Weed Technology

www.cambridge.org/wet

Annual weed management in isoxaflutole-resistant soybean using a two-pass weed control strategy

Andrea Smith[1], Nader Soltani[2], Allan J. Kaastra[3], David C. Hooker[4], Darren E. Robinson[5] and Peter H. Sikkema[5]

[1]Graduate Student, Department of Plant Agriculture, University of Guelph, Ridgetown, ON, Canada; [2]Adjunct Professor, Department of Plant Agriculture, University of Guelph, ON, Canada; [3]Senior Agronomic Development Representative, Bayer Inc., Guelph, ON, Canada; [4]Associate Professor, Department of Plant Agriculture, University of Guelph, Ridgetown, ON, Canada and [5]Professor, Department of Plant Agriculture, University of Guelph, Ridgetown, ON, Canada

Research Article

Cite this article: Smith A, Soltani N, Kaastra AJ, Hooker DC, Robinson Darren E., Sikkema PH (2019) Annual weed management in isoxaflutole resistant soybean using a two-pass weed control strategy. Weed Technol **33**: 411–425. doi: 10.1017/wet.2019.21

Received: 15 January 2019
Revised: 28 February 2019
Accepted: 4 March 2019
First published online: 29 April 2019

Associate Editor:
Kevin Bradley, University of Missouri

Keywords:
Critical weed-free period; herbicide resistance; glufosinate; HPPD; rate; yield

Nomenclature
Glyphosate; isoxaflutole; metribuzin; barnyardgrass, *Echinochloa crus-galli* (L.) P. Beav.; common lambsquarters, *Chenopodium album* L.; common ragweed, *Ambrosia artemisiifolia* L.; giant foxtail, *Setaria faberi* Herrm.; green foxtail, *Setaria viridis* L. P. Beauv.; horseweed, *Erigeron canadensis* L. Cronq.; Powell amaranth, *Amaranthus powellii* S. Watson; redroot pigweed, *Amaranthus retroflexus* L.; soybean, *Glycine max* (L.) Merr.; velvetleaf, *Abutilon theophrasti* Medik.; waterhemp, *Amaranthus tuberculatus* Moq. J. D. Sauer

Author for correspondence: Nader Soltani, Email: soltanin@uoguelph.ca

Abstract

Transgenic crops are being developed with herbicide resistance traits to expand innovative weed management solutions for crop producers. Soybean with traits that confer resistance to the hydroxyphenylpyruvate dioxygenase herbicide isoxaflutole is under development and will provide a novel herbicide mode of action for weed management in soybean. Ten field experiments were conducted over 2 years (2017 and 2018) on five soil textures with isoxaflutole-resistant soybean to evaluate annual weed control using one- and two-pass herbicide programs. The one-pass weed control programs included isoxaflutole plus metribuzin, applied PRE, at a low rate (52.5 + 210 g ai ha^{-1}), medium rate (79 + 316 g ai ha^{-1}), and high rate (105 + 420 g ai ha^{-1}); and glyphosate applied early postemergence (EPOST) or late postemergence (LPOST). The two-pass weed control programs included isoxaflutole plus metribuzin, applied PRE, followed by glyphosate applied LPOST, and glyphosate applied EPOST followed by LPOST. At 4 weeks after the LPOST application, control of common lambsquarters, pigweed species, common ragweed, and velvetleaf was variable at 25% to 69%, 49% to 86%, and 71% to 95% at the low, medium, and high rates of isoxaflutole plus metribuzin, respectively. Isoxaflutole plus metribuzin at the low, medium, and high rates controlled grass species evaluated (i.e., barnyardgrass, foxtail, crabgrass, and witchgrass) 85% to 97%, 75% to 99%, and 86% to 100%, respectively. All two-pass weed management programs provided 98% to 100% control of all species. Weed control improved as the rate of isoxaflutole plus metribuzin increased. Two-pass programs provided excellent, full-season annual grass and broadleaf weed control in isoxaflutole-resistant soybean.

Introduction

Weed interference reduces soybean yield, especially when weeds are present during the critical weed-free period (CWFP). The CWFP in soybean to prevent a 2.5% yield loss occurs from emergence to the V4 growth stage; that is, approximately from soybean emergence to 30 days after emergence (Van Acker et al. 1993). In North America, it has been estimated that if no weed control measures are implemented, there is an average soybean yield loss of 52% due to weed interference; however, greater losses can occur depending on relative time of crop and weed emergence, weed species composition, weed density, soil nutrient status, and weather conditions (Soltani et al. 2017). For example, competition from green foxtail at densities of 128 plants m^{-2} reduced soybean yield 80% (Weaver 2001). Crop-weed competition models show that populations of common ragweed, common lambsquarters, common cocklebur (*Xanthium strumarium* L.), velvetleaf, and jimsonweed (*Datura stramonium* L.) at high densities can reduce soybean yield by 75% (Weaver 1991; Weaver 2001).

Crop cultivars with herbicide-resistant traits have been widely adopted over the past two decades. The introduction of glyphosate-resistant soybean in 1996 quickly gained popularity among soybean producers to the point that greater than 95% of soybean was seeded to cultivars with this resistance trait in the United States (Young 2006). More recently, soybean cultivars with resistance to synthetic auxin herbicides, including dicamba and 2,4-D, have been developed. The use of these cultivars and herbicides will provide improved control of some annual, biennial, and perennial broadleaf weeds and control of selected herbicide-resistant broadleaf weed species that would otherwise have limited chemical control options in soybean (Behrens et al. 2007; Spaunhorst and Johnson 2017). Herbicide-resistant traits have advanced weed management in soybean by increasing efficiency through the use of more efficacious

© Weed Science Society of America 2019.

herbicides, and their use has resulted in lower cost of herbicides, labor, machinery, and fuel (Fernandez-Cornejo et al. 2002).

The introduction of hydroxyphenylpyruvate dioxygenase (HPPD)-resistant soybean cultivars, which are currently under development, will allow for the application of isoxaflutole to soybean and thus an additional mode of action that, when used judiciously in an integrated weed management program, can aid in slowing the evolution of glyphosate-resistant weed species, including Palmer amaranth, waterhemp, and horseweed. This can be accomplished by controlling such species before they set seed (Ditschun et al. 2016; Meyer et al. 2015; Schryver et al. 2017).

HPPD-inhibiting herbicides represent the most recently discovered class of herbicides used for weed management in field crop production; they were first commercialized in Canada in the late 1990s. These herbicides inhibit the HPPD enzyme, which is responsible for the biosynthesis of plastoquinone, an essential cofactor for the production of carotenoids, and an electron transporter in the photosynthetic electron transport chain (Pallet et al. 1998). The HPPD-inhibiting herbicides are injurious to most dicotyledonous crops; therefore, most HPPD-inhibiting herbicides are used for weed management in corn, with two active ingredients, pyrasulfotole and bicyclopyrone, registered for use in cereal crops.

The use of isoxaflutole on isoxaflutole-resistant soybean could provide residual control of some annual grass and broadleaf weed species. Adequate rainfall is required after application to dissolve the herbicide in soil water solution so it can be absorbed by the developing weed seedlings that are shorter than 5 cm; it will not control larger weeds when applied PRE (OMAFRA 2016). The length of residual activity depends on weather conditions and rate applied; season-long control of most species can be expected with application of isoxaflutole at 105 g ai ha^{-1} or greater (Anonymous 2017). If lower rates of isoxaflutole are applied, or if little to no rainfall occurs within 14 days of herbicide application, weed control may be reduced. However, weed escapes may be controlled with herbicides applied POST. In addition to resistance to isoxaflutole, these soybean cultivars also have transgenes that confer resistance to glyphosate or glufosinate, providing a POST-applied, nonselective herbicide option for the control of weed escapes.

Two-pass weed control programs that include a soil-applied residual herbicide, applied PRE, followed by (fb) a nonselective POST herbicide can provide effective, full-season weed control as part of an integrated weed management strategy. Glyphosate and glufosinate provide broad-spectrum control of emerged weeds at the time of application that offers a safety net to control weeds not controlled with the soil-applied residual herbicide, without concern of crop injury. The PRE application of a residual herbicide fb glyphosate or glufosinate applied POST provides multiple sites of action that will reduce the evolution of herbicide-resistant weed biotypes (Gressel and Segel 1990). The use of residual herbicides fb glyphosate applied POST compared with glyphosate alone increased control of redroot pigweed and common lambsquarters by 20% and giant foxtail by 4% to 19% (Tharp and Kells 2002). Similarly, the same study showed the application of a residual herbicide before glufosinate applied POST increased control of common ragweed and giant foxtail. Generally, two-pass weed control strategies provide improved weed control and reduce the selection intensity for herbicide-resistant weeds.

The purpose of the current study was to determine the level of weed control in isoxaflutole-resistant soybean achieved with two-pass weed control programs on different soil textures in Ontario, Canada.

Materials and methods

A total of 10 field experiments were completed over 2 years (2017 and 2018) near Cambridge, Ennotville, Exeter, and Ridgetown (two sites), Ontario. Trials were conducted on soils with varying characteristics that were selected to represent typical soil textures found within Ontario. Sites were organized in descending order on the basis of clay content (Table 1). Land was prepared using conventional tillage methods. Regionally appropriate isoxaflutole-resistant soybean cultivars were planted 5-cm deep in rows spaced 0.76-m apart at approximately 372,500 seeds ha^{-1}.

Treatments were arranged in a randomized complete block design with three or four replications depending on space availability at each site. Plots measured 3-m wide (four soybean rows) by 8- or 10-m long. Herbicides were applied at three different times: (1) PRE, applied after soybean planting and before soybean emergence; (2) early postemergence (EPOST), applied when weeds in the untreated weedy control were an average of 7.5-cm tall; and (3) late postemergence (LPOST), applied when weeds were 7.5-cm tall in the plots treated with a PRE herbicide. Isoxaflutole plus metribuzin was applied at three different rates: low (52.5 + 210 g ai ha^{-1}), medium (79 + 316 g ai ha^{-1}), and high (105 + 420 g ai ha^{-1}). Glyphosate (900 g ae ha^{-1}) was applied EPOST, LPOST, and EPOST fb LPOST. Herbicides were applied using a CO_2-pressurized backpack sprayer calibrated to deliver 200 L ha^{-1} at 240 kPa equipped with a 1.5-m boom with four 120-02 ultra low-drift nozzles (Hypro Ultra low drift 120-02; Pentair, New Brighton, MN) spaced 50-cm apart, resulting in a spray width of 2 m.

