Weed Technology 2017 31:828–837

Control of Glyphosate-Resistant Common waterhemp (*Amaranthus rudis*) in Three New Herbicide-Resistant Soybean Varieties in Ontario

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Glyphosate-resistant (GR) common waterhemp (CW) is a localized weed in Ontario and one of the most problematic weeds in the US Corn Belt. First confirmed in Ontario in 2014, GR CW has now been confirmed in forty fields in three counties in Ontario as of 2015. Historically, the primary POST herbicides used for the control of CW in soybean were glyphosate, acifluorfen and fomesafen, but resistance to all three has been confirmed in many US states. Research was conducted in 2015 and 2016 to determine the control of GR CW with some of the new herbicide-resistant soybean technologies including glufosinate (LibertyLink), 2,4-D and glyphosate (Enlist), and isoxaflutole, mesotrione, and glufosinate (HPPD-resistant). Glyphosate-resistant CW was controlled (≥90%) all season with a two-pass weed control system across all herbicide-resistant soybean technologies evaluated. The two-pass weed control system in this research is defined as a PRE herbicide followed by a POST herbicide. At 12 WAA, the two-pass programs in LibertyLink, Enlist, and HPPD-resistant systems controlled GR CW up to 98, 98, and 92%, respectively, and reduced GR CW densities to 0 to 2% of the weedy control at 4 WAA. The two-pass programs provided greater GR CW control than PRE or POST herbicides alone. This study found that the use of two-pass weed control programs in glufosinate-resistant, glyphosate DMA/2,4-D choline-resistant and HPPD-resistant soybean can provide excellent control of GR CW, and can be valuable tools to reduce the selection intensity for herbicide-resistant weeds. Through the rotational use of different technologies, growers may be able to better manage their weed populations in reducing the risk of resistance when compared to the use of one herbicide repeatedly.

Nomenclature: Glufosinate; glyphosate; common waterhemp, *Amaranthus rudis* Sauer; soybean; *Glycine max* (L.) Merr.

Key words: Enlist soybean, glufosinate resitance, glyphosate resistance, glyphosate susceptible, 4-hydroxyphenylpyruvate dioxygenase–resistant soybean, LibertyLink soybean.

Common waterhemp (CW) is a small-seeded, summer annual broadleaf weed that is a member of the *Amaranthus* genus and is closely related to many commonly found pigweed species in Ontario. Common waterhemp can be distinguished from other *Amaranthus* species by the entirely hairless leaves and stems and its dioecious nature with separate male and female plants, which are visually discernable later in the growing season (Costea et al. 2005). Vyn et al. (2007) reported that CW interference can reduce soybean yields by up to 73%, and Schryver et al. (2017b) found up to 98% yield loss in extremely competitive glyphosate-resistant (GR) CW environments with densities of greater than 1,200 plants m^{-2}. Although related to many commonly found *Amaranthus* species, CW has several traits that make this species difficult to control, including prolonged emergence pattern, rapid growth habit, and genetic diversity.

Common waterhemp has an extended emergence pattern resulting in ineffective control with many soil-applied herbicides. In Ontario, CW begins emergence in early May and continues to emerge until September (Vyn et al. 2007) or October

DOI: 10.1017/wet.2017.81

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(Schryver et al. 2017b). Seed can remain viable in the soil for up to seventeen years with a germination rate of 3% (Burnside et al. 1996). Common waterhemp plants that survive are able to contribute to the soil seedbank and thus ensure CW persistence in a crop production system for many years (Sellers et al. 2003). Later-emerged CW have reduced seed production and dry weight by up to 90% and contribute less to the soil seedbank (Grundy 2003; Uscanga-Mortera et al. 2007), but recent work has found later emerging plants to contribute more to the soil seedbank than previously thought (Wu and Owen 2014). The prolonged emergence pattern and long viability of the seed in the soil make CW a very persistent weed once it has been established in a given area.

