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Activity of Isoxaflutole plus Metribuzin Tankmixes in Isoxaflutole-Resistant Soybean

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Abstract

Isoxaflutole-resistant soybean is currently in development for commercialization in North America. Proposals to use isoxaflutole + metribuzin as the main herbicide tank-mixture raise concerns as there is limited grass control with these herbicides. Strategies are needed to improve grass control with isoxaflutole + metribuzin. Nine experiments were conducted over a two-year period (2017, 2018) to determine the efficacy of isoxaflutole + metribuzin (52.5 + 210 g a·i· ha^{-1}) applied alone and co-applied with pendimethalin, dimethenamid-P, pethoxamid, pyroxasulfone or S-metolachlor applied preemergence (PRE). Comparisons were made with isoxaflutole + metribuzin at a low rate (52.5 + 210 g a·i· ha^{-1}), medium rate (79 + 315 g a·i· ha^{-1}) and a high rate (105 + 420 g a·i· ha^{-1}). Eight weed species were evaluated including common lambsquarters, green and redroot pigweed, common ragweed, velvetleaf, green and giant foxtail, yellow foxtail, barnyardgrass and witchgrass. All herbicides were affected by amount of rainfall following application; less rainfall resulted in reduced weed control. The addition of pendimethalin, dimethenamid-P, pethoxamid, pyroxasulfone or S-metolachlor to the low rate ofisoxaflutole + metribuzin provided equivalent control of all weed species evaluated compared toisoxaflutole + metribuzin at the low, medium, or high rate.

Keywords

Glyphosate Resistance, HPPD Transgenic Soybean Cultivars, Preemergence Herbicides, Rainfall, Soybean Yield, Weed Management

1. Introduction

New hydroxyphenylpyruvate dioxygenase (HPPD) transgenic soybean cultivars are in development with resistance to a suite of herbicides including isoxaflutole and glyphosate; isoxaflutole, glyphosate and glufosinate; and isoxaflutole, mesotrione and glufosinate. Once commercialized, one weed management program will be the application of isoxaflutole + metribuzin applied preplant (PP) or preemergence (PRE) for residual control of annual grass and broadleaf weeds. These two herbicides, when used together, have complementary activity for the control of glyphosate-resistant (GR) Canada fleabane (*Conyza canadensis* L. Cronq.) [1]. However, this mixture does not provide full-season control of some annual grasses such as green foxtail (*Setaria viridis* L. P. Beauv.) and barnyardgrass (*Echinochloa crus-galli* L. P. Beauv.) [2] [3].

Isoxaflutole is an HPPD-inhibiting herbicide; this enzyme catalyzes the production of tocopherols and plastoquinone; a cofactor essential for carotenoid biosynthesis and an electron transporter in the electron transport chain [4]. Previously, isoxaflutole was only used in corn and sugarcane production. Metribuzin is a photosystem II (PSII)-inhibiting herbicide that displaces plastoquinone on the D1 protein of PSII causing a buildup of electrons in the electron transport chain [5]. Metribuzin primarily provides control of annual broadleaf weeds, although it does have some activitiy on annual grass weeds [6]. Therefore, one concern with the combined use of isoxaflutole and metribuzin in HPPD-resistant soybean is annual grass weed escapes.

Grass competition with soybean can cause a yield reduction; the amount of yield loss is influenced by weed species, density, relative time of weed and crop emergence, weather patterns, soil nutrient status and time of removal. Populations of Johnsongrass (*Sorghum halepense* L. Pers.) of 16 plants per 10 m of soybean row caused a 48% soybean yield loss; increases in weed density caused 88% yield loss [6]. Giant foxtail (*Setaria faberi* Herrm.) in competition with soybean at 177 plants·m^{-1} of row reduced soybean yield by 28% if they emerged early in the season; however, later emerging individuals caused little to no yield loss [7]. Quackgrass (*Elymus repens* L. Gould) caused an 11% soybean yield reduction when allowed to compete with soybean for 6 weeks; an additional 2 weeks of competition caused an additional 12% yield loss [8].

Herbicides applied preemergence (PRE) with grass activity mitigates yield limiting soybean stress from grass weed competition early in the season. Soil applied grass herbicide families for soybean include dinitroaniline, chloroacetamide, chloroacetanilide and isoxazoline. Herbicides within these families control annual grasses and small-seeded broadleaf weeds; generally, they control barnyardgrass, crabgrass species (*Digitaria* sp.), *Panicum* species, foxtail species (*Setaria* spp.), *Amaranthus* species and common lambsquarters (*Chenopodium album* L.) although the weed spectrum controlled is active ingredient specific [6] [9] [10]. Herbicidal activity is dependent on rainfall within 7 days of application to ensure that the herbicide is dissolved in soil water solution so it can be absorbed by emerging weed seedlings [10]. Residual activity of dinitroaniline, chloroacetamide, chloroacetanilide and isoxazoline herbicides vary depending on soil moisture and individual soil-herbicide interactions. Pyroxasulfone + dimethenamid-P (200 + 1138 g a·i· ha^{-1}) and metolachlor (1800 g a·i· ha^{-1}) can provide 63 and 93 days residual control of barnyardgrass, respectively [11]. Other results show pethoxamid and pendimethalin have a relatively short residual activity of 4 weeks [9] [12].

The purpose of this study was a) to determine the benefit of adding a soil-applied grass herbicide to isoxaflutole + metribuzin and b) to develop an understanding of which soil-applied grass herbicides used in combination with isoxaflutole + metribuzin provided the best control of specific annual grass and broadleaf weeds in isoxaflutole-resistant soybean.

2. Materials and Methods

2.1. Study Establishment

There were nine experiments conducted in 2017 (4 trials) and 2018 (5 trials) in south-western Ontario. The trial sites were located near Exeter, Ennotville, Cambridge and Ridgetown (two sites in 2018). Prior to seeding isoxaflutole-resistant soybean, the land was conventionally tilled. Soybean was planted to a depth of approximately 5 cm, in rows spaced 0.75 m apart at approximately 372,500 seeds per hectare. Soil characteristics, seeding dates, herbicide application dates and cumulative rainfall 0 to 7 and 0 to 14 days after treatment application (DAA) are presented in **Table 1**.

Herbicide treatments were arranged in a randomized complete block design with four replications at each site. All plots measured 3 m wide (4 soybean rows) by 8 or 10 m long based on available space. Control treatments included an untreated weedy and weedfree plot in each replication. The weedfree control was maintained weedfree with imazethapyr (100 g a·i· ha^{-1}) plus metribuzin (400 g a·i· ha^{-1}) applied PRE followed by glyphosate (900 g a·i· ha^{-1}) applied postemergence (POST) and subsequent hand weeding if required. Herbicide treatments were applied using a CO_2 pressurized backpack sprayer calibrated to deliver 200 $L·ha^{-1}$ at 240 kPa. The sprayer was equipped with a 1.5 m boom with four Hypro ULD 120-02 nozzles (Pentair, New Brighton, MN) spaced 50 cm apart resulting in a 2.0 m spray width. The treatments in this study were applied PRE and included the grass herbicides: pendimethalin (1000 g a·i· ha^{-1}), dimethenamid-P (544 g a·i· ha^{-1}), pethoxamid (840 g a·i· ha^{-1}), pyroxasulfone (125 g a·i· ha^{-1}) and S-metolachlor (1050 g a·i· ha^{-1}). Isoxaflutole + metribuzin was applied at three different rates: 52.5 + 210, 79 + 315 and 105 + 420 g a·i· ha^{-1} hereafter referred to as low, medium and high rates, respectively and the grass herbicides applied with the low rate of isoxaflutole + metribuzin.

2.2. Data Collected

Soybean injury was evaluated 1, 2 and 4 weeks after soybean emergence (WAE) on a scale of 0 to 100, where 0 represented no injury and 100 was recorded when the soybean was dead. At 4, 8 and 12 weeks after application (WAA), visible control of naturally occurring weed species was evaluated on a scale of 0 to 100 with 0 being assigned when treatments provided no control relative to the

Table 1. Soil characteristics, planting date, application date, and rainfall 7 and 14 days after treatment application (DAA) of 9 trials conducted in southwestern Ontario, Canada in 2017 and 2018.

#	Location	Year	Soil Type	Sand	Silt	Clay	OM	pH	CEC	Planting Date	Application Date PRE	Rainfall 7 DAA	Rainfall 14 DAA
				%	%	%	%		meq 100 g^{-1}			mm	mm
1	Ridgetown	2018	Clay Loam	35	30	35	4.2	6.7	19	May 25	May 29	5.0	7.3
2	Ridgetown	2017	Clay Loam	41	28	31	4.0	7.1	14	June 2	June 7	2.7	24.8
3	Ridgetown	2018	Clay Loam	43	26	31	3.6	6.8	16	May 31	June 1	4.9	7.2
4	Exeter	2018	Loam	41	35	24	2.9	7.7	27	May 18	May 22	5.2	14.7
5	Exeter	2017	Loam	35	43	22	3.9	7.8	30	June 3	June 5	0.8	12.5
6	Ennotville	2017	Silt Loam	41	52	7	3.8	7.8	18	May 31	June 2	9.8	22.7
7	Ennotville	2018	Silt Loam	41	52	7	3.8	7.8	18	May 25	May 28	14.9	15.8
8	Cam-bridge	2017	Sandy Loam	68	26	6	2.2	7.2	9	May 31	June 2	5.9	7.3
9	Cam-bridge	2018	Sandy Loam	68	26	6	2.2	7.2	9	May 25	May 28	10.8	14.0

weedy control and 100 assigned when all weeds of the species evaluated were completely dead. At 8 WAA, weed density was determined for each species by counting the number of individual plants within two 0.5 m^2 quadrats per plot. The weeds in the quadrats were cut at the soil surface and placed by species in paper bags, which were dried at 60˚C until constant moisture and then dry weight (biomass) was recorded. Soybean yield was measured at maturity by harvesting the centre two rowsof each plot with a small-plot research combine; yield was adjusted to 13% moisture.