Visible soybean injury was assessed 1, 2, and 4 weeks after soybean emergence (WAE) on a scale of 0 (no visible crop injury) to 100 (complete plant death). Visible weed control was assessed by weed species before each POST herbicide application and 4 and 8 weeks after the LPOST application (WAA) on a scale of 0 (no visible weed control) to 100 (no weeds present). In addition, at 4 WAA, weed density was determined by counting the number of weeds by species in two 0.5-m^2 quadrats per plot. The weeds were cut at the soil surface, placed in bags by species, dried at 60 C to constant moisture, and weighed. Soybean was harvested at maturity with a small-plot research combine; seed weight and moisture were recorded. Soybean yield was adjusted to 13% moisture before analysis.

SAS, version 9.4 (SAS Institute, Inc. Cary, NC) was used to analyze data with the GLIMMIX procedure. An initial analysis was conducted to determine if there was a significant site-by-treatment interaction for injury, weed control, and yield. In this initial analysis, site, treatment, and the site-by-treatment interaction were fixed effects, and replication within site was a random effect. If the site-by-treatment effect was significant, a Tukey-Kramer multiple means-comparison test was conducted to determine how the sites grouped; otherwise, data from all sites were pooled. This step was only conducted during the first weed control evaluation at the EPOST application timing. The same site groupings were held constant for the remaining control, density, and biomass evaluations for each weed species. Soybean injury, weed control, and yield were analyzed to assess treatment differences with a mixed model.

The fixed effect was treatment and the random effects included site, the site-by-treatment interaction, and replication within site. The Wald test was used to test the significance of random effects, whereas the F test was used to test the significance of fixed effects. The assumptions that errors were random, independent, homogenous, and normally distributed were confirmed by residual plots and the Shapiro-Wilks normality test. Data were transformed

https://doi.org/10.1017/wet.2019.21 Published online by Cambridge University Press

Table 1. Soil characteristics, planting date, and rainfall between the PRE and LPOST application dates at 10 trial locations in Ontario, Canada, in 2017 and 2018.

Site no.	Location	Year	Soil texture	Soil characteristics						Planting date	Application date			Rainfall PRE to LPOST
				Sand	Silt	Clay	OM[a]	pH	CEC		PRE	EPOST	LPOST	
				%					meq/100 g					mm
1	Ridgetown	2017	Clay loam	33	30	37	4.0	7.0	24	June 9	June 13	July 5	July 11	59
2	Ridgetown	2018	Clay loam	35	30	35	4.2	6.7	19	May 25	May 29	June 21	June 28	41
3	Ridgetown	2017	Clay loam	41	28	31	4.0	7.1	14	June 2	June 7	June 28	July 5	25
4	Ridgetown	2018	Clay loam	43	26	31	3.6	6.8	16	May 31	June 1	July 4	July 13	60
5	Exeter	2018	Loam	41	35	24	2.9	7.7	27	May 18	May22	June 6	June 15	17
6	Exeter	2017	Loam	35	43	22	3.9	7.8	30	June 3	June 5	June 28	July 4	85
7	Ennotville	2017	Silt loam	41	52	7	3.8	7.8	18	May 31	June 2	June 26	July 15	134
8	Ennotville	2018	Silt loam	41	52	7	3.8	7.8	18	May 25	May 28	June 29	July 5	64
9	Cambridge	2017	Sandy loam	68	26	6	2.2	7.2	9	May 31	June 2	June 26	July 15	125
10	Cambridge	2018	Sandy loam	68	26	6	2.2	7.2	9	May 25	May 28	June 20	June 29	68

[a]Abbreviations: EPOST, early postemergence; LPOST, late postemergence; OM, organic matter.

when necessary with the natural log and arcsine square root transformations. When transformation occurred, data were compared on the transformed scale; however, for presentation purposes, data were converted back to the original scale. Means were separated using a Tukey-Kramer multiple means comparison test at $P < 0.05$.

Results and discussion

Soybean injury

At 1 WAE, there was no soybean injury from any of the herbicides evaluated (Table 2). At 2 WAE at sites 6 and 7, isoxaflutole plus metribuzin applied at the high rate caused 3% to 4% soybean bleaching, which is characteristic of isoxaflutole phytotoxicity. At 4 WAE at sites 1, 3, 4, 7, and 9, isoxaflutole plus metribuzin at the low, medium, and high rates caused 1% to 2%, 4% to 5%, and 8% soybean bleaching, respectively. At 4 WAE at site 6, isoxaflutole plus metribuzin at the low, medium, and high rates caused 16% to 20%, 22% to 26%, and 29% to 30% soybean bleaching, respectively. No soybean injury was observed at sites 2, 5, 8, or 10. Generally, soybean injury was more pronounced at the sites with greater rainfall after application (Table 1).

Increased rainfall after herbicide application increases isoxaflutole absorption in corn, reduces metabolism, and elevates isoxaflutole concentration within the plant, resulting in greater phytotoxic effects (Soukup et al. 2004). Soils with high pH have decreased adsorption of diketonitrile, the first and more toxic metabolite of isoxaflutole, allowing for greater absorption by plants (Mitra et al. 2001). We suggest that the higher level of soybean injury at site 6 was due to a combination of greater rainfall after application and a more alkaline soil. No injury symptoms were observed from the glyphosate applications.

Common lambsquarters

Common lambsquarters control was evaluated at eight sites in this study. There was a significant treatment-by-site interaction for common lambsquarters control (data not shown); therefore, results from sites 3 and 5 are presented separately from results from sites 1, 4, 6, 7, 9, and 10.

At the EPOST application timing, there was no difference in common lambsquarters control at the low, medium, and high rates of isoxaflutole plus metribuzin within either of the combined site groups (Table 3). At the sites with more rainfall (i.e., sites 1, 4, 6, 7, 9, and 10), isoxaflutole plus metribuzin at the low, medium, and high rates controlled common lambsquarters 97% to 100%. In contrast, at the sites with less rainfall (i.e., sites 3 and 5), isoxaflutole plus metribuzin at the low, medium, and high rates controlled common lambsquarters 12% to 18%, 29% to 62%, and 64% to 67%, respectively.

At the LPOST application timing, there was no difference in common lambsquarters control among the herbicide treatments evaluated at the sites with more rainfall; all herbicide treatments controlled common lambsquarters 97% to 100% (Table 3). In contrast, at the sites with less rainfall, isoxaflutole plus metribuzin applied at the low, medium, and high rates controlled common lambsquarters 9% to 12%, 31% to 55%, and 55% to 79%, respectively. Glyphosate (900 g ha^{-1}) applied EPOST controlled common lambsquarters 100%. The medium and high rates of isoxaflutole plus metribuzin applied PRE and glyphosate applied EPOST provided similar control of common lambsquarters.

At 4 WAA, at the sites with greater rainfall, isoxaflutole plus metribuzin applied at the low and high rates resulted in a small

https://doi.org/10.1017/wet.2019.21 Published online by Cambridge University Press

Table 2. Visible estimates of soybean bleaching due to isoxaflutole plus metribuzin application at 1, 2, and 4 WAE from 10 field experiments conducted in Ontario, Canada, in 2017 and 2018.

			Visible injury[b]			
			1 WAE	2 WAE	4 WAE	
Treatment[a]	Application timing	Rate	All sites	Sites 6, 7	Sites 1, 3, 4, 7, 9	Site 6
		g ai or ae ha^{-1}	%			
Isoxaflutole + metribuzin	PRE	52.5 + 210	0	0a	1a	16a
Isoxaflutole + metribuzin	PRE	79 + 315	0	0a	4abc	22abc
Isoxaflutole + metribuzin	PRE	105 + 420	0	4b	8c	29c
Glyphosate	EPOST	900	0	-	-	-
Glyphosate	LPOST	900	0	-	-	-
Glyphosate fb glyphosate	EPOST	900	0	-	-	-
	LPOST	900				
Glyphosate fb glyphosate	PRE	52.5 + 210	0	0a	2ab	20ab
	LPOST	900				
Isoxaflutole + metribuzin fb glyphosate	PRE	79 + 315	0	1ab	5bc	26bc
	LPOST	900				
Isoxaflutole + metribuzin fb glyphosate	PRE	105 + 420	0	3b	8c	30c
	LPOST	900				

[a]Abbreviations: EPOST, EPOST, early postemergence; fb, followed by; LPOST, late postemergence; WAE, weeks after emergence.
[b]Means followed by the same letter within a column are not significantly different according to the Tukey-Kramer multiple range test at $P < 0.05$.

but significant increase in common lambsquarters control, from 97% to 100% (Table 3). Glyphosate applied EPOST, LPOST, and EPOST fb LPOST controlled common lambsquarters 96% to 99%. At the sites with less rainfall, isoxaflutole plus metribuzin applied at the low, medium, and high rates controlled common lambsquarters 42%, 83%, and 91%, respectively. At both site groups, as the rate of isoxaflutole plus metribuzin was increased, there was an increase in common lambsquarters control. There was a difference in control between the low and high rates. The medium rate did not differ from either the low or high rate. There was no difference in common lambsquarters control with glyphosate applied EPOST, LPOST, and EPOST fb LPOST. At all sites, the two-pass program of isoxaflutole plus metribuzin applied PRE fb glyphosate applied LPOST controlled lambsquarters 100%. There was an increase in common lambsquarters control with an application of glyphosate after isoxaflutole plus metribuzin applied PRE at the low rate. When isoxaflutole plus metribuzin were applied at the medium or high rate, there was no increase in common lambsquarters control when glyphosate was applied LPOST.