Common waterhemp has substantial phenotypic plasticity, which allows it to thrive in a wide range of environments (Costea et al. 2005; OMAF 2004). Common waterhemp is a C_4 plant with the ability to grow 1.6 mm per growing degree day and reach heights of up to 3 m (Horak and Loughin 2000). This plant can be described as a thermophyte, mesophyte to hygrophyte, heliophyte, and nitrophyte, allowing for rapid growth in many environments (Costea et al. 2005). In addition to environment, growth of CW is influenced by intra- and interspecific competition (Uscanga-Mortera et al. 2007; Wu and Owen 2014). Common waterhemp vegetative dry matter accumulation was reduced 10-fold when grown in the presence of soybean (Uscanga-Mortera et al. 2007). The length of time CW remains in the vegetative stage depends on photosensitivity of individual plants within a population, with individuals reaching the reproductive stage at different times (Wu and Owen 2014). The phenotypic plasticity of CW and its rapid growth rate contribute to the competiveness of this weed in diverse environments.

Common waterhemp is a dioecious species with separate male and female plants. This method of reproduction allows for more efficient resource allocation in female plants resulting in up to 4.8 million seeds per plant under ideal conditions, contributing to the rapid increase in CW densities in crop production areas (Hartzler et al. 2004). Due to its dioecious reproduction, CW has the ability to acquire new traits rapidly through pollen transfer with nearby plants (Costea et al. 2005). Consequently, this species has high genetic diversity, contributing to rapid evolution of herbicide resistance (Wu and Owen 2014).

The species *Amaranthus tuberculatus* (moq.) Sauer, or tall waterhemp, is native to Ontario and western Quebec, while *Amaranthus rudis*, or common waterhemp, is thought to have been introduced to Ontario via a demonstration combine near Petrolia in Lambton County in 2002 (Costea et al. 2005). In 2015, common waterhemp had been observed in a number of Ontario counties (Schryver et al. 2017a). In a survey conducted by Schryver et al. (2017a) in southwestern Ontario, 81% of fields where CW seed was collected had individuals that were resistant to glyphosate (Group 9), 76% had individuals resistant to atrazine (Group 5), and 100% had individuals resistant to imazethapyr (Group 2). Of the 49 samples collected, Schryver et al. (2017a) reported that 61% of the sites had individuals that were resistant to each of the three herbicides tested. This greatly reduces the number of herbicide options for the control of this weed in corn and soybean production in affected fields.

The spread of multiple-resistant herbicide populations of CW in Ontario is similar to what has occurred in the midwestern United States. Glyphosate-resistant CW was first confirmed in 2005 in Missouri, and now has been confirmed in 19 US states (Heap 2017). Common waterhemp has evolved resistance to herbicides from six groups: 2, 4, 5, 9, 14, and 27 (Heap 2017). In addition to GR populations, multiple resistance also occurs. For example, an Illinois population has resistance to herbicide groups 2, 4, 5, 14, and 27 (Heap 2017); another population in Illinois was found to be resistant to four groups including 2, 5, 9, and 14 (Bell et al. 2013); and a population in Missouri is resistant to groups 2, 9, and 14 (Legleiter and Bradley 2008). The above results highlight the importance of resistance management through the use of integrated weed management and the use of alternative technologies.

New technologies show promise for the control of multiple-resistant CW. Soybean cultivars with traits conferring resistance to combinations of glufosinate (LibertyLink); 2,4-D and glyphosate (Enlist); and isoxaflutole, mesotrione, and glufosinate [4-hydroxyphenylpyruvate dioxygenase (HPPD)-resistant] are in development. In addition to the near-term advantages for control of multiple resistant CW, these technologies present options for a more sustainable weed management strategy with diversity in

https://doi.org/10.1017/wet.2017.81 Published online by Cambridge University Press

