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Control of Multiple-Herbicide-Resistant Green Pigweed (*Amaranthus powellii*) With Preemergence and Postemergence Herbicides in Ontario Corn Production

Isabelle K. Aicklen[1], Nader Soltani[1], François J. Tardif[1], Darren E. Robinson[1] & Peter H. Sikkema[1]

[1] Department of Plant Agriculture, University of Guelph, ON, Canada

Correspondence: Nader Soltani, Department of Plant Agriculture, University of Guelph, 120 Main St. East, Ridgetown, ON, N0P 2C0, Canada. E-mail: soltanin@uoguelph.ca

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Abstract

Green pigweed [*Amaranthus powellii* S.Wats.] is a prolific annual dicot weed that is a prominent weed of crop production in northeastern North America. Green pigweed interference has been documented to reduce corn yields up to 54% in the absence of control strategies. In 2021, a green pigweed biotype from a field near Dresden, Ontario, Canada was determined to be resistant to MCPA, mecoprop, dichlorprop-p, aminocyclopyrachlor (synthetic auxins), and imazethapyr (acetolactate synthase-(ALS)-inhibitor), further impacting control of this weed biotype. Two field studies, with herbicides applied preemergence (PRE) or postemergence (POST), were conducted in 2020 and repeated in 2021. The objective of the research was to determine the most effective PRE and POST herbicides for the control of multiple-herbicide-resistant (MHR) green pigweed in Ontario corn production. 18 PRE and 18 POST herbicide treatments were evaluated in separate studies. Visible crop injury, visible green pigweed control at specified timepoints after herbicide application, green pigweed density, green pigweed biomass, and corn yield at harvest maturity were collected. In the PRE study, rimsulfuron + mesotrione was identified as the most efficacious treatment providing 88% control at 8 WAA. In the POST study, atrazine was identified as the most efficacious treatment providing 94% control at 8 WAA. Control with all PRE herbicide treatments was impacted by rainfall following application. MCPA ester applied POST controlled green pigweed 30% at 8 WAA; reduced control is attributed to herbicide resistance in this biotype. When compared to similar studies, control of green pigweed was reduced with some of the POST herbicides tested. While MHR green pigweed represents an additional challenge for growers, there are efficacious herbicide treatments that would allow it to be managed in corn production.

Keywords: ALS-inhibitors, corn, green pigweed, herbicide resistance, HPPD-inhibitors, PSII-inhibitors, synthetic auxins, VLCFAE-inhibitors

1. Introduction

Green pigweed [*Amaranthus powellii* S. Wats.] is one of several weed species that is a member of the Amaranthaceae family and is closely related to other monoecious *Amaranthus* species found in Ontario which include *Amaranthus retroflexus* L. (redroot pigweed) and *Amaranthus hybridus* L. (smooth pigweed) (Weaver & McWilliams, 1980). Although green pigweed is native to South America, it has been found in North American crop production as early as the 1940s (Sauer, 1967; Weaver & McWilliams, 1980). Green pigweed is a small-seeded, C4, annual, broadleaf weed with prolonged germination and emergence throughout the late spring and summer months (Uva et al., 1997; Elmore & Paul, 1983). Similar to redroot pigweed and smooth pigweed, green pigweed is a prolific seed producer, producing up to 250,000 seeds per plant (Sellers et al., 2003). These monoecious *Amaranthus* species are primarily self-pollinated with green pigweed having a competitive advantage by exhibiting rapid germination and early growth and prolonged emergence (Frost, 1971; Weaver, 1984; McWilliams, 1966). Based on these competitive attributes, control of green pigweed is critical to minimize corn yield losses from green pigweed interference and maximize net returns for producers.

In corn production, when redroot pigweed emerged with the crop, crop yield was reduced up to 34% at high densities (Knezevic et al., 1994). To achieve high corn yields, the use of mechanical tillage and dicot selective herbicides are effective for green pigweed control (Weaver, 2001). Green pigweed's prolonged emergence allows it to escape early spring herbicide applications; these late-emerging cohorts can return seed to the soil seedbank.

Consequently, it is necessary to consider the use of both soil-applied and postemergence (POST) herbicides (McWilliams, 1966; Weaver, 2001; Weaver & McWilliams, 1980). Although herbicides are effective in mitigating yield losses due to hard-to-control weeds such as green pigweed, several weed species have evolved herbicide resistance due to repeated applications of herbicides with the same mode of action (Beckie et al., 2001; Heap, 2014).

Herbicide resistance occurs when a weed survives a previously lethal dose of herbicide and reproduces to pass on the resistance trait (Holt & LeBaron, 1990; Vencill et al., 2012). In Ontario the presence of green pigweed biotypes resistant to acetolactate synthase (ALS)-inhibiting and photosystem II (PSII)-inhibiting herbicides have previously been confirmed (Ferguson et al., 2001; Diebold et al., 2003). In 2021, a green pigweed biotype from a field near Dresden, Ontario, Canada was confirmed to be resistant to MCPA, dichlorprop-p, mecoprop, aminocyclopyrachlor, and imazethapyr (Aicklen et al., unpublished). Multiple-herbicide-resistant (MHR) green pigweed could pose a threat to Ontario corn production, therefore, making it necessary to find alternative control solutions.