At 8 WAA, there were different trends in common lambsquarters control between the two site groups (Table 3). At the sites with more rainfall, there were no differences in common lambsquarters control among the three rates of isoxaflutole plus metribuzin evaluated. The sequential application of glyphosate applied EPOST fb LPOST controlled common lambsquarters 4% more than did the EPOST application. At the sites with less rainfall, isoxaflutole plus metribuzin applied at the low, medium, and high rates controlled common lambsquarters 49%, 82%, and 96%, respectively. Glyphosate applied EPOST, LPOST, and EPOST fb LPOST controlled common lambsquarters 89% to 96%. At all sites, the two-pass programs of isoxaflutole plus metribuzin applied PRE fb glyphosate applied LPOST controlled common lambsquarters 100%.

At 4 WAA, at the sites with more rainfall, isoxaflutole plus metribuzin reduced common lambsquarters density by 97% or more (Table 4). There was no difference in common lambsquarters density among the three rates evaluated. Glyphosate applied EPOST, LPOST, and EPOST fb LPOST reduced common lambsquarters density 85% to 93%. At the sites with less rainfall, isoxaflutole plus metribuzin applied PRE reduced common lambsquarters density 83% to 96%; there was no difference among the three rates evaluated. Glyphosate applied EPOST, LPOST, and EPOST fb LPOST reduced common lambsquarters density 74% to 91%. At both groups of sites, the two-pass program including isoxaflutole plus metribuzin applied PRE fb glyphosate applied POST reduced common lambsquarters density 98% to 100%. There was no weed control benefit of a two-pass program compared with a one-pass program with isoxaflutole plus metribuzin; however, a two-pass program with diverse herbicide modes of action can delay the selection of resistant weed biotypes.

At 4 WAA, at sites with more rainfall, common lambsquarters biomass was reduced 92% to 99%; there was no difference among herbicide treatments evaluated (Table 4). At the sites with less rainfall, isoxaflutole plus metribuzin applied at the low, medium, and high rates reduced common lambsquarters biomass 58%, 91%, and 98%, respectively. The low rate did not differ from the weedy control. Glyphosate applied EPOST, LPOST, and EPOST fb LPOST reduced common lambsquarters biomass 97% to 99%; there was no difference among the glyphosate application timings. At both groups of sites, the two-pass programs of isoxaflutole plus metribuzin applied PRE fb glyphosate applied POST reduced common lambsquarters biomass 99%.

At the sites with less rainfall, common lambsquarters control with isoxaflutole plus metribuzin applied PRE increased over time. This may have been due to the reactivation of isoxaflutole plus metribuzin by late spring/early summer rains or to advanced soybean growth that shaded out the weeds. In contrast, common lambsquarters control with glyphosate decreased over time. This is not surprising, because glyphosate does not provide residual herbicide activity and would not be efficacious on later emerging common lambsquarters. The herbicide treatment by soil texture interaction was not significant for common lambsquarters control. Common lambsquarters control was more closely correlated with rainfall: sites receiving more rainfall had greater common lambsquarters control. The results of this study are consistent with those

https://doi.org/10.1017/wet.2019.21 Published online by Cambridge University Press

Table 3. Visible estimates of common lambsquarters control at EPOST and LPOST application timings and 4 and 8 WAA from eight field experiments conducted in Ontario, Canada, in 2017 and 2018.

			Visible control[b]									
			EPOST		LPOST		4 WAA		8 WAA			
Treatment[a]	Application timing	Rate	Sites 1, 4, 6, 7, 9, 10	Sites 3, 5	Sites 1, 4, 6, 7, 9, 10	Sites 3, 5	Sites 1, 4, 6, 7, 9, 10	Sites 3, 5	Sites 1, 4, 6, 7, 9, 10	Sites 3, 5
		g ai or ae ha^{-1}	%							
Isoxaflutole + metribuzin	PRE	52.5 + 210	97a	18a	98a	12b	97bc	42b	98abc	49c
Isoxaflutole + metribuzin	PRE	79 + 315	99a	29a	99a	31ab	99ab	83ab	99ab	82b
Isoxaflutole + metribuzin	PRE	105 + 420	100a	67a	100a	55ab	100a	91a	100a	96ab
Glyphosate	EPOST	900	—	—	97a	100a	96c	95a	95c	89b
Glyphosate	LPOST	900	—	—	—	—	97bc	96a	97bc	95ab
Glyphosate fb glyphosate	EPOST	900	—	—	97a	100a	99abc	99a	99ab	96ab
	LPOST	900								
Isoxaflutole + metribuzin fb glyphosate	PRE	52.5 + 210	97a	12a	97a	9b	100a	100a	100a	100a
	LPOST	900								
Isoxaflutole + metribuzin fb glyphosate	PRE	79 + 315	99a	62a	99a	55ab	100a	100a	100a	100a
	LPOST	900								
Isoxaflutole + metribuzin fb glyphosate	PRE	105 + 420	99a	64a	100a	79ab	100a	100a	100a	100a
	LPOST	900								

[a]Abbreviations: —, no data; EPOST, early postemergence; fb, followed by; LPOST, late postemergence; WAA, weeks after late postemergence application; WAE, weeks after emergence.
[b]Means followed by the same letter within a column are not significantly different according to the Tukey-Kramer multiple range test at $P < 0.05$.

of a study conducted in corn by Chomas and Kells (2004), in which isoxaflutole controlled common lambsquarters 52% to 72% and 97% to 100% in years receiving limited and abundant rainfall after application, respectively. Similarly, application of isoxaflutole plus atrazine (79 + 800 g ha^{-1}) controlled common lambsquarters 78% and 100% with 66% less rainfall in May and June than the 30-year average and a year with normal rainfall, respectively (Stewart et al. 2012).

Pigweeds

Redroot pigweed and Powell amaranth were combined during weed control assessments in this study, and are hereafter referred to as pigweeds. These pigweeds were evaluated at eight sites and the treatment-by-site interaction was not significant (data not shown); therefore, data were pooled across all sites.

At the EPOST application timing, isoxaflutole plus metribuzin, applied at the low rate, controlled pigweeds 87% to 89% (Table 5). Isoxaflutole plus metribuzin, applied at the medium or high rate, controlled pigweeds 94% to 98%. The low rate of isoxaflutole plus metribuzin provided 5% to 11% lower control of pigweeds than the medium and high rates; there was no difference in pigweed control between the medium and high rates.

At the LPOST application timing, the low, medium, and high rates of isoxaflutole plus metribuzin controlled pigweeds 81% to 86%, 95% to 96%, and 97% to 98%, respectively (Table 5). Oddly, on average, the low rate of isoxaflutole plus metribuzin, which was intended to receive an LPOST application of glyphosate, controlled pigweeds 81%. This was less control than the high rate of isoxaflutole plus metribuzin, which provided 97% to 98% control. This result may be an artifact of variable pigweed density throughout the experimental area. Glyphosate applied EPOST controlled pigweeds 100%, which was higher than isoxaflutole plus metribuzin applied at the low rate.

At 4 and 8 WAA, pigweed control assessments with isoxaflutole plus metribuzin were similar, suggesting that isoxaflutole plus metribuzin provides full-season residual control of pigweeds (Table 5). There was no difference in pigweed control among the three rates of isoxaflutole plus metribuzin evaluated. Glyphosate applied EPOST, LPOST, or EPOST fb LPOST controlled pigweeds 98% to 100%. Glyphosate applied LPOST after isoxaflutole plus metribuzin at the low or medium rate improved pigweed control 6% to 12% compared with PRE herbicides alone. All the two-pass programs of isoxaflutole plus metribuzin applied PRE fb glyphosate applied LPOST controlled pigweeds 100%.

At 4 WAA, all treatments reduced pigweed density 85% to 99%, compared with the weedy control (Table 6). All rates of isoxaflutole plus metribuzin with and without glyphosate applied LPOST reduced pigweed density similarly between 97% to 99%. The medium and high rates of isoxaflutole plus metribuzin, applied PRE, and all three rates of isoxaflutole plus metribuzin fb glyphosate applied LPOST decreased pigweeds 13% to 15% more than glyphosate applied EPOST or LPOST. Pigweed biomass was reduced 92% to 99% by all treatments, compared with the weedy control; there were no differences among the herbicide treatments evaluated. The results of this study are similar to those of Butts et al. (2016), with greater decrease in pigweed density observed with PRE fb POST herbicide applications compared with a single POST application.

https://doi.org/10.1017/wet.2019.21 Published online by Cambridge University Press

Table 4. Common lambsquarters density and biomass data at 4 wk after LPOST application from eight field experiments conducted in Ontario, Canada, in 2017 and 2018.

Treatment[a]	Application timing	Rate	Density[b]		Biomass[b]	
			Sites 1, 4, 6, 7, 9, 10	Sites 3, 5	Sites 1, 4, 6, 7, 9, 10	Sites 3, 5
		g ai or ae ha^{-1}	m^{-2}		g m^{-2}	
Weedy control	—	—	22.61d	29.91b	17.90b	34.22c
Isoxaflutole + metribuzin	PRE	52.5 + 210	0.68abc	5.09ab	1.51a	14.50bc
Isoxaflutole + metribuzin	PRE	79 + 315	0.18ab	1.45a	0.37a	2.95ab
Isoxaflutole + metribuzin	PRE	105 + 420	0.19ab	1.14a	0.17a	0.76a
Glyphosate	EPOST	900	3.07bc	4.30ab	1.32a	1.08ab
Glyphosate	LPOST	900	3.48c	7.66ab	0.51a	0.44a
Glyphosate fb Glyphosate	EPOST	900	1.66abc	2.66ab	0.12a	0.44a
	LPOST	900				
Isoxaflutole + metribuzinfb glyphosate	PRE	52.5 + 210	0.19ab	0.71a	0.21a	0.25a
	LPOST	900				
Isoxaflutole + metribuzin fb glyphosate	PRE	79 + 315	0.16ab	0.08a	0.04a	0.08a
	LPOST	900				
Isoxaflutole + metribuzin fb glyphosate	PRE	105 + 420	0.06a	0.18a	0.04a	0.17a
	LPOST	900				

[a]Abbreviations: —, no data; EPOST, early postemergence; fb, followed by; LPOST, late postemergence.
[b]Means followed by the same letter within a column are not significantly different according to the Tukey-Kramer multiple range test at $P < 0.05$.

Table 5. Visible estimates of control of pigweed species at EPOST and LPOST application timings and 4 and 8 WAA at sites 1, 3, 4, 5, 7, 8, 9, and 10 in Ontario, Canada, in 2017 and 2018.

