Weed Technology

www.cambridge.org/wet

Multiple herbicide-resistant waterhemp control with Group 15 herbicides

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

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

Research Article

Cite this article: Symington HE, Soltani N, Kaastra AC, Hooker DC, Robinson DE, Sikkema PH (2023) Multiple herbicide-resistant waterhemp control with Group 15 herbicides. Weed Technol. **37**: 251–258. doi: 10.1017/wet.2023.29

Received: 27 January 2023
Revised: 20 March 2023
Accepted: 31 March 2023
First published online: 8 May 2023

Associate Editor:
William Johnson, Purdue University

Nomenclature:
Giant foxtail; *Setaria faberi* Herrm.; pigweed; *Amaranthus* spp.; velvetleaf; *Abutilon theophrasti* Medik.; waterhemp; *Amaranthus tuberculatus* (Moq.) J.D. Sauer; woolly cupgrass; *Eriochloa villosa* (Thunb.) Kunth.

Keywords:
Waterhemp control; waterhemp biomass; waterhemp density; waterhemp emergence; residual herbicides

Corresponding author: Nader Soltani; Email: soltanin@uoguelph.ca

Abstract

Waterhemp has evolved resistance to seven herbicide modes of action in the United States and to five in Canada, which limits weed control options for producers. The objective of this research was to quantify the level and duration of residual control of multiple herbicide-resistant (MHR) waterhemp with five Group 15 herbicides (acetochlor, dimethenamid-p, flufenacet, pyroxasulfone, and *S*-metolachlor) applied preemergence in a non-crop area. Four field trials were conducted over a 2-yr period (2021, 2022) in southwestern Ontario, Canada. By 4 wk after application (WAA) 91% of waterhemp had emerged in the nontreated control area. The numerical control of waterhemp with all Group 15 herbicides, with the exception of pyroxasulfone, was greatest at 4 WAA, then control declined. Flufenacet provided the lowest waterhemp control; dimethenamid-p and *S*-metolachlor provided intermediate control, and acetochlor and pyroxasulfone provided the highest control. Waterhemp control with pyroxasulfone peaked at 6 WAA with 99% and declined to 77% at 12 WAA. Flufenacet (low and high rates) was predicted to reduce waterhemp emergence by 50% for 42 to 44 d after application (DAA). Dimethenamid-p, *S*-metolachlor, and acetochlor (both formulations and three rates) were predicted to reduce waterhemp emergence by 80% for 36, 43, and 33 to 51 DAA, respectively; in contrast, pyroxasulfone was predicted to reduce waterhemp emergence by 80% for 82 DAA. This study concludes that of the Group 15 herbicides evaluated, flufenacet provides the lowest and shortest residual control of waterhemp, and pyroxasulfone provides the highest and longest residual control of waterhemp.

Introduction

Waterhemp is becoming an increasingly challenging weed to control because it continues to evolve resistance to more herbicide modes of action. Its extended emergence pattern and rapid growth rate contribute to its competitiveness. Although the presence of waterhemp in the United States dates to the early 1900s, its significance as an agricultural weed was not realized until almost a century later (Hartzler 2019). Originally, waterhemp was primarily found in floodplains and marshes; however, waterhemp biotypes have adapted to much drier and hotter conditions, allowing it to spread rapidly throughout North America (Costea et al. 2005).

Waterhemp has rapidly evolved resistance to many different herbicide modes of action due to its high fecundity and wide genetic diversity. Waterhemp is a dioecious species; to produce viable offspring separate plants must cross-pollinate, which results in great genetic diversity among offspring (Bell and Tranel 2020; Montgomery et al. 2019). Since the first report in 1993 of waterhemp resistance to acetolactate synthase (ALS)–inhibiting herbicides (a Group 2 herbicide as categorized by the Weed Science Society of America [WSSA]), waterhemp has evolved resistance to six additional modes of action including the synthetic auxins (Group 4), and those that inhibit photosystem II (PS II, Group 5), 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS, Group 9), protoporphyrinogen oxidase (PPO, Group 14), very long-chain fatty acid elongases (VLCFAEs, Group 15), and 4-hydroxyphenylpyruvate dioxygenase (HPPD, Group 27) (Heap 2021). In the United States and Ontario, Canada, six- and five-way herbicide-resistant waterhemp has been reported, respectively (Heap 2021; Shergill et al. 2018; Symington et al. 2022). Despite the presence of multiple herbicide-resistant (MHR) biotypes, when used properly, effective herbicides are still a critically important tool in a diversified, integrated waterhemp management program.

Waterhemp has many characteristics that contribute to its success as a weed. It is a competitive weed that can drastically reduce crop yield. In studies completed in the United States and Ontario, Canada, waterhemp interference has reduced soybean and corn yields by up to 73% and 74%, respectively, when no control measures were implemented (Steckel and

Sprague 2004; Vyn et al. 2007). Waterhemp has a season-long emergence pattern that is unlike many other annual broadleaf weeds (Jhala et al. 2021). In Canada and the United States, waterhemp begins emerging in May and continues to emerge into the fall (Costea et al. 2005). Vyn et al. (2006) and Schryver et al. (2017) documented that in Ontario, waterhemp began emerging after seedbed preparation in conventionally tilled fields and continued to emerge throughout the summer months. Vyn et al. (2006) noted that peak waterhemp emergence occurred in mid-June with some emerging through October (Schryver et al. 2017). Hartzler et al. (1999) reported that waterhemp continued to germinate and emerge later into the growing season than velvetleaf, woolly cupgrass, and giant foxtail. Leon and Owen (2006) reported that in no-till systems, the majority of waterhemp emerged during the latter part of June, whereas in tilled systems, most waterhemp emerged in May and early June; emergence declined substantially over the remainder of the growing season. Franca (2015) found that 90% of cumulative waterhemp emergence occurred by the end of June regardless of tillage treatment; soil temperature followed by soil moisture were the greatest indicators of waterhemp emergence. Waterhemp germinates between 25 to 35 C (Guo and Al-Khatib 2003). Waterhemp is also resilient and can thrive in water-stressed and shaded environments (Sarangi et al. 2016; Steckel et al. 2003).

