 2012; U.S. Department of Agriculture–Economic Research Service [USDA-ERS] 2013). Within the glyphosate-resistant soybean production system, glyphosate provides broad-spectrum activity, a wide application window, and low phytotoxicity. However, over time, the increased selection pressure on weed populations due to overreliance on glyphosate as potentially the only means for weed control (Beckie 2011; Johnson et al. 2009; Young 2006) threatens the longevity of this technology

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with a rise in the frequency and geographical distribution of glyphosate-resistant weed biotypes (Heap 2013; Johnson et al. 2009; Owen 2008). Alternative herbicide tolerance traits have been developed to increase the diversity of modes of action used in soybean (e.g., glufosinate, dicamba, and 2,4-D) to mitigate glyphosate-resistance evolution in weeds and to institute better integrated weed management (IWM) practices. Utilizing PRE or preplant (PP) residual herbicides can also reduce the selection pressure for resistant biotypes by altering the spectrum of emerged weeds (Corrigan and Harvey 2000) and decreasing the need for multiple POST glyphosate applications (Ellis and Griffin 2002; Gonzini et al. 1999; Legleiter et al. 2009).

Fierce® (Valent U.S.A. Corporation, Walnut Creek, CA 94596) is a newly registered PP and PRE herbicide premix of flumioxazin (33.5%) and pyroxasulfone (42.5%) for use in soybean and other crops (Anonymous 2013). One component of this premix, flumioxazin, a light-dependent peroxidizing herbicide affecting the protoporphyrinogen oxidase enzyme, has been extensively studied for over a decade (Alister et al. 2008; Carbonari et al. 2009, 2010; Ferrell and Vencill 2003; Ferrell et al. 2005; Jaremtchuk et al. 2009; Johnson et al. 2012; Kwon et al. 2004; Niekamp et al. 1999; Taylor-Lovell et al. 2001, 2002). The other premix component is a relatively new herbicide, pyroxasulfone, which inhibits very long chain fatty acid synthesis (Tanetani et al. 2009) in broadleaf and grass weeds commonly found in soybean fields such as velvetleaf, redroot pigweed, smooth pigweed, common ragweed, common lambsquarters, green foxtail, and giant foxtail (Anonymous 2012).

The labeled use rates of flumioxazin/pyroxasulfone in soybean are 160 (flumioxazin at 71 g ai ha^{-1} plus pyroxasulfone at 89 g ai ha^{-1}) and 200 (flumioxazin at 88 g ai ha^{-1} plus pyroxasulfone at 112 g ai ha^{-1}) g ai ha^{-1} for coarse- to medium- and fine-textured soils, respectively (Anonymous 2013). Flumioxazin/pyroxasulfone has been shown to have a long period of residual activity (Bernards et al. 2010; Refsell et al. 2009; Young et al. 2010), yet the duration of residual weed control can be reduced following tillage or other soil disturbance (Anonymous 2013). There are limited published data on the performance of flumioxazin/pyroxasulfone in conventional- and no-till soybean. Therefore, in order to incorporate this new premix successfully into an IWM strategy, the biologically effective rate of flumioxazin/pyroxasulfone should be determined (Knezevic et al. 1998; Sikkema et al. 1999). The biologically effective rate provides a desired level of weed control, to either eradicate or reduce the growth of a target weed, depending on the management objectives (Dieleman et al. 1996). Although biologically effective rates are environment and weed-species dependent (Dieleman et al. 1996; Knezevic et al. 1998; Miller et al. 2012; Moran et al. 2011; Sikkema et al. 1999), PRE herbicides when used in conjunction with glyphosate POST can achieve full-season weed control (Johnson et al. 2012; Miller et al. 2012; Moran et al. 2011). Therefore, the first objective of this research was to evaluate PRE and PP treatments of flumioxazin/pyroxasulfone on crop injury, weed control, and soybean yield in comparison to industry-standard herbicides currently available in the marketplace. The second objective was to determine the biologically effective rate of flumioxazin/pyroxasulfone.

Materials and Methods

A total of 11 field experiments were conducted from 2010 to 2012 at the Huron Research Station, Exeter, Ontario and at the University of Guelph, Ridgetown Campus, Ridgetown, Ontario (Table 1). Treatments were arranged in a randomized complete block with four replications, with plots 2 m wide by 8 or 10 m long. Glyphosate-resistant soybean was seeded 3 to 4 cm deep with a 75-cm row spacing with the use of either a conventional- or no-till planter. Herbicide treatments were applied PP or PRE at the no-till or conventional tillage field sites, respectively, with the use of a CO_2-pressurized backpack sprayer calibrated to deliver 200 L ha^{-1} of water at 207 kPa through four Hypro Ultra-low drift 120-02 nozzles (Hypro, New Brighton, MN 55112) spaced 50 cm apart. Weedy and weed-free control plots were included in each replicate of each trial, and the weed-free controls were maintained with the use of glyphosate and hand weeding as needed. In the herbicide-treated plots, no additional methods of weed control were used for the remainder of the growing season.