2.3. Statistical Analysis

Data were analyzed in SAS software (ver. 9.4., SAS Institute, Inc., Cary, NC) using the GLIMMIX procedure. When analyzing injury, weed control and yield sites were sorted into groups based on a Tukey-Kramer multiple means comparison test when there was a significant site by treatment interaction using a mixed model where the fixed effects were site, treatment and site by treatment and the random effects were replication within site. Site groupings from weed control at 4 WAA were kept constant throughout control ratings at 8 and 12 WAA, in addition to density and biomass for each species. If the site by treatment interaction was not significant all sites were pooled. When data were pooled across sites, the treatments were considered a fixed effect and the random effects include site, site by treatment and replication within site. An F-test was performed to test the significance of fixed effects and a Wald test was conducted to test the significance of random effects. Residual plots were used to confirm the assumptions that the variances were randomly distributed, independent and homogenous across treatments. Additionally, a Shapiro-Wilk test was performed to test the assumption of normally distributed residuals as described by Shapiro and

Wilk in 1965 [13]. Natural log and arcsine square root transformations were used when necessary to normalize data; transformed means were transformed back to the original scale for presentation of results. A Tukey-Kramer test was conducted to compare means at a confidence level of 0.05.

3. Results and Discussion

Although weed control was visually assessed at 4, 8 and 12 WAA, only the 12 WAA assessments are presented in **Tables 3-10** to minimize the number of tables in the manuscript.

3.1. Soybean Injury

At 1 WAE, no soybean injury was visually evident from any of the herbicides applied (**Table 2**). At 2 WAE, soybean at sites 2, 4, 5, 6, 7 and 9 displayed leaf deformity injury, resembling soybean drawstring symptoms typical of Group 15 herbicides. There was a significant site by treatment interaction (data not shown); site 9 was analyzed independently and the remaining sites were pooled together. At sites 2, 4, 5, 6 and 7, isoxaflutole + metribuzin at all three rates did not cause soybean injury. Pendimethalin, dimethenamid-P, pethoxamid, pyroxasulfone and S-metolachlor, with and without isoxaflutole + metribuzin caused ≤ 3% soybean injury. There was no difference in soybean injury among the five soil-applied grass herbicides. At site 9, higher levels of injury were observed. At 2 WAE, pendimethalin, dimethenamid-P, pethoxamid, pyroxasulfone and S-metolachlor caused 18%, 5%, 7%, 2% and 11% soybean leaf deformity, respectively. There was no statistical increase in soybean injury with the addition of isoxaflutole + metribuzin to the grass herbicides evaluated.

At 4 WAE, the herbicides caused soybean leaf deformity and bleaching of the foliage at some locations. Leaf deformity occurred at sites 1, 4, 5, 6, 7, 8 and 9. Due to a significant site by treatment interaction (data not shown), site 6 was analyzed separately. At sites 1, 4, 5, 7, 8 and 9, pendimethalin, S-metolachlor and pendimethalin, dimethenamid-P and S-metolachlor with the addition of isoxaflutole + metribuzin caused 1% soybean injury (**Table 2**). At site 6, higher levels of injury occurred; pendimethalin, dimethenamid-P, pethoxamid, pyroxasulfone and S-metolachlor caused 16%, 2%, 3%, 4% and 11% leaf deformity, respectively. There was no statistical increase in soybean leaf deformity when isoxaflutole + metribuzin were added to the soil-applied grass herbicides. Soybean leaf bleaching injury occurred at sites 1, 2, 3, 5, 6 and 8. There was a significant site by treatment interaction (data not shown); therefore, sites 5 and 8 were analyzed independently and the remaining sites were pooled. At sites 1, 2, 3 and 6, isoxaflutole + metribuzin at the low, medium and high rate caused 1%, 2% and 4% soybean bleaching, respectively. There was no increase in soybean leaf bleaching when a grass herbicide was added to isoxaflutole + metribuzin. At site 8, soybean was injured more by isoxaflutole + metribuzin. The low, medium and high rates caused 7%, 10% and 13% injury, respectively. The grass herbicides plus

Table 2. Visible soybean injury symptoms at 1, 2 and 4 WAE from 9 field experiments in Ontario, Canada in 2017 and 2018.

		1 WAE	2 WAE				4 WAE		
Treatment	Rate	All sites	Sites 2, 4, 5, 6, 7	Sites 9	Sites 1, 4, 5, 7, 8, 9	Site 6	Site 1, 2, 3, 6	Site 8	Site 5
	g a·i· ha^{-1}		% Leaf deformity injury				% Bleaching injury		
Pendimethalin	1000	0	1abc	18fg	1b	16d	0a	0a	0a
Dimethenamid-P	544	0	2abc	5bcd	0ab	2ab	0a	0a	0a
Pethoxamid	840	0	1abc	7cde	0ab	3abc	0a	0a	0a
Pyroxasulfone	125	0	1abc	2b	0ab	4bc	0a	0a	0a
S-metolachlor	1050	0	2bc	11def	1ab	11cd	0a	0a	0a
Isoxaflutole + Metribuzin	52.5 + 210	0	0a	0a	0a	0a	1bcd	7abc	16b
Isoxaflutole + Metribuzin	79 + 315	0	0a	0a	0a	0a	2cd	10bc	25c
Isoxaflutole + Metribuzin	105 + 420	0	0a	0a	0a	0a	4d	13c	30c
Pendimethalin + Isoxaflutole + Metribuzin	1000 + 52.5 + 210	0	2abc	20f	1b	14d	0abc	7abc	15b
Dimethenamid-P + Isoxaflutole + Metribuzin	544 + 52.5 + 210	0	2abc	4bc	1ab	0a	2cd	5ab	15b
Pethoxamid + Isoxaflutole + Metribuzin	840 + 52.5 + 210	0	1abc	4bc	0ab	6bcd	0ab	9bc	17b
Pyroxasulfone + Isoxaflutole + Metribuzin	125 + 52.5 + 210	0	1abc	3bc	0ab	3abc	1abcd	4a	15b
S-metolachlor + Isoxaflutole + Metribuzin	1050 + 52.5 + 210	0	3c	13efg	1ab	11cd	0abc	5ab	17b

Note: Means followed by the same letter within a column are not statistically different according to the Tukey-Kramer multiple range test at $p < 0.05$.

isoxaflutole + metribuzin caused 4% to 9% bleaching injury, which was similar toisoxaflutole + metribuzin. At site 5, isoxaflutole + metribuzin at the low medium and high rate caused 16%, 25% and 30% soybean bleaching, respectively. The grass herbicides plus isoxaflutole + metribuzin caused 15% to 17% soybean bleaching, similar to isoxaflutole + metribuzin.

Soybean displayed the most sensitivity to pendimethalin and S-metolachlor. Rainfall after application appeared to influence the level of soybean leaf deformity at the various sites. Soybean at sites with more rainfall after application displayed more severe leaf deformity compared to sites receiving less rainfall. This was probably due to higher herbicide uptake in soybean with higher rainfall. Based on visible observations in the field, as soybean continued to grow, the leaf deformity injury occurred on the first 3 trifoliate leaves with no leaf deformity observed on new soybean growth after the third trifoliate.

Soybean leaf bleaching symptoms were observed at 4 WAE on the 3rd and 4th trifoliate leaves. This injury appeared to be influenced by rainfall received 14 to 21 DAA. Soybean injury (≤30%) was observed at sites 1, 2, 3, 5, 6 and 8 which received 12.3 to 43.5 mm of rain in the 21 days after herbicide application; in contrast sites 4, 7 and 9 received < 3 mm of rain in the 21 days after application and no soybean injury was observed. Rainfall during this period of time after herbicide application probably dissolved the herbicides into soil water solution, allowing for the absorption by the soybean, resulting in a higher herbicide concentration within the plant which the soybean could not metabolize quickly enough to avoid herbicide injury. Bleaching symptoms were evident one week later when injury was evaluated. As the 5th trifoliate leaves were emerging, no bleaching symptoms were present at any sites, as the soybean was probably able to metabolize isoxaflutole by that time.

3.2. Common Lambsquarters

Common lambsquarters control was assessed at seven sites in this study. A significant treatment by site interaction occurred for common lambsquarters control (data not shown); therefore, results from sites 2 and 4 were combined, sites 3, 5, 8 and 9 were combined and site 7 was analyzed separately (**Table 3**).