Treatment[a]	Application timing	Rate	Visible control[b]			
			EPOST	LPOST	4 WAA	8 WAA
		g ai or ae ha^{-1}	%			
Isoxaflutole + metribuzin	PRE	52.5 + 210	89c	86bc	88c	89c
Isoxaflutole + metribuzin	PRE	79 + 315	94b	95abc	94bc	94bc
Isoxaflutole + metribuzin	PRE	105 + 420	98ab	97ab	97abc	97abc
Glyphosate	EPOST	900	—	100a	98ab	98abc
Glyphosate	LPOST	900	—	—	98abc	99ab
Glyphosate fb Glyphosate	EPOST	900	—	100a	100ab	100ab
	LPOST	900				
Isoxaflutole + metribuzin fb glyphosate	PRE	52.5 + 210	87c	81c	100ab	100a
	LPOST	900				
Isoxaflutole + metribuzin fb glyphosate	PRE	79 + 315	96ab	96abc	100a	100a
	LPOST	900				
Isoxaflutole + metribuzin fb glyphosate	PRE	105 + 420	98a	98ab	100ab	100a
	LPOST	900				

[a]Abbreviations: —, no data; EPOST, early postemergence; fb, followed by; LPOST, late postemergence; WAA, weeks after late postemergence application.
[b]Means followed by the same letter within a column are not significantly different according to the Tukey-Kramer multiple range test at $P < 0.05$.

Common ragweed

Common ragweed populations were evaluated at four sites in this study. There was a significant treatment-by-site interaction; therefore, results from site 2 are presented separately from those from sites 1, 4, and 6.

At the EPOST application timing, at sites that received more rainfall (sites 1, 4, and 6), isoxaflutole plus metribuzin applied at the low, medium, and high rates controlled common ragweed 93% to 94%, 97% to 98%, and 99%, respectively (Table 7). In contrast, at the site with less rainfall (site 2), isoxaflutole plus metribuzin, applied PRE, controlled common ragweed 25% to 90%, with no differences observed among rates.

At the LPOST application timing, there was no difference in common ragweed control with the low, medium, or high rate of isoxaflutole plus metribuzin or with glyphosate applied EPOST within either of the combined site groups (Table 7). At sites with more rainfall, isoxaflutole plus metribuzin applied at the low, medium, and high rates controlled common ragweed 96% to 97%, 100%, and 100%, respectively. Glyphosate applied EPOST controlled common ragweed 74%. At the site with less rainfall, isoxaflutole plus metribuzin applied at the low, medium, and high rates controlled common ragweed 53% to 62%, 71% to 72%, and 50% to 77%, respectively, and glyphosate applied EPOST controlled common ragweed 60% to 64%. Common ragweed control with isoxaflutole plus metribuzin was 19% to 50% higher at the sites with more rainfall compared with site 2, which had less rainfall.

At 4 WAA, at the sites with more rainfall, there was no difference in common ragweed control among the herbicides evaluated; all treatments controlled common ragweed 97% to 100% (Table 7). In contrast, at site 2, the high rate of isoxaflutole plus metribuzin

https://doi.org/10.1017/wet.2019.21 Published online by Cambridge University Press

Table 6. Density and biomass of pigweed species at 4 WAA at sites 1, 3, 4, 5, 7, 8, 9, and 10 in Ontario, Canada, in 2017 and 2018.

Treatment[a]	Application timing	Rate	Density[b]	Biomass[b]
		g ai or ae ha^{-1}	m^{-2}	g m^{-2}
Weedy control	—	—	22.61d	17.90b
Isoxaflutole + metribuzin	PRE	52.5 + 210	0.68abc	1.51a
Isoxaflutole + metribuzin	PRE	79 + 315	0.18ab	0.37a
Isoxaflutole + metribuzin	PRE	105 + 420	0.19ab	0.17a
Glyphosate	EPOST	900	3.07bc	1.32a
Glyphosate	LPOST	900	3.48c	0.51a
Glyphosate fb Glyphosate	EPOST	900	1.66abc	0.12a
	LPOST	900		
Isoxaflutole + metribuzin fb glyphosate	PRE	52.5 + 210	0.19ab	0.21a
	LPOST	900		
Isoxaflutole + metribuzin fb glyphosate	PRE	79 + 315	0.16ab	0.04a
	LPOST	900		
Isoxaflutole + metribuzin fb glyphosate	PRE	105 + 420	0.06a	0.04a
	LPOST	900		

[a]Abbreviations: —, no data; EPOST, early postemergence; fb, followed by; LPOST, late postemergence; WAA, weeks after late postemergence application.
[b]Means followed by the same letter within a column are not significantly different according to the Tukey-Kramer multiple range test at $P < 0.05$.

Table 7. Visible estimates of common ragweed control at EPOST and LPOST application timings and 4 and 8 WAA from four field experiments conducted in Ontario, Canada, in 2017 and 2018.

			Visible control[b]							
			EPOST		LPOST		4 WAA		8 WAA	
Treatment[a]	Application Timing	Rate	Sites 1, 4, 6	Site 2	Sites 1, 4, 6	Site 2	Sites 1, 4, 6	Site 2	Sites 1, 4, 6	Site 2
		g ai or ae ha^{-1}	%							
Isoxaflutole + metribuzin	PRE	52.5 + 210	93c	68a	97a	53a	98a	69b	99a	81a
Isoxaflutole + metribuzin	PRE	79 + 315	98ab	25a	100a	72a	100a	86ab	99a	83a
Isoxaflutole + metribuzin	PRE	105 + 420	99a	90a	100a	50a	100a	95ab	100a	98a
Glyphosate	EPOST	900	—	—	74a	64a	97a	88ab	97a	75a
Glyphosate	LPOST	900	—	—	—	—	97a	94ab	98a	99a
Glyphosate fb Glyphosate	EPOST	900	—	—	74a	60a	99a	98ab	100a	100a
	LPOST	900								
Isoxaflutole + metribuzin fb glyphosate	PRE	52.5 + 210	94bc	71a	96a	62a	100a	98ab	100a	99a
	LPOST	900								
Isoxaflutole + metribuzin fb glyphosate	PRE	79 + 315	97abc	84a	100a	71a	100a	99ab	100a	100a
	LPOST	900								
Isoxaflutole + metribuzin fb glyphosate	PRE	105 + 420	99a	78a	100a	77a	100a	100a	100a	100a
	LPOST	900								

[a]Abbreviations: —, no data; EPOST, early postemergence; fb, followed by; LPOST, late postemergence; WAA, weeks after late postemergence application.
[b]Means followed by the same letter within a column are not significantly different according to the Tukey-Kramer multiple range test at $P < 0.05$.

applied PRE fb glyphosate applied LPOST controlled common ragweed 100%. The low rate of isoxaflutole plus metribuzin without a second pass provided 69% control. At site 2, all other treatments controlled common ragweed 86% to 99%.

At 8 WAA, there was no difference in common ragweed control with any treatment among the combined site groups (Table 7). At sites with higher rainfall, all treatments controlled common ragweed 97% to 100%. However, at the site with less rainfall, common ragweed was controlled 75% to 100%.

At 4 WAA, at sites with more rainfall, common ragweed density and biomass were reduced 83% to 99 and 96% to 99%, respectively. All herbicide treatments reduced common ragweed density, with the exception of glyphosate applied LPOST (Table 8). The greater density with glyphosate applied LPOST suggests that glyphosate is less efficacious on larger weeds. This is supported by findings of Soltani et al. (2016), whose results showed an improvement in common ragweed control when glyphosate was applied to weeds 10- or 20-cm tall compared to 30-cm weeds. At site 2, there was no decrease in common ragweed density and biomass with the herbicide treatments evaluated.

In this study, at sites with more rainfall, isoxaflutole plus metribuzin applied PRE provided consistent common ragweed control throughout the season (Table 8). This may be due to herbicide activation early in the growing season preventing new weeds from emerging. In contrast, at site 2, which received less rainfall, control decreased between the assessments at the EPOST and LPOST applications but increased after the LPOST application. This was due to a flush of common ragweed emerging between the EPOST and LPOST application timings, which may have then been controlled by reactivation of isoxaflutole plus metribuzin and closure of the soybean canopy. Stewart et al. (2012) reported similar results: 97% common ragweed control was obtained with application of isoxaflutole plus atrazine (79 + 800 g ai ha^{-1}) at sites that received higher levels of rainfall in comparison with only 83%

https://doi.org/10.1017/wet.2019.21 Published online by Cambridge University Press

Table 8. Common ragweed density and biomass data at 4 wk after LPOST application from four field experiments conducted in Ontario, Canada, in 2017 and 2018.

Treatment[a]	Application timing	Rate	Density[b]		Biomass[b]	
			Sites 1, 4, 6	Site 2	Sites 1, 4, 6	Site 2
		g ai or ae ha^{-1}	m^{-2}		g m^{-2}	
Weedy control	—	—	31.48c	5.99a	22.95b	3.97a
Isoxaflutole + metribuzin	PRE	52.5 + 210	0.23ab	0.43a	0.04a	0.18a
Isoxaflutole + metribuzin	PRE	79 + 315	0.12a	1.28a	0.03a	3.53a
Isoxaflutole + metribuzin	PRE	105 + 420	0.12a	0.14a	0.14a	0.18a
Glyphosate	EPOST	900	1.99ab	5.93a	0.39a	1.43a
Glyphosate	LPOST	900	5.29bc	2.89a	0.94a	0.34a
Glyphosate fb Glyphosate	EPOST	900	0.35ab	2.65a	0.06a	0.23a
	LPOST	900				
Isoxaflutole + metribuzin fb glyphosate	PRE	52.5 + 210	0.12a	0.81a	0.03a	0.55a
	LPOST	900				
Isoxaflutole + metribuzin fb glyphosate	PRE	79 + 315	0.06a	1.07a	0.03a	2.19a
	LPOST	900				
Isoxaflutole + metribuzin fb glyphosate	PRE	105 + 420	0.06a	0.43a	0.03a	0.20a
	LPOST	900				

[a]Abbreviations: —, no data; EPOST, early postemergence; fb, followed by; LPOST, late postemergence.
[b]Means followed by the same letter within a column are not significantly different according to the Tukey-Kramer multiple range test at $P < 0.05$.

control obtained with the same treatment at sites that received less rainfall.