Crop injury and weed control were estimated visually on a scale of 0 (no injury/control) to 100% (complete plant death). Soybean injury was rated at

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Table 1. Environment; soil characteristics; soybean seeding method, rate, and date; and spray date and for studies evaluating flumioxazin/pyroxasulfone in Ontario, Canada in 2010 to 2012.[a]

Environment		Soil characteristics			Soybean seeding			
Location	Year	Texture	OM	pH	Method	Rate	Date	Spray date
			%			seeds ha^{-2}		
Ridgetown	2010	Loam	5.0	7.4	Conventional	480,000	May 26	May 27
		Sandy loam	4.8	6.9	No-till	480,000	May 21	May 10
		Loamy sand	4.0	6.8	No-till	480,000	May 21	May 10
	2011	Sandy clay loam	2.3	7.4	Conventional	370,000	June 3	June 3
		Sandy loam	4.4	6.4	No-till	370,000	June 7	June 3
		Sandy loam	4.4	6.4	No-till	370,000	June 7	June 3
	2012	Clay loam	3.7	7.8	Conventional	370,000	May 24	May 25
		Loamy sand	4.0	6.8	No-till	380,000	May 24	May 25
Exeter	2010	Clay loam	4.1	7.9	Conventional	410,000	May 25	May 26
	2011	Clay loam	4.3	7.8	Conventional	360,000	June 3	June 6
	2012	Clay loam	4.5	7.8	Conventional	360,000	May 15	May 17

[a] Abbreviation: OM, organic matter.

2, 4, and 8 wk after herbicide treatment (WAT) and control of velvetleaf, a mixture of smooth and redroot pigweed referred to hereafter as pigweed species, common ragweed, common lambsquarters, green foxtail, and giant foxtail was rated at 4 and 8 WAT. Soybean was harvested at maturity with a small-plot combine, weight and moisture were recorded, and yields were adjusted to 13% moisture.

Data for crop injury, weed control at 4 WAT, moisture at harvest, and yield were analyzed using PROC MIXED (SAS Ver. 9.2, SAS Institute Inc., Cary, NC 27513). Variances were divided into fixed (herbicide treatment) and random effects [environment (i.e., location–year combinations), the herbicide treatment by environment interaction, and replication within environment]. Significance of the fixed effect was tested with the use of an F test, and random effects were tested with the use of a Z-test of the variance estimate. Environments were divided into conventional tillage and no-till and analyzed by tillage system for all variables. PROC UNIVARIATE in SAS was used to test data for normality and homogeneity of variance. Crop injury ratings for the weedy and weed-free controls, both of which were assigned zero values, and the weed control ratings for the nontreated control were excluded from the analyses. However, all values were compared independently to zero to evaluate treatment differences with the controls. To satisfy the assumptions of ANOVA, crop injury and weed control data were transformed as needed, and treatment means were separated with the use of Fisher's protected LSD at $P < 0.05$. Data compared on the transformed scale were converted back to the original scale for presentation of results.

Nonlinear regression (PROC NLIN in SAS) was used to evaluate weed control with flumioxazin/pyroxasulfone 8 WAT. A four-parameter log-logistic function was used to regress weed control assessments against flumioxazin/pyroxasulfone rate (Seefeldt et al. 1995):

$$Y = C + (D - C)/\{1 + \exp[-b(\ln\text{RATE} - \ln I_{50})]\}, \quad [1]$$

where Y is percent weed control, C is the lower asymptote, D is the upper asymptote, b is the slope, and I_{50} is the dose that gives a response halfway between C and D. Regression equations were used to calculate R_{80}, the predicted biologically effective rate of flumioxazin/pyroxasulfone required to give 80% control of a given weed species. The herbicide performance level of 80% control was used in this research to conform to the standard established by the Pest Management Regulatory Agency to support a label claim for control of a weed species (Health Canada 2003). If any rate was predicted to be higher than 480 g ha^{-1}, it was simply expressed as > 480, as it would be improper to extrapolate outside the range of rates evaluated in these experiments.