At 12 WAA, at sites 2 and 4, pendimethalin, dimethenamid-P, pethoxamid, pyroxasulfone and S-metolachlor controlled common lambsquarters 4% to 23% (**Table 3**). These treatments did not differ from one another. Isoxaflutole + metribuzin at the low, medium and high rate controlled common lambsquarters 37%, 68% and 86%, respectively. There was no difference in common lambsquarters control among the three rates of isoxaflutole + metribuzin; however, the medium and high rate provided as much as 82% higher control than dimethenamid-P, pyroxasulfone and S-metolachlor. Pendimethalin, dimethenamid-P, pethoxamid, pyroxasulfone, or S-metolachlor plus isoxaflutole + metribuzin controlled common lambsquarters 41% to 68%. There were no differences in common lambsquarters control between these treatments and isoxaflutole + metribuzin applied at the low, medium or high rate or the corresponding grass herbicides applied alone. At sites 3, 5, 8 and 9, pendimethalin, dimethenamid-P, pethoxamid, pyroxasulfone and S-metolachlor controlled common lambsquarters 24% to 58%. Isoxaflutole + metribuzin at the low, medium and high rate provided 94%, 99% and 100% control, respectively. Isoxaflutole + metribuzin provided greater control than all the grass herbicides applied alone with the exception of pendimethalin. Pendimethalin, dimethenamid-P, pethoxamid, pyroxasulfone, or S-metolachlor plus isoxaflutole + metribuzin provided 99%, 94%, 97%, 93% and 94% common lambsquarters control, respectively. All grass herbicides with the exception of pendimethalin, benefitted from the addition of isoxaflutole + metribuzin in the tank-mix. At site 7, pendimethalin, dimethenamid-P, pethoxamid, pyroxasulfone and S-metolachlor controlled common lambsquarters 91%, 85%, 85%, 93% and 67%, respectively. Isoxaflutole + metribuzin at each rate as well as the tank-mix of the grass herbicides with isoxaflutole + metribuzin provided 100% control of common lambsquarters. The addition of isoxaflutole + metribuzin to dimethenamid-P, pethoxamid, or S-metolachlor improved common lambsquarters control 15%, 15% and 33%, respectively.

At 8 WAA, at all three site groupings, common lambsquarters density was reduced with application of pendimethalin, isoxaflutole + metribuzin at the low, medium or high rate, or any grass herbicide with the addition of isoxaflutole + metribuzin compared to the untreated control (**Table 3**). In contrast, dimethenamid-P, pethoxamid, pyroxasulfone and S-metolachlor did not reduce

Table 3. Common lambsquarters control at 12 WAA and density and biomass at 8 WAA from 7 field experiments conducted in Ontario, Canada in 2017 and 2018[a].

Treatment	Rate	Control 12 WAA			Density			Biomass		
		Sites 2, 4	Sites 3, 5, 8, 9	Site 7	Sites 2, 4	Sites 3, 5, 8, 9	Site 7	Sites 2, 4	Sites 3, 5, 8, 9	Site 7
	g a·i· ha^{-1}	%			#m^{-2}			g·m^{-2}		
Untreated Control					32.5d	21.5e	2.5b	31.4a	16.5abc	8.6bc
Pendimethalin	1000	23abcd	58ab	91ab	5.6abc	4.5bcd	0.2a	3.5a	4.2abc	0.3ab
Dimethenamid-P	544	6cd	25b	85b	14.8cd	15.0de	0.7ab	24.9a	24.5c	6.abc
Pethoxamid	840	11bcd	26b	85b	8.1bcd	10.0de	1.3ab	22.7a	15.7abc	3.3abc
Pyroxasulfone	125	7cd	34b	93ab	14.2cd	7.0cde	0.4ab	50.6a	18.8bc	1.3abc
S-metolachlor	1050	4d	24b	67b	12.1cd	19.8de	2.7b	25.1a	22.9c	14.5c
Isoxaflutole + Metribuzin	52.5 + 210	37abcd	94a	100a	4.8abc	1.4abc	0.2a	11.7a	3.3abc	0.1a
Isoxaflutole + Metribuzin	79 + 315	68ab	99a	100a	2.4ab	0.6ab	0.2a	4.9a	1.3abc	0.8ab
Isoxaflutole + Metribuzin	105 + 420	86a	100a	100a	1.3a	0.2a	0.02a	2.0a	0.7a	0.1a
Pendimethalin + Isoxaflutole + Metribuzin	1000 +52.5 + 210	68ab	99a	100a	2.0ab	0.7ab	0.02a	2.3a	0.8ab	0.1a
Dimethenamid-P + Isoxaflutole + Metribuzin	544 + 52.5 + 210	57abcd	94a	100a	2.1ab	1.4abc	0.02a	6.5a	5.6abc	0.1a
Pethoxamid + Isoxaflutole + Metribuzin	840 + 52.5 + 210	60abc	97a	100a	4.3abc	1.1abc	0.04a	6.5a	3.7abc	0.1a
Pyroxasulfone + Isoxaflutole + Metribuzin	125 + 52.5 + 210	57abcd	93a	100a	4.2abc	0.9ab	0.02a	10.0a	2.9abc	0.1a
S-metolachlor + Isoxaflutole + Metribuzin	1050 + 52.5 + 210	41abcd	94a	100a	3.6abc	1.3abc	0.02a	9.9a	2.1abc	0.1a

[a]Means followed by the same letter within a column are not statistically different according to the Tukey-Kramer multiple range test at $p < 0.05$.

common lambsquarters density compared to the untreated control. At site 2 and 4, the above-mentioned herbicide treatments reduced common lambsquarters density 83 to 96%. There was no difference in common lambsquarters density among pendimethalin, dimethenamid-P, pethoxamid, pyroxasulfone, S-metolachlor, the low rate of isoxaflutole + metribuzin or the combination of pethoxamid, pyroxasulfone or S-metolachlor with the addition of isoxaflutole + metribuzin. At sites 3, 5, 8 and 9, the above-mentioned herbicide treatments reduced common lambsquarters density 79% to 99%. Isoxaflutole + metribuzin reduced common lambsquarters density 20% more than pendimethalin. The addition of isoxaflutole + metribuzin to dimethenamid-P, pethoxamid, pyroxasulfone and S-metolachlor reduced common lambsquarters density 63%, 41%, 29% and 86% more than the grass herbicides applied alone, respectively. At site 7 there was a 92% to 99% reduction in common lambsquarters density with the above mentioned herbicide treatments compared to the untreated control. Pendimethalin, all three rates of isoxaflutole + metribuzin and the grass herbicides + isoxaflutole + metribuzin reduced density compared to the untreated control and S-metolachlor.

At 8 WAA, at sites 2 and 4 and sites 3, 5, 8 and 9, common lambsquarters biomass was not reduced significantly with any herbicide treatment compared to the untreated control (**Table 3**). However, at sites 3, 5, 8 and 9, isoxaflutole +

metribuzin at the high rate reduced common lambsquarters biomass compared to dimethenamid-P, pyroxasulfone and S-metolachlor. At site 7, isoxaflutole + metribuzin at the low and high rate and all the grass herbicides + isoxaflutole + metribuzin decreased common lambsquarters biomass 99%. Additionally, those treatments decreased common lambsquarters biomass more than S-metolachlor.

In summary, common lambsquarters control was influenced by rainfall and weed density. Site 7, which received 14.9 mm of rainfall within 7 DAA and had the lowest common lambsquarters density and the highest level of common lambsquarters control. Sites 3, 5, 8 and 9, received 0.8 to 10.8 mm of rainfall 0 to 7 DAA; this probably was sufficient rainfall for the herbicide to be dissolved in soil water solution so that it could be taken up by weed seedlings. Site 5 received only 0.8 mm which would likely not be enough rain to activate the herbicide; it also may not be enough rain to allow for weeds to germinate. This site had delayed germination; therefore, after the rainfall 7 to 14 DAA, the herbicide was activated and controlled the late emerging weeds. The selectivity of each herbicide is highlighted in this group of sites; although, pendimethalin has very low water solubility (0.275 $mg \cdot L^{-1}$), it still provided greater common lambsquarters control than the Group 15 herbicides. Chomas and Kells [14] reported similar results where pendimethalin and metolachlor controlled common lambsquarters 91 and 0%, respectively, in a year with limited activating rainfall compared to 98 to 100 and 50% to 75% control, respectively, in years when higher levels of rain occurred. Sites 2 and 4 received only 2.7 and 5.2 mm of rainfall 0 to 7 DAA, which reduced common lambsquarters control with all of the herbicides evaluated. Overall, isoxaflutole + metribuzin at the medium and high rate provided the highest level of common lambsquarters control. The grass herbicide which provided the highest common lambsquarters control was pendimethalin; however, the addition of pendimethalin to isoxaflutole + metribuzin only increased control early in the season when limited rainfall occurred compared to isoxaflutole + metribuzin alone at the low rate.