the modes of action used (Norsworthy et al. 2012). In a study across six US states, CW control was better with the use of some of the new technologies than it was with current technologies (Meyer et al. 2015). Assessments showed that CW densities were reduced to 0% to 13% of the weedy control when pyroxasulfone plus flumioxazin (70 + 89 g ai ha^{-1}) was applied PRE followed by glufosinate (594 g ai ha^{-1}) or 2,4-D (1,065 g ae ha^{-1}) applied POST (Meyer et al. 2015). These findings are consistent with other studies that found excellent control of GR CW with 2,4-D or glufosinate applied POST (Chanhal and Johnson 2012; Craigmyle et al. 2013a, b). In greenhouse experiments, glufosinate at 450, 590, and 730 g ha^{-1} applied POST when CW was up to 15 cm in height controlled CW 75%, 76%, and 92% 15 days after application, respectively (Craigmyle et al. 2013a). In the same experiment, 2,4-D at 560, 840, and 1,120 g ha^{-1} provided 78%, 95%, and 95% CW control, respectively (Craigmyle et al. 2013a). In a study with isoxaflutole, mesotrione, and glufosinate–resistant soybean cultivars, CW density was reduced by 96% to 100% with *S*-metolachlor (1,068 to 1,872 g ai ha^{-1}) plus isoxaflutole (105 g ai ha^{-1}) plus metribuzin (420 to 630 g ai ha^{-1}) applied PRE or *S*-metolachlor (1,068 to 1,872 g ai ha^{-1}) plus mesotrione (185 g ai ha^{-1}) plus metribuzin (420 to 630 g ai ha^{-1}) PRE followed by fomesafen (263 g ai ha^{-1}) applied POST (Meyer et al. 2015). Management strategies that included three or more modes of action in a two-pass weed control program with a soil-applied residual herbicide followed by a POST herbicide have been found to be most effective (Craigmyle et al. 2013b; Meyer et al. 2015).

The use of new soybean technologies provides not only an effective strategy for the control of existing herbicide-resistant weeds, but also a more sustainable management strategy moving forward if used in an integrated weed management program. The purpose of this study was to investigate control of GR CW in LibertyLink, Enlist, and HPPD-resistant soybean. This is the first study on the control of GR CW using three new soybean herbicide technologies in Ontario.

Materials and Methods

Three separate studies were conducted using three types of soybean technologies. Each study consisted of four experiments, or site–years, in 2015 and 2016. The technologies tested included LibertyLink, Enlist, and HPPD-resistant soybean. The HPPD-resistant soybean studies were conducted in the absence of the soybean because the seed was not available when the study was initiated. Research was conducted on Walpole Island, Lambton County, Ontario in 2015 on the first confirmed case of GR CW in Canada (Schryver et al. 2017b) Although planting dates were identical in 2015, application dates for treatments were applied approximately 1 week apart from the other trial. In 2016, research was conducted on the previously described site in addition to a field found during a GR CW survey of Ontario (Schryver et al. 2017b) near Cottam in Essex County. These differences in timing and location resulted in four different environments for statistical analysis, which will be described later. Treatments were arranged in a completely randomized block design with four replications. Plots were 2.25 m wide (three soybean rows spaced 0.75 m apart) and 8 m long. Following a cover spray of glyphosate (1,800 g ai ha^{-1}) to kill emerged weeds, seedbed preparation consisted of two passes with an s-tine cultivator with rolling basket harrows. Common waterhemp plants had not yet emerged at the time of planting. Soybean was seeded to a depth of 4 cm using a no-till planter at approximately 400,000 seeds ha^{-1} for the LibertyLink (Pride 2295 LL) and 300,000 seed ha^{-1} for the Enlist soybean. Differences in seeding population were due to limited availability of seed for the Enlist experiments.

The PRE herbicides were applied within 5 days after soybean seeding. The POST herbicides were applied when escaped CW plants reached an average height of 10 cm in plots treated with PRE herbicides. This determination made for a late POST herbicide application timing as PRE treatments performed well, particularly in 2015. Herbicides were applied with a compressed CO_2 backpack sprayer equipped with a handheld 1.5 m boom with four ULD 120-02 nozzles (Hypro, New Brighton, MN) spaced 50 cm apart. Herbicides were applied using a carrier volume of 200 L h^{-1} at 280 kPa. Experimental site locations, soil characteristics, seeding dates, herbicide information, herbicide application dates, and CW height and density at the POST application are presented in Tables 1 and 2.

In each replicate untreated weedy and weed-free controls were included. The weed-free control was maintained weed-free with *S*-metolachlor/metribuzin

https://doi.org/10.1017/wet.2017.81 Published online by Cambridge University Press

Table 1. Herbicides used as well as their trade name, rate, manufacturer, and manufacturer address for experiments.