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Results and Discussion

Early-season soybean injury in the conventional-till sites was observed for all PRE treatments, except pyroxasulfone applied alone at 89 g ha^{-1}. Flumioxazin/pyroxasulfone caused 1 to 19% injury 4 WAT (Table 2). Soybean injury symptoms caused by flumioxazin/pyroxasulfone included delayed emergence, decreased stand, stunted plants, puckered leaf tissue, and necrosis. Injury tended to increase with flumioxazin/pyroxasulfone rate and decrease over time. By 8 WAT, no differences in injury among the treated and nontreated soybean were detected, except for the highest rates of flumioxazin/pyroxasulfone (240 and 480 g ha^{-1}) (Table 2). At harvest, the impact of early-season injury was negligible, as soybean yields were similar across the labeled use rates, common industry-standard treatments, and the nontreated control. Observations of significant, yet transient soybean injury from flumioxazin/pyroxasulfone are consistent with other studies (Refsell et al. 2009; Stachler et al. 2010; Stachler and Luecke 2011; Young et al. 2010). Flumioxazin/pyroxasulfone provided 95 to 100% control of common lambsquarters and pigweed species across all tested rates, and was comparable to the industry standards and the weed-free control (Table 3). This is similar to other studies that demonstrated excellent control of common lambsquarters (Bernards et al. 2010; Refsell et al. 2009; Young et al. 2010) and various *Amaranthus* species (Bernards et al. 2010; Refsell et al. 2009; Stachler et al. 2010; Stachler and Luecke 2011; Young et al. 2010) with flumioxazin/pyroxasulfone. Flumioxazin/pyroxasulfone (80 g ai ha^{-1}) provided suppression of velvetleaf, common ragweed, and green foxtail, and, in general, the level of control increased with flumioxazin/pyroxasulfone rate. Velvetleaf control with flumioxazin/pyroxasulfone applied at 80 g ai ha^{-1} was equivalent to the level of control provided by 160 g ha^{-1} of flumioxazin/pyroxasulfone and to the tank mixes of dimethenamid-p plus imazethapyr plus metribuzin and *S*-metolachlor plus metribuzin (Table 3). Bernards et al. (2010) reported a similar level of velvetleaf activity with 160 g ha^{-1} of flumioxazin/pyroxasulfone in soybean. For common ragweed, decreased efficacy was not unexpected because of the overall weakness of flumioxazin/pyroxasulfone on this species (Stachler and Carlson 2013), especially at low rates (Anonymous 2013; Stachler and Luecke 2011).

In the no-till system, marked differences were observed in soybean injury, yield, and weed control. In general, soybean injury ratings were greatly reduced for most PP treatments compared to the corresponding PRE treatments (Table 2), and were similar to the nontreated control across all obser-

Table 2. Visual estimates of soybean injury, crop moisture at harvest, and yield with various rates of flumioxazin/pyroxasulfone and several industry standards applied PRE in conventional tillage soybean at Exeter, ON and Ridgetown, ON in 2010 to 2012.[a]

Treatment	Rate	Soybean injury[b]			Moisture	Yield
		2 WAT	4 WAT	8 WAT		
	g ai ha^{-1}	%				kg ha^{-1}
Weed-free control		0 a	0 a	0 a	13.7	3,960 a
Weedy control		0 a	0 a	0 a	14.2	2,740 d
Flumioxazin/pyroxasulfone (35/45)[c]	80	1.1 bc	0.9 b	0.1 ab	14.1	3,240 c
Flumioxazin/pyroxasulfone (71/89)	160	2.7 bc	3.1 bc	0.2 ab	14.2	3,590 abc
Flumioxazin/pyroxasulfone (88/112)	200	4.7 cd	5.4 cd	0.5 ab	14.1	3,670 ab
Flumioxazin/pyroxasulfone (105/134)	240	7.6 de	8.9 d	1.2 b	13.9	3,690 ab
Flumioxazin/pyroxasulfone (211/268)	480	13.8 e	19.0 e	3.7 c	14.1	3,730 ab
Flumioxazin	71	1.2 bc	1.9 bc	0.1 ab	14.1	3,380 bc
Pyroxasulfone	89	0 a	0 a	0 a	14.0	3,250 c
S-metolachlor + metribuzin	1,600 + 653	0.4 ab	2.8 bc	0.2 ab	13.9	3,610 abc
Flumioxazin + imazethapyr + metribuzin	71 + 75 + 425	1.2 bc	1.4 b	0 a	13.8	3,970 a
Dimethenamid-p + imazethapyr + metribuzin	544 + 75 + 425	1.2 bc	0.9 b	0.3 ab	13.7	3,940 a
S-metolachlor + metribuzin + chlorimuron-ethyl	1,600 + 653 + 9	0.2 ab	1.9 bc	0.1 ab	13.8	3,860 a

[a] Abbreviations: PRE, preemergence; WAT, weeks after treatment.

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

[c] Numbers in parentheses represent the approximate rate (g ai ha^{-1}) for each component of the flumioxazin/pyroxasulfone premix.