Velvetleaf

Velvetleaf was evaluated at three sites in this study. No significant treatment-by-site interaction was observed (data not shown); thus, data from these sites were combined.

At the EPOST and LPOST application timings, isoxaflutole plus metribuzin controlled velvetleaf 50% to 84% and 56% to 89%, respectively; there was no rate effect (Table 9). Glyphosate applied EPOST controlled velvetleaf 46% to 58%.

At 4 WAA, isoxaflutole plus metribuzin at the low, medium, and high rates controlled velvetleaf 84%, 98%, and 99%, respectively (Table 9). The low rate provided lower velvetleaf control than the high rate, whereas the medium rate resulted in similar control as the low and high rates. Glyphosate applied EPOST, LPOST, or EPOST fb LPOST controlled velvetleaf 90% to 98%. The two-pass programs of isoxaflutole plus metribuzin applied PRE fb glyphosate applied LPOST controlled velvetleaf 99% to 100%. At the respective rates of isoxaflutole plus metribuzin applied PRE, there was no improvement in velvetleaf control with glyphosate applied LPOST.

At 8 WAA, all treatments in this study provided 93% to 100% velvetleaf control (Table 9). The high rate of isoxaflutole plus metribuzin applied PRE fb glyphosate applied LPOST controlled velvetleaf 7% more than a single application of glyphosate applied EPOST.

At 4 WAA, the herbicide treatments evaluated reduced velvetleaf density 79% to 99% compared with the weedy control (Table 10). The low and high rates of isoxaflutole plus metribuzin applied PRE fb glyphosate applied LPOST decreased density 21% more than a single application of glyphosate did at the EPOST or LPOST application timings. All treatments evaluated reduced velvetleaf biomass 91% to 99% compared with the weedy control, except isoxaflutole plus metribuzin applied PRE at the low rate, which reduced velvetleaf biomass 76%. The inconsistency in the density and biomass data suggests that glyphosate applied EPOST and LPOST resulted in suppression of velvetleaf, but the plants were still present at 4 WAA. There was a 91% reduction in density with isoxaflutole plus metribuzin applied PRE at the low rate, although the plants that did escape grew quite large.

Velvetleaf control increased over time, which may have been a result of the residual activity of isoxaflutole plus metribuzin and soybean canopy closure (Table 10). Glyphosate was slower acting on velvetleaf compared with other weed species, as evidenced by the low level of control at the LPOST evaluation timing. The dense hairs on velvetleaf may reduce glyphosate absorption. Because of the lack of residual control by glyphosate, there was a flush of velvetleaf after application, which is supported by the density and biomass evaluations 4 WAA. Sequential applications of either isoxaflutole plus metribuzin applied PRE fb glyphosate applied LPOST or glyphosate applied EPOST fb LPOST increased velvetleaf control and reduced density and biomass. The results of this study are similar to those of Wiesbrook et al. (2001), who found improved velvetleaf control with sequential glyphosate applications.

Barnyardgrass

Barnyardgrass was evaluated at sites 1, 2, 4, 6, and 10. The site-by-treatment interaction was not significant (data not shown); therefore, data from the five sites were pooled.

At the EPOST application timing, isoxaflutole plus metribuzin applied PRE at the low, medium, and high rates controlled barnyardgrass 40% to 52%, 68% to 69%, and 73% to 81%, respectively (Table 11). There was a trend toward improved barnyardgrass control with increasing rates of isoxaflutole, although differences were not always statistically significant. This may have occurred because of natural variability in the population of barnyardgrass across sites and the susceptibility of barnyardgrass to isoxaflutole plus metribuzin, compared with other species.

At the LPOST application timing, barnyardgrass control was similar among the three rates of isoxaflutole plus metribuzin evaluated; control ranged from 63% to 89% (Table 11). Glyphosate applied EPOST controlled barnyardgrass 94% to 95%.

At 4 WAA, isoxaflutole plus metribuzin applied PRE controlled barnyardgrass 77% to 93%; there were no differences among rates evaluated (Table 11). Glyphosate applied EPOST, LPOST, or EPOST fb LPOST controlled barnyardgrass 95% to 99%. The

https://doi.org/10.1017/wet.2019.21 Published online by Cambridge University Press

Table 9. Velvetleaf control at EPOST and LPOST application timings and 4 and 8 WAA at sites 1, 2, and 3 in Ontario, Canada, in 2017 and 2018.

Treatment[a]	Application timing	Rate	Visible control[b]			
			EPOST	LPOST	4 WAA	8 WAA
		g ai or ae ha^{-1}	%			
Isoxaflutole + metribuzin	PRE	52.5 + 210	68a	74a	84b	95ab
Isoxaflutole + metribuzin	PRE	79 + 315	79a	79a	98ab	97ab
Isoxaflutole + metribuzin	PRE	105 + 420	79a	83a	99a	100ab
Glyphosate	EPOST	900	—	58a	90ab	93b
Glyphosate	LPOST	900	—	—	95ab	98ab
Glyphosate fb Glyphosate	EPOST	900	—	46a	98ab	99ab
	LPOST	900				
Isoxaflutole + metribuzin fb glyphosate	PRE	52.5 + 210	50a	56a	99ab	100ab
	LPOST	900				
Isoxaflutole + metribuzin fb glyphosate	PRE	79 + 315	71a	76a	100a	100ab
	LPOST	900				
Isoxaflutole + metribuzin fb glyphosate	PRE	105 + 420	84a	89a	100a	100a
	LPOST	900				

[a]Abbreviations: —, no data; EPOST, early postemergence; fb, followed by; LPOST, late postemergence; WAA, weeks after late postemergence application.
[b]Means followed by the same letter within a column are not significantly different according to the Tukey-Kramer multiple range test at $P < 0.05$.

Table 10. Velvetleaf density and biomass data at 4 wk after LPOST application at sites 1, 2, and 3 in Ontario, Canada, in 2017 and 2018.

Treatment[a]	Application timing	Rate	Density[b]	Biomass[b]
		g ai or ae ha^{-1}	m^{-2}	g m^{-2}
Weedy control	—	—	9.53c	9.16b
Isoxaflutole + metribuzin	PRE	52.5 + 210	0.86ab	2.24ab
Isoxaflutole + metribuzin	PRE	79 + 315	0.27ab	0.29a
Isoxaflutole + metribuzin	PRE	105 + 420	0.24ab	0.52a
Glyphosate	EPOST	900	2.00b	0.68a
Glyphosate	LPOST	900	2.03b	0.84a
Glyphosate fb Glyphosate	EPOST	900	0.80ab	0.10a
	LPOST	900		
Isoxaflutole + metribuzin fb glyphosate	PRE	52.5 + 210	0.02a	0.05a
	LPOST	900		
Isoxaflutole + metribuzin fb glyphosate	PRE	79 + 315	0.28ab	0.19a
	LPOST	900		
Isoxaflutole + metribuzin fb glyphosate	PRE	105 + 420	0.02a	0.05a
	LPOST	900		

[a]Abbreviations: —, no data; EPOST, early postemergence; fb, followed by; LPOST, late postemergence.
[b]Means followed by the same letter within a column are not significantly different according to the Tukey-Kramer multiple range test at $P < 0.05$.

two-pass programs of isoxaflutole plus metribuzin applied PRE fb glyphosate applied LPOST controlled barnyardgrass 99% to 100%. The LPOST application of glyphosate after isoxaflutole plus metribuzin applied PRE at the low and medium rate improved barnyardgrass control 22% and 14%, respectively. A sequential application of glyphosate after application of the high rate of isoxaflutole plus metribuzin did not increase control.

At 8 WAA, isoxaflutole plus metribuzin applied at the low, medium, and high rates controlled barnyardgrass 79%, 86%, and 96%, respectively; and glyphosate applied EPOST, LPOST, or EPOST fb LPOST controlled barnyardgrass 97% to 99% (Table 11). Similar to findings at 4 WAA, there was a 14% to 21% increase in barnyardgrass control when glyphosate was applied LPOST after isoxaflutole plus metribuzin was applied at the low or medium rate. There was no increase in barnyardgrass control when glyphosate was applied LPOST after the high rate of isoxaflutole plus metribuzin applied PRE. The two-pass programs of isoxaflutole plus metribuzin applied PRE fb glyphosate applied LPOST controlled barnyardgrass 100%.

At 4 WAA, barnyardgrass density was reduced by 83% to 96% with all herbicide treatments except the low and medium rates of isoxaflutole plus metribuzin when applied PRE (Table 12). Isoxaflutole plus metribuzin applied PRE at the low, medium, and high rates reduced barnyardgrass density 44%, 74%, and 83%, respectively. Glyphosate applied EPOST, LPOST, or EPOST fb LPOST reduced barnyardgrass density 81% to 96%; there was no difference among application timings. Isoxaflutole plus metribuzin applied PRE fb glyphosate applied LPOST reduced barnyardgrass density 92% to 96%.

At 4 WAA, barnyardgrass biomass was reduced by 94% to 99% with all herbicide treatments except isoxaflutole plus metribuzin applied PRE (Table 12). Isoxaflutole plus metribuzin applied PRE at the low, medium, and high rates reduced barnyardgrass biomass 22%, 60%, and 82%, respectively. Glyphosate applied EPOST, LPOST, or EPOST fb LPOST reduced barnyardgrass biomass 94% to 99%; there was no difference among application timings. Isoxaflutole plus metribuzin applied PRE fb glyphosate applied LPOST reduced barnyardgrass biomass 98%.

https://doi.org/10.1017/wet.2019.21 Published online by Cambridge University Press

Table 11. Barnyardgrass control data at EPOST and LPOST application timing and 4 and 8 WAA at sites 1, 2, 4, 6, and 10 in Ontario, Canada, in 2017 and 2018.