Waterhemp produces copious amounts of seed, which increases the weed problem in succeeding years. When not subjected to competition, a single waterhemp plant can produce up to 4.8 million seeds (Hartzler et al. 2004). Waterhemp seed production is highly influenced by surrounding plant competition and time of emergence. Steckel et al. (2003) reported that even late emerging waterhemp and other plants subjected to up to 68% shade can produce an abundance of seed. Late flushes of waterhemp are often uncontrolled, allowing these plants to contribute viable seeds to the weed seed bank in the soil.

With the evolution of MHR waterhemp, the development of two-pass weed control programs is increasing, with an effective soil-applied residual herbicide in the first pass (Beckie 2011; Gonzini et al. 1999; Mahoney et al. 2014; Wuerffel et al. 2015). Mahoney et al. (2014) reported ≥99% control of pigweed, a close relative of waterhemp, with various soil-applied residual herbicides applied preemergence (PRE). Meyer et al. (2015) found that a PRE application of dicamba + acetochlor (1,120 + 2,307 g ae/ai ha^{-1}) was effective at controlling MHR waterhemp; it provided >90% control at 6 to 7 wk after application, which was similar to PRE followed by early postemergence (POST) herbicide programs. A study conducted by Harder et al. (2012) also demonstrated the importance of using PRE herbicides for controlling waterhemp. With the exception of the POST application of mesotrione + crop oil concentrate + diammonium sulfate (110 g ai ha^{-1} + 1% vol/vol + 9.5 kg ha^{-1}) in 2002, control with a POST herbicide did not exceed 72%, whereas control with PRE herbicides was >84%; in 2003, control with PRE herbicides ranged from 90% to 95%, whereas POST herbicides controlled waterhemp by 0% to 68% with one POST herbicide providing 87% control. These results corroborate those of other studies that have shown that PRE-residual herbicides provide greater waterhemp control than POST-alone herbicide programs (Johnson et al. 2012; Legleiter et al. 2009; Taylor-Lovell et al. 2002). Legleiter et al. (2009) found that PRE-only and POST-only herbicides reduced waterhemp seed production by 61% to 94% and 21% to 71%, respectively.

The Group 15 herbicides include eight chemical families (Boger et al. 2000; Shaner 2003). Herbicides from four chemical families were evaluated in the current study: the chloroacetamide, chloroacetanilide, isoxazoline, and oxyacetamide chemical families, which represent the most frequently used Group 15 herbicides for Ontario row crop production. Some of the most common active ingredients that belong to the Group 15 herbicides are acetochlor, dimethenamid-p, flufenacet, *S*-metolachlor, and pyroxasulfone (Boger et al. 2000; Shaner 2003). Group 15 herbicides inhibit VLCFAEs (Tanetani et al. 2009; Trenkamp et al. 2004). Very long-chain fatty acids are important components of cell membranes and are important for lipids, cell division, polar auxin transport, cuticular wax development, and regulation of cell morphology. The Group 15 herbicides inhibit shoot elongation, which causes most susceptible seedlings to fail to emerge; those that do emerge appear distorted (Shaner 2014; Tanetani et al. 2009). The Group 15 soil-residual herbicides are used primarily for small-seeded annual grass control; however, they do have some activity on some small-seeded broadleaf weeds, including waterhemp (Weisshaar and Boger 1987). Acetochlor is registered in the United States for control of 11 monocotyledonous and nine dicotyledonous weeds (Anonymous 2020a, 2020b).

With the increasing prevalence of MHR waterhemp in Ontario, it is crucial that growers have access to weed control programs that provide full-season control to minimize weed seed return to the soil and maximize farm profitability. The use of Group 15 herbicides is one component of a waterhemp control strategy. Although some studies have been conducted on waterhemp control with soil-applied residual herbicides (Jhala et al. 2015; Steckel et al. 2002; Strom et al. 2019), the research presented in this study focuses on MHR waterhemp control with several Group 15 herbicides. The objective of this research was to quantify the level and length of MHR waterhemp control provided by several Group 15 herbicides applied PRE in Ontario.

Materials and Methods

Four site-years of data were collected between 2021 and 2022 from commercial fields with naturally occurring MHR waterhemp. Waterhemp seed was collected and cleaned in the fall of 2019, 2020, and 2021 from female plants throughout each site. Seed samples were stratified for 6 wk to aid with seed germination and screened in the greenhouse for herbicide resistance using imazethapyr, atrazine, metribuzin, glyphosate, lactofen, and mesotrione; all sites contained five-way resistant biotypes to the herbicides in Groups 2, 5, 9, 14, and 27. All sites demonstrated high resistance levels to the herbicides in Groups 2, 5, 9, and 27; the level of Group 14 resistance varied between sites. Field trials were conducted near Cottam, ON (42.149046°N, 82.683986°W) in 2021 and 2022 (E1 and E3, respectively). and near Newbury, ON (42.690833°N, 81.822589°W) (E2 and E4), in 2021 and 2022. Soil characteristics for each site are presented in Table 1. The sites were vertically tilled in the fall followed by a pass with a tandem disc and another pass of a field cultivator in the spring. The previous crop in Cottam 2021 and Newbury 2022 was soybean, whereas the previous crop in Cottam 2022 and Newbury 2021 was corn.