Table 3. Visual estimates of percent weed control 4 WAT with various rates of flumioxazin/pyroxasulfone and several industry standards applied PRE in conventional tillage soybean at Exeter, ON and Ridgetown, ON in 2010 to 2012.[a]

Treatment	Rate	Weed control[b] Velvetleaf	Pigweed	Common ragweed	Common lambsquarters	Green foxtail
	g ai ha^{-1}	%				
Weed-free control		100 a	100 a	100 a	100 a	100 a
Weedy control		0 d	0 b	0 f	0 c	0 f
Flumioxazin/pyroxasulfone (35/45)[c]	80	79.2 b	100 a	74.0 d	95.2 a	82.6 e
Flumioxazin/pyroxasulfone (71/89)	160	98.5 ab	100 a	94.4 bc	99.3 a	93.5 d
Flumioxazin/pyroxasulfone (88/112)	200	99.9 a	100 a	95.9 abc	99.5 a	95.5 cd
Flumioxazin/pyroxasulfone (105/134)	240	99.9 a	100 a	98.7 ab	99.9 a	97.7 bcd
Flumioxazin/pyroxasulfone (211/268)	480	100 a	100 a	99.0 ab	100 a	99.3 ab
Flumioxazin	71	93.3 ab	99.5 a	86.5 cd	95.3 a	78.4 e
Pyroxasulfone	89	31.9 c	99.8 a	45.3 e	76.3 b	85.9 e
S-metolachlor + metribuzin	1,600 + 653	99.3 ab	100 a	95.5 bc	99.9 a	98.7 abc
Flumioxazin + imazethapyr + metribuzin	71 + 75 + 425	100 a	100 a	99.0 ab	100 a	97.9 bcd
Dimethenamid-p + imazethapyr + metribuzin	544 + 75 + 425	99.4 ab	100 a	96.5 abc	99.9 a	98.2 abcd
S-metolachlor + metribuzin + chlorimuron-ethyl	1,600 + 653 + 9	99.9 a	100 a	99.7 ab	100 a	97.4 bcd

[a] Abbreviations: PRE, preemergence; WAT, weeks after treatment.
[b] Means followed by the same letter within a column are not significantly different according to Fisher's protected LSD at $P < 0.05$.
[c] Numbers in parentheses represent the approximate rate (g ai ha^{-1}) for each component of the flumioxazin/pyroxasulfone.

vation timings (Table 4). Early-season soybean injury tended to increase with flumioxazin/pyroxasulfone rate and was the most evident at 480 g ha^{-1} with 4% injury at 2 and 4 WAT (Table 4). No injury symptoms were observed across all treatments by 8 WAT; however, soybean yields were reduced compared to the weed-free control and to the analogous PRE treatments (Table 2). It was unclear as to exactly why the magnitude of injury ratings differed between PRE and PP treatments; while

Table 4. Visual estimates of soybean injury, crop moisture at harvest and yield with various rates of flumioxazin/pyroxasulfone and several industry standards applied PP in no-till soybean at Ridgetown, ON in 2010 to 2012.[a]

Treatment[b]	Rate	Soybean injury[c] 2 WAT	4 WAT	8 WAT	Moisture	Yield
	g ai ha^{-1}	%				kg ha^{-1}
Weed-free control		0 a	0 a	0	15.4	3,750 a
Weedy control		0 a	0 a	0	16.5	730 e
Flumioxazin/pyroxasulfone (35/45)[d]	80	0 a	0 a	0	17.1	1,160 de
Flumioxazin/pyroxasulfone (71/89)	160	0 a	0 a	0	17.1	1,570 cd
Flumioxazin/pyroxasulfone (88/112)	200	1.0 b	0.3 a	0	16.9	1,780 c
Flumioxazin/pyroxasulfone (105/134)	240	1.2 b	1.5 a	0	17.1	1,910 c
Flumioxazin/pyroxasulfone (211/268)	480	3.7 c	4.2 b	0.6	16.6	2,520 b
Flumioxazin	71	0 a	0 a	0	17.4	1,140 de
Pyroxasulfone	89	0 a	0 a	0	17.4	1,560 cd
S-metolachlor + metribuzin	1,600 + 653	0 a	0 a	0	16.8	1,780 c
Flumioxazin + imazethapyr + metribuzin	71 + 75 + 425	0 a	0 a	0	16.3	2,480 b
Dimethenamid-p + imazethapyr + metribuzin	544 + 75 + 425	0 a	0.3 a	0	16.3	2,890 b
S-metolachlor + metribuzin + chlorimuron-ethyl	1,600 + 653 + 9	0 a	0 a	0	17.0	1,890 c

[a] Abbreviations: PP, preplant; WAT, weeks after treatment.
[b] All herbicide treatments included glyphosate at 1,350 g ae ha^{-1}.
[c] Means followed by the same letter within a column are not significantly different according to Fisher's protected LSD at $P < 0.05$.
[d] Numbers in parentheses represent the approximate rate (g ai ha^{-1}) for each component of the flumioxazin/pyroxasulfone premix.

