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Author for correspondence:

Nader Soltani, Department of Plant Agriculture, University of Guelph Ridgetown Campus, 120 Main Street East, Ridgetown, ON, Canada N0P 2C0. Email: soltanin@uoguelph.ca

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Strategies to improve the control of glyphosate-resistant horseweed (*Erigeron canadensis*) with glufosinate applied preplant to soybean

Meghan Dilllotti¹ , Nader Soltani² , David C. Hooker³ , Darren E. Robinson⁴ and Peter H. Sikkema⁵

¹Graduate Student, Department of Plant Agriculture, University of Guelph, Ridgetown, ON, Canada; ²Adjunct Professor, Department of Plant Agriculture, University of Guelph, Ridgetown, ON, Canada; ³Associate Professor, Department of Plant Agriculture, University of Guelph, Ridgetown, ON, Canada; ⁴Professor, Department of Plant Agriculture, University of Guelph, Ridgetown, ON, Canada and ⁵Professor, Department of Plant Agriculture, University of Guelph, Ridgetown, ON, Canada

Abstract

The objectives of this study were to determine if the level and consistency of glyphosate-resistant (GR) horseweed control prior to soybean planting can be improved by (i) adding halauxifen-methyl, 2,4-D ester, saflufenacil, metribuzin, or dicamba to glufosinate, (ii) increasing the rate of glufosinate from 500 to 1,000 g ai ha⁻¹, and (iii) adding 28% urea ammonium nitrate (UAN) as the carrier solution. During a 2-yr period (2020–2021), four field trials were conducted on commercial farms located in southwestern Ontario, Canada, with confirmed GR horseweed. Glufosinate controlled GR horseweed 65%, 66%, and 63% at 2, 4, and 8 wk after application (WAA), respectively, and reduced density and biomass 46% and 33% at 8 WAA, respectively. There was no improvement in GR horseweed control from the addition of halauxifen-methyl, 2,4-D ester or saflufenacil to glufosinate and no decrease in density and biomass, with the exception that the addition of saflufenacil to glufosinate reduced density 30% compared to glufosinate alone. The addition of metribuzin to glufosinate improved GR horseweed control by 22%, 22%, and 28% at 2, 4, and 8 WAA, respectively, and further reduced density and biomass 50% and 47%, respectively, at 8 WAA, respectively. The addition of dicamba to glufosinate improved GR horseweed control by 19%, 26%, and 30% at 2, 4, and 8 WAA, respectively, and further reduced density and biomass 54% and 60%, respectively, at 8 WAA. There was no improvement in GR horseweed control by increasing the rate of glufosinate from 500 to 1,000 g ai ha⁻¹ or when using 28% UAN as the carrier solution. The addition of all herbicides to glufosinate, increasing the rate of glufosinate, or using 28% UAN as the carrier solution improved the consistency of GR horseweed control.

Introduction

Horseweed is a broadleaf weed from the Asteraceae family. In 1996, the introduction of glyphosate-resistant (GR) crops helped to facilitate no-till or reduced-till practices (Dill 2005; Givens et al. 2009). By 2012, approximately 93%, 85%, and 82% of soybean, corn (*Zea mays* L.), and cotton (*Gossypium hirsutum* L.) in the United States, respectively, were seeded to GR cultivars/hybrids (ERS 2013). The adoption of no-till crop production practices and GR crop cultivars/hybrids and the concomitant rise in glyphosate use created the ideal confluence of events for intense selection intensity for the evolution of GR horseweed. Four years after the introduction of GR soybean, GR horseweed was documented in the state of Delaware (VanGessel 2001). Currently, GR horseweed has been confirmed in 13 countries (Heap 2020).

Horseweed has a prolonged emergence period. The lack of seed dormancy allows for germination under favorable conditions year-round (Buhler and Owen 1997); however, most plants emerge during the fall or the spring (Weaver 2001). Fall-emerged horseweed has a competitive advantage over weed species and annual crops that emerge in the spring (Main et al. 2006; Regehr and Bazzaz 1976). Horseweed may emerge after the initial preplant (PP) burn-down application in a no-tillage system; if so, an in-crop postemergence herbicide would be required for control. The variable emergence pattern can make it difficult to achieve acceptable control of GR horseweed in identity-preserved and GR soybean.

Horseweed can produce greater than 1 million seeds per plant (Davis et al. 2009), although when in competition with soybean, horseweed has been reported to produce approximately 30,000 to 72,000 seeds per plant (Davis and Johnson 2008). Horseweed seeds measure approximately 1 to 2 mm, with an attached pappus measuring approximately 3 to 5 mm (Frankton and Mulligan 1987). The pappus is made up of a plumose crown of hairs that can mimic a parachute when airborne (Andersen 1993). The seeds may travel from a few meters (Dauer et al. 2006) or

up to hundreds of kilometers (Shields et al. 2006) from the mother plant via wind dissemination, which results in the spread to adjacent and distant fields.