3.3. Pigweed Spp.

Redroot pigweed (*Amaranthus retroflexus* L.) and green pigweed (*Amaranthus powellii* S. Watson) were combined during evaluations. Pigweed spp. were assessed at 7 sites in this study and due to a significant treatment by site interaction, sites were separated (data not shown); sites 2 and 4 were combined and sites 3, 6, 7, 8 and 9 were combined for analysis (**Table 4**).

At 12 WAA, at sites 2 and 4, pendimethalin, dimethenamid-P, pethoxamid, pyroxasulfone and S-metolachlor controlled pigweed spp. 4%, 10%, 13%, 32% and 6%, respectively (**Table 4**). The grass herbicides provided similar control of pigweed spp. Isoxaflutole + metribuzin at the low, medium and high rate controlled pigweed spp. 27%, 59% and 81%, respectively; there was no difference among rates. Isoxaflutole + metribuzin at the medium rate provided 53% and 55% higher pigweed spp. Control than pendimethalin and S-metolachlor, respectively. Isoxaflutole + metribuzin at the high rate provided 68% to 77%

Table 4. Pigweed control at 12 WAA and density and biomass at 8 WAA from 7 field experiments conducted in Ontario, Canada in 2017 and 2018[a].

Treatment	Rate	Control 12 WAA		Density		Biomass	
		Sites 2, 4	Sites 3, 6, 7, 8, 9	Sites 2, 4	Sites 3, 6, 7, 8, 9	Sites 2,4	Sites 3, 6, 7, 8, 9
	g a·i· ha^{-1}	%		#m^{-2}		g·m^{-2}	
Untreated Control				33.7a	23.2d	183.8ab	40.3e
Pendimethalin	1000	4d	63cd	43.5a	15.9cd	205.1b	29.6de
Dimethenamid-P	544	10cd	70cd	25.5a	3.9abc	140.4ab	10.5bcde
Pethoxamid	840	13bcd	52d	33.1a	7.9bcd	123.2ab	22.5de
Pyroxasulfone	125	32abcd	85bc	32.3a	3.4abc	93.8ab	4.7abcde
S-metolachlor	1050	6d	66cd	33.2a	8.7bcd	130.4ab	16.2cde
Isoxaflutole + Metribuzin	52.5 + 210	27abcd	93ab	18.7a	1.9ab	55.9ab	3.3abcd
Isoxaflutole + Metribuzin	79 + 315	59abc	95ab	15.6a	0.6a	61.5ab	1.1ab
Isoxaflutole + Metribuzin	105 + 420	81a	97ab	7.3a	0.4a	25.4a	1.2ab
Pendimethalin + Isoxaflutole + Metribuzin	1000 + 52.5 + 210	65ab	95ab	13.1a	0.8a	51.8ab	2.2abc
Dimethenamid-P + Isoxaflutole + Metribuzin	544 + 52.5 + 210	54abcd	98ab	12.7a	0.2a	70.6ab	0.4a
Pethoxamid + Isoxaflutole + Metribuzin	840 + 52.5 + 210	48abcd	97ab	11.7a	0.5a	38.7ab	1.2ab
Pyroxasulfone + Isoxaflutole + Metribuzin	125 + 52.5 + 210	67ab	99a	14.3a	0.5a	54.7ab	0.8ab
S-metolachlor + Isoxaflutole + Metribuzin	1050 + 52.5 + 210	38abcd	98ab	16.5a	0.7a	72.3ab	1.3ab

[a]Means followed by the same letter within a column are not statistically different according to the Tukey-Kramer multiple range test at $p < 0.05$.

higher pigweed spp. control than pendimethalin, dimethenamid-P, pethoxamid and S-metolachlor. Pendimethalin, dimethenamid-P, pethoxamid, pyroxasulfone and S-metolachlor with the addition of isoxaflutole + metribuzin controlled pigweed spp. 38% to 67%; there was no difference in control among the grass herbicides. The addition of isoxaflutole + metribuzin to pendimethalin increased pigweed spp. control 61% compared to pendimethalin applied alone. At sites 2 and 4, there was no increase in pigweed spp. control when a grass herbicide was added to isoxaflutole + metribuzin. This was expected as these herbicides generally do not control broadleaved weeds such as pigweed species. At sites 3, 6, 7, 8 and 9, pendimethalin, dimethenamid-P, pethoxamid, pyroxasulfone and S-metolachlor controlled pigweed spp. 63%, 70%, 52%, 85% and 66%, respectively. Pyroxasulfone provided greater control than pethoxamid; all other grass herbicides provided similar pigweed spp. control. Isoxaflutole + metribuzin at the varying rates provided 93% to 97% control and did not differ among rates. Isoxaflutole + metribuzin provided greater pigweed spp. control than the grass herbicides with the exception ofpyroxasulfone. Pendimethalin, dimethenamid-P, pethoxamid, pyroxasulfone, or S-metolachlor applied in a tank-mix with isoxaflutole + metribuzin controlled pigweed spp. 95% to 99%. The addition of isoxaflutole + metribuzin to the grass herbicides increased control compared to the respective grass herbicide applied alone. There was no improvement in pigweed spp. control with the addition of a grass herbicide to isoxaflutole + metribuzin.

At 8 WAA, at sites 2 and 4, no herbicide treatment reduced pigweed spp. density compared to the untreated control and there was no difference in pigweed spp. density among the herbicide treatments evaluated (**Table 4**). At sites 3, 6, 7, 8 and 9, dimethenamid-p, pyroxasulfone, isoxaflutole + metribuzin at all three rates and the tank-mixtures of a grass herbicides plus isoxaflutole + metribuzin reduced pigweed density 83 to 99% compared to the untreated control. Isoxaflutole + metribuzin at the low rate, dimethenamid-P, pethoxamid, pyroxasulfone and S-metolachlor reduced pigweed spp. density similarly; isoxaflutole + metribuzin reduced pigweed density 61% more than pendimethalin. Pendimethalin, pethoxamid or S-metolachlor plus isoxaflutole + metribuzin provided 65, 32 and 34% greater reduction in density compared to the respective grass herbicide applied alone. The addition of isoxaflutole + metribuzin to dimethenamid-P orpyroxasulfone did not increase the reduction in pigweed spp. density.

At 8 WAA, at sites 2 and 4, no treatment reduced pigweed spp. biomass compared to the untreated control (**Table 4**). There were no treatment differences with the exception of isoxaflutole + metribuzin at the high rate provided a greater reduction in pigweed spp. biomass than pendimethalin. At sites 3, 6, 7, 8 and 9 isoxaflutole + metribuzin at the low, medium and high rate and the tank-mixtures of a grass herbicides plus isoxaflutole + metribuzin reduced pigweed spp. biomass 92% to 99% compared to the untreated control. The grass herbicides applied alone did not reduce pigweed spp. biomass. The addition of isoxaflutole + metribuzin to pendimethalin, dimethenamid-P, pethoxamid, or S-metolachlor reduced biomass an additional 68%, 25%, 53% and 37%, respectively, compared to the grass herbicide applied alone. The addition of isoxaflutole + metribuzin to pyroxasulfone did not differ in biomass reduction compared to pyroxasulfone alone. The addition of a grass herbicide to isoxaflutole + metribuzin did not provide an additional reduction in pigweed spp. biomass compared to isoxaflutole + metribuzin applied alone.

In summary, pigweed spp. control was influenced by rainfall after application. Pigweed spp. control was lower at sites 2 and 4 which received 2.7 and 0.8 mm of rainfall 0 to 7 DAA, respectively. In contrast, pigweed spp. control was greater at sites 3, 6, 7, 8 and 9 which received higher rainfall of 4.9 to 14.9 mm 0 to 7 DAA. Of the grass herbicides evaluated, pyroxasulfone provided the highest pigweed spp. control across sites with differing levels of rainfall. Redroot pigweed is very sensitive to pyroxasulfone; rates as low as 93 g a·i· ha^{-1} controlled pigweed 90% [15]. Generally, the addition of pyroxasulfone to isoxaflutole + metribuzin at the low rate improved pigweed control compared to isoxaflutole and metribuzin alone; however, isoxaflutole + metribuzin at the high rate provided better pigweed spp. control than pyroxasulfone + isoxaflutole + metribuzin at the low rate.

3.4. Common Ragweed

Common ragweed (*Ambrosia artemisiifolia* L.) populations were present at sites 1, 3 and 5 in this study (**Table 5**). There was a significant treatment by site interaction, each site was analyzed separately (data not shown).

At 12 WAA, at site 1, pendimethalin, dimethenamid-P, pethoxamid, pyroxasulfone and S-metolachlor controlled common ragweed 28% to 62%; there was no difference in control among the grass herbicides (Table 5). Isoxaflutole + metribuzin at the low, medium and high rate controlled common ragweed 82%, 90% and 98%, respectively. The high rate provided 70% and 67% greater common ragweed control than dimethenamid-P and pethoxamid, respectively. Pendimethalin, dimethenamid-P, pethoxamid, pyroxasulfone, or S-metolachlor plus isoxaflutole + metribuzin controlled common ragweed 66% to 100%. The grass herbicides plus isoxaflutole + metribuzin did not differ among each other and did not provide any additional control compared to isoxaflutole + metribuzin. The addition of isoxaflutole + metribuzin to dimethenamid-P increased control 72% compared to dimethenamid-P alone. At site 3, pendimethalin, dimethenamid-P, pethoxamid, pyroxasulfone and S-metolachlor controlled common ragweed 20% to 54%, there was no difference in common ragweed control among the grass herbicides. Isoxaflutole + metribuzin at the low, medium and high rate controlled common ragweed 97% to 100%. The addition of a grass herbicide to isoxaflutole + metribuzin did not increase common ragweed control. Similarly, at site 5, the grass herbicides alone provided less common ragweed control than isoxaflutole + metribuzin at the low, medium and high rate, or any combination of a grass herbicide plus isoxaflutole + metribuzin.