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only conjecture, differences in organic matter (OM) and/or microbial degradation could be a possibility. The no-till soils had comparatively greater amounts of OM than the soil found at the conventional tillage locations (Table 1). Soil OM has been shown to be a preferential adsorption site for both flumioxazin (Alister et al. 2008; Ferrell et al. 2005) and pyroxasulfone (Knezevic et al. 2009; Szmigielski et al. 2013) and higher rates of flumioxazin/pyroxasulfone are required for soils with high OM to maintain efficacy (Anonymous 2013). In addition, microbial degradation, an important dissipation pathway for flumioxazin (Ferrell et al. 2003) and pyroxasulfone (Szmigielski et al. 2013) in the soil environment, is enhanced in no-till systems and influences herbicide efficacy (Locke and Bryson 1997). Geier et al. (2006) similarly found that PRE herbicide efficacy can differ between conventional- and no-till field sites, impacting yield. In this study, the overall reduction in soybean yield between PRE and PP treatments, however, could be attributed to weed interference. In four out of five site-years, moderate to high populations of giant foxtail, ranging from 100 to 300 plants m^{-2} (data not shown), were observed in the weedy control plots throughout the duration of the experiment (C Shropshire, personal communication). Generally, soybean yield increased with flumioxazin/pyroxasulfone rate (Table 4). The highest soybean yields recorded, although less than the weed-free control, ranged from 2,480 to 2,890 kg ha^{-1} in plots treated with flumioxazin/pyroxasulfone (480 g ha^{-1}) and the tank-mix treatments of flumioxazin plus imazethapyr plus metribuzin and dimethenamid-p plus imazethapyr plus metribuzin (Table 4). The imazethapyr component of these industry-standard tank-mix treatments likely contributed to a better overall control of giant foxtail (Ontario Ministry of Agriculture, Food and Rural Affairs [OMAFRA] 2012). Weed species varied in their response to flumioxazin/pyroxasulfone. For example, 80 g ha^{-1} of flumioxazin/pyroxasulfone applied PP provided 17 to 53% control across all weed species; for pigweed species and common lambsquarters, control was similar to *S*-metolachlor plus metribuzin (Table 5). Control of velvetleaf and pigweed species (flumioxazin/pyroxasulfone rates from 160 to 480 g ha^{-1}) and common lambsquarters and giant foxtail (flumioxazin/pyroxasulfone rates at 240 and 480 g ha^{-1}) were similar to the weed-free control and to many of the industry-standard treatments (Table 5). Common ragweed control increased with flumioxazin/pyroxasulfone rate and, in plots treated with at least 200 g ha^{-1}, control was equivalent to the industry standards (Table 5). These data suggest that common ragweed may be one of the first weeds to escape the uppermost labeled use rate of flumioxazin/pyroxasulfone.

The biologically effective rates of flumioxazin/pyroxasulfone on the weed species tested varied substantially between the conventional- and no-till systems. For example, at 8 WAT, the rate of flumioxazin/pyroxasulfone required to provide 80% control (R_{80}) of pigweed was 3 and 273 g ha^{-1} in the conventional- and no-till system, respectively (Table 6). The R_{80}s for velvetleaf and common lambsquarters were fourfold lower under conventional tillage compared to no-till and were lower than the lowest labeled rate (i.e., 160 g ha^{-1}). For common ragweed, the R_{80} approached the low labeled rate (i.e., 158 g ha^{-1}) under conventional tillage; yet, under no-till, the flumioxazin/pyroxasulfone rate was nonestimable, as the upper asymptote of the dose–response curve never reached 80%, indicating that common ragweed was difficult to control (see Equation 1; Table 6). The rate required for 80% control of giant foxtail was predicted to be greater than 480 g ha^{-1} (Table 6), which was consistent with Young et al. (2010), who reported marginal control with flumioxazin/pyroxasulfone in soybean. Miller et al. (2012) similarly found that the biologically effective rates of PRE herbicides can vary and that environmental conditions (i.e., temperature and moisture) had a substantial influence on the results. In these experiments, however, discrepancies in the biologically effective rates of flumioxazin/pyroxasulfone observed between the conventional- and no-till systems cannot be ascribed to environment alone, because the trials were, for the most part, conducted concurrently (Table 1). Furthermore, at the Ridgetown and Exeter locations, rainfall patterns were sufficient in all 3 yr to provide activation of the PRE and PP treatments (data not shown). Moran et al. (2011) found that the biologically effective rate of saflufenacil + dimethenamid-p ranged widely because of the weed species inherent to a location, as some weeds were more difficult to control than others. In this study, heavy giant foxtail pressure in

Table 5. Visual estimates of percent weed control 4 WAT with various rates of flumioxazin/pyroxasulfone and several industry standards applied PP in no-till soybean at Ridgetown, ON in 2010 to 2012.[a]