Trials were set up as a randomized complete block design with four replications. All trials were carried out with no crop planted to quantify waterhemp emergence and control in the absence of crop competition. Treatments included six Group 15 herbicides applied at different rates. There were 12 treatments in total: 1) an emulsifiable concentrate (EC) formulation of acetochlor (Harness®; Bayer Crop Science, St. Louis, MO) applied at 1,225, 2,100, and 2,950 g ai ha^{-1}; 2) a capsule suspension formulation of

https://doi.org/10.1017/wet.2023.29 Published online by Cambridge University Press

Table 1. Year, site, and soil characteristics for four field trials conducted in southwestern Ontario in 2021 and 2022.[a,b]

Env	Year	Site	Soil Texture	Sand	Silt	Clay	OM	pH	CEC
				———	———	%	———		
E1	2021	Cottam	Sandy loam	62	23	15	2.3	5.9	7.7
E2	2021	Newbury	Loamy sand	79	14	6	2.8	6.5	7.9
E3	2022	Cottam	Sandy loam	55	27	17	2.2	5.7	9.1
E4	2022	Newbury	Loamy sand	84	11	4	2.5	6.7	11.6

[a]Abbreviations: CEC, cation exchange capacity; Env, environment; OM, organic matter.
[b]Soil analysis was performed by A&L Canada Laboratories Inc. (2136 Jetstream Road, London, ON, N5V 3P5 Canada) from soil cores taken to depths of 15 cm.

acetochlor (Warrant®; Bayer Crop Science, St. Louis, MO) applied at 1,050, 1,375, and 1,700 g ai ha^{-1}; 3) dimethenamid-p (Frontier® Max; BASF Canada, Mississauga, ON) applied at 693 g ai ha^{-1}; 4) flufenacet (Define SC®; Bayer Crop Science, Calgary, AB) applied at 500 and 750 g ai ha^{-1}; 5) *S*-metolachlor (Dual II Magnum®; Syngenta Canada, Guelph, ON) applied at 1,600 g ai ha^{-1}; and 6) pyroxasulfone (Zidua® SC; BASF Canada, Mississauga, ON) applied at 246.5 g ai ha^{-1}. All rates were established on the basis of label recommendations or proposed label rates where applicable for corn or soybean. A nontreated control was included in each replicate. Plots were 8 m long and 2 m wide with a 2-m alley between each replicate. Each plot was split into a front and back half to conduct two separate assessments within the same plot. Each half measured 4 m long and 2 m wide. In the front half of each plot, three randomly placed, permanent 0.25-m^2 quadrats were established prior to herbicide application to measure waterhemp emergence. All quadrats were placed in the center 1 m of each plot to avoid lower rates at plot edges. All quadrats remained in place for the duration of the trial. All herbicide treatments were applied prior to waterhemp emergence with the use of a CO_2-pressurized backpack sprayer that was calibrated to deliver 200 L ha^{-1} at 240 kPa. The boom consisted of four ultra-low drift (ULD 120-02; Hypro, Pentair Ltd., London, UK) nozzles that were spaced 50 cm apart to deliver a spray width of 2 m. Table 2 lists the application date for each site-year.

Waterhemp control and emergence assessments commenced at 2 WAA and were performed at biweekly intervals with the final assessment at 12 WAA. Visible waterhemp control ratings were assessed from the back half of each plot by assigning a value of 0 to 100, which represented the estimated waterhemp biomass reduction relative to the nontreated control in each replicate; 0 represented no MHR waterhemp control and 100 indicated complete waterhemp control. At each assessment timing, the number of waterhemp that had emerged in the prior 14 d within each quadrat in the front half of the plot was recorded and then removed with an application of glufosinate (Liberty® 200 SN; BASF Canada, Mississauga, ON) at 500 g ha^{-1} that was applied perpendicular to the plot length across the front 4 m of each replicate.

Statistical Analysis

All data analyses were conducted using SAS software (v. 9.4; SAS Institute Inc., Cary, NC). Control data were analyzed using linear mixed-model variance analysis, the GLIMMIX procedure. Herbicide treatment was considered the fixed effect, whereas environment (site-year), replicate within environment, and treatment by environment were random effects. Data across all environments were pooled for analysis. The assumption that residuals were random, independent of treatment and design effects, have a mean of zero, homogenous, and normally distributed was confirmed by plotting the studentized residuals and referencing the Shapiro-Wilk test statistic.

Waterhemp emergence data were regressed against time in days using the NLIN procedure with SAS software. Two different equations were evaluated and compared for each treatment. Where waterhemp emergence over the course of the study followed a negative linear relationship, Equation 1 was used.

$$Y = (m * x) + b \quad [1]$$

where y = response parameter, m = slope, and b = y intercept.

Where waterhemp emergence followed a descending dose-response curve, then Equation 2 was used.

$$Y = c + (d - c)/\left(1 + e^{(b*(log(x) - log(I)))}\right)0 \quad [2]$$

where y = response parameter, c = upper asymptote, d = lower asymptote, b = slope about I, and I = days eliciting a response equidistant between c and d.

Where P values were significant at $P < 0.05$ for a sum of squares reduction test for each treatment, sites were separated. Predicted parameter values from the nonlinear regression were used to compute the number of days that each treatment provided a 50%, 80%, and 95% reduction in waterhemp emergence relative to the nontreated control for each 2-wk period. Where values were not computable, they were deemed to be not estimable, represented by NE in Table 3. Where values were able to be computed but they fell outside of the assessment range evaluated 0 to 84 d, they were expressed as NA, or not applicable.

Results and Discussion

Rainfall (≥28 mm) occurred within 2 wk of herbicide application at all sites in 2021 and 2022 (Table 2). This amount was likely sufficient to dissolve the herbicides into the soil water solution. The average monthly temperatures in all four environments were equal to or higher than the 30-yr average (Table 2).

Multiple Herbicide-Resistant Waterhemp Emergence

Cumulative waterhemp emergence was between 493 and 2,583 plants m^{-2} in the 12 wk following herbicide application in the nontreated control (Figure 1). On average, 91% of waterhemp emergence occurred within 4 wk of the herbicide application; this correlated to the second or third week of June. Waterhemp continued to emerge during the months of June, July, August, and September but at progressively lower rates. Similarly, Franca (2015) noted that by the end of June, 90% of cumulative

https://doi.org/10.1017/wet.2023.29 Published online by Cambridge University Press

Table 2. Year, site, application date, rainfall, and average temperature for four field trials conducted in southwestern Ontario in 2021 and 2022.