As MHR green pigweed can pose a threat to achieving profitable corn yields; it is important to identify efficacious herbicides that control this MHR biotype. The objective of this research is to determine the most efficacious herbicides for the control of green pigweed applied preemergence (PRE) and POST in corn. Herbicides that provide > 90% control will be considered effective control solutions. If effective control can be achieved with some of the herbicides tested, this will allow for strategies to be developed to prevent the spread of MHR green pigweed biotypes in Ontario, Canada.

2. Materials and Methods

Two studies, each consisting of two field trials, were conducted in 2020 and 2021 with the trials arranged as a randomized complete block design with four blocks. The trials were conducted at a field site near Dresden, Ontario, Canada (42.582811, -82.113953). The first study evaluated PRE herbicides and the second study POST herbicides. Soil information, corn planting, emergence, harvest dates, and herbicide application dates are presented in Table 1.

Table 1. Soil, corn agronomic, and herbicide application information for four trials conducted near Dresden, ON, Canada in 2020 and 2021

Year	Soil Characteristics[a]						Corn Information			Herbicide Application Dates	
	Texture	Sand	Silt	Clay	OM[b]	pH	Planting Date	Emergence Date	Harvest Date	PRE[c]	POST[d]
		-------------- % --------------									
2020	Sandy Loam	55	27	19	3.4	7.1	27 May	2 June	6 November	28 May	12 June
2021	Loam	41	33	26	3.1	6.8	13 May	21 May	11 November	15 May	3 June

Note. [a] Soil characteristics were obtained from samples taken at a 15 cm depth below the soil surface and analyzed by A&L Canada Laboratories Inc. (2136 Jetstream Rd., London, ON, Canada, N5V 3P5); [b] OM, organic matter; [c] PRE, preemergence; [d] POST, postemergence.

Prior to planting, the trial area was conventionally tilled, and 448 kg ha^{-1} of urea was applied during the growing season to meet the corn N requirements. The Enlist corn hybrid B79N56PWE (Corteva Agriscience Canada Company, 215-2nd Street SW, Suite 2450, Calgary, AB, Canada, T2P 1M4) was planted in May at approximately 83,000 seeds ha^{-1} to a depth of approximately 4 cm. Plot size was 2.25 m wide (3 corn rows spaced 0.75 m apart) and 10 m long. The weed free-control was maintained weed-free with *S*-metolachlor/atrazine/mesotrione/bicyclopyrone (Acuron®, Syngenta Canada Inc., 140 Research Lane, Guelph, ON, Canada, N1G 4Z3) at 2022 (1259/588/140/35) g a.i. ha^{-1} applied PRE followed by glyphosate (Roundup WeatherMax®, Bayer CropScience Inc., 160 Quarry Park Boulevard, Calgary, AB, Canada, T2C 3G3) at 900 g a.e. ha^{-1} applied POST. Quizalofop-p-ethyl (AMVAC Assure® II, 36 g a.i. ha^{-1}, plus Sure-Mix, 0.5% v/v, Belchim Crop Protection Canada, 104 Copper Dr., Unit 3, Guelph, ON, Canada, N1C 0A4) was applied POST to control annual grasses in the trial area.

Herbicides were applied with a CO_2 pressurized backpack sprayer with a hand-held boom at an operating pressure of 207 kPa calibrated to deliver a water volume of 200 L ha^{-1}. The hand-held boom was fitted with four ULD-120-02 (Pentair Canada Inc., 490 Pinebush Rd., Cambridge, ON, Canada, N1T 0A5) nozzles at a spacing of 50 cm producing a spray width of 2 m. Within 3 days of planting, prior to corn emergence, the PRE herbicides were applied. The POST herbicides were applied when green pigweed was an average of 7 to 8 cm in height. Corn height and development stage and green pigweed height, leaf number, and density at POST application are presented in Table 2. In 2020 and 2021, the PRE trials received 25 mm and 23 mm of rainfall within 11 and 13 days of application, respectively. Herbicide active ingredients, trade names, and manufacturers for the PRE and POST studies are presented in Tables 3 and 5, respectively. Herbicide active ingredients and application rates for the PRE and POST studies are presented in Tables 4 and 6, respectively.

Table 2. Average corn height and development stage; and green pigweed (*A. powellii*) height, leaf number, and density at POST herbicide application timing for two trials conducted near Dresden, ON, Canada in 2020 and 2021

Year	Corn		Green pigweed[b]		
	Height	Development stage[a]	Height	Leaf number	Density
	cm		cm		plants m^{-2}
2020	20	V3	8	6	985
2021	22	V3	7	8	160

Note. [a] Based on corn growth staging by McWilliams et al. (1999); [b] Average height, leaf number, and density were recorded from two 0.25 m^2 quadrats in the non-treated control plots.