Herbicide	Trade name	Rate g ai ha^{-1}	Manufacturer	Manufacturer address
Pyroxasulfone/flumioxazin	Fierce	240	Valent Canada Inc.	3-728 Victoria Rd. S. Guelph, ON N1L 1C6
Pyroxasulfone/sulfentrazone	Authority Supreme	300	FMC Canada	#3 402 Ludlow St, P.O. Box 32033 Saskatoon, SK S7S 1M7
S-metolachlor/metribuzin	Boundary	1,943	Syngenta Crop Protection Canada Inc.	140 Research Lane, Research Park Guelph, ON N1G 4Z3
Glyphosate DMA/2,4-D choline	Enlist Duo	1,720	Dow AgroSciences Canada Inc.	2400, 215 - 2nd St. S.W. Calgary, AB T2P 1M4
Glufosinate	Liberty	500	Bayer Canada	Calgary AB T2C 3G3
Mesotrione	Callisto	140	Syngenta Crop Protection Canada Inc.	140 Research Lane, Research Park Guelph, ON N1G
Isoxaflutole	Balance Flexx	105	Bayer Canada	Calgary, AB T2C 3G3
Metribuzin	Sencor	420	Bayer Canada	Calgary, AB T2C 3G3
Fomesafen	Reflex	240	Syngenta Crop Protection Canada Inc.	140 Research Lane, Research Park Guelph, ON N1G 4Z3

(1,943 g ai ha^{-1}) applied PRE followed by hand-hoeing as required. The LibertyLink experiment consisted of pyroxasulfone/flumioxazin (240 g ai ha^{-1}) with a composition of 80.4/102 g ai ha^{-1} respectively of each, pyroxasulfone/sulfentrazone (300 g ai ha^{-1}) containing 150 g ai ha^{-1} of each, or *S*-metolachlor/metribuzin (1943 g ai ha^{-1}) with 1,570 and 372.5 g ai ha^{-1} respectively of each active ingredient, applied PRE. Glufosinate (500 g ai ha^{-1}) was applied POST, and the two-pass programs of the PRE herbicides followed by glufosinate applied POST (Table 3). The Enlist experiment had the same three PRE herbicide treatments, glyphosate dimethylamine (DMA)/2,4-D choline (1,720 g ai ha^{-1}) applied POST, and the sequential program of the PRE herbicides followed by glyphosate DMA/2,4-D choline applied POST (Table 4). The HPPD-resistant soybean experiment consisted of mesotrione (140 g ai ha^{-1}), isoxaflutole (105 g ai ha^{-1}), metribuzin (420 g ai ha^{-1}), mesotrione plus metribuzin or isoxaflutole plus metribuzin applied PRE, fomesafen (240 g ai ha^{-1}) plus Turbocharge® 0.5% (v/v) applied POST, and the two-pass programs of a PRE residual herbicide followed by fomesafen applied POST (Table 5). Turbocharge is a mineral oil–surfactant blend (50% and 39.5%, respectively) used as a spray-tank adjuvant.

Soybean injury was visually estimated on a scale of 0% (no injury) to 100% (complete plant death) in 1% increments at 2 and 4 weeks after crop emergence and 1, 2, and 4 weeks after the POST application (WAA). Common waterhemp control was estimated on the day of the POST application and 2, 4, 8, and 12 WAA, and was ranked from 0% (no control) to 100% (complete control). Evaluations accounted for any newly emerged CW or CW that had survived the herbicide treatment. In addition to qualitative assessments, a random subsample of common waterhemp plants was taken from the middle 0.5 m^2 of each plot at 4 WAA for a quantitative evaluation of density and dry weight. Common waterhemp plants were counted, cut at the soil surface, placed in a paper bag, and dried in a kiln at 60 C for approximately 3 weeks, followed by a measurement of weight. Soybean was harvested by hand from the middle 2 m of the center row of each plot. The harvested plants were threshed in a stationary threshing machine and weighed. The seed weight and moisture content were measured and weights were adjusted to 13% moisture for calculation of yield.

Statistical analysis was performed using PROC MIXED in SAS (version 9.4, SAS Institute Inc., Cary, NC). Variance was partitioned into the fixed effect of the herbicide treatment, and random effects included block, environment, and block by environment and environment by treatment interactions. Environment was defined as differences in location and year of the experiment. Data were pooled across all four environments for each trait. Residuals were plotted by predicted, treatment, and block for each variable to confirm assumptions of variance, including that errors were independent, homogeneous, and normally distributed. Normality was tested using PROC UNIVARIATE and Shaprio-Wilk's test, and

Table 2. Field site and herbicide application information for glyphosate-resistant common waterhemp studies in 2015 and 2016 in Ontario.