Treatment[b]	Rate	Weed control[c] Velvetleaf	Pigweeds	Common ragweed	Common lambsquarters	Giant foxtail
	g ai ha^{-1}	%				
Weed-free control		100 a	100 a	100 a	100 a	100 a
Weedy control		0 c	0 e	0 e	0 f	0 f
Flumioxazin/pyroxasulfone (35/45)[d]	80	16.7 c	52.7 d	18.3 d	33.5 de	51.5 e
Flumioxazin/pyroxasulfone (71/89)	160	86.5 ab	79.4 abcd	46.7 cd	65.9 cd	80.7 cd
Flumioxazin/pyroxasulfone (88/112)	200	93.7 a	96.0 abc	71.6 bc	84.6 bc	91.7 bcd
Flumioxazin/pyroxasulfone (105/134)	240	93.7 a	99.0 ab	73.9 bc	89.8 abc	93.6 abcd
Flumioxazin/pyroxasulfone (211/268)	480	99.8 a	99.9 a	85.6 b	96.9 ab	98.0 ab
Flumioxazin	71	27.7 bc	60.3 cd	23.6 d	41.3 de	44.1 e
Pyroxasulfone	89	12.0 c	63.6 bcd	19.3 d	18.6 e	79.0 d
S-metolachlor + metribuzin	1,600 + 653	96.4 a	42.0 d	87.8 ab	61.2 cd	88.0 bcd
Flumioxazin + imazethapyr + metribuzin	71 + 75 + 425	99.2 a	100 a	96.0 ab	97.8 ab	92.7 bcd
Dimethenamid-p + imazethapyr + metribuzin	544 + 75 + 425	98.4 a	99.5 ab	89.8 ab	100 a	96.8 abc
S-metolachlor + metribuzin + chlorimuron-ethyl	1,600 + 653 + 9	94.4 a	97.9 ab	86.2 b	98.4 ab	94.0 abcd

[a] Abbreviations: PRE, preemergence; WAT, weeks after treatment.
[b] All herbicide treatments included glyphosate at 1,350 g ae ha^{-1}.
[c] Means followed by the same letter within a column are not significantly different according to Fisher's protected LSD at $P < 0.05$.
[d] Numbers in parentheses represent the approximate rate (g ai ha^{-1}) for each component of the flumioxazin/pyroxasulfone.

the no-till field sites may have contributed to the differences observed, and further studies may be needed to elucidate the biologically effective rate of flumioxazin/pyroxasulfone under no-till.

This research demonstrated that PP and PRE applications of flumioxazin/pyroxasulfone can be effective on weed species common to soybean fields, some of which are known to be herbicide resistant

Table 6. Regression parameter estimates and predicted flumioxazin/pyroxasulfone rates from the dose–response model of weed control 8 WAT in conventional tillage soybean at Exeter, ON and Ridgetown, ON in 2010 to 2012 and no-till soybean at Ridgetown, ON in 2010 to 2012.[a]

Weed species	Parameter estimates[b] (± SE) *C*		*D*		*b*		I_{50}		R_{80}[c]
Conventional	%						g ai ha^{-1}		
Velvetleaf	0	(5)	100	(0)	3.5	(1.0)	74	(6)	110
Pigweeds	0	(0)	100	(0)	5.9	(14.0)	3	(21)	3
Common ragweed	0	(5)	100	(0)	1.6	(0.3)	66	(11)	158
Common lambsquarters	0	(4)	100	(0)	2.0	(0.5)	46	(10)	92
Green foxtail	0	(0)	99	(4)	2.0	(0.6)	57	(6)	116
No-till[d]									
Velvetleaf	0	(14)	100	(0)	1.5	(0.8)	171	(55)	439
Pigweeds	1	(9)	100	(0)	1.8	(0.5)	127	(24)	273
Common ragweed	2	(7)	78	(17)	3.2	(2.2)	218	(43)	
Common lambsquarters	0	(6)	100	(0)	2.2	(0.5)	215	(22)	408
Giant foxtail	2	(6)	100	(0)	1.8	(0.4)	255	(28)	> 480

[a] Abbreviation: WAT, weeks after treatment.
[b] Dose–response parameters: *b*, slope; *C*, lower asymptote; *D*, upper asymptote; I_{50}, rate required for 50% response.
[c] R_{80} is the predicted rate required to give 80% weed control for a given weed species.
[d] No-till herbicide treatments included glyphosate at 1,350 g ae ha^{-1}.

(Heap 2013). Furthermore, under certain conditions and with specific weed species, the rates of flumioxazin/pyroxasulfone are flexible and could be used alone to provide season-long control without the need for a POST herbicide application. Caution would be advised before advocating a widespread adoption of flumioxazin/pyroxasulfone rate cutting and relying on this or other soil-applied herbicides as the sole means for weed control as exemplified by our results under no-till conditions. In our no-till scenario, flumioxazin/pyroxasulfone could have served as a setup for an additional POST graminicide application, which could have contributed to better overall weed control and soybean yield. However, this only is speculative, as others have reported no yield benefit in soybean when POST glyphosate follows a soil-applied herbicide (Corrigan and Harvey 2000; Ellis and Griffin 2002; Miller et al. 2012). Regardless, we were limited by the constructs of our experimental objectives and this was not examined.