Table 3. Herbicide active ingredients, trade names, and manufacturers for the PRE herbicide treatments

Herbicide name	Trade name	Manufacturer
Pendimethalin	Prowl® H_2O	BASF Canada Inc., 100 Milverton Drive, Mississauga, ON, Canada, L5R 4H1
Dimethenamid-p	Frontier® Max	
Pyroxasulfone	Zidua® SC	
Saflufenacil/dimethenamid-p	Integrity®	
Dicamba/atrazine	Marksman®	
S-metolachlor	Dual II Magnum®	Syngenta Canada Inc., 140 Research Lane, Guelph, ON, Canada, N1G 4Z3
Atrazine	Aatrex® Liquid 480	
Mesotrione	Callisto® 480 SC	
S-metolachlor/atrazine	Primextra® II Magnum®	
S-metolachlor/atrazine/mesotrione	Lumax® EZ	
S-metolachlor/mesotrione/bicyclopyrone	Acuron® Flexi	
S-metolachlor/atrazine/mesotrione/bicyclopyrone	Acuron®	
Dicamba	Xtendimax™	Bayer CropScience Inc., 160 Quarry Park Boulevard, Calgary, AB, Canada, T2C 3G3
Isoxaflutole	Converge® Flexx	
Flumetsulam	Broadstrike™ RC	Corteva Agriscience Canada Company, 215-2nd Street SW, Suite 2450, Calgary, AB, Canada, T2P 1M4
Rimsulfuron	Prism™ SG	

Table 4. Green pigweed (*A. powellii*) control, density, biomass, and corn yield as impacted by PRE herbicide treatments from two field trials conducted in 2020 and 2021 near Dresden, Ontario, Canada.

Treatment[a]	Rate	Green pigweed control			Density	Biomass	Corn yield[c]
		2 WAA[b]	4 WAA	8 WAA			
	g a.i. ha^{-1}	----------------- % -----------------			no. m^{-2}	g m^{-2}	t ha^{-1}
Non-treated control	-	0	0	0	127a	205a	5.4e
Weed-free control	-	100	100	100	0	0	9.2a
S-metolachlor	1600	2f	0f	1h	88a-c	184ab	6.0de
Pendimethalin	1680	3f	0f	1h	89a-c	191a	7.0b-e
Dimethenamid-p	693	30e	9ef	15gh	45b-d	91b-d	6.3c-e
Dicamba	600	27e	22e	29f-h	116ab	127a-c	7.4a-e
Flumetsulam	78	51cd	56cd	34e-g	35c-e	83cd	7.4a-e
Saflufenacil/dimethenamid-p	74 +661	50d	43d	44d-g	22d-f	83cd	6.9b-e
S-metolachlor/atrazine/mesotrione	1405 +516 + 145	57a-d	56cd	45c-g	20d-g	77cd	7.9a-d
Dicamba/atrazine	494 + 960	58a-d	68bc	53b-f	47a-d	44cd	8.4a-c
S-metolachlor/mesotrione/bicyclopyrone	40 + 203 + 1783	51cd	60cd	55b-f	15d-h	62cd	8.3a-c
Atrazine	1490	74a	74a-c	57b-f	43b-d	42cd	8.8ab
Mesotrione + atrazine	140 + 1490	61a-d	69bc	62a-e	17d-h	44cd	9.0ab
S-metolachlor/atrazine	1613 + 1267	69ab	75a-c	68a-d	14e-h	35cd	8.3a-d
Pyroxasulfone	247	55b-d	74a-c	73a-d	7h	48cd	8.6ab
Isoxaflutole + atrazine	105 + 1063	67a-c	84ab	75a-c	12f-h	43cd	8.3a-d
S-metolachlor/atrazine/mesotrione/bicyclopyrone	1259 + 588+ 140 + 35	58a-d	84ab	76ab	13e-h	37cd	8.3a-c
Mesotrione + rimsulfuron	144 + 15	51cd	93a	88a	8gh	15d	9.0ab

Note. [a] Treatments containing multiple active ingredients are separated into either pre-formulated mixtures using "/" or separate products as part of a mix using "+"; [b] Wk after application; [c] Yield is adjusted to 15.5% moisture.

Means followed by the same letter within each variable column are not statistically different based on Tukey's HSD ($p < 0.05$).

Table 5. Herbicide active ingredients, trade names, and manufacturers for the POST herbicide treatments

Herbicide name	Trade name	Manufacturer
Dicamba[a]	Banvel® II	BASF Canada Inc., 100 Milverton Drive, Mississauga, ON, Canada, L5R 4H1
Dicamba/diflufenzopyr[ab]	Distinct®	
Dicamba/atrazine	Marksman®	
Glufosinate ammonium	Liberty® 200 SN	
Topramezone[abc]	Armezon®	
Topramezone/dimethenamid-p	Armezon® PRO	
Prosulfuron[a]	Peak® 75 WG	Syngenta Canada Inc., 140 Research Lane, Guelph, ON, Canada, N1G 4Z3
Atrazine[abcd]	Aatrex® Liquid 480	
Mesotrione[a]	Callisto® 480 SC	
Glyphosate/*S*-metolachlor/ mesotrione[a]	Halex® GT	
Dicamba	Xtendimax™	Bayer CropScience Inc., 160 Quarry Park Boulevard, Calgary, AB, Canada, T2C 3G3
Bromoxynil	Pardner®	
Glyphosate	Roundup WeatherMax®	
MCPA ester	MCPA Ester 600	Nufarm Agriculture Inc., 5101, 333 - 96th Ave NE Calgary, AB, Canada, T3K 0S3
2,4-D amine	2,4-D Amine 600	
Halosulfuron[a]	Permit® WG	Gowan Canada, 100-135 Innovation Drive, Winnipeg, MB, Canada, R3T 6A8
Tolpyralate[abe]	Shieldex™ 400 SC	ISK Biosciences Corporation, 740 Auburn Road, Concord, OH, USA, 44077