Experiment	Location	Year	Nearest city	Soil Characteristics: Texture	OM %	pH	Seeding date	Herbicide application: PRE[a] App. date	POST App. date	Height (cm)[b]	Density (plants m^2)[b]
Glufosinate-resistant soybean	Walpole1	2015	Wallaceburg	Sandy Loam	5.5	7.7	May 28	May 29	July 28	40	454
	Walpole2	2015	Wallaceburg	Sandy Loam	5.5	7.7	May 28	June 2	August 5	48	235
	Walpole1	2016	Wallaceburg	Sandy Loam	6.4	7.6	May 30	June 1	July 11	21	59
	Nelson	2016	Kingsville	Sandy Loam	2.9	6.5	May 23	May 24	June 29	24	1,805
2,4-D-resistant soybean	Walpole1	2015	Wallaceburg	Sandy Loam	5.5	7.7	May 28	May 29	July 28	28	438
	Walpole2	2015	Wallaceburg	Sandy Loam	5.5	7.7	May 28	June 2	August 5	48	352
	Walpole1	2016	Wallaceburg	Sandy Loam	6.4	7.6	May 30	June 1	July 11	14	49
	Nelson	2016	Kingsville	Sandy Loam	2.9	6.5	May 23	May 24	June 29	25	41
Mesotrione, isoxaflutole resistant soybean	Walpole1	2015	Wallaceburg	Sandy Loam	5.5	7.7		May 29	July 15	37	427
	Walpole2	2015	Wallaceburg	Sandy Loam	5.5	7.7		June 2	July 23	23	268
	Walpole1	2016	Wallaceburg	Sandy Loam	6.4	7.6		June 1	July 6	28	349
	Nelson	2016	Kingsville	Sandy Loam	2.9	6.5		May 24	June 29	28	67

[a] Abbreviations: PRE, preemergence; POST, postemergence; OM, organic matter; App, application.

[b] Size and density from nontreated control at the time of POST application.

data transformations included arcsine square-root transformation, square-root transformation, and log transformation to meet the above assumptions. All research was compared using PROC MIXED COVTEST for nonorthogonal contrasts and estimates to compare PRE herbicides and herbicide combinations in addition to herbicide timing of PRE, POST, and PRE followed by POST. Tukey's test was used with significance of $P = 0.05$.

Results and Discussion

LibertyLink. There was excellent soybean tolerance to the herbicides evaluated, with less than 2% crop injury (data not shown). Pyroxasulfone/flumioxazin provided greater control of GR CW (92% to 96%) than did pyroxasulfone/sulfentrazone (75% to 85%) at 2, 4, 8, and 12 WAA, and there was a greater reduction in GR CW dry weight, but there was no difference in GR CW density and soybean yield (Table 3). With the exception of 2 WAA, pyroxasulfone/flumioxazin and *S*-metolachlor/metribuzin provided equivalent control of GR CW. Pyroxasulfone/sulfentrazone and *S*-metolachlor/metribuzin provided equivalent control of GR CW for all parameters assessed and equivalent soybean yield. At 2, 4, 8, and 12 WAA, glufosinate controlled GR CW 41% to 62%. At 2, 4, 8, and 12 WAA (Table 3), a PRE herbicide followed by glufosinate POST controlled GR CW >96%. With respect to herbicide timing, the PRE herbicides provided better GR CW control (83% to 91%) than did a single application of glufosinate applied POST (41% to 62%) with the exception of dry weight 4 WAA. Because of the contact nature of glufosinate, coverage was critical; glufosinate will only control emerged CW plants because it has no residual activity in the soil. In general, the control of GR CW was improved when glufosinate was applied POST after a PRE herbicide, and the control of GR CW was improved when a PRE herbicide was applied prior to glufosinate applied POST. The only significant difference in soybean yield was observed when glufosinate was applied after a PRE herbicide, which increased yield from 1.28 to 1.76 T ha^{-1}. There was a 23% difference between the yield of POST and PRE followed by POST timings, but this was not significant ($P = 0.066$). Soybean yield among the four experiments ranged from 0 to 4.34 T ha^{-1}, partly because of CW interference (data not shown).

https://doi.org/10.1017/wet.2017.81 Published online by Cambridge University Press

Table 3. Means and nonorthogonal contrasts for glyphosate-resistant common waterhemp control using the glufosinate-resistant soybean system in Ontario in 2015 and 2016.