Year	Site	Application date	Rainfall								Average air temperature							
			Weeks after application															
			0–2	2–4	4–6	6–8	8–10	10–12	12–14	14–16	0–2	2–4	4–6	6–8	8–10	10–12	12–14	14–16
			mm								degrees C							
2021	Cottam	May 21	49	16	79	25	105	74	27	32	18	23	23	23	23	22	23	22
2021	Newbury	May 26	50	32	167	45	11	82	23	66	19	20	23	20	21	22	21	19
2022	Cottam	May 18	28	21	2	1	27	43	26	16	19	19	23	23	24	24	21	22
2022	Newbury	May 13	44	82	37	8	34	48	26	58	17	18	21	21	22	22	22	21
	Thirty-year average[a]			May 80		June 72	July 79		August 69	September 81		May 14		June 19	July 21		August 20	Sept. 17

[a]Thirty-year average values are based on data collected from the Ridgetown campus weather station (Ridgetown, ON), central to all sites, from 1991 to 2022.

waterhemp had emerged. These trends are similar to those observed by Leon and Owen (2006), in which regardless of the tillage system, most waterhemp emerged in May and June, and emergence declined over the remainder of the summer and fall months.

At the E1 (Cottam 2021), E2 (Newbury 2021), and E3 (Cottam 2022) locations, it was estimated that flufenacet (500 g ha^{-1}) reduced waterhemp emergence by 50% for 44 days after application (DAA; Table 3); the number of DAA that flufenacet reduced waterhemp emergence by 80% and 95% was not estimable because it never provided >80% reduction in emergence. At E4 (Newbury 2022) the number of DAA that flufenacet reduced waterhemp emergence by 50%, 80%, and 95% was nonestimable. The high rate of flufenacet (750 g ha^{-1}) was predicted to provide a 50% reduction in waterhemp emergence for 42 DAA; the number of DAA that flufenacet reduced waterhemp emergence by 80% or 95% was nonestimable. At E1, E2, and E3, it is estimated that *S*-metolachlor reduced waterhemp emergence by 50%, 80%, and 95% for 70, 43, and 12 DAA; in contrast, at E4 (high-density environment) it is estimated that *S*-metolachlor reduced waterhemp density by 50% for 22 DAA; the number of DAA that *S*-metolachlor reduced waterhemp emergence by 80% and 95% was nonestimable. Similarly, dimethenamid-p was estimated to reduce waterhemp emergence by 50%, 80%, and 95% at 46, 36, and 26 DAA at the E1, E2, and E3 locations, respectively; in contrast at the high-density environment (E4) dimethenamid-p was estimated to reduce waterhemp emergence by 50% for 42 DAA; an 80% and 95% reduction in waterhemp emergence at E4 was nonestimable. The low rate of acetochlor CS (1,050 g ha^{-1}) was predicted to provide a 50% reduction in waterhemp emergence for greater than the duration of the assessments, while an 80% and 95% reduction was estimated for 33 and 5 DAA, respectively. The medium rate of acetochlor CS (1,375 g ha^{-1}) was predicted to reduce waterhemp emergence by 50%, 80%, and 95% for 78, 34, and 12 DAA, respectively. The length of residual waterhemp control with the high rate of acetochlor CS (1,700 g ha^{-1}) varied between environments. At E1, E2, and E3, the 50% predicted emergence reduction was beyond the assessment range, whereas the estimated 80% and 95% reductions were 51 and 23 DAA, respectively. At E4, a 50% reduction in emergence was predicted for 49 DAA but emergence reductions for 80% or 95% were nonestimable. With acetochlor EC at the low rate (1,225 g ha^{-1}), 50%, 85%, and 95% reductions in waterhemp emergence were estimated for 65, 33, and 17 DAA, respectively. Acetochlor EC (2,100 g ha^{-1}), was predicted to reduce waterhemp emergence by 50% and 80% for 54 and 38 DAA, respectively; a 95% reduction in waterhemp emergence was nonestimable. The high rate of acetochlor EC (2,950 g ha^{-1}) was estimated to reduce waterhemp emergence by 50%, 80%, and 95% for 66, 37, and 22 DAA, respectively. Pyroxasulfone (246.5 g ha^{-1}) was estimated to reduce waterhemp emergence by 80% and 95% for 82 and 5 DAA, respectively; the 50% emergence reductions could not be estimated because they exceeded the assessment range.

Based on the results of these trials, the longer residual activity of Group 15 herbicides was achieved in lower density waterhemp environments. Shorter 50%, 80%, and 95% emergence reductions were achieved at the E4 location, which contained the greatest cumulative emergence of waterhemp of the four sites (Figure 1). Similarly, Willemse et al. (2021) reported that in environments with greater waterhemp density and biomass, control was as much as 34% lower than in low-density waterhemp environments. Therefore, in high weed pressure fields, active scouting is needed

https://doi.org/10.1017/wet.2023.29 Published online by Cambridge University Press

Table 3. Predicted number of days that each herbicide reduces multiple herbicide-resistant waterhemp emergence by 50%, 80%, and 95% for four field trials conducted in a non-cropped area in southwestern Ontario in 2021 and 2022.[a]