Note. [a] Halosulfuron, prosulfuron + dicamba, dicamba/diflufenzopyr, mesotrione + atrazine, and glyphosate/S-metolachlor/mesotrione + atrazine applied POST were mixed with 0.25% v/v, 0.20% v/v, 0.25% v/v, 0.20% v/v, and 0.20% v/v of the adjuvant Agral®90 (Syngenta Canada Inc., 140 Research Lane, Guelph, ON, Canada, N1G 4Z3); [b] Dicamba/diflufenzopyr, topramezone + atrazine, and tolpyralate + atrazine applied POST were mixed with 1.25% v/v, 1.25% v/v, and 2.50% v/v of urea ammonium nitrate (UAN-28-0-0); [c] Topramezone + atrazine applied POST was mixed with 1.25% v/v of the adjuvant Merge® (BASF Canada Inc., 100 Milverton Drive, Mississauga, ON, Canada, L5R 4H1); [d] Atrazine applied alone POST was mixed with 17 L ha^{-1} of the adjuvant Assist® (BASF Canada Inc., 100 Milverton Drive, Mississauga, ON, Canada, L5R 4H1); [e] Tolypyralate + atrazine applied POST was mixed with 0.50 % v/v of the adjuvant MSO Concentrate® (Loveland Products Inc., 3005 Rocky Mountain Ave., Loveland, CO, USA, 80538).

Table 6. Green pigweed (*A. powellii*) control, density, biomass, and corn yield as impacted by POST herbicide treatments from two field trials conducted in 2020 and 2021 near Dresden, Ontario, Canada

Treatment[a]	Rate	Green pigweed control				Density	Biomass	Corn yield[c]
		1 WAA[b]	2 WAA	4 WAA	8 WAA			
	g a.i. ha^{-1}	--------------------	%	--------------------		no. m^{-2}	g m^{-2}	t ha^{-1}
Non-treated control	-	0	0	0	0	200a	382a	4.5c
Weed-free control	-	100	100	100	100	0	0	9.8a
MCPA Ester	850	34cd	38h	29i	30h	124ab	173b	6.4a-c
Glufosinate	500	81ab	58g	33i	33h	85b-d	135b-d	8.5a-c
Halosulfuron	68	38cd	41h	45hi	39gh	123ab	140bc	5.3bc
2,4-D Amine	564	33d	60fg	53gh	46f-h	97bc	108b-d	7.0a-c
Glyphosate	900	91ab	78c-e	54f-h	51e-g	79b-e	77c-e	9.6ab
Topramezone + atrazine	12.4 + 480	89ab	72d-f	54e-h	51e-g	60b-f	109b-d	9.3ab
Tolpyralate + atrazine	40+560	96a	80c-e	70d-f	60d-f	40c-h	74de	9.7ab
Topramezone/dimethenamid-p + atrazine	630 + 12.5 + 480	89ab	81b-e	71c-e	61d-f	47c-h	121b-d	9.5ab
Prosulfuron + dicamba	10 + 140	41cd	63fg	69d-g	66c-e	59b-g	35ef	8.7a-c
Bromoxynil + atrazine	340 + 1490	86ab	82b-d	77b-d	69c-e	27d-h	33ef	9.8a
Mesotrione + atrazine	100 + 280	95a	86a-c	77b-d	72b-d	22e-h	34ef	10.2a
Dicamba/diflufenzopyr	143 + 57	55bc	71d-f	75b-d	80a-c	50b-h	18ef	8.6a-c
Dicamba	600	37cd	69e-g	78b-d	87ab	16f-h	6f	9.0ab
Glyphosate/*S*-metolachlor/mesotrione + atrazine	1047 + 1047 111 + 280	98a	93ab	88a-c	89ab	6h	4f	10.8a
Dicamba/atrazine	494 + 960	78ab	88a-c	91ab	89ab	8gh	3f	9.5ab
Atrazine	1488	98a	97a	96a	94a	2h	5f	10.5a

Note. [a] Treatments containing multiple active ingredients are separated into either pre-formulated mixtures using "/" or separate products as part of a mix using "+"; [b] Wk after application; [c] Yield is adjusted to 15.5% moisture.

Means followed by the same letter within each variable column are not statistically different based on Tukey's HSD ($p < 0.05$).

Data collection consisted of visible corn injury, visible green pigweed control, density, and biomass, and crop yield at harvest maturity. For the PRE trials, corn injury was assessed 1, 2, and 4 wk after crop emergence (WAE), visible green pigweed control was assessed at 2, 4, and 8 wk after application (WAA), green pigweed density and biomass were assessed at 8 WAA, and corn yield was collected at harvest maturity. For the POST trials, corn injury was assessed at 1, 2, and 4 WAA, visible green pigweed control was assessed at 1, 2, 4, and 8 WAA, green pigweed density and biomass were assessed at 8 WAA, and corn yield was collected at harvest maturity.

Corn injury was assessed on a scale from 0% to 100% where 0% indicated no corn injury and 100% indicated complete corn death. Green pigweed control was evaluated on a 0% to 100% scale by estimating the percent reduction in aboveground biomass compared to the weedy control in each replicate. Weed density and biomass were determined from two areas of each plot using a square quadrat measuring 0.25 m^2. Weed density was determined by counting the number of plants in the quadrat. After recording density, the plants in each quadrat were cut at the soil surface and placed into paper bags which were dried in a kiln for approximately 14 days at 60 ^oC to constant moisture. At corn harvest maturity, the center 2 rows of each plot were harvested with a small plot combine, and the weight and moisture were recorded. Corn yield was adjusted to 15.5% moisture prior to analysis.