At 8 WAA, at site 1, the herbicide treatments evaluated did not reduce common ragweed density compared to the untreated control (Table 5). Dimethenamid-P+ isoxaflutole + metribuzin reduced density compared to dimethenamid-P or S-metolachlor alone. At site 3, the grass herbicides did not reduce common ragweed density compared to the untreated control; however, isoxaflutole + metribuzin at all three rates and the addition of a grass herbicide to isoxaflutole + metribuzin reduced common ragweed density 98% to 99% compared to the untreated control. At site 5, pendimethalin, dimethenamid-P, pethoxamid and S-metolachlor did not reduce common ragweed density compared to the untreated control. Pyroxasulfone reduced common ragweed density 73%. Pyroxasulfone reduced common ragweed density more than pendimethalin and S-metolachlor; however, it did not differ from dimethenamid-P and pethoxamid. Isoxaflutole + metribuzin at the low, medium and high rate, or any combination of a grass herbicide plus isoxaflutole + metribuzin reduced common ragweed density 96% to 99% compared to the untreated control.

At 8 WAA, at site 1, none of the herbicide treatments evaluated reduced common ragweed biomass compared to the untreated control, additionally, there were no treatment differences (Table 5). At site 3, the grass herbicides applied alone, isoxaflutole + metribuzin at the medium rate and pendimethalin, pethoxamid, pyroxasulfone or S-metolachlor plus isoxaflutole + metribuzin did not reduce common ragweed biomass compared to the untreated control. Isoxaflutole + metribuzin at the low and high rate and dimethenamid-P + isoxaflutole +

Table 5. Common ragweed control at 12 WAA and density and biomass at 8 WAA from 7 field experiments conducted in Ontario, Canada in 2017 and 2018[a].

Treatment	Rate	Site 1	Site 3	Site 5	Site 1	Site 3	Site 5	Site 1	Site 3	Site 5
	g a·i· ha^{-1}		%			#m^{-2}			g·m^{-2}	
Untreated Control					5.7ab	64.8b	74.2c	0.5a	14.6bcd	65.6b
Pendimethalin	1000	55abc	20b	0b	3.5ab	71.7b	58.9c	0.3a	31.3d	98.7b
Dimethenamid-P	544	28c	46b	0b	11.0b	50.6b	43.1bc	5.8a	19.8cd	66.9b
Pethoxamid	840	31c	54b	1b	4.3ab	34.4b	38.4bc	0.8a	9.9abcd	46.6b
Pyroxasulfone	125	62abc	45b	0b	1.1ab	28.4b	20.1b	1.0a	17.1cd	45.6b
S-metolachlor	1050	43bc	40b	0b	10.8b	71.2b	79.8c	3.7a	33.4d	82.4b
Isoxaflutole + Metribuzin	52.5 +210	82abc	97a	100a	0.4ab	0.6a	0.01a	1.1a	0.5a	0.02a
Isoxaflutole + Metribuzin	79 + 315	90abc	99a	100a	0.4ab	0.2a	0.01a	0.2a	0.8ab	0.02a
Isoxaflutole + Metribuzin	105 + 420	98ab	100a	100a	0.4ab	0.02a	0.01a	0.3a	0.1a	0.02a
Pendimethalin + Isoxaflutole + Metribuzin	1000 + 52.5 + 210	66abc	99a	99a	0.6ab	0.6a	0.2a	0.8a	2.2abc	0.1a
Dimethenamid-P + Isoxaflutole + Metribuzin	544 + 52.5 + 210	100a	98a	100a	0.1a	0.02a	0.01a	0.1a	0.1a	0.02a
Pethoxamid + Isoxaflutole + Metribuzin	840 + 52.5 + 210	90abc	97a	100a	0.7ab	0.7a	0.01a	1.3a	2.0abc	0.02a
Pyroxasulfone + Isoxaflutole + Metribuzin	125 + 52.5 + 210	95ab	100a	100a	1.0ab	0.7a	0.01a	3.2a	1.9abc	0.02a
S-metolachlor + Isoxaflutole + Metribuzin	1050 + 52.5 + 210	98ab	98a	98a	1.2ab	0.2a	0.3a	0.9a	1.3abc	0.2a

[a]Means followed by the same letter within a column are not statistically different according to the Tukey-Kramer multiple range test at $p < 0.05$.

metribuzin reduced biomass 96% to 99% compared to the untreated control. At site 5, the grass herbicides applied alone did not reduce common ragweed biomass relative to the untreated control. Isoxaflutole + metribuzin and the tank-mixtures of a grass herbicide plus isoxaflutole + metribuzin reduced common ragweed biomass 99%.

In summary, common ragweed control was influenced by rainfall after application and weed density. Sites 1, 3 and 5 had 5.0, 4.9 and 0.8 mm of rain within 7 DAA, respectively. Although the low rain at all three sites was probably inadequate to sufficiently activate the soil-applied grass herbicides; the grass herbicides would have provided minimal control of ragweed. In contrast, isoxaflutole + metribuzin was activated sufficiently and controlled common ragweed 82% to 100% 12 WAA. By 14 DAA, sites 1, 3 and 5 received 7.3, 7.2 and 12.5 mm of rainfall. At 4 WAA the grass herbicides provided 0% to 14% common ragweed control which is similar to a study by Soltani *et al.* [16], who found dimethenamid-P, pethoxamid, pyroxasulfone and S-metolachlor controlled common ragweed 8% to 27% and did not reduce biomass. The same study reported that isoxaflutole (105 g a·i· ha^{-1}) + atrazine (1063 g a·i· ha^{-1}) controlled common ragweed 97% to 98% which is consistent with isoxaflutole + metribuzin in this study. Generally, the addition of a grass herbicide to isoxaflutole + metribuzin did not enhance common ragweed control compared to isoxaflutole + metribuzin applied alone.

3.5. Velvetleaf

Velvetleaf (*Abutilon theophrasti* Medik.) was assessed at 3 sites in this study (**Table 6**). There was a significant site by treatment interaction (data not shown); sites were separated into two groups, site 1 and 2 were combined and site 3 was analyzed separately.

At 12 WAA, at sites 1 and 2, pendimethalin, dimethenamid-P, pethoxamid, pyroxasulfone and S-metolachlor controlled velvetleaf 58, 46, 43, 52 and 33%; they did not differ statistically (**Table 6**). Isoxaflutole + metribuzin at the low, medium and high rates controlled velvetleaf 91% to 100%. The high rate provided higher velvetleaf control than the grass herbicides, the medium rate controlled velvetleaf more than dimethenamid-P, pethoxamid and S-metolachlor and the low rate controlled velvetleaf better than S-metolachlor. Pendimethalin, dimethenamid-P, pethoxamid, pyroxasulfone or S-metolachlor plus isoxaflutole + metribuzin controlled velvetleaf 99%, 99%, 89%, 99% and 93%, respectively. Each tank-mix improved velvetleaf control compared to the grass herbicide alone with the exception of pethoxamid. There was no increase in velvetleaf control with the addition of a grass herbicide to isoxaflutole + metribuzin compared to isoxaflutole + metribuzin alone. At site 3, all grass herbicides provided similar velvetleaf control ranging from 33% to 72%. Isoxaflutole + metribuzin at the low, medium and high rate controlled velvetleaf 99% to 100%, providing higher control than pethoxamid and S-metolachlor. The grass herbicides plus isoxaflutole + metribuzin controlled velvetleaf 98% to 100%. There was no improvement in velvetleaf control when isoxaflutole + metribuzin was added to pendimethalin, dimethenamid-P and pyroxasulfone. The addition of a grass herbicide to isoxaflutole + metribuzin did not improve velvetleaf control.

At 8 WAA, at sites 1 and 2, no treatment reduced velvetleaf density compared to the untreated control (**Table 6**). Pendimethalin, dimethenamid-P or S-metolachlor plus isoxaflutole + metribuzin reduced density 96%, 93% and 90%, respectively, compared to the respective grass herbicide applied alone. Isoxaflutole + metribuzin at the high rate reduced velvetleaf density more than the grass herbicides applied alone. The medium rate reduced velvetleaf density more than pendimethalin, dimethenamid-P and S-metolachlor applied alone and the low rate did not differ from any herbicide treatment. At site 3, no herbicide treatment reduced density compared to the untreated control and there were no treatment differences.

At 8 WAA, at sites 1 and 2, there was no reduction in velvetleaf biomass with any of the herbicides treatments compared to the untreated control (**Table 6**). At site 3, no herbicide treatment reduced velvetleaf biomass compared to the untreated control; however, isoxaflutole + metribuzin at the low and medium rate and pendimethalin, dimethenamid-P or S-metolachlor plus isoxaflutole + metribuzin reduced velvetleaf biomass compared to pethoxamid applied alone.