Treatment	Rate (g ai ha^{-1})	App timing	2 WAA[a] (% control)	4 WAA (% control)	8 WAA (% control)	12 WAA (% control)	Density 4 WAA (% of nontreated control)	Dry weight 4 WAA (% of nontreated control)	Soybean yield (T ha^{-1})
Nontreated control			0	0	0	0			0.80
Weed-free			100	100	100	100			1.38
Pyroxasulfone/flumioxazin	240	PRE	96	96	94	92	4	12	1.33
Pyroxasulfone/sulfentrazone	300	PRE	85	84	79	75	13	45	1.26
S-metolachlor/metribuzin	1,943	PRE	89	86	83	80	9	29	1.25
Glufosinate	500	POST	62	57	47	41	95	41	1.36
Pyroxasulfone/flumioxazin	240	PRE	99	99	99	98	0	0	1.81
Glufosinate	500	POST							
Pyroxasulfone/sulfentrazone	300	PRE	99	99	99	98	1	0	1.94
Glufoinate	500	POST							
S-metolachlor/metribuzin	1,943500	PRE	97	97	97	96	3	3	1.54
Glufosinate		POST							
Contrasts									
Pyroxasulfone/flumioxazin vs. pyroxasulfone/sulfentrazone			96 vs 85*	96 vs 84*	94 vs 79*	92 vs 75*	4 vs 13	12 vs 45*	1.33 vs 1.26
Pyroxasulfone/flumioxazin vs. *S*-metolachlor/metribuzin			96 vs 89*	96 vs 86	94 vs 83	92 vs 80	4 vs 9	12 vs 29	1.33 vs 1.25
Pyroxasulfone/sulfentrazone vs. *S*-metolachlor/metribuzin			85 vs 89	84 vs 86	79 vs 83	75 vs 80	13 vs 9	45 vs 29	1.26 vs 1.25
PRE vs. POST			91 vs 62**	89 vs 57**	86 vs 47**	83 vs 41**	9 vs 95**	27 vs 41	1.28 vs 1.36
PRE vs. PRE fb POST			91 vs 99**	89 vs 99*	86 vs 98*	83 vs 98*	9 vs 1	27 vs 1**	1.28 vs 1.76*
POST vs. PRE fb POST			62 vs 99**	57 vs 99**	47 vs 98**	41 vs 98**	95 vs 1**	41 vs 1**	1.36 vs 1.76

[a] Abbreviations: WAA, weeks after application; fb, followed by; vs, versus; PRE, preemergence; POST, postemergence; *, $P < 0.05$; **, $P < 0.001$.

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Table 4. Means and nonorthogonal contrasts for glyphosate-resistant common waterhemp control using the 2,4-D resistant soybean system in Ontario in 2015 and 2016.