The data was analyzed in SAS 9.4 (SAS Institute Inc., 100 SAS Campus Dr., Cary, NC, USA, 27513) using the GLIMMIX procedure to incorporate fixed and random effects. The fixed effects were determined to be treatment and environment (year) and the random effect was the block. The data across the site-years was pooled to meet the objective of determining the most efficacious PRE- and POST-applied herbicides for the control of MHR green pigweed in corn. To meet the normality assumptions, the residuals were plotted against predicted, treatment, block, and year. The UNIVARIATE procedure was used to determine the Shapiro-Wilk statistic for normality. Data for all variables except for the density data for both the PRE and POST trials were fitted to a normal distribution. To ensure the assumptions of normality were met, a lognormal distribution was used to evaluate weed density data. The data was back transformed to a normal distribution for presentation. A significance level of $p = 0.05$ was used to separate treatments using Tukey's HSD.

3. Results and Discussion

3.1 Efficacy of Preemergence Herbicides

Across all time points, all 18 treatments controlled green pigweed less than 90% (Table 4). Several of the herbicides failed to provide efficacious control of green pigweed with only one treatment providing over 80% control at 8 WAA (Table 4). Although control at 2 and 4 WAA will be discussed, results will focus on control at 8 WAA. *S*-metolachlor and pendimethalin controlled green pigweed ≤ 3% at 2, 4, and 8 WAA. Dimethenamid-p, dicamba, flumetsulam, saflufenacil/dimethenamid-p, and *S*-metolachlor/atrazine/mesotrione controlled green pigweed 15, 29, 34, 44, and 45% at 8 WAA. Dicamba/atrazine, *S*-metolachlor/mesotrione/bicyclopyrone, and atrazine controlled green pigweed 53 to 57% at 8 WAA. Mesotrione + atrazine, *S*-metolachlor/atrazine, pyroxasulfone, isoxaflutole + atrazine, *S*-metolachlor/atrazine/mesotrione/bicyclopyrone, and mesotrione + rimsulfuron controlled green pigweed 62 to 88% at 8 WAA, these herbicides provided similar green pigweed control.

S-metolachlor, pendimethalin, dicamba, and dicamba/atrazine did not reduce green pigweed density relative to the non-treated control at 8 WAA (Table 4). Dimethenamid-p, atrazine, flumetsulam, saflufenacil/dimethenamid-p, and *S*-metolachlor/atrazine/mesotrione reduced green pigweed density similarly by 65 to 88% at 8 WAA. This group of treatments reduced green pigweed density relative to the non-treated control, but the reduction was less than with the most efficacious herbicides. Mesotrione + atrazine, *S*-metolachlor/mesotrione/bicyclopyrone, *S*-metolachlor/atrazine, *S*-metolachlor/atrazine/mesotrione/bicyclopyrone, isoxaflutole + atrazine, mesotrione + rimsulfuron, and pyroxasulfone provided the greatest reduction in green pigweed density at 87 to 94%.

Pendimethalin, *S*-metolachlor, and dicamba did not reduce aboveground green pigweed biomass relative to the non-treated control at 8 WAA (Table 4). Dimethenamid-p, flumetsulam, saflufenacil/dimethenamid-p, *S*-metolachlor/atrazine/mesotrione, *S*-metolachlor/mesotrione/bicyclopyrone, pyroxasulfone, dicamba/atrazine, mesotrione + atrazine, isoxaflutole + atrazine, atrazine, *S*-metolachlor/atrazine/mesotrione/bicyclopyrone, *S*-metolachlor/atrazine, and mesotrione + rimsulfuron reduced green pigweed biomass similarly 56 to 93% at 8 WAA (Table 4). Soltani et al. (2019) reported that, *S*-metolachlor, dimethenamid-p, and pyroxasulfone at rates of 1050, 544, and 100 g a.i. ha^{-1}, respectively, reduced redroot pigweed density and biomass to the extent that they were similar to the weed-free control at 8 WAA. In contrast, this study found that *S*-metolachlor and dimethenamid-p did not reduce green pigweed density and biomass; however, pyroxasulfone, another Group 15 herbicide, reduced green pigweed density and biomass 94 and 77%, respectively which was similar to the most efficacious treatments in this study.

Green pigweed interference in the untreated control plots reduced corn yield 42% (Table 4). Similarly, because they provided little control of green pigweed, plots treated with *S*-metolachlor, pendimethalin, dimethenamid-p, dicamba, flumetsulam, and saflufenacil/dimethenamid-p treatments resulted in corn yields that were similar to the non-treated control. Conversely, as *S*-metolachlor/atrazine/mesotrione, dicamba/atrazine, *S*-metolachlor/ mesotrione/bicyclopyrone, atrazine, mesotrione + atrazine, *S*-metolachlor/atrazine, pyroxasulfone, isoxaflutole + atrazine, *S*-metolachlor/atrazine/mesotrione/bicyclopyrone, and mesotrione + rimsulfuron efficiently controlled green pigweed, interference was reduced resulting in corn yields that were similar to the weed-free control.