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Literature Cited

Alister C, Rojas S, Gomez P, Kogan M (2008) Dissipation and movement of flumioxazin in soil at four field sites in Chile. Pest Manag Sci 64:579–583

Anonymous (2012) Zidua® herbicide product label. NVA 2012-04-388-0031. Research Triangle Park, NC: BASF. 12 p

Anonymous (2013) Fierce® herbicide product label. Form 2013-FIE-0013. Walnut Creek, CA: Valent. 8 p

Beckie HJ (2011) Herbicide-resistant weed management: focus on glyphosate. Pest Manag Sci 67:1037–1048

Bernards ML, Dale TM, Hartzler BG, Owen MD, Peterson D, Shoup DE, Gunsolus J, Knezevic SZ, Wilson RG, Zollinger R, Moechnig MJ, Refsell D, Pawlak JA (2010) Residual activity of flumioxazin + pyroxasulfone in the western soybean belt. Abstract 108 *in* Proceedings of the North Central Weed Science Society. Lexington, KY: North Central Weed Science Society

Carbonari CA, Gomes CLGC, Velini ED (2009) Effects of flumioxazin permanence period in soil and in corn and oat mulch on weed control efficacy. Rev Bras Herbic 8:85–95 [In Portuguese with English abstract]

Carbonari CA, Gomes CLGC, Velini ED (2010) Effects of different periods without rain occurrence in the efficacy of flumioxazin applied in soil and in sugarcane mulch. Rev Bras Herbic 9:81–88 [In Portuguese with English abstract]

Corrigan KA, Harvey RG (2000) Glyphosate with and without residual herbicides in no-till glyphosate-resistant soybean (*Glycine max*). Weed Technol 14:569–577

Dieleman A, Hamill AS, Fox GC, Swanton CJ (1996) Decision rules for postemergence control of pigweed (*Amaranthus* spp.) in soybean (*Glycine max*) Weed Sci 44:126–132

Ellis JM, Griffin JL (2002) Benefits of soil-applied herbicides in glyphosate-resistant soybean (*Glycine max*). Weed Technol 16:541–547

Ferrell JA, Vencill WK (2003) Flumioxazin soil persistence and mineralization in laboratory experiments. J Agric Food Chem 51:4719–4721

Ferrell JA, Vencill WK, Xia K, Grey TL (2005) Sorption and desorption of flumioxazin to soil clay minerals and ion-exchange resin. Pest Manag Sci 61:40–46

Geier PW, Stahlman PW, Frihauf JC (2006) KIH-485 and *S*-metolachlor efficacy comparisons in conventional and no-tillage corn. Weed Technol 20:622–626

Gonzini LC, Hart SE, Wax LM (1999) Herbicide combinations for weed management in glyphosate-resistant soybean (*Glycine max*). Weed Technol 13:354–360

Health Canada (2003) PMRA (DIR2003-04) Regulatory Directive: Efficacy Guidelines for Plant Protection Products. http://www.hc-sc.gc.ca/cps-spc/pubs/pest/_pol-guide/dir2003-04/index-eng.php. Accessed on October 28, 2013

Heap I (2013) The international survey of herbicide resistant weeds. http://www.weedscience.org. Accessed on August 2, 2013

James C (2012) Global status of commercialized biotech/GM crops: 2012. http://www.isaaa.org/resources/publications/briefs/44/executivesummary/default.asp. Accessed October 24, 2013

Jaremtchuk CC, Constantin J, Oliveira Jr. RS, Alonso DG, Arantes JGZ, Biffe DF, Roso AC, Cavalieri SD (2009) Residual effect of flumioxazin on weed emergence in soils of distinct textures. Planta Daninha 27:191–196 [In Portuguese with English abstract]

Johnson G, Breitenbach F, Behnken L, Miller R, Hoverstad T, Gunsolus J (2012) Comparison of herbicide tactics to minimize species shifts and selection pressure in glyphosate-resistant soybean. Weed Technol 26:189–194

Johnson WG, Davis VM, Kruger GR, Weller, SC (2009) Influence of glyphosate-resistant cropping systems on weed species shifts and glyphosate-resistant weed populations. Eur J Agron 31:162–172

Knezevic SZ, Datta A, Scott J, Porpiglia PJ (2009) Dose–response curves of KIH-485 for preemergence weed control in corn. Weed Technol 23:34–39

Knezevic SZ, Sikkema PH, Tardif F, Hamill AS, Chandler K, Swanton CJ (1998) Biologically effective dose and selectivity of RPA 201772 for preemergence weed control in corn (*Zea mays*). Weed Technol 12:670–676