Treatment	Rate (g ai ha^{-1})	App. timing	2 WAA[a] (% control)	4 WAA (% control)	8 WAA (% control)	12 WAA (% control)	Density 4 WAA (% of nontreated control)	Dry weight 4WAA (% of nontreated control)	Soybean yield (T ha^{-1})
Nontreated control			0	0	0	0			0.82
Weed-free			100	100	100	100			0.99
Pyroxasulfone/flumioxazin	240	PRE	98	96	95	94	2	4	0.94
Pyroxasulfone/sulfentrazone	300	PRE	91	88	85	79	6	15	0.97
S-metolachlor/m99etribuzin	1,943	PRE	89	85	83	82	3	28	0.86
Glyphosate DMA/2,4-D choline	1,720	POST	77	78	77	80	18	12	1.05
Pyroxasulfone/flumioxazin	240	PRE	100	99	99	98	0	0	0.98
Glyphosate DMA/2,4-D choline	1,720	POST							
Pyroxasulfone/sulfentrazone	300	PRE	99	99	99	98	0	0	1.07
Glyphosate DMA/2,4-D choline	1,720	POST							
S-metolachlor/metribuzin	1,943	PRE	99	99	99	98	0	0	0.92
Glyphosate DMA/2,4-D choline	1,720	POST							
Contrasts									
Pyroxasulfone/flumioxazin vs. pyroxasulfone/sulfentrazone			98 vs 91	96 vs 88*	95 vs 85	94 vs 79	2 vs 6	12 vs 45	0.94 vs 0.97
Pyroxasulfone/flumioxazin vs. *S*-metolachlor/metribuzin			98 vs 89	96 vs 85	95 vs 83	94 vs 82	2 vs 3	12 vs 29*	0.94 vs 0.86
Pyroxasulfone/sulfentrazone vs. *S*-metolachlor/metribuzin			91 vs 89	88 vs 85	85 vs 83	79 vs 82	6 vs 3	45 vs 29	0.97 vs 0.86
PRE vs. POST			93 vs 77*	91 vs 78	88 vs 77	85 vs 80	3 vs 18*	14 vs 12	0.92 vs 1.05
PRE vs. PRE fb POST			93 vs 99*	91 vs 99*	88 vs 99*	85 vs 98*	3 vs 0	14 vs 0*	0.92 vs 0.99
POST vs. PRE fb POST			77 vs 99*	78 vs 99*	77 vs 99*	80 vs 98*	18 vs 0*	12 vs 0*	1.05 vs 0.99

[a] Abbreviations: WAA, weeks after application; fb, followed by; vs, versus; PRE, preemergence; POST, postemergence; *, $P < 0.05$; **, $P < 0.001$.

Table 5. Means and nonorthogonal contrasts for glyphosate-resistant common waterhemp control using the mesotrione, glufosinate, and isoxaflutole–resistant soybean system in Ontario in 2015 and 2016.

Treatment	Rate (g ai ha^{-1})	App.[a] timing	2 WAA (% control)	4 WAA (% control)	8 WAA (% control)	12 WAA (% control)	Density 4 WAA (% of nontreated control)	Dry weight 4 WAA (% of nontreated control)
Nontreated control			0	0	0	0		
Weed-free			100	100	100	100		
Mesotrione	140	PRE	56	37	26	18	13	64
Isoxaflutole	105	PRE	73	64	49	42	10	50
Metribuzin	420	PRE	56	48	18	6	10	67
Mesotrione	140	PRE	77	68	54	45	6	47
Metribuzin	420	PRE						
Isoxaflutole	105	PRE	88	83	75	69	5	54
Metribuzin	420	PRE						
Fomesafen	240	POST	60	54	41	34	62	42
Mesotrione fb	140	PRE	95	94	91	90	3	13
Fomesafen	240	POST						
Isoxaflutole fb	105	PRE	98	98	96	94	1	5
Fomesafen	240	POST						
Metribuzin fb	420	PRE	94	91	85	84	3	13
Fomesafen	240	POST						
Mesotrione,	140	PRE	98	98	95	93	1	8
Metribuzin fb	420	PRE						
Fomesafen	240	POST						
Isoxaflutole,	105	PRE	99	99	98	97	1	4
Metribuzin fb	420	PRE						
Fomesafen	240	POST						
Contrasts								
Mesotrione vs. isoxaflutole			56 vs 73	37 vs 64*	26 vs 49	18 vs 42	13 vs 10	64 vs 50
Mesotrione vs. metribuzin			56 vs 56	37 vs 48	26 vs 18	18 vs 6	13 vs 10	64 vs 67
Isoxaflutole vs. metribuzin			73 vs 56	64 vs 48	49 vs 18*	42 vs 6*	10 vs 10	50 vs 67
Mesotrione vs. mesotrione + metribuzin			56 vs 77*	37 vs 68*	26 vs 54	18 vs 45	13 vs 6*	64 vs 47
Isoxaflutole vs. isoxaflutole + metribuzin			73 vs 88	64 vs 83	49 vs 75	42 vs 69	10 vs 5	50 vs 54
Mesotrione and isoxaflutole vs. mesotrione + metribuzin and isoxaflutole + metribuzin			65 vs 83*	51 vs 76*	36 vs 65*	30 vs 57*	11 vs 6*	57 vs 51
PRE vs. POST			71 vs 60	61 vs 54	44 vs 41	34 vs 34	9 vs 62**	56 vs 42
PRE vs. PRE fb POST			71 vs 97**	61 vs 96**	44 vs 94**	34 vs 92**	9 vs 2**	56 vs 9**
POST vs. PRE fb POST			60 vs 97**	54 vs 96**	41 vs 94**	34 vs 92**	62 vs 2**	42 vs 9*