Delayed rainfall may have impacted green pigweed control with the PRE herbicides. Rainfall within 1 to 2 WAA after application is required to dissolve the herbicide in soil water solution so that it can be taken up by the developing weed seedlings (Stewart et al., 2012; Hartzler, 2021; Buhler, 1991; Stickler et al., 1969). Rainfall increases soil moisture and allows for adequate absorption of the herbicide (Stickler et al., 1969). The ability of the herbicide to bind to the soil colloids is influenced by rainfall and if there is a lack of rainfall after application, some herbicides will bind more tightly to soil colloids and will not be taken up as easily by the plant (Hartzler, 2021; Loux et al., 2013). Pendimethalin requires relatively more rainfall to be released from soil colloids which may explain the poor control with this treatment as more herbicide may have been adsorbed to the soil colloids (Lyon & Wilson, 2005; Hartzler, 2021). In a tank mixture, if the efficacy of one of the components is reduced due to adverse weather conditions, overall control may be compromised (Stewart et al., 2010). Although rainfall in 2020 and 2021 occurred within the 2-week window following application, in both years the first rain event was more than 1 week after application which could have contributed to reduced weed control with the PRE treatments.

Green pigweed control with the VLCFAE-inhibitors was variable; while at 8 WAA *S*-metolachlor, and dimethenamid-p provided 1 and 15% green pigweed control, respectively, pyroxasulfone gave 73% control (Table 4). When *S*-metolachlor was in a preformulated mixture with atrazine + mesotrione, mesotrione + bicyclopyrone, atrazine, or atrazine + mesotrione + bicyclopyrone control of green pigweed improved from 45 to 55 to 68 to 76% at 8 WAA. In a study by Soltani et al. (2019), control of redroot pigweed at 8 WAA in corn with

S-metolachlor, dimethenamid-p, and pyroxasulfone was 96, 99, and 99% at rates of 1050, 544, and 100 g a.i. ha^{-1} respectively. The rates of the VLCFAE-inhibitors used in the aforementioned study were lower than in the current study but the control of redroot pigweed, a biologically similar monoecious *Amaranthus* species, was much higher than the control of green pigweed in this study. A study by Geier et al. (2006), found that Palmer amaranth, a dioecious *Amaranthus* species, was controlled 76 to 94% at 75 days after treatment (DAT) across trial years with *S*-metolachlor at a rate of 1420 g a.i. ha^{-1} in conventional corn. Control of Palmer amaranth with *S*-metolachlor + atrazine at 1070 + 1340 g a.i. ha^{-1} was 92 to 100% at 75 DAT (Geier et al., 2006) which is much higher than green pigweed control in the current study. In the same trial, Geier et al. (2006) found that Palmer amaranth was controlled 87 to 99% at 75 DAT across trial years with pyroxasulfone at 250 g a.i. ha^{-1} which is greater than the 73% green pigweed control at 8 WAA in the current study. Pyroxasulfone at 250 g a.i. ha^{-1} and *S*-metolachlor at 1786 g a.i. ha^{-1} controlled Palmer amaranth 98% at 9 weeks after treatment (Steele et al., 2005). Although not evaluating the control of green pigweed directly, both studies reported greater control of *Amaranthus* species at lower rates of *S*-metolachlor. In the present study, when dimethenamid-p was applied in a preformulated mixture with saflufenacil, control of green pigweed was improved by 20 and 34 percentage points at 2 and 4 WAA, respectively; there was no improvement in control at 8 WAA and no difference in density and biomass or corn yield. A study to evaluate the saflufenacil + dimethenamid-p dose required to control *Amaranthus* species by 95% was found to be 186 g a.i. ha^{-1} (Moran et al., 2011). In comparison to the aforementioned studies, the green pigweed control with VLCFAE-inhibitor herbicides in the present study was lower than expected.

Control of green pigweed with 4-hydroxyphenylpyruvate dioxygenase (HPPD)-inhibitors was variable across treatments that included PRE applications of mesotrione, bicyclopyrone, and isoxaflutole with efficacy ranging between 51 and 89% (Table 4). In a study by Benoit et al. (2019), the efficacy of treatments containing HPPD inhibitors was higher and more consistent with mesotrione + rimsulfuron providing 72% control, mesotrione + atrazine and isoxaflutole + atrazine 82%, *S*-metolachlor/mesotrione/atrazine 93%, and *S*-metolachlor/mesotrione/bicyclopyrone/atrazine 94% waterhemp control at 8 WAA. The addition of atrazine to *S*-metolachlor/mesotrione/bicyclopyrone in the current study improved green pigweed control 16, 24, and 19 percentage points at 2, 4, and 8 WAA although differences were not always statistically significant. Green pigweed control with mesotrione + rimsulfuron in this study was greater than the waterhemp control in the study by Benoit et al. (2019).

Flumetsulam, an ALS-inhibiting herbicide controlled green pigweed 34% at 8 WAA and reduced density and biomass 72 and 60%, respectively. Mesotrione + rimsulfuron at 4 and 8 WAA controlled green pigweed and reduced density and biomass equal to, or greater, than the other herbicide treatments evaluated in this study. Benoit et al. (2019) found that there was a significant difference between flumetsulam and rimsulfuron + mesotrione at 8 WAA with flumetsulam providing 40% control and rimsulfuron + mesotrione providing 72% control of waterhemp. Although flumetsulam and rimsulfuron are in different herbicide families of ALS-inhibiting herbicides, it can be inferred based on the findings of Benoit et al. (2019) that control of *Amaranthus* species is greater with the combination of rimsulfuron + mesotrione.