In summary, generally, the grass herbicides evaluated provided poor control of velvetleaf. At site 3, dimethenamid-P and pyroxasulfone provided suppression

Table 6. Velvetleaf control at 12 WAA and density and biomass at 8 WAA from 7 field experiments conducted in Ontario, Canada in 2017 and 2018[a].

Treatment	Rate	Control 12 WAA		Density		Biomass	
		Sites 1, 2	Sites 3	Sites 1, 2	Sites 3	Sites 1, 2	Sites 3
	g a·i· ha^{-1}	%		#m^{-2}		g·m^{-2}	
Untreated Control				2.7abcd	4.6a	1.6a	8.0ab
Pendimethalin	1000	58bcd	56ab	5.4d	1.8a	2.0a	2.5ab
Dimethenamid-P	544	46cd	61ab	4.3cd	3.7a	2.0a	4.6ab
Pethoxamid	840	43cd	36b	4.0bcd	3.9a	1.8a	12.0b
Pyroxasulfone	125	52bcd	72ab	4.6bcd	0.9a	5.4a	0.7ab
S-metolachlor	1050	33d	33b	3.2cd	2.0a	1.9a	10.9ab
Isoxaflutole + Metribuzin	52.5 + 210	91abc	99a	0.3abcd	0.5a	0.6a	0.3a
Isoxaflutole + Metribuzin	79 + 315	96ab	99a	0.2ab	0.1a	0.4a	0.1a
Isoxaflutole + Metribuzin	105 + 420	100a	100a	0.2a	2.2a	0.4a	2.1ab
Pendimethalin + Isoxaflutole + Metribuzin	1000 + 52.5 + 210	99a	98a	0.2a	0.1a	0.1a	0.1a
Dimethenamid-P + Isoxaflutole + Metribuzin	544 + 52.5 + 210	99a	100a	0.3a	0.1a	0.3a	0.1a
Pethoxamid + Isoxaflutole + Metribuzin	840 + 52.5 + 210	89abc	99a	1.0abcd	0.3a	1.6a	0.5ab
Pyroxasulfone + Isoxaflutole + Metribuzin	125 + 52.5 + 210	99a	98a	0.5abc	0.3a	1.2a	0.8ab
S-metolachlor + Isoxaflutole + Metribuzin	1050 + 52.5 + 210	93abc	99a	0.3ab	0.1a	0.4a	0.1a

[a] Means followed by the same letter within a column are not statistically different according to the Tukey-Kramer multiple range test at $p < 0.05$.

of velvetleaf. Among the grass herbicides, pyroxasulfone provided the greatest control of velvetleaf, however, at 12 WAA, control only reached 72%. In contrast, other studies have reported that pyroxasulfone (125 g a·i· ha^{-1}) controlled velvetleaf 90% [15] [17]; however, other studies required rates as high as 166 [18] and 382 g a·i· ha^{-1} for the same level of control [19]. At sites 1 and 2, the addition of a grass herbicide to isoxaflutole + metribuzin increased velvetleaf control compared to isoxaflutole + metribuzin at the low rate. At site 3, there was no improvement in velvetleaf control when a grass herbicide was co-applied with isoxaflutole + metribuzin.

3.6. Foxtail Spp.

Green foxtail and giant foxtail were combined during evaluations in this study (Table 7). Foxtail spp. populations were present at seven sites and the site by treatment interaction was significant therefore sites were divided into two groups (data not shown); sites 1, 2 and 4 were combined and sites 3, 5, 7 and 9 were combined.

At 12 WAA, at sites 1, 2 and 4, pendimethalin, dimethenamid-P, pethoxamid, pyroxasulfone and S-metolachlor controlled foxtail spp. 24% to 38%, there was no difference in foxtail spp. control among the five soil-applied grass herbicides (Table 7). Isoxaflutole + metribuzin at the low, medium and high rate controlled

Table 7. Green and giant foxtail control at 12 WAA and density and biomass at 8 WAA from 7 field experiments conducted in Ontario, Canada in 2017 and 2018[a].

Treatment	Rate	Control 12 WAA		Density		Biomass	
		Sites 1, 2, 4	Sites 3, 5, 7, 9	Sites 1, 2, 4	Sites 3, 5, 7, 9	Sites 1, 2, 4	Sites 3, 5, 7, 9
	g a·i· ha^{-1}	%		#m^{-2}		g·m^{-2}	
Untreated Control				64.5a		59.2b	44.4b
Pendimethalin	1000	34cde	70bc	30.7a	13.4a	21.4ab	6.5a
Dimethenamid-P	544	26e	84abc	25.1a	7.5a	35.9ab	6.6a
Pethoxamid	840	24e	59c	26.8a	18.2ab	35.1ab	11.6ab
Pyroxasulfone	125	38bcde	83abc	29.8a	19.2ab	29.0ab	8.8ab
S-metolachlor	1050	31de	86abc	32.7a	6.8a	38.8ab	3.0a
Isoxaflutole + Metribuzin	52.5 +210	50abcde	84abc	27.5a	6.8a	31.4ab	6.0a
Isoxaflutole + Metribuzin	79 + 315	58abcde	90abc	21.9a	8.5a	20.2ab	6.3a
Isoxaflutole + Metribuzin	105 + 420	78a	96a	17.4a	6.8a	14.8ab	3.3a
Pendimethalin + Isoxaflutole + Metribuzin	1000 + 52.5 + 210	81abc	87abc	16.1a	5.2a	10.2a	3.3a
Dimethenamid-P + Isoxaflutole + Metribuzin	544 + 52.5 + 210	84ab	96ab	19.8a	2.7a	16.5ab	1.67a
Pethoxamid + Isoxaflutole + Metribuzin	840 + 52.5 + 210	53abcde	88abc	29.3a	7.9a	30.3ab	5.0a
Pyroxasulfone + Isoxaflutole + Metribuzin	125 + 52.5 + 210	65abcd	93ab	18.8a	8.1a	17.0ab	4.4a
S-metolachlor + Isoxaflutole + Metribuzin	1050 + 52.5 + 210	59abcde	96a	18.3a	2.7a	19.2ab	2.3a

[a]Means followed by the same letter within a column are not statistically different according to the Tukey-Kramer multiple range test at $p < 0.05$.

foxtail spp. 50%, 58% and 78%, respectively. Control among the rates of isoxaflutole + metribuzin did not differ, additionally the low and medium rate did not differ compared to the grass herbicides; however, the high rate provided 40% to 54% greater foxtail spp. control compared to the grass herbicides. The tank-mixtures of a grass herbicides plus isoxaflutole + metribuzin controlled foxtail spp. 53% to 84%, there was no difference in control with these five herbicide treatments. Dimethenamid-P was the only grass herbicide which benefited from the addition of isoxaflutole + metribuzin where control increased 58%. The grass herbicides plus isoxaflutole + metribuzin did not differ from the varying rates of isoxaflutole + metribuzin. At sites 3, 5, 7 and 9, pendimethalin, dimethenamid-P, pethoxamid, pyroxasulfone and S-metolachlor controlled foxtail spp. 59% to 86%; there were no differences in foxtail spp.control with the grass herbicides. Isoxaflutole + metribuzin at the low, medium and high rate controlled foxtail spp. 84%, 90% and 96%, respectively; there was no difference in control among the three rates evaluated. The low and medium rate did not differ from the grass herbicides. The high rate provided 26% and 37% greater control than pendimethalin and pethoxamid, respectively, but did not differ from dimethenamid-P, pyroxasulfone and S-metolachlor. The grass herbicides plus isoxaflutole + metribuzin controlled foxtail spp. 87% to 96% and did not differ among each other or with isoxaflutole + metribuzin at the low, medium or high rate.

There was no difference in foxtail spp. control with the grass herbicides applied alone or in a tank-mixture with isoxaflutole + metribuzin. S-metolachlor + isoxaflutole + metribuzin controlled foxtail spp. 26% and 37% more than pendimethalin and pethoxamid, respectively. Additionally, dimethenamid-P or pyroxa-s ulfone plus isoxaflutole + metribuzin controlled foxtail spp. 34% to 37% more than pethoxamid.

At 8 WAA, at sites 1, 2 and 4, there was no decrease in foxtail spp. density with the herbicide treatments evaluated (Table 7). At sites 3, 5, 7 and 9 all herbicide treatments reduced foxtail spp. density 85% to 97% except for pethoxamid and pyroxasulfone. There was no difference in foxtail spp. density among the herbicide treatments evaluated.

At 8 WAA, at sites 1, 2 and 4, pendimethalin + isoxaflutole + metribuzin was the only treatment that reduced foxtail spp. biomass compared to the untreated control, it reduced biomass 83% (Table 7). There were no other treatment differences. At sites 3, 5, 7 and 9, all treatments reduced biomass 85% to 96% compared to the untreated control except for pethoxamid and pyroxasulfone. No herbicide treatments differed among each other.