Treatment[a]	Application Timing	Rate	Visible control[b]			
			EPOST	LPOST	4 WAA	8 WAA
		g ai or ae ha^{-1}			%	
Isoxaflutole + metribuzin	PRE	52.5 + 210	40c	67b	77c	79c
Isoxaflutole + metribuzin	PRE	79 + 315	69ab	81ab	86bc	86bc
Isoxaflutole + metribuzin	PRE	105 + 420	81a	89ab	93abc	96ab
Glyphosate	EPOST	900	—	94a	95ab	97ab
Glyphosate	LPOST	900	—	—	98ab	99a
Glyphosate fb Glyphosate	EPOST	900	—	95a	99a	99a
	LPOST	900				
Isoxaflutole + metribuzin fb glyphosate	PRE	52.5 + 210	52bc	63b	99a	100a
	LPOST	900				
Isoxaflutole + metribuzin fb glyphosate	PRE	79 + 315	68ab	83ab	100a	100a
	LPOST	900				
Isoxaflutole + metribuzin fb glyphosate	PRE	105 + 420	73ab	88ab	100a	100a
	LPOST	900				

[a]Abbreviations: —, no data; EPOST, early postemergence; fb, followed by; LPOST, late postemergence; WAA, weeks after late postemergence application.
[b]Means followed by the same letter within a column are not significantly different according to the Tukey-Kramer multiple range test at $P < 0.05$.

Table 12. Barnyardgrass density and biomass data at 4 wk after LPOST application at sites 1, 2, 4, 6, and 10 in Ontario, Canada, in 2017 and 2018.

Treatment[a]	Application timing	Rate	Density[b]	Biomass[b]
		g ai or ae ha^{-1}	m^{-2}	g m^{-2}
Weedy control	—	—	9.03c	6.39c
Isoxaflutole + metribuzin	PRE	52.5 + 210	5.05bc	4.98bc
Isoxaflutole + metribuzin	PRE	79 + 315	2.38abc	2.57abc
Isoxaflutole + metribuzin	PRE	105 + 420	1.58ab	1.18abc
Glyphosate	EPOST	900	1.74ab	0.40ab
Glyphosate	LPOST	900	1.29ab	0.14a
Glyphosate fb Glyphosate	EPOST	900	0.39a	0.09a
	LPOST	900		
Isoxaflutole + metribuzin fb glyphosate	PRE	52.5 + 210	0.69ab	0.13a
	LPOST	900		
Isoxaflutole + metribuzin fb glyphosate	PRE	79 + 315	0.70ab	0.12a
	LPOST	900		
Isoxaflutole + metribuzin fb glyphosate	PRE	105 + 420	0.40a	0.11a
	LPOST	900		

[a]Abbreviations: —, no data; EPOST, early postemergence; fb, followed by; LPOST, late postemergence.
[b]Means followed by the same letter within a column are not significantly different according to the Tukey-Kramer multiple range test at $P < 0.05$.

Over time, there was an increase in barnyardgrass control with isoxaflutole plus metribuzin. This may have been due to residual control of isoxaflutole plus metribuzin preventing the emergence of new individuals and a reduction in barnyardgrass growth due to soybean canopy closure. By the end of the season, stunted barnyardgrass plants in plots where isoxaflutole plus metribuzin was applied PRE were shaded and not able to fully develop. The application of glyphosate applied LPOST after isoxaflutole plus metribuzin at the low rate improved barnyardgrass control and decreased density and biomass. Similarly, Stephenson and Bond (2012) found that isoxaflutole plus atrazine (90 + 1,120 g ha^{-1}) controlled barnyardgrass 84%; the sequential application of glyphosate applied POST increased control by 7%.

Foxtail

Green foxtail and giant foxtail populations were combined during assessments. These species occurred at the following eight sites: 1, 2, 3, 4, 5, 6, 8, and 10. There was no significant site-by-treatment interaction (data not shown); thus, data from these sites were combined (Table 13).

At the EPOST application timing, isoxaflutole plus metribuzin at the low, medium, and high rates controlled foxtails 43% to 44%, 55% to 57%, and 63% to 71%, respectively (Table 13). At the LPOST application timing, isoxaflutole plus metribuzin controlled foxtail 42% to 73%; there was no difference among the rates evaluated (Table 13). Glyphosate applied EPOST controlled foxtails 97%.

At 4 WAA, isoxaflutole plus metribuzin applied PRE at the low, medium, and high rates controlled foxtail 58%, 75%, and 86%, respectively. The high rate provided better control than the low rate; however, control with the medium rate did not differ from the low or high rate (Table 13). Glyphosate applied EPOST, LPOST, and EPOST fb LPOST controlled foxtails 94% to 99%. The sequential application of isoxaflutole plus metribuzin applied PRE fb glyphosate applied LPOST controlled foxtail 100%. Application of glyphosate LPOST after isoxaflutole plus metribuzin applied PRE at the low, medium, and high rates increased foxtail control 42%, 25%, and 14%, respectively.

https://doi.org/10.1017/wet.2019.21 Published online by Cambridge University Press

Table 13. Control of species of foxtail at EPOST and LPOST application timing and 4 and 8 WAA at sites 1, 2, 3, 4, 5, 6, 8, and 10 in Ontario, Canada, in 2017 and 2018.

Treatment[a]	Application timing	Rate	Visible control[b]			
			EPOST	LPOST	4 WAA	8 WAA
		g ai or ae ha^{-1}	%			
Isoxaflutole + metribuzin	PRE	52.5 + 210	44c	42c	58d	71e
Isoxaflutole + metribuzin	PRE	79 + 315	57b	65c	75cd	84de
Isoxaflutole + metribuzin	PRE	105 + 420	71a	73abc	86bc	92dc
Glyphosate	EPOST	900	—	97ab	94abc	95bcd
Glyphosate	LPOST	900	—	—	98ab	98abc
Glyphosate fb Glyphosate	EPOST	900	—	97a	99ab	100abc
	LPOST	900				
Isoxaflutole + metribuzin fb glyphosate	PRE	52.5 + 210	43c	46c	100a	100a
	LPOST	900				
Isoxaflutole + metribuzin fb glyphosate	PRE	79 + 315	55bc	64c	100a	100ab
	LPOST	900				
Isoxaflutole + metribuzin fb glyphosate	PRE	105 + 420	63ab	71bc	100a	100a
	LPOST	900				

[a]Abbreviations: —, no data; EPOST, early postemergence; fb, followed by; LPOST, late postemergence; WAA, weeks after late postemergence application.
[b]Means followed by the same letter within a column are not significantly different according to the Tukey-Kramer multiple range test at $P < 0.05$.

Table 14. Density and biomass of species of foxtail at 4 wk after LPOST application at sites 1, 2, 3, 4, 5, 6, 8, and 10 in Ontario, Canada, in 2017 and 2018.

Treatment[a]	Application timing	Rate	Density[b]	Biomass[b]
		g ai or ae ha^{-1}	m^{-2}	g m^{-2}
Weedy control	—	—	74.78f	45.24d
Isoxaflutole + metribuzin	PRE	52.5 + 210	16.72e	13.37c
Isoxaflutole + metribuzin	PRE	79 + 315	10.78de	7.95bc
Isoxaflutole + metribuzin	PRE	105 + 420	5.99cde	3.68b
Glyphosate	EPOST	900	3.26bcd	0.48a
Glyphosate	LPOST	900	1.81abc	0.14a
Glyphosate fb Glyphosate	EPOST	900	1.79abc	0.06a
	LPOST	900		
Isoxaflutole + metribuzin fb glyphosate	PRE	52.5 + 210	0.40a	0.07a
	LPOST	900		
Isoxaflutole + metribuzin fb glyphosate	PRE	79 + 315	0.62ab	0.06a
	LPOST	900		
Isoxaflutole + metribuzin fb glyphosate	PRE	105 + 420	0.26a	0.04a
	LPOST	900		

[a]Abbreviations: —, no data; EPOST, early postemergence; fb, followed by; LPOST, late postemergence.
[b]Means followed by the same letter within a column are not significantly different according to the Tukey-Kramer multiple range test at $P < 0.05$.

At 8 WAA, isoxaflutole plus metribuzin applied PRE at the low, medium, and high rates controlled foxtails 71%, 84%, and 92%, respectively (Table 13). Similar to observations at 4 WAA, the high rate controlled foxtail better than did the low rate, whereas control at the medium rate did not differ from either the low or high rate. Glyphosate applied EPOST, LPOST, and EPOST fb LPOST controlled foxtails 95% to 100%. The sequential application of isoxaflutole plus metribuzin PRE fb glyphosate applied LPOST controlled foxtail 100%. Glyphosate applied LPOST after isoxaflutole plus metribuzin applied PRE at the low, medium, and high rates increased foxtail control 29%, 16%, and 8%, respectively.

At 4 WAA, all treatments decreased foxtail density 78% to 99%, compared with the untreated control (Table 14). Isoxaflutole plus metribuzin applied PRE reduced foxtail density by 78% to 92%; there was no difference among the rates evaluated. Glyphosate applied EPOST, LPOST, and EPOST fb LPOST reduced foxtail density 96% to 98%. The sequential application of isoxaflutole plus metribuzin applied PRE fb glyphosate applied LPOST reduced foxtail density 99%. In comparison, foxtail biomass was reduced 70% to 99% with all herbicide treatments. Similar to findings in the weed control assessments, the high application rate of isoxaflutole plus metribuzin reduced foxtail biomass by an additional 21% compared with the low rate; however, the decrease in biomass at the medium rate did not differ from either the low or high rate. Glyphosate applied EPOST, LPOST, or EPOST fb LPOST and the sequential PRE application of isoxaflutole plus metribuzin fb glyphosate applied LPOST reduced foxtail biomass 99%.

Grass weed species, including foxtail, were less sensitive to isoxaflutole plus metribuzin than broadleaf species (Table 14). The low and medium rates of isoxaflutole plus metribuzin cannot be relied on as effective foxtail control strategies, especially with high populations such as those present in this study. Glyphosate applied LPOST is very efficacious for the control of foxtails that escape the PRE herbicide. The results from this study are similar to those of Schultz et al. (2015), who reported that where isoxaflutole plus *S*-metolachlor plus metribuzin was applied PRE fb glyphosate applied POST, giant foxtail was controlled 99%.

https://doi.org/10.1017/wet.2019.21 Published online by Cambridge University Press

Table 15. Crabgrass control at EPOST and LPOST application timings and 4 and 8 WAA at sites 4, 8, 9, and 10 in Ontario, Canada, in 2017 and 2018.