3.2 Efficacy of Postemergence Herbicides

For most POST herbicide treatments, the control of green pigweed decreased over time (Table 6). For the treatments providing the least (MCPA ester) and highest (atrazine) control of green pigweed, control remained relatively constant (< 10% difference). MCPA ester provided the poorest green pigweed control of 34, 38, 29, and 30% whereas, atrazine provided the highest green pigweed control of 98, 97, 96, and 94% at 1, 2, 4, and 8 WAA, respectively (Table 6).

Green pigweed control at 1, 2, 4, and 8 WAA is presented in Table 6, however the discussion will focus on control at 8 WAA. MCPA ester, glufosinate, halosulfuron, and 2,4-D amine controlled green pigweed similarly at 30 to 46% at 8 WAA (Table 6). Glyphosate, topramezone + atrazine, tolpyralate + atrazine, topramezone/dimethenamid-p + atrazine, prosulfuron + dicamba, and bromoxynil + atrazine controlled green pigweed similarly at 51 to 69% at 8 WAA (Table 6). Dicamba/diflufenzopyr, dicamba, glyphosate/*S*-metolachlor/mesotrione + atrazine, dicamba/atrazine, and atrazine controlled green pigweed similarly at 80 to 94% at 8 WAA (Table 6). Atrazine was the most efficacious treatment based on control of green pigweed at 1, 2, 4, and 8 WAA.

At 8 WAA, MCPA ester and halosulfuron did not reduce green pigweed density relative to the non-treated control (Table 6). 2,4-D amine, glufosinate, glyphosate, topramezone + atrazine, and prosulfuron + dicamba, reduced green pigweed density similarly at 52 to 71% relative to the non-treated control at 8 WAA. Dicamba/diflufenzopyr, topramezone/dimethenamid-p + atrazine, tolpyralate + atrazine, bromoxynil + atrazine, mesotrione + atrazine, dicamba, glyphosate/*S*-metolachlor/mesotrione + atrazine, dicamba/atrazine, and atrazine reduced green pigweed density similarly at 75 to 99% relative to the non-treated control.

All herbicide treatments reduced green pigweed biomass relative to the control at 8 WAA (Table 6). MCPA ester, halosulfuron, glufosinate, topramezone/dimethenamid-p + atrazine, topramezone + atrazine, and 2,4-D reduced green pigweed biomass 55, 63, 65, 68, 71, and 72% at 8 WAA, biomass reduction was similar and the least among the herbicide treatments evaluated. Glyphosate reduced green pigweed biomass 80%. The remaining herbicide treatments evaluated reduced green pigweed biomass similarly at 81 to 99% at 8 WAA (Table 6).

Green pigweed interference reduced corn yield 54% in this study (Table 6). Green pigweed interference with halosulfuron, 2,4-D, MCPA ester, and glufosinate resulted in corn yield that was similar to the non-treated control. Reduced green pigweed interference with the remaining herbicide treatments evaluated resulted in corn yield that was similar to the weed-free control.

There were significant differences in green pigweed control with the three synthetic auxin herbicides: MCPA ester, 2,4-D amine, and dicamba. At 8 WAA, the control of green pigweed with MCPA ester was 30%, the poor control is attributed to the evolution of herbicide resistance in this biotype. As of 2021, this biotype was confirmed to be resistant to MCPA, aminocyclopyrachlor, dichlorprop-p, and mecoprop through dose-response experiments (Aicklen et al. unpublished). Interestingly, this biotype remains susceptible to dicamba, and 2,4-D. MCPA is rated as a "9" (90-100% control) in the provincial weed control guide in Ontario (Ontario Ministry of Agriculture, Food and Rural Affairs, 2021). The improved control with dicamba applied alone can be attributed to the higher application rate (600 g a.e. ha^{-1}) compared to when it was applied as a tank mix or in a preformulated mixture (140-494 g a.e. ha^{-1}). Lawrence et al. (2018) found that an early POST application of 2,4-D at 0.56 kg a.e. ha^{-1} controlled Palmer amaranth 59% and reduced dry weight 51% relative to the non-treated control at 28 DAA in a non-crop trial. The findings are similar to the results of the current study which found that the application of 2,4-D amine controlled green pigweed 53% at 4 WAA and reduced aboveground biomass 52% relative to the non-treated control. Compared to MCPA ester and 2,4-D amine, the control of green pigweed with dicamba was greater at 87% at 8 WAA (Table 6). In a study by Spaunhorst and Bradley (2013), dicamba (560 g a.e. ha^{-1}) applied POST controlled 7.5 cm waterhemp 26% at 3 WAA in a non-crop trial. The authors suggest that even when dicamba is applied to smaller *Amaranthus* plants that dicamba alone may not provide sufficient control (Spaunhorst and Bradley, 2013). Benoit et al. (2019) found that dicamba applied at 600 g a.e. ha^{-1} controlled waterhemp 74% at 4 WAA in corn. Both studies used similar rates and application timings as the present study but found that the control of waterhemp was reduced between 3 and 4 WAA compared to the control of green pigweed in the present study. Treatments with dicamba/diflufenzopyr (57/143 g a.e. ha^{-1}) and dicamba/atrazine (504 g a.e. ha^{-1}/997 g a.i. ha^{-1}) controlled waterhemp 74 and 87%, respectively, at 8 WAA (Benoit et al., 2019). The reduction in weed density and biomass with these treatments was 67 and 73% and 89 and 93%, respectively; reduced waterhemp interference resulted in corn yield that was similar to the weed-free control (Benoit et al., 2019). These findings were consistent with the findings of the present study where dicamba/diflufenzopyr and dicamba/atrazine controlled green pigweed 80 and 89%, respectively, and reduced green pigweed interference resulting in a corn yield that was similar to that of the weed-free control. Based on studies published in the peer-reviewed literature and the current study it can be concluded that dicamba alone and in combination with other herbicides provides superior control of *Amaranthus* species relative to MCPA ester and 2,4-D amine.