Kwon JW, Armbrust KL, Grey TL (2004) Hydrolysis and photolysis of flumioxazin in aqueous buffer solutions. Pest Manag Sci 60:939–943

Legleiter TR, Bradley KW, Massey RE (2009) Glyphosate resistant waterhemp (*Amaranthus rudis*) control and economic

returns with herbicide programs in soybean. Weed Technol 23:54–61
Locke MA, Bryson, CT (1997) Herbicide-soil interactions in reduced tillage and plant residue management systems. Weed Sci 45:307–320
Miller RT, Soltani N, Robinson DE, Kraus TE, Sikkema PH (2012) Biologically effective rate of saflufenacil/dimethenamid-p in soybean (*Glycine max*). Can J Plant Sci 92:517–531
Moran M, Sikkema PH, Swanton CJ (2011) Efficacy of saflufenacil plus dimethenamid-p for weed control in corn. Weed Technol 25:330–334
Niekamp JW, Johnson WG, Smeda RJ (1999) Broadleaf weed control with sulfentrazone and flumioxazin in no-tillage soybean. Weed Technol 13:233–238
[OMAFRA] Ontario Ministry of Agriculture, Food and Rural Affairs (2012) Guide to weed control. Publication 75. Toronto, Canada: OMAFRA. 400 p
Owen MDK (2008) Weed species shifts in glyphosate resistant crops. Pest Manag Sci 64:377–387
Refsell DE, Ott EJ, Dale TM, Pawlak JA (2009) V-10233 performance in midwest soybean fields. Abstract 82 *in* Proceedings of the North Central Weed Science Society. Champaign, IL: North Central Weed Science Society
Seefeldt SS, Jensen JE, Fuerst EP (1995) Log-logistic analysis of dose–response relationships. Weed Technol 9:218–227
Sikkema PH, Knezevic SZ, Hamill AS, Tardif FJ, Chandler K, Swanton CJ (1999) Biologically effective dose and selectivity of SAN 1269H (BAS 662H) for weed control in corn (*Zea mays*). Weed Technol 13:283–289
Stachler JM, Carlson AL (2013) Herbicide programs for glufosinate and glyphosate-resistant soybean. Abstract 228 *in* Proceedings of the Weed Science Society of America/Northeastern Weed Science Society. Baltimore, MD: Weed Science Society of America/Northeastern Weed Science Society
Stachler JM, Luecke JL (2011) The utility of preemergence herbicides in glufosinate-resistant soybean in a sugarbeet rotation in Minnesota and North Dakota. Abstract 151 *in* Proceedings of the North Central Weed Science Society. Milwaukee, WI: North Central Weed Science Society
Stachler JM, Luecke JL, Fisher JM (2010) Controlling glyphosate-resistant ragweed and waterhemp with preemergence soybean herbicides having safety to sugarbeet in rotation. Abstract 172 *in* Proceedings of the North Central Weed Science Society. Lexington, KY: North Central Weed Science Society
Szmigielski AM, Schoenau JJ, Johnson EN (2013) Bioactivity and dissipation of pyroxasulfone herbicide in Saskatchewan soils. Abstract 60 *in* Proceedings of the Western Society of Weed Science. San Diego: Western Society of Weed Science
Tanetani Y, Kaku K, Kawai K, Fujioka T, Shimizu T (2009) Action mechanism of a novel herbicide, pyroxasulfone. Pestic Biochem Physiol 95:47–55
Taylor-Lovell S, Wax LM, Ballero G (2002) Preemergence flumioxazin and pendimethalin and postemergence herbicide systems for soybean (*Glycine max*). Weed Technol 16:502–511
Taylor-Lovell S, Wax LM, Nelson R (2001) Phytotoxic response and yield of soybean (*Glycine max*) varieties treated with sulfentrazone or flumioxazin. Weed Technol 15:95–102
[USDA-ERS] US Department of Agriculture–Economic Research Service (2013) Adoption of Genetically Engineered Crops in the U.S. http://www.ers.usda.gov/data-products/adoption-of-genetically-engineered-crops-in-the-us/recent-trends-in-ge-adoption. Accessed August 8, 2013
Young BG (2006) Changes in herbicide use patterns and production practices resulting from glyphosate-resistant crops. Weed Technol 20:301–307
Young BG, Bradley KW, Bernards ML, Hager AG, Hartzler BG, Johnson WG, Loux MM, Peterson D, Sprague CL, Slack C, Ott EJ, Refsell D, Dale TM, Cranmer JR, Kirfman GW, Pawlak JA (2010) Length of residual weed control with V-10266 and other preemergence soybean herbicides. Abstract 153 *in* Proceedings of the North Central Weed Science Society. Lexington, KY: North Central Weed Science Society

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