		Regression parameters						
Treatment	Rate	m (± SE)		b (± SE)		DR_{50}	DR_{80}	DR_{95}
	g ai ha^{-1}							
Negative linear[b]								
Acetochlor CS	1,050	−0.53 (0.15)		97.67 (7.81)		NA[d]	33	5
Acetochlor CS	1,375	−0.69 (0.14)		103.5 (7.59)		78	34	12
Acetochlor CS								
E1, E2, E3	1,700	−0.52 (0.12)		106.80 (6.43)		NA	51	23
E4	1,700	−0.50 (0.36)		74.57 (19.99)		49	NE	NE
Acetochlor EC	1,225	−0.94 (0.14)		111.10 (7.48)		65	33	17
Acetochlor EC	2,950	−1.01 (0.12)		116.90 (6.68)		66	37	22
Pyroxasulfone	246.5	−0.19 (0.12)		95.92 (6.59)		NA	82	5
Descending dose-response[c]		C (± SE)	D (± SE)	b (± SE)	I_{50} (± SE)			
Flufenacet								
E1, E2, E3	500	30.85 (10.04)	68.03 (8.14)	8.83 (15.34)	43.91 (7.26)	44	NE	NE
E4	500	0.00 (0.00)	41.47 (8.60)	14.54 (14.89)	48.54 (7.50)	NE	NE	NE
Flufenacet	750	35.31 (5.02)	72.81 (5.84)	71.60 (855.50)	42.05 (0.00)	42	NE	NE
S-metolachlor								
E1, E2, E3	1,600	8.30 (111.00)	95.24 (9.90)	3.37 (3.96)	68.58 (54.48)	70	43	12
E4	1,600	0.00 (0.00)	52.73 (17.72)	2.66 (3.17)	63.91 (24.19)	22	NE	NE
Dimethenamid-p								
E1, E2, E3	693	31.61 (9.19)	93.08 (9.48)	6.82 (6.23)	40.59 (4.81)	46	36	26
E4	693	5.92 (8.57)	55.29 (11.21)	73.76 (165.40)	43.53 (0.00)	42	NE	NE
Acetochlor EC	2,100	36.19 (9.58)	94.11 (6.94)	6.57 (4.76)	45.22 (4.94)	54	38	NE

[a]Abbreviations: CS, capsule suspension; EC, emulsifiable concentrate; E1, Cottam 2021; E2, Newbury 2021; E3, Cottam 2022; E4, Newbury 2022; DR_{50}, DR_{80}, and DR_{95} denote the predicted number of days that each treatment provides 50%, 80%, and 95% density reductions of multiple herbicide-resistant waterhemp, respectively (based on the respective nonlinear regression equation and its parameters); NE, nonestimable; NA, not applicable; SE, standard error.
[b]Negative linear equation represented by $y = m*x + b$ where m = slope and b = y-intercept.
[c]Descending dose response equation represented by $y = c + (d - c)/(1 + e^{(b * (\log(x) - \log(I)))})$ where c = upper asymptote, d = lower asymptote, b = slope about I, and I_{50} = days eliciting a response equidistant between c and d.
[d]Number of days exceeds trial period evaluated.

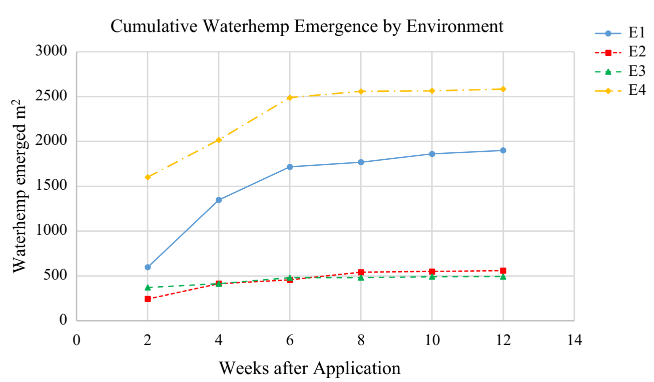

Figure 1. Cumulative waterhemp emergence for each environment based on the average of four replications of the nontreated control treatment. E1, Cottam 2021; E2, Newbury 2021; E3, Cottam 2022; E4, Newbury 2022.

for the timely application of POST herbicides to control later emerging waterhemp flushes.

Multiple Herbicide-Resistant Waterhemp Control

Across all herbicides tested, flufenacet (500 g ha^{-1}) controlled waterhemp the least, at 54% at 2 WAA, and it was similar to that of flufenacet (750 g ha^{-1}), *S*-metolachlor, dimethenamid-p, and acetochlor CS (1,050, 1,375, and 1,700 g ha^{-1}), which varied numerically from 59% to 77% (Table 4). Acetochlor EC at 1,225, 2,100, and 2,950 g ha^{-1} provided numerically better control than the aforementioned treatments 2 WAA at 88%, 91%, and 91% respectively. The medium and high rates of acetochlor EC provided greater control than flufenacet (500 and 750 g ha^{-1}) and *S*-metolachlor. Pyroxasulfone controlled waterhemp 84% at 2 WAA, which was greater than flufenacet (500 g ha^{-1}) and *S*-metolachlor but similar to all other treatments.

MHR waterhemp control increased from 2 to 4 WAA with all treatments (Table 4). Flufenacet (500 and 750 g ha^{-1}) controlled MHR waterhemp 77% to 80%, which was lower than the medium rate of acetochlor CS, all rates of acetochlor EC, and pyroxasulfone. Waterhemp control with *S*-metolachlor was 87%; similar to all other treatments. Dimethenamid-p provided 92% waterhemp control, which was greater than the low rate of flufenacet. Acetochlor (CS and EC formulations) at the low, medium, and high rates and pyroxasulfone controlled waterhemp similarly at 91% to 98%. Hausman et al. (2013) reported that acetochlor EC (1,680 g ha^{-1}) and pyroxasulfone (210 g ha^{-1}) controlled waterhemp 87% in corn and soybean at 4 WAA, which is similar to the results from the current study. Steckel et al. (2002) reported that acetochlor EC (1,960 g ha^{-1}) provided 98% waterhemp control, and Oliveira et al. (2017) documented that pyroxasulfone (270 g ha^{-1}) applied PRE provided 95% control of waterhemp at 4 WAA, consistent with the results from this study.