Treatment[a]	Application timing	Rate	Visible control[b]			
			EPOST	LPOST	4 WAA	8 WAA
		g ai or ae ha^{-1}	%			
Isoxaflutole + metribuzin	PRE	52.5 + 210	99a	99a	97b	98b
Isoxaflutole + metribuzin	PRE	79 + 315	99a	98a	99ab	99ab
Isoxaflutole + metribuzin	PRE	105 + 420	100a	99a	100ab	100ab
Glyphosate	EPOST	900	—	100a	99ab	99ab
Glyphosate	LPOST	900	—	—	100ab	100a
Glyphosate fb Glyphosate	EPOST	900	—	100a	100a	100ab
	LPOST	900				
Isoxaflutole + metribuzin fb glyphosate	PRE	52.5 + 210	98a	97a	100a	100a
	LPOST	900				
Isoxaflutole + metribuzin fb glyphosate	PRE	79 + 315	99a	99a	100a	100a
	LPOST	900				
Isoxaflutole + metribuzin fb glyphosate	PRE	105 + 420	99a	97a	100a	100a
	LPOST	900				

[a]Abbreviations: —, no data; EPOST, early postemergence; fb, followed by; LPOST, late postemergence; WAA, weeks after late postemergence application.
[b]Means followed by the same letter within a column are not significantly different according to the Tukey-Kramer multiple range test at $P < 0.05$.

Table 16. Crabgrass density and biomass at 4 wk after LPOST application at sites 4, 8, 9, and 10 in Ontario, Canada, in 2017 and 2018.

Treatment[a]	Application timing	Rate	Density[b]	Biomass[b]
		g ai or ae ha^{-1}	m^{-2}	g m^{-2}
Weedy control	—	—	5.17b	4.95b
Isoxaflutole + metribuzin	PRE	52.5 + 210	0.94a	0.77a
Isoxaflutole + metribuzin	PRE	79 + 315	0.88a	0.33a
Isoxaflutole + metribuzin	PRE	105 + 420	0.46a	0.21a
Glyphosate	EPOST	900	0.68a	0.21a
Glyphosate	LPOST	900	1.22ab	0.25a
Glyphosate fb Glyphosate	EPOST	900	0.16a	0.03a
	LPOST	900		
Isoxaflutole + metribuzin fb glyphosate	PRE	52.5 + 210	0.16a	0.06a
	LPOST	900		
Isoxaflutole + metribuzin fb glyphosate	PRE	79 + 315	0.13a	0.01a
	LPOST	900		
Isoxaflutole + metribuzin fb glyphosate	PRE	105 + 420	0.16a	0.08a
	LPOST	900		

[a]Abbreviations: —, no data; EPOST, early postemergence; fb, followed by; LPOST, late postemergence.
[b]Means followed by the same letter within a column are not significantly different according to the Tukey-Kramer multiple range test at $P < 0.05$.

Crabgrass

Large crabgrass [*Digitaria sanguinalis* (L.) Scop.] was evaluated at four sites in this study. The site-by-treatment interaction was not significant (data not shown), so data from the sites were pooled.

At the EPOST and LPOST application timings, isoxaflutole plus metribuzin controlled large crabgrass 98% to 100% and 97% to 99%, respectively; there was no difference in large crabgrass control among the rates of isoxaflutole plus metribuzin evaluated (Table 15). At the LPOST application timing, glyphosate, applied EPOST controlled large crabgrass 100%.

At 4 and 8 WAA, the three rates of isoxaflutole plus metribuzin controlled large crabgrass 97% to 100% and 98% to 100%, respectively, with no difference in crabgrass control observed among the rates evaluated (Table 15). Glyphosate applied EPOST, LPOST, and EPOST fb LPOST and the sequential PRE applications of isoxaflutole plus metribuzin fb glyphosate applied LPOST controlled large crabgrass 99% to 100%. There was no increase in large crabgrass control when glyphosate was applied LPOST after isoxaflutole plus metribuzin applied PRE at the medium or high rate.

At 4 WAA, all the herbicide treatments evaluated reduced large crabgrass density by 82% to 97%, with the exception of glyphosate applied LPOST, which did not reduce density (Table 16). The herbicide treatments evaluated reduced large crabgrass biomass by 84% to 99%.

Large crabgrass had the lowest density of all species evaluated in this study. This may have contributed to the high level of control (>97%) across all herbicide treatments and assessment timings. The medium and high rates of isoxaflutole plus metribuzin provided similar large crabgrass control and reduction in density and biomass, and there was no additional benefit of glyphosate applied LPOST. These data suggest that large crabgrass is very sensitive to isoxaflutole plus metribuzin, especially at higher rates.

Residual properties of isoxaflutole plus metribuzin in addition to competition with soybean as the canopy closed prevented emergence of new crabgrass. By the end of the season, large crabgrass

https://doi.org/10.1017/wet.2019.21 Published online by Cambridge University Press

Table 17. Witchgrass control at EPOST and LPOST application timings and 4 and 8 WAA at sites 1, 4, and 6 in Ontario, Canada, in 2017 and 2018.[a]

Treatment	Application timing	Rate	Visible control			
			EPOST	LPOST	4 WAA	8 WAA
		g ai or ae ha^{-1}	%			
Isoxaflutole + metribuzin	PRE	52.5 + 210	95a	98a	95d	96d
Isoxaflutole + metribuzin	PRE	79 + 315	99a	100a	97bcd	98bcd
Isoxaflutole + metribuzin	PRE	105 + 420	99a	100a	99abc	99abcd
Glyphosate	EPOST	900	—	98a	96cd	97dc
Glyphosate	LPOST	900	—	—	100abc	100abc
Glyphosate fb Glyphosate	EPOST	900	—	99a	100ab	100ab
	LPOST	900				
Isoxaflutole + metribuzin fb glyphosate	PRE	52.5 + 210	98a	97a	100ab	100a
	LPOST	900				
Isoxaflutole + metribuzin fb glyphosate	PRE	79 + 315	99a	100a	100a	100a
	LPOST	900				
Isoxaflutole + metribuzin fb glyphosate	PRE	105 + 420	99a	99a	100ab	100a
	LPOST	900				

[a]Abbreviations: —, no data; EPOST, early postemergence; fb, followed by; LPOST, late postemergence; WAA, weeks after late postemergence application.
[b]Means followed by the same letter within a column are not significantly different according to the Tukey-Kramer multiple range test at $P < 0.05$.

that survived herbicide application had died due to soybean canopy closure, which did not allow large crabgrass to intercept incident radiation, owing to its prostrate growth habit.

Results from this study support findings by Schultz et al. (2015), showing that large crabgrass was controlled 99% with application of three rate combinations of isoxaflutole plus *S*-metolachlor plus metribuzin fb glyphosate. The same study showed glyphosate applied EPOST fb LPOST controlled large crabgrass 99%, which is also consistent with results of the current study.

Witchgrass

Witchgrass (*Panicum capillare* L.) was evaluated at three sites in this study. The site-by-treatment effect was not significant (data not shown) for this species; therefore, data from the three sites were pooled.

At the EPOST and LPOST application timings, all rates of isoxaflutole plus metribuzin controlled witchgrass 95% to 100%; there was no difference among the rates of isoxaflutole plus metribuzin evaluated (Table 17). Glyphosate applied EPOST controlled witchgrass 98% to 99% at the LPOST evaluation timing.

At 4 WAA, isoxaflutole plus metribuzin at the low, medium, and high rates controlled witchgrass 95%, 97%, and 99%, respectively (Table 17). The high rate provided better control than did the low rate, whereas control at the medium rate was similar to both the low and high rates. Glyphosate applied EPOST, LPOST, or EPOST fb LPOST controlled witchgrass 96%, 100%, and 100%, respectively. The two-pass programs of isoxaflutole plus metribuzin applied PRE fb glyphosate applied LPOST controlled witchgrass 100%. Witchgrass control at 8 WAA was similar to that at 4 WAA.

At 4 WAA, the herbicide treatments evaluated reduced witchgrass density and biomass 91% to 99% and 96% to 99%, respectively (Table 18). There was no difference among the herbicide treatments evaluated.

Soybean Yield

Soybean yield was separated by site because of a significant site-by-treatment interaction (data not shown) by which the corresponding treatments at sites 1, 2, 4, 5, 7, 8, and 9 had 1.32 to 1.85 tons ha^{-1} higher yields compared with sites 3, 6, and 10 (Table 19). At sites 1, 2, 4, 5, 7, 8, and 9, weed interference reduced soybean yield 31%. Reduced weed interference with all the herbicide treatments resulted in soybean yield that was 1.0 to 1.5 tons ha^{-1} higher than the weedy control and was similar to the weed-free control. There was no difference in soybean yield among the herbicide treatments evaluated. At sites 3, 6, and 10, weed interference reduced soybean yield 51%. Soybean yield was lower at these sites; however, reduced weed interference with the herbicide treatments evaluated resulted in a yield increase of 1.3 to 1.9 tons ha^{-1}, except at the low rate of isoxaflutole plus metribuzin. The reduction in yield after application of isoxaflutole plus metribuzin at the low rate was likely due to poor weed control during the CWFP. The numerically lower soybean yield at sites 3, 6, and 10 may have been due to several potential factors. For example, site 3 did not receive an activating rainfall after the PRE application, which resulted in reduced weed control. Site 6 had the highest level of injury, which may have affected soybean yield, and site 10 had extremely high densities of foxtail species, pigweed species, and common lambsquarters compared with the other sites, which would compete with soybean and potentially result in lower yield.

In conclusion, isoxaflutole plus metribuzin applied PRE or a single application of glyphosate applied POST provided excellent control of all weeds at some sites. The sequential application of glyphosate applied EPOST fb LPOST or isoxaflutole plus metribuzin applied PRE fb glyphosate applied LPOST provided excellent full-season weed control and resulted in soybean yield that was similar to the weed-free control at all sites. Reduced weed control with isoxaflutole plus metribuzin was correlated with insufficient levels of rainfall to activate the PRE herbicides. In these cases, glyphosate applied LPOST reduced weed interference to the extent that there was no yield loss relative to the weed-free control. Butt et al. (2016) also found that a PRE fb POST two-pass program was the best weed control strategy. All annual weeds in our study were effectively controlled with a two-pass program consisting of glyphosate applied EPOST and LPOST. Although effective, this application is not recommended, because it increases the selection intensity for glyphosate-resistant weeds.

https://doi.org/10.1017/wet.2019.21 Published online by Cambridge University Press

Table 18. Witchgrass density and biomass data at 4 wk after LPOST application at sites 1,4, and 6 in Ontario, Canada, in 2017 and 2018.