Control of green pigweed with halosulfuron was ≤ 45% at 1, 2, 4, and 8 WAA. Benoit et al. (2019) found that halosulfuron (70 g a.i. ha^{-1}) controlled waterhemp 31% at 8 WAA which was similar to the green pigweed control in this study. As with flumetsulam in the PRE study, control with ALS-inhibiting herbicides was less than optimal at 8 WAA. Testing is required to determine the cross-resistance pattern of this green pigweed biotype to ALS-inhibiting herbicides.

The control of green pigweed with HPPD-inhibiting herbicides, topramezone, tolpyralate, and mesotrione mixed with atrazine was lower compared to previous studies. Metzger et al. (2018) reported that tolpyralate + atrazine (30 + 1000 g a.i. ha^{-1}), mesotrione + atrazine (100 + 280 g a.i. ha^{-1}), and topramezone + atrazine (12.5 + 500 g a.i. ha^{-1}) applied POST in corn controlled *Amaranthus* species 97, 91, and 86%, respectively at 8 WAA. Benoit et al. (2019) found that the control of waterhemp in corn with topramezone + atrazine (12.5 + 500 g a.i. ha^{-1}), and mesotrione + atrazine (100 + 280 g a.i. ha^{-1}) applied POST was 83 and 92%, respectively at 8 WAA. The level of *Amaranthus* species control in the two aforementioned studies was greater compared to the control of green pigweed in the present study. Topramezone/dimethenamid-p + atrazine and glyphosate/*S*-metolachlor/mesotrione + atrazine were more efficacious in controlling green pigweed than topramezone + atrazine and mesotrione + atrazine (Table 6). Topramezone/dimethenamid-p + atrazine is expected to control *Amaranthus* species 90% POST in corn which is greater than the 61% control obtained in the present study at 8 WAA (Ontario Ministry of Agriculture, Food and

Rural Affairs, 2021). Willemse et al. (2021) found that glyphosate/*S*-metolachlor/mesotrione (1050/1050/105 g a.i. ha^{-1}) + atrazine (280 g a.i. ha^{-1}) POST in corn controlled waterhemp 94, 97, and 100% across field sites at 8 WAA. The level of control of green pigweed with HPPD-inhibiting herbicides in the present study was less than expected.

Atrazine was identified as the most efficacious treatment in the POST study providing 94% control of green pigweed at 8 WAA. The improved control with atrazine applied alone can be attributed to the higher rate (1488 g a.i. ha^{-1}) compared to when it was applied as a tank mix or in a preformulated mixture (280-960 g a.i. ha^{-1}). All herbicide rates used in this study are consistent with the highest recommended rate on the label in Canada. Vyn et al. (2006), found that bromoxynil (280 g a.i. ha^{-1}) + atrazine (1500 g a.i. ha^{-1}) POST in corn controlled waterhemp 57 to 100% across two sites at 28 DAA. In the present study, bromoxynil + atrazine controlled green pigweed 77% at 4 WAA which is within the previously observed range (Vyn et al., 2006). In addition, atrazine applied alone at 1500 g a.i. ha^{-1} controlled waterhemp 0 to 100% across sites due to the presence of atrazine-resistant waterhemp, with the latter control being similar to the 96% control of green pigweed in the present study at 4 WAA (Vyn et al., 2006). Atrazine provides excellent control of *Amaranthus* species including MHR green pigweed.

Crop injury ratings for both PRE and POST studies indicated crop injury of less than 5% across all treatments and site years at the different evaluation time points. This finding indicates that the treatments are safe for application on corn and can therefore not be attributed to any differences in yield across treatments.

4. Conclusions

The results of the PRE and POST studies indicate that there are effective options for the control of MHR green pigweed in corn production in Ontario, Canada. In the PRE study, rimsulfuron + mesotrione provided the highest control across all variables evaluated. In the POST study atrazine provided the highest control across all variables evaluated. Reduced green pigweed interference with the aforementioned herbicides in the PRE and POST studies resulted in corn yields that were similar to the weed-free control. Upon reviewing related studies, it appears there are some inconsistencies across the different herbicide classes in terms of the control of *Amaranthus* species. This variability may be due to differences in environment, weather conditions, weed density, application timing, and herbicide resistance which vary across studies. The use of diverse weed management strategies is required to provide control of green pigweed and minimize weed seed return to the soil and prevent the spread of herbicide resistance in Ontario. Based on the findings from this research there are suitable PRE and POST-applied herbicides to control MHR green pigweed in Ontario corn production.

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