MHR waterhemp control started declining from 4 WAA with all treatments except pyroxasulfone (Table 4). Waterhemp control with flufenacet (500 and 750 g ha^{-1}), *S*-metolachlor, and dimethenamid-p decreased by 20%, 16%, 9%, and 9%, respectively, from 4 to 6 WAA. S-metolachlor provided 78% waterhemp control 6 WAA; waterhemp control with *S*-metolachlor applied PRE at similar rates was extremely variable from 6% to 95% (Hausman et al. 2013; Steckel et al. 2002; Strom et al. 2019); the results from this study were within this range. Waterhemp control with

https://doi.org/10.1017/wet.2023.29 Published online by Cambridge University Press

Table 4. Mean percent control of multiple herbicide-resistant waterhemp at 2, 4, 6, 8, 10, and 12 wk after PRE application of Group 15 herbicides in a non-cropped area for four field trials conducted in southwestern Ontario in 2021 and 2022.[a,b]

		Control					
Treatment	Rate	2 WAA	4 WAA	6 WAA	8 WAA	10 WAA	12 WAA
	g ai ha^{-1}						
Flufenacet	500	54 c	77 c	57 d	38 d	24 d	21 d
Flufenacet	750	65 bc	80 bc	64 cd	47 cd	31 cd	23 cd
S-metolachlor	1,600	59 c	87 abc	78 bc	64 bcd	47 bcd	40 bcd
Dimethenamid-p	693	74 abc	92 ab	83 ab	67 bc	47 bcd	34 bcd
Acetochlor CS	1,050	74 abc	91 abc	82 aabc	67 bc	52 bcd	44 bcd
Acetochlor CS	1,375	77 abc	95 a	83 aab	73 ab	58 abc	41 bcd
Acetochlor CS	1,700	73 abc	93 ab	86 aab	81 ab	67 ab	52 abc
Acetochlor EC	1,225	88 ab	98 a	91 aab	76 ab	66 ab	53 abc
Acetochlor EC	2,100	91 a	99 a	93 aab	78 ab	56 abc	39 bcd
Acetochlor EC	2,950	91 a	98 a	96 aab	83 ab	68 ab	53 ab
Pyroxasulfone	246.5	84 ab	98 a	99 aa	97 a	82 a	77 a

[a]Abbreviations: CS, capsule suspension; EC, emulsifiable concentrate; WAA, weeks after application.
[b]Means followed by the same letter (a–d) within a column are not significantly different according to Tukey-Kramer grouping at $P < 0.05$.

acetochlor CS declined by 9%, 12%, and 7% from 4 to 6 WAA for the low, medium, and high rates, respectively. The two formulations of acetochlor at all three rates provided similar waterhemp control. This corresponds to the acetochlor label, which claims up to 4 wk residual control (Anonymous 2020a, 2020b). Pyroxasulfone provided the highest control of waterhemp (99%) at 6 WAA, which was similar to all acetochlor treatments and dimethenamid-p.

MHR waterhemp control with all treatments decreased from 6 to 12 WAA in each respective 2-wk increment (Table 3). Steckel et al. (2002) reported 61% and 57% control of waterhemp in corn with dimethenamid (1,050 g ha^{-1}) and *S*-metolachlor (1,420 g ha^{-1}) applied PRE, respectively at 8 WAA. This is consistent with the findings of 67% and 64% control with dimethenamid-p and *S*-metolachlor, respectively, in this study at 8 WAA. Another study by Hausman et al. (2013) investigated waterhemp control in corn and soybean and concluded that in soybean *S*-metolachlor (1,425 g ha^{-1}) applied PRE provided 55% waterhemp control; however, in corn *S*-metolachlor (1,600 g ha^{-1}) applied PRE provided only 7% waterhemp control, demonstrating that waterhemp control with *S*-metolachlor is dependent on rate and environment. Acetochlor CS at 1,050, 1,375, and 1,700 g ha^{-1} controlled waterhemp by 67%, 73%, and 81%, respectively, at 8 WAA. Steckel et al. (2002) reported that acetochlor CS at a higher rate of 1,960 g ha^{-1} controlled waterhemp by 85% to 95%. Acetochlor EC at 1,225, 2,100, and 2,950 g ha^{-1} controlled waterhemp by 76%, 78%, and 83%, respectively, at 8 WAA. Pyroxasulfone controlled waterhemp 97%, which was similar to all rates of acetochlor EC and the medium and high rates of acetochlor CS. Among all treatments evaluated, only pyroxasulfone provided greater than 80% waterhemp control up to 10 WAA.

Waterhemp control was similar across herbicides at 10 and 12 WAA. At 12 WAA, all herbicides controlled waterhemp 21% to 53%, with the exception of pyroxasulfone (Table 4). Pyroxasulfone controlled waterhemp by 77%, which was greater than all treatments except the high rate of acetochlor CS and the low and high rate of acetochlor EC.

One limitation of this study is that waterhemp emergence may occur much differently in the presence of crop competition. Waterhemp emergence has been shown to be influenced by soil moisture and soil temperature (Franca 2015), which will vary in a cropped field. The current study mimics fallow ground, and soil parameters such as soil moisture have been found to vary substantially in fallow ground situations (McGuire et al. 1998; Tanaka and Aase 1987); therefore, those same parameters would likely vary in a corn, soybean, or other row crops compared to the results observed from the current study. However, the presence of a crop such as corn or soybean will also act as a control method against waterhemp emergence due to competition and may reduce overall emergence. Soil residual herbicides require rainfall for activation; in the absence of rainfall to dissolve herbicides like those in Group 15, lower control, and shorter residual activity will likely be observed (Hartzler 2021).