Treatment[a]	Application timing	Rate	Density[b]	Biomass[b]
		g ai or ae ha^{-1}	m^{-2}	g m^{-2}
Weedy control	—	—	12.55b	8.15b
Isoxaflutole + metribuzin	PRE	52.5 + 210	1.19a	0.29a
Isoxaflutole + metribuzin	PRE	79 + 315	1.01a	0.21a
Isoxaflutole + metribuzin	PRE	105 + 420	0.08a	0.20a
Glyphosate	EPOST	900	1.08a	0.32a
Glyphosate	LPOST	900	0.64a	0.11a
Glyphosate fb Glyphosate	EPOST	900	0.35a	0.07a
	LPOST	900		
Isoxaflutole + metribuzin fb glyphosate	PRE	52.5 + 210	0.08a	0.04a
	LPOST	900		
Isoxaflutole + metribuzin fb glyphosate	PRE	79 + 315	0.04a	0.04a
	LPOST	900		
Isoxaflutole + metribuzin fb glyphosate	PRE	105 + 420	0.21a	0.05a
	LPOST	900		

[a]Abbreviations: —, no data; EPOST, early postemergence; fb, followed by; LPOST, late postemergence.
[b]Means followed by the same letter within a column are not significantly different according to the Tukey-Kramer multiple range test at $P < 0.05$.

Table 19. Soybean yield from 10 field experiments conducted in Ontario, Canada, in 2017 and 2018.

Treatment[a]	Application timing	Rate	Sites 1, 2, 4, 5, 7, 8, 9	Sites 3, 6, 10
		g ai or ae ha^{-1}	tons ha^{-1}	
Weedy control	—	—	3.50b	1.68b
Weed free	—	—	5.06a	3.43a
Isoxaflutole + metribuzin	PRE	52.5 + 210	4.56a	2.71ab
Isoxaflutole + metribuzin	PRE	79 + 315	4.54a	3.01a
Isoxaflutole + metribuzin	PRE	105 + 420	4.52a	2.99a
Glyphosate	EPOST	900	4.74a	3.27a
Glyphosate	LPOST	900	4.74a	3.41a
Glyphosate fb Glyphosate	EPOST	900	5.00a	3.51a
	LPOST	900		
Isoxaflutole + metribuzin fb glyphosate	PREL	52.5 + 210	4.98a	3.53a
	POST	900		
Isoxaflutole + metribuzin fb glyphosate	PRE	79 + 315	4.74a	3.42a
	LPOST	900		
Isoxaflutole + metribuzin fb glyphosate	PRE	105 + 420	4.77a	3.41a
	LPOST	900		

[a]Abbreviations: —, no data; EPOST, early postemergence; fb, followed by; LPOST, late postemergence.
[b]Means followed by the same letter within a column are not significantly different according to the Tukey-Kramer multiple range test at $P < 0.05$.

In the current study, soybean yield was not reduced with a total POST herbicide program. However, relying on POST herbicides for weed control may reduce grain yield if timely applications are missed because of unexpected rain events, windy conditions, or mechanical breakdowns, which may delay herbicide application. In the current study, there was no significant interaction of isoxaflutole plus metribuzin relative to soil characteristics.

Common lambsquarters and common ragweed were the only species for which there was a significant herbicide treatment-by-site interaction. These differences were more closely correlated with variations in rainfall. Rainfall is required to dissolve isoxaflutole and metribuzin in soil water solution so it can be taken up by the developing weed seedling. Moisture was sufficient for weed seed germination; however, there was inadequate rainfall to move and dissolve the soil-applied herbicides in soil water solution to be absorbed by the weeds at concentrations needed to cause toxic effects. The use of isoxaflutole plus metribuzin applied PRE within an integrated weed management program can effectively control many annual weed species when adequate rainfall occurs to dissolve the herbicides in soil water solution; otherwise, a POST application of glyphosate can be used to control weed escapes to provide season-long weed control.

Author ORCIDs. Nader Soltani https://orcid.org/0000-0001-8687-4371

Acknowledgments. The authors gratefully acknowledge Christy Shropshire, Lynette Brown, and Todd Cowan for their technical contributions to this project. Funding for this project was provided in part by the Ontario Centre of Excellence and Bayer CropScience Canada Inc. No conflicts of interest have been declared.

References

Anonymous (2017) Converge® Flexx herbicide label. Pest Control Products Act. Reg. No. 22071. Calgary, Canada: Bayer CropScience Canada Inc.

Behrens MR, Mutlu N, Chakraborty S, Dumitru R, Jiang WZ, Lavallee B J, Herman PL, Clemente TE, Weeks DP (2007) Dicamba resistance: enlarging and preserving biotechnology-based weed management strategies. Science 316:1185–1188

Butts TR, Norsworthy JK, Kruger GR, Sandell LD, Young BG, Steckel LE, Loux MM, Bradley KW, Conley SP, Stotenberg DE, Arriaga FJ, Davis VM (2016) Management of pigweed (Amaranthus spp.) in glufosinate-resistant soybean in the Midwest and mid-south. Weed Technol 30:355–365

Chomas AJ, Kells JJ (2004) Triazine-resistant common lambsquarters (*Chenopodium album*) control in corn with preemergence herbicides. Weed Technol 18:551–554

Ditschun S, Soltani N, Robinson DE, Tardiff FJ, Kaastra AC, Sikkema PH (2016) Control of glyphosate-resistant Canada fleabane (*Conyza canadensis (L.) Cronq.*) with isoxaflutole and metribuzin tank mix. Can J Plant Sci 96:72–80

Fernandez-Cornejo J, Klotz-Ingram C, Jans S (2002) Farm-level effects of adopting herbicide-tolerant soybeans in the U.S.A. J Agr Appl Econ 34:149–163

Gressel J, Segel LA (1990) Modelling the effectiveness of herbicide rotations and mixtures as strategies to delay or preclude resistance. Weed Technol 4:186–198

Meyer CJ, Norsworthy JK, Young BG, Steckel LE, Bradley KW, Johnson WG, Loux MM, Davis VM, Kruger GR, Bararpour MT (2015) Herbicide program approaches for managing glyphosate-resistant palmer amaranth (*Amaranthus palmeri*) and waterhemp (*Amaranthus tuberculatus and Amaranthus rudis*) in future soybean-trait technologies. Weed Technol 29:716–729

Mitra S, Bhowmik PC, Xing B (2001) Physical and chemical properties of soil influence the sorption of the diketonitrile metabolite of RPA 201772. Weed Sci 49:423–430

[OMAFRA] Ontario Ministry of Agriculture, Food and Rural Affairs (2016) Publication 75: Guide to weed control. http://www.omafra.gov.on.ca/english/crops/pub75/pub75toc.htm. Accessed: March 16, 2019

Pallett KE, Little JP, Sheekey M, Veerasekaran P (1998) The mode of action of isoxaflutole: physiological effects, metabolism and selectivity. Pestic Biochem Phys 62:113–124

Schryver MG, Soltani N, Hooker DC, Robinson DE, Tranel PJ, Sikkema PH (2017) Control of glyphosate-resistant common waterhemp (*Amaranthus rudis*) in three new herbicide-resistant soybean varieties in Ontario. Weed Technol 31:828–837

Schultz JL, Weber M, Allen J, Bradley KW (2015) Evaluation of weed management programs and response of FG72 soybean to HPPD-inhibiting herbicides. Weed Technol 29:653–664

Soltani N, Nurse RE, Sikkema PH (2016) Biologically effective dose of glyphosate as influenced by weed size in corn. Can J Plant Sci 96:455–460

Soltani N, Dille JA, Burke IC, Everman WJ, VanGessel MJ, Davis VM, Sikkema PH (2017) Perspectives on potential soybean yield losses from weeds in North America. Weed Technol 31:148–154

Soukup J, Jursik M, Hamouz P, Holec J, Krupka J (2004) Influence of soil pH, rainfall, dosage, and application timing of herbicide Merlin 750 WG (isoxaflutole on phytotoxicity level in maize (*Zea mays L.*). Plant Soil Environ 50:88–94

Spaunhorst DJ, Johnson WG (2017) Variable tolerance among palmer amaranth (*Amaranthus palmeri*) biotypes to glyphosate, 2, 4-D amine, and premix formulation of glyphosate plus 2, 4-D choline (*Enlist Duo*) herbicide. Weed Sci 65:787–797

Stephenson DO IV, Bond JA (2012) Evaluation of thiencarbazone-methyl and isoxaflutole-based herbicide programs in corn. Weed Technol 26:37–42

Stewart CL, Soltani N, Nurse RE, Hamil AS, Sikkema PH (2012) Precipitation influences pre- and post- emergence herbicide efficacy in corn. Am J Plant Sci 3:1193–1204

Tharp BE, Kells JJ (2002) Residual herbicides used in combination with glyphosate and glufosinate in corn (*Zea mays*). Weed Technol 16:274–281

Van Acker RC, Swanton CJ, Weise SF (1993) The critical period of weed control in soybean [*Glycine max* (L.) Merr.]. Weed Sci 41:194–200

Weaver SE (1991) Size-dependent economic thresholds for three broadleaf weed species in soybeans. Weed Technol 5:674–679

Weaver SE (2001) Impact of lamb's-quarters, common ragweed and green foxtail on yield of corn and soybean in Ontario. Can J Plant Sci 81: 821–828

Wiesbrook ML, Johnson WG, Hart SE, Bradley PR, Wax LM (2001) Comparison of weed management systems in narrow-row, glyphosate- and glufosinate-resistant soybean (*Glycine max*). Weed Technol 15:122–128

Young BG (2006) Changes in herbicide use patterns and production practices resulting from glyphosate-resistant crops. Weed Technol 20:301–307

https://doi.org/10.1017/wet.2019.21 Published online by Cambridge University Press