In summary, at sites 1, 2 and 4, there was lower weed control than at sites 3, 5, 7 and 9. Generally, more rainfall was received at sites 3, 5, 7 and 9, by 28 DAA, compared to sites 1, 2 and 4 which may partially explain the reduced foxtail spp. control at sites 1, 2 and 4; however, site 3 received a lower amount of rain during this time period than site 2. Generally, at sites 1, 2 and 4, pyroxasulfone was the grass herbicide that provided the best control of foxtail spp.; in contrast, at sites 3, 5, 7 and 9, S-metolachlor provided the best control. At both site groups the grass herbicides plus isoxaflutole + metribuzin provided higher foxtail spp. control than isoxaflutole + metribuzin at the low rate.

3.7. Yellow Foxtail

Yellow foxtail (*Setaria pumila* Poir. Roem. & Schult.) was evaluated at sites 7 and 9 in this study (Table 8). The site by treatment interaction was not significant. Therefore, the sites were pooled for analysis (data not shown).

At 12 WAA, the grass herbicides controlled yellow foxtail 55% to 90%, there was no difference in control among the five herbicides (Table 8). Isoxaflutole + metribuzin at the low, medium and high rate controlled yellow foxtail 81% to 92% which was similar to pendimethalin, dimethenamid-P, pethoxamid, pyroxasulfone and S-metolachlor. The tank-mixtures of a grass herbicide plus isoxaflutole + metribuzin controlled yellow foxtail 87% to 97%. The addition of isoxaflutole + metribuzin to a grass herbicide did not increase control compared to the respective grass herbicide applied alone; however, pendimethalin, dimethenamid-P or S-metolachlor plus isoxaflutole + metribuzin provided greater yellow foxtail control than pethoxamid. At 8 WAA, the herbicide treatments evaluated did not reduce yellow foxtail density or biomass compared to the untreated control (Table 8).

Table 8. Yellow foxtail control at 12 WAA and density and biomass at 8 WAA from 7 field experiments conducted in Ontario, Canada in 2017 and 2018[a].

Treatment	Rate	Control 12 WAA	Density	Biomass
		Sites 7 9	Sites 7, 9	Sites 7, 9
	g a·i· ha^{-1}	%	#m^{-2}	g·m^{-2}
Untreated Control			11.4a	10.1a
Pendimethalin	1000	79ab	3.8a	3.1a
Dimethenamid-P	544	75ab	3.2a	2.3a
Pethoxamid	840	55b	3.5a	2.2a
Pyroxasulfone	125	80ab	6.7a	6.3a
S-metolachlor	1050	90ab	2.2a	1.7a
Isoxaflutole + Metribuzin	52.5 + 210	81ab	2.9a	2.9a
Isoxaflutole + Metribuzin	79 + 315	90ab	4.3a	2.8a
Isoxaflutole + Metribuzin	105 + 420	92ab	2.2a	1.5a
Pendimethalin + Isoxaflutole + Metribuzin	1000 + 52.5 + 210	94a	2.5a	2.6a
Dimethenamid-P + Isoxaflutole + Metribuzin	544 + 52.5 + 210	94a	1.2a	0.6a
Pethoxamid + Isoxaflutole + Metribuzin	840 + 52.5 + 210	87ab	3.8a	2.8a
Pyroxasulfone + Isoxaflutole + Metribuzin	125 + 52.5 + 210	90ab	4.5a	2.3a
S-metolachlor + Isoxaflutole + Metribuzin	1050 + 52.5 + 210	97a	0.8a	0.8a

[a]Means followed by the same letter within a column are not statistically different according to the Tukey-Kramer multiple range test at $p < 0.05$.

In summary, the addition of a grass herbicide to isoxaflutole + metribuzin numerically increased yellow foxtail control, although differences were not statistically significant. S-metolachlor with and without isoxaflutole + metribuzin had the highest level of control at 12 WAA and the largest reduction in density and biomass compared to the other grass herbicides.

3.8. Barnyardgrass

Barnyardgrass control was assessed at five sites in this study (Table 9). There was a significant site by treatment interaction, therefore, sites 1 and 2 were combined and sites 5, 6 and 9 were combined for analysis (data not shown).

At 12 WAA, at sites 1 and 2, there were no treatment differences, all herbicides controlled barnyardgrass 32 to 81% (Table 9). At sites 5, 6 and 9, pendimethalin, dimethenamid-P, pethoxamid, pyroxasulfone and S-metolachlor controlled barnyardgrass48, 96, 72, 95 and 98%, respectively. Dimethenamid-P, pyroxasulfone and S-metolachlor provided better control than pendimethalin. Isoxaflutole + metribuzin at the low, medium and high rates controlled barnyardgrass 92% to 97% and did not differ, they generally higher barnyardgrass control than pendimethalin. The tank-mixtures of a grass herbicide plus isoxaflutole + metribuzin controlled barnyardgrass 91% to 100% and did not differ.

Table 9. Barnyardgrass control at 12 WAA and density and biomass at 8 WAA from 7 field experiments conducted in Ontario, Canada in 2017 and 2018[a].

Treatment	Rate	Control 12 WAA		Density		Biomass	
		Sites 1, 2	Sites 5, 6, 9	Sites 1, 2	Sites 5, 6, 9	Sites 1, 2	Sites 5, 6, 9
	g a·i· ha^{-1}	%		#m^{-2}		g·m^{-2}	
Untreated Control				13.1a	5.8b	11.6a	5.3ab
Pendimethalin	1000	53a	48c	7.0a	2.9ab	3.7a	6.7b
Dimethenamid-P	544	45a	96ab	7.8a	0.9ab	7.0a	0.3a
Pethoxamid	840	56a	72bc	7.7a	2.6ab	5.3a	3.3ab
Pyroxasulfone	125	47a	95ab	7.4a	1.4ab	4.9a	1.4ab
S-metolachlor	1050	32a	98ab	6.3a	0.7ab	7.8a	0.7ab
Isoxaflutole + Metribuzin	52.5 + 210	61a	92ab	4.9a	0.8ab	9.1a	0.8ab
Isoxaflutole + Metribuzin	79 + 315	59a	95ab	9.1a	1.0ab	9.3a	1.9ab
Isoxaflutole + Metribuzin	105 + 420	69a	97ab	10.1a	0.6a	12.2a	0.3a
Pendimethalin + Isoxaflutole + Metribuzin	1000 + 52.5 + 210	68a	91ab	5.6a	0.7ab	3.7a	1.6ab
Dimethenamid-P + Isoxaflutole + Metribuzin	544 + 52.5 + 210	81a	100a	4.2a	0.4a	1.5a	0.2a
Pethoxamid + Isoxaflutole + Metribuzin	840 + 52.5 + 210	70a	93ab	5.6a	0.6ab	3.7a	0.9ab
Pyroxasulfone + Isoxaflutole + Metribuzin	125 + 52.5 + 210	73a	99ab	4.6a	0.5a	3.0a	0.5a
S-metolachlor +Isoxaflutole + Metribuzin	1050 + 52.5 + 210	77a	99ab	8.5a	0.3a	4.3a	0.4a

[a]Means followed by the same letter within a column are not statistically different according to the Tukey-Kramer multiple range test at $p < 0.05$.

Dimethenamid-P + isoxaflutole + metribuzin provided 52% and 28% better control than pendimethalin and pethoxamid, respectively.

At 8 WAA, at sites 1 and 2, there was no decrease in barnyardgrass density with the herbicide treatments evaluated compared to the untreated control (Table 9). At sites 5, 6 and 9, isoxaflutole + metribuzin at the high rate, and dimethenamid-P, pyroxasulfone or S-metolachlor plus isoxaflutole + metribuzin reduced barnyardgrass density 90% to 94% compared to the untreated control. The other herbicide treatments evaluated did not reduce barnyardgrass density relative to the untreated control.

At 8 WWA, at sites 1 and 2, the herbicide treatments evaluated did not reduce barnyardgrass biomass compared to the untreated control (Table 9). At sites 5, 6 and 9, no treatments reduced biomass compared to the untreated control but there were treatment differences. Dimethenamid-P, isoxaflutole + metribuzin at the high rate and dimethenamid-P, pyroxasulfone or S-metolachlor plus isoxaflutole + metribuzin reduced biomass 93% to 97% compared to pendimethalin.

In summary, barnyardgrass control was influenced by amount of rainfall 0 to 7 DAA and 0 to 14 DAA. Sites 1 and 2 received 5 and 2.7 mm of rain 0 to 7 DAA, respectively and had poorer weed control than sites 5, 6 and 9 which received 0.8, 9.8 and 10.8 mm of rain, respectively. Although site 5, had less rainfall than sites 1 and 2, it received more rain by 14 DAA, which allowed for activation of the herbicides. At sites 5, 6 and 9, S-metolachlor provided 50% higher control than pendimethalin 12 WAA. However, opposite results were found by Janak and Grichar [20] where pendimethalin provided 29% greater control than S-metolachlor and dimethenamid-P provided 31% greater barnyardgrass control than pyroxasulfone.

3.9. Witchgrass

Witchgrass populations occurred at sites 6 and 7 in this study (**Table 10**). There was no significant site by treatment interaction thus sites were pooled for analysis (data not shown). At12WAA, the herbicide treatments evaluated controlled witchgrass 83 to 98% (**Table 10**). There was no difference in witchgrass control among the herbicide treatments evaluated.