[a] Abbreviations: App., Application; WAA, weeks after application; fb, followed by; vs, versus; PRE, preemergence; POST, postemergence; *, $P < 0.05$; **, $P < 0.001$.

Enlist Soybean. There was excellent soybean tolerance to the herbicides evaluated, with less than 2% crop injury (data not shown). GR CW control in this study (Enlist soybean) was similar to that observed in the LibertyLink study. There was a striking difference in the control of GR CW with glyphosate DMA/2,4-D choline, which was observed to be more effective than glufosinate. This reflects previous work in greenhouses showing improved CW control with 2,4-D (Craigmyle et al. 2013a). In general, there were very few differences in GR CW control among the three PRE herbicides (pyroxasulfone/flumioxazin, pyroxasulfone/sulfentrazone, and *S*-metolachlor/metribuzin) evaluated. At 2, 4, 8, and 12 WAA, glyphosate DMA/2,4-D choline controlled GR CW 77% to 80%. At 2, 4, 8, and 12 WAA, there was numerically higher control of GR CW and a greater reduction in density and dry weight with the PRE herbicides than there was with glyphosate DMA/2,4-D choline POST, although differences were not always statistically significant. The herbicide glyphosate DMA/2,4-D POST following a PRE

https://doi.org/10.1017/wet.2017.81 Published online by Cambridge University Press

herbicide, or the application of a PRE herbicide prior to glyphosate DMA/2,4-D POST resulted in improved control of GR CW and a greater reduction in GR CW density and dry weight, although differences were not always statistically significant. Across treatments, there were no differences in soybean yield. This particular variety did not thrive in the soil at Walpole Island, Lambton County, and performed better near Cottam, Essex County. The reduction in seeding population may have also played a role in poor yields.

HPPD-Resistant Soybean. In general, mesotrione, isoxaflutole, metribuzin, mesotrione plus metribuzin, and isoxaflutole plus metribuzin provided similar control of GR CW, although there were a few statistical differences (Table 5). At 2 and 4 WAA, the addition of metribuzin to mesotrione resulted in improved control of GR CW, and there was a greater reduction in GR CW density. At 2, 4, 8, and 12 WAA, the control of GR CW was improved when metribuzin was added to either mesotrione or isoxaflutole, and there was a greater reduction in GR CW density but there was no difference in dry weight. In general, the PRE herbicides and fomesafen applied POST provided equivalent control of GR CW with the exception of GR CW density. For all parameters, there was improved GR CW control when fomesafen was applied POST following a PRE herbicide; control of GR CW was improved when a PRE herbicide was applied prior to fomesafen applied POST. This research was conducted on bare ground and it would be hypothesized that control of GR CW reported would be improved due to competition with a soybean crop.

In conclusion, among all of the herbicide-resistant soybean technologies evaluated, a two-pass weed control program was more efficacious for full-season control of GR CW, with ≥90% control 12 WAA. The use of these new herbicide-resistant soybean cultivars in conjunction with the appropriate herbicides will provide Ontario producers with new tools to manage GR CW. Use of diverse herbicide modes of action will reduce the selection intensity for other herbicide-resistant weeds, and hopefully reduce the geographic spread of this competitive weed. These technologies play a role in the rotation of practices and technologies to ensure that CW populations are manageable for years to come. Although recently developed herbicide technologies have a place in modern practices, good agronomic principles such as a diverse crop rotation, cover crops, narrow row spacing, strategic tillage, and high planting densities can all contribute to a sustainable common waterhemp management strategy moving forward.

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Received February 2, 2017, and approved August 18, 2017.

Associate Editor for this paper: Aaron Hager, University of Illinois.