In conclusion, pyroxasulfone provided the highest waterhemp control and provided the longest residual control. Group 15 herbicides provided >80% waterhemp control for 6 WAA except for flufenacet and *S*-metolachlor. Dimethenamid-p, acetochlor EC, *S*-metolachlor, acetochlor CS, and pyroxasulfone reduced waterhemp emergence by 80% for up to 36, 38, 43, 51, and 82 DAA, respectively; flufenacet (500 and 750 g ha^{-1}) never reduced waterhemp emergence more than 80% in this study. Pyroxasulfone applied PRE was the most efficacious Group 15 herbicide evaluated in this study for waterhemp control. It controlled MHR waterhemp >80% up to 10 WAA. Acetochlor provided good control of waterhemp; however, control began to decline after 6 WAA. *S*-metolachlor and dimethenamid-p provided intermediate control, and flufenacet was the least efficacious on waterhemp. However, in the absence of crop competition, these herbicides did not provide season-long control; late-emerging plants may be capable of contributing viable seeds to the soil weed seed bank. These herbicides are one component of a diversified, integrated waterhemp control program; however, POST-applied herbicides may be required to control late flushes that emerge beyond the residual period provided by Group 15 herbicides. An effective POST herbicide applied after the PRE application of pyroxasulfone or acetochlor would also reduce the selection pressure for the evolution of Group 15–resistant waterhemp. Given the confirmation of Group 15–resistant waterhemp in the United States and Canada, it is of utmost importance that selection pressure on currently effective herbicides is minimized.

Practical Implications

Waterhemp is a challenge to control and continues to evolve resistance to new herbicide modes of action. To achieve adequate control of this troublesome weed and reduce further seed return to the soil seed bank, the use of a soil-applied residual herbicide is necessary. However, not all soil-applied herbicides are effective in controlling MHR waterhemp, and the length of residual control varies with those herbicides that are effective. Group 15 resistant waterhemp has not been reported in Ontario. Group 15 herbicides are considered effective soil-applied chemistry to control waterhemp. The results of this research are helpful in quantifying the soil residual capacity of various Group 15 herbicides to control MHR waterhemp in Ontario. Additionally, herbicide manufacturers are currently awaiting registration from the Pest Management Regulatory Agency in Canada to approve acetochlor use in Canada. If acetochlor becomes registered for use in Ontario, this research will provide weed management practitioners with reliable data to demonstrate that pyroxasulfone or acetochlor are the most efficacious Group 15 herbicides to combat MHR waterhemp. This research also provides growers and agronomists with a strong base from which to establish a two-pass weed control strategy to control MHR waterhemp. The results of this study clearly demonstrate that a Group 15 herbicide such as pyroxasulfone or acetochlor can reduce waterhemp emergence. Given that waterhemp can emerge throughout the season and even late emerging plants can contribute seed to the soil weed seed bank, it is unlikely that any of these PRE Group 15 herbicides would provide sufficient weed control alone and should be applied in a two-pass system.

Acknowledgments. We thank Dr. Michelle Edwards for her statistical support; the University of Guelph, Ridgetown Campus summer staff for their field support; and Bayer Crop Science Inc., Ontario Bean Growers (OBG), and the Ontario Agri-Food Innovation Alliance for the funding to conduct this research. A co-author of this manuscript, Allan Kaastra, is the Senior Agronomic Development Representative, Bayer Crop Science Inc. Other authors have no conflict of interest to declare.

References

Anonymous (2020a) HARNESS® Herbicide Label. Bayer CropScience, St. Louis, MO

Anonymous (2020b) WARRANT® Herbicide Label. Bayer CropScience, St. Louis, MO

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

Bell MS, Tranel PJ (2010) Time requirement from pollination to seed maturity in waterhemp (*Amaranthus tuberculatus*). Weed Sci 58:163–173

Boger P, Matthes B, Schmalfu J (2000) Towards the primary target of chloroacetamides – New findings pave the way. Pest Manag Sci 56:497–508

Costea M, Weaver SE, Tardif FJ (2005) The biology of invasive alien plants in Canada. 3. *Amaranthus tuberculatus* (Moq.) Sauer var. *rudis* (Sauer). Can J Plant Sci 85:507–522

Franca LX (2015) Emergence patterns of common waterhemp and palmer amaranth in southern Illinois. Master's thesis. Carbondale: Southern Illinois University

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

Guo P, Al-Khatib K (2003) Temperature effects on germination and growth of redroot pigweed (*Amaranthus retroflexus*), Palmer amaranth (*A. palmeri*), and common waterhemp (*A. rudis*). Weed Sci 51:869–875

Harder DB, Nelson KA, Smeda RJ (2012) Management options and factors affecting control of a common waterhemp (*Amaranthus rudis*) biotype resistant to protoporphyrinogen oxidase-inhibiting herbicides. Int J Agron 2012:1–7

Hartzler B (2019) Waterhemp: A 'Friendly' native evolves into the Cornbelt's worst weed problem. Ames: Iowa State University Extension and Outreach. https://crops.extension.iastate.edu/blog/bob-hartzler/waterhemp-friendly-native-evolves-cornbelts-worst-weed-problem. Accessed: November 18, 2022

Hartzler B (2021) Preemergence herbicides, dry soils and rain. Preemergence Herbicides, Dry Soils and Rain | Integrated Crop Management (iastate.edu). Ames: Iowa State University Extension and Outreach. Accessed: December 23, 2022

Hartzler RG, Battles BA, Nordby D (2004) Effect of common waterhemp (*Amaranthus rudis)* emergence date on growth and fecundity in soybean. Weed Sci 52:242–245

Hartzler RG, Buhler DD, Stoltenberg DE (1999) Emergence characteristics of four annual weed species. Weed Sci 47:578–584

Hausman NE, Tranel PJ, Riechers DE, Maxwell DJ, Gonzini LC, Hager AG (2013) Responses of an HPPD inhibitor-resistant waterhemp (*Amaranthus tuberculatus*) population to soil-residual herbicides. Weed Technol 27: 714–711