At 8 WAA, dimethenamid-P, pyroxasulfone, S-metolachlor, isoxaflutole + metribuzin at the three rates and the grass herbicides plus isoxaflutole + metribuzin reduced witchgrass density 96% to 99% compared to the untreated control (**Table 10**). Pendimethalin and pethoxamid did not reduce witchgrass density compared to the untreated control, although they did reduce witchgrass density similar to the other herbicide treatments evaluated.

At 8 WAA, all treatments reduced witchgrass biomass 98% to 99% compared to the untreated control with the exception of pendimethalin and pethoxamid which did not differ from the untreated control or other herbicide treatments (**Table 10**).

In summary, the addition of a grass herbicide to isoxaflutole + metribuzin did not improve witchgrass control compared to isoxaflutole + metribuzin at the low, medium or high rate, this may have been due to the high level of control provided by isoxaflutole + metribuzin.

3.10. Soybean Yield

Soybean yield had a significant site by treatment interaction (data not shown), therefore sites 1, 2, 3, 4, 5 and 8 were combined, site 6 and 7 were combined and site 9 was analyzed independently (**Table 11**). At sites 6 and 7, there were no yield differences, all treatments yielded 4.3 to 5.8 $T \cdot ha^{-1}$. At sites 1, 2, 3, 4, 5 and 8, weed interference reduced soybean yield 34%. The only herbicide treatments that resulted in soybean yield similar to the weed-free control were isoxaflutole + metribuzin at the high rate and pyroxasulfone + isoxaflutole + metribuzin. Isoxaflutole at all three rates, in addition to all the grass herbicides plusisoxaflutole + metribuzin yielded 0.7 to 1.0 $T \cdot ha^{-1}$ higher than the untreated control. Soybean yield with the grass herbicides alone did not differ from the untreated control. Soybean yield at site 9 in the weed-free control was lower than at the other site groups. Weed interference reduced soybean yield 76% at this site. Equivalent yields to the weed-free control of 2.6 to 3.8 $T \cdot ha^{-1}$ were obtained with the application of isoxaflutole + metribuzin at the medium and high rate, as well as the grass herbicides plus isoxaflutole + metribuzin. Soybean yield with dimethenamid-P, pethoxamid, pyroxasulfone and S-metolachlor did not differ

Table 10. Witchgrass control at 12 WAA and density and biomass at 8 WAA from 7 field experiments conducted in Ontario, Canada in 2017 and 2018[a].

Treatment	Rate	Control 12 WAA	Density	Biomass
		Site 6, 7	Site 6, 7	Site 6, 7
	g a·i· ha^{-1}	%	#m^{-2}	g·m^{-2}
Untreated Control			25.3b	19.8b
Pendimethalin	1000	83a	2.4ab	2.7ab
Dimethenamid-P	544	96a	0.8a	0.3a
Pethoxamid	840	83a	3.9ab	2.6ab
Pyroxasulfone	125	98a	0.7a	0.3a
S-metolachlor	1050	91a	1.0a	0.3a
Isoxaflutole + Metribuzin	52.5 + 210	94a	0.8a	0.4a
Isoxaflutole + Metribuzin	79 + 315	99a	0.6a	0.2a
Isoxaflutole + Metribuzin	105 + 420	99a	0.4a	0.2a
Pendimethalin + Isoxaflutole + Metribuzin	1000 + 52.5 + 210	100a	0.2a	0.1a
Dimethenamid-P + Isoxaflutole + Metribuzin	544 + 52.5 + 210	99a	0.2a	0.1a
Pethoxamid + Isoxaflutole + Metribuzin	840 + 52.5 + 210	98a	0.4a	0.1a
Pyroxasulfone + Isoxaflutole + Metribuzin	125 + 52.5 + 210	99a	0.2a	0.1a
S-metolachlor + Isoxaflutole + Metribuzin	1050 + 52.5 + 210	100a	0.1a	0.1a

[a]Means followed by the same letter within a column are not statistically different according to the Tukey-Kramer multiple range test at $p < 0.05$.

Table 11. Soybean yield from 9 field experiments in Ontario, Canada in 2017 and 2018[a].

Treatment	Rate	Soybean seed yield		
		Sites 6, 7	Sites 1, 2, 3, 4, 5, 8	Sites 9
	g a·i· ha^{-1}		T·ha^{-1}	
Untreated Control		4.3a	3.1e	0.9g
Weed Free		5.8a	4.7a	3.8a
Pendimethalin	1000	5.0a	3.5bcde	1.9bcdef
Dimethenamid-P	544	5.2a	3.4cde	1.5defg
Pethoxamid	840	5.1a	3.3ed	1.5efg
Pyroxasulfone	125	4.9a	3.5bcde	1.6cdefg
S-metolachlor	1050	4.9a	3.3ed	1.1fg
Isoxaflutole + Metribuzin	52.5 + 210	4.8a	3.8bcd	0.3bcde
Isoxaflutole + Metribuzin	79 + 315	5.2a	4.0b	2.6abcd
Isoxaflutole + Metribuzin	105 + 420	5.1a	4.1ab	2.9ab
Pendimethalin + Isoxaflutole + Metribuzin	1000 + 52.5 + 210	4.9a	4.0b	3.1ab
Dimethenamid-P + Isoxaflutole + Metribuzin	544 + 52.5 + 210	5.2a	4.1b	2.7abc
Pethoxamid + Isoxaflutole + Metribuzin	840 + 52.5 + 210	4.7a	3.9bc	2.9ab
Pyroxasulfone + Isoxaflutole + Metribuzin	125 + 52.5 + 210	5.3a	4.1ab	2.9ab
S-metolachlor + Isoxaflutole + Metribuzin	1050 + 52.5 + 210	4.8a	4.0b	2.7abcd

[a]Means followed by the same letter within a column are not statistically different according to the Tukey-Kramer multiple range test at $p < 0.05$.

from the untreated control. Reduced weed interference with the application of pendimethalin and isoxaflutole + metribuzin at the low rate resulted in increased soybean yield of 1.0 and 1.4 T·ha^{-1} compared to the untreated control; however, were not equivalent to the weed-free control. The yield potential was lower at site 9 due to low levels of rainfall throughout the growing season.

4. Conclusion

General trends suggest the addition of a grass herbicide to isoxaflutole + metribuzin at the low rate increases control of pigweed spp., green and giant foxtail and yellow foxtail regardless of site or assessment timing. Control of other species usually increased with the addition of a grass herbicide to isoxaflutole + metribuzin at the low rate although this was not consistent across all grass herbicides, especially when the low rate of isoxaflutole + metribuzin provided a high level of control. Generally, isoxaflutole + metribuzin at the medium or high rate provided equivalent or better control of most species evaluated than the grass herbicides applied alone or with isoxaflutole + metribuzin at the low rate. The addition of pendimethalin, dimethenamid-P, pethoxamid, pyroxasulfone or S-metolachlor to isoxaflutole + metribuzin may provide an additional effective mode of action which will reduce the selection intensity for the evolution of herbicide-resistant weed biotypes. Weed control varied by species. The grass herbicides, as the name suggests, controlled the grass weed species the best. However, when sites received > 4.9 mm of rainfall within 7 DAA, control of the pigweed spp. and common lambsquarters with pendimethalin, dimethenamid-P and pyroxasulfone was 85% to 93% and 62% to 85%, respectively. The grass herbicides controlled ragweed and velvetleaf < 65% and < 72%, respectively. Generally, across all sites, pendimethalin and pyroxasulfone provided greater broadleaf weed control than the other grass herbicides. The grass herbicides provided lower control of grass species at sites 1, 2 and 4 than sites 3, 5, 6, 7, 8 and 9. This may be due to lack of activating rainfall; general trends occur where sites 1, 2 and 4 received 2.7 to 5.2 mm of rain 0 to 7 DAA and sites 3, 5, 6, 7, 8 and 9 received 0.8 to 14.9 mm of rain 0 to 7 DAA. Site 5 received 0.8 mm of rain 0 to 7 DAA, but there was delayed weed emergence at this location due to the lack of moisture. By 14 DAA, site 5 had received 12.5 mm of rain which provided moisture to activate the herbicides and control weeds prior to emergence. In general, S-metolachlor provided the most consistent grass control in this study. There was a numeric improvement in the control of all weed species with increasing rates of isoxaflutole + metribuzin in this study. The medium and high rates typically provided higher numeric control of all the species than the grass herbicides applied alone, while the low rate rarely provided similar control to the best grass herbicide for each species.

5. Limitations

Due to natural environmental variability, weed species composition, and unforeseen outcomes within these studies, there are limitations on the conclusions obtained. Interspecies weed competition may have affected weed control otherwise accounted for by the herbicides in this study due to the variation in weed species and populations at the 10 sites. Some weed species are more competitive in nature, which would potentially suppress other species. Additionally, the competitiveness of differing species at each site may have altered the impact of weed interference on soybean yield. However, in real field situations, it is highly unlikely that two fields will have the exact same weed populations and species, therefore, results in these studies give a general trend to the efficacy of the herbicides.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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