Heap I (2021) The International Herbicide-Resistant Weed Database. http://www.weedscience.org/. Accessed: February 18, 2022

Jhala AJ, Malik MS, Willis JB (2015) Weed control and crop tolerance of micro-encapsulated acetochlor applied sequentially in glyphosate-resistant soybean. Can J Plant Sci 95:973–981

Jhala AJ, Norsworthy JK, Ganie ZA, Sosnoskie LM, Beckie HJ, Mallory-Smith CA, Liu J, Wei W, Wang J, Stoltenberg DE (2021) Pollen-mediated gene flow and transfer of resistance alleles from herbicide-resistant broadleaf weeds. Weed Technol 35:173–187

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

Legleiter TR, Bradley KW, Massey RE (2009) Glyphosate-resistant waterhemp (*Amaranthus rudis*) control and economic returns with herbicide programs in soybean. Weed Technol 23:54–56

Leon RG, Owen MD (2006) Tillage systems and seed dormancy effects on common waterhemp (*Amaranthus tuberculatus*) seedling emergence. Weed Sci 54:1037–1044

Mahoney KJ, Shropshire C, Sikkema PH (2014) Weed management in conventional-and no-till soybean using flumioxazin/pyroxasulfone. Weed Technol 28:298–306

McGuire AM, Bryant DC, Denison RF (1998) Wheat yields, nitrogen uptake, and soil moisture following winter legume cover crop vs. fallow. Agron J 90:404–410

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

Montgomery JS, Sadeque A, Giacomini DA, Brown PJ, Tranel PJ (2019) Sex-specific markers for waterhemp (*Amaranthus tuberculatus*) and Palmer amaranth (*Amaranthus palmeri*). Weed Sci 67:412–418

Oliveira MC, Jhala AJ, Gaines T, Irmak S, Amundsen K, Scott JE, Knezevic SZ (2017) Confirmation and control of HPPD-inhibiting herbicide–resistant waterhemp (*Amaranthus tuberculatus*) in Nebraska. Weed Technol 31:67–79

Sarangi D, Irmak S, Lindquist JL, Knezevic SZ, Jhala AJ (2016) Effect of water stress on the growth and fecundity of common waterhemp (*Amaranthus rudis*). Weed Sci 64:42–52

Schryver MG, Soltani N, Hooker DC, Robinson DE, Tranel PJ, Sikkema PH (2017) Control of glyphosate-resistant common waterhemp (*Amaranthus tuberculatus* var. *rudis*) in soybean in Ontario. Weed Technol 31:811–821

Shaner DL (2003) Herbicide safety relative to common targets in plants and animals. Pest Manag Sci 60:17–24

Shaner DL (2014). Pages 22–23 *in* Herbicide Handbook. 10th Edition. Lawrence, KS: Weed Science Society of America

Shergill LS, Barlow BR, Bish MD, Bradley KW (2018) Investigations of 2,4-D and multiple herbicide resistance in a Missouri waterhemp (*Amaranthus tuberculatus*) population. Weed Sci 66:386–394

Steckel LE, Sprague CL (2004) Common waterhemp (*Amaranthus rudis*) interference in corn Weed Sci 52:359–364

Steckel LE, Sprague CL, Hager AG (2002) Common waterhemp (*Amaranthus rudis*) control in corn (*Zea mays*) with single preemergence and sequential applications of residual herbicides. Weed Technol 16:755–761

Steckel LE, Sprague CL, Hager AG, Simmons FW, Bollero GA (2003) Effects of shading on common waterhemp (*Amaranthus rudis*) growth and development. Weed Sci 51:898–903

Strom SA, Gonzini LC, Mitsdarfer C, Davis AS, Riechers DE, Hager AG (2019) Characterization of multiple herbicide–resistant waterhemp (*Amaranthus tuberculatus*) populations from Illinois to VLCFA-inhibiting herbicides. Weed Sci 67:369–379

Symington HE, Soltani N, Sikkema PH (2022) Confirmation of 4-hydroxyphenylpyruvate dioxygenase inhibitor-resistant and 5-way multiple-herbicide-resistant waterhemp in Ontario, Canada. J Agric Sci. 14:53

Tanaka DL, Aase JK (1987) Fallow method influences on soil water and precipitation storage efficiency. Soil Tillage Res 9:307–316

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

Taylor-Lovell S, Wax LM, Bollero G (2002) Preemergence flumioxazin and pendimethalin and postemergence herbicide systems for soybean (*Glycine max*). Weed Technol 16:502–511

Trenkamp S, Martin W, Tietjen K (2004) Specific and differential inhibition of very-long-chain fatty acid elongases from *Arabidopsis thaliana* by different herbicides. Proc Natl Acad Sci USA 101:11903–11908

Vyn JD, Swanton CJ, Weaver SE, Sikkema PH (2007) Control of herbicide-resistant common waterhemp (*Amaranthus tuberculatus* var. *rudis*) with pre- and post-emergence herbicides in soybean. Can J Plant Sci 87:175–182

Vyn JD, Swanton CJ, Weaver SE, Sikkema PH (2006). Control of *Amaranthus tuberculatus* var. *rudis* (common waterhemp) with pre and post-emergence herbicides in *Zea mays* L. (maize). Crop Prot 25:1051–1056

Weisshaar H, Boger P (1987) Primary Effects of chloroacetamides. Pest Biochem Physiol 28:286–293

Willemse C, Soltani N, Benoit L, Hooker DC, Jhala AJ, Robinson DE, Sikkema P (2021) Herbicide programs for control of waterhemp (*Amaranthus tuberculatus*) resistant to three distinct herbicide sites of action in corn. Weed Technol 35:753–760

Wuerffel RJ, Young JM, Matthews JL, Young BG (2015) Characterization of PPO-inhibitor–resistant waterhemp (*Amaranthus tuberculatus*) response to soil-applied PPO-inhibiting herbicides. Weed Sci 63:511–521