GR horseweed is difficult to control in soybean. Studies have reported up to 93% yield loss due to GR horseweed interference in soybean (Byker et al. 2013a). Postemergence applications of glyphosate or cloransulam-methyl were once effective for GR horseweed control, but the evolution of biotypes resistant to Group 2 and 9 herbicides made these herbicides ineffective in soybean (Byker et al. 2013b). Byker et al. (2013b) reported that current postemergence herbicides registered for use in identity-preserved and GR soybean do not provide greater than 95% control. Control of GR horseweed must precede soybean emergence to prevent yield loss.

Glufosinate-ammonium is a glutamine synthetase-inhibiting herbicide that belongs to the organophosphorus chemical family (WSSA Group 10) (Zhou et al. 2020). Commercial glufosinate formulations contain a combination of D and L stereoisomers from the natural product L-phosphinothricin. Only the L-isomer inhibits glutamine synthetase, but commercial formulations include the racemic mixture because of the cost of production (Green and Gradley 2018). Glufosinate primarily has contact activity, though it has limited translocation in the apoplast (Coetzer et al. 2001; Dröge-Laser et al. 1994). The fast phytotoxic action of glufosinate is dependent on light to generate reactive oxygen species, resulting in cell membrane lipid peroxidation and ultimately plant death (Takano et al. 2019). Thorough spray coverage is crucial for effective weed control, especially when weed densities are high (Eubank et al. 2008). Glufosinate is most efficacious when applied under warm air temperatures (Kumaratilake and Preston 2005), high relative humidity (Coetzer et al. 2001), and full-sunlight conditions (Takano and Dayan 2020; Takano et al. 2019). Glufosinate is non-selective and provides control of susceptible young annual grass and broadleaf weeds.

Glufosinate applied alone has provided variable GR horseweed control. Zimmer et al. (2018) observed a 59% control of 3- to 33-cm-tall GR horseweed with glufosinate (594 g ai ha⁻¹) applied PP to soybean at 5 WAA. In this study, the average air temperature and relative humidity at the time of application were 19 C and 61%, respectively (Zimmer et al. 2018). Eubank et al. (2008) reported a minimum of 90% control of 25- to 30-cm-tall GR horseweed with glufosinate (590 g ai ha⁻¹) applied PP to soybean at 4 WAA; air temperature and relative humidity at the time of application were 27 C and 53%, respectively. Only a few studies have investigated GR horseweed control with glufosinate-based mixtures. Byker et al. (2013a) reported that glufosinate (500 g ai ha⁻¹) plus glyphosate (900 g ae ha⁻¹) provided 35% to 91% control of GR horseweed up to 11 cm tall at 4 WAA; 35% control was reported at a site with a high GR horseweed density (158 to 184 plants m⁻²) at application, and 91% control was reported at sites with a low GR horseweed density (7 to 81 plants m⁻²) at application. In another study, when dicamba (280 g ae ha⁻¹), 2,4-D ester (840 g ae ha⁻¹), or metribuzin (420 g ai ha⁻¹) were added to glufosinate (470 g ai ha⁻¹), up to 96%, 97%, and 96% control of 25- to 30-cm GR horseweed, respectively, was reported at 4 WAA (Eubank et al. 2008); air temperature and relative humidity at the time of application were 27 C and 53%, respectively. Budd et al. (2016a) observed the addition of saflufenacil (25 g ai ha⁻¹) to glyphosate (900 g ae ha⁻¹) plus glufosinate (500 g ai ha⁻¹) provided 93% control of up to 14-cm-tall GR horseweed at 8 WAA. Complete control of 15-cm-tall GR horseweed was reported with glufosinate (494 g ha⁻¹) plus a 1:1 ratio mixture of water and 28% urea ammonium nitrate (UAN) (total carrier

volume of 187 L ha⁻¹) and 28% UAN (187 L ha⁻¹) in a growth-room study (M Cowbrough, personal communication). Glufosinate-based mixtures have provided acceptable control of GR horseweed applied PP in soybean, though research is limited.

Control of GR horseweed has been variable with glufosinate alone, but based on the available research, glufosinate-based mixtures have provided improved control of GR horseweed. There is a need to explore additional glufosinate-based mixture options to control GR horseweed in soybean applied PP. Therefore, the objectives of this study were to determine if the level and consistency of GR horseweed control applied PP to soybean can be improved with (i) adding herbicides labeled for PP to soybean that are known to have herbicidal activity on GR horseweed: halauxifen-methyl, 2,4-D ester, saflufenacil, metribuzin, or dicamba to glufosinate; (ii) increasing the rate of glufosinate from 500 to 1,000 g ai ha⁻¹, and (iii) adding 28% UAN as the carrier solution, which has been observed to have activity on GR horseweed.

Materials and Methods

Experimental Methods

Field trials were conducted in 2020 and 2021 on four commercial farms in southern Ontario. In 2020, the trials were located near Ridgetown (42.27° N; 81.51° W) and Moraviantown (42.3304° N; 81.50194° W), and in 2021 the trials were located near Kintyre (42.33549° N; 81.46226° W) and Bothwell (42.37043° N; 81.54457° W). The year, location, soil characteristics, air temperature, and relative humidity at the time of treatment application, treatment application dates, and soybean seeding and emergence dates are listed in Table 1.

Horseweed size and density at the PP application and the resistance profile of the populations at each location are listed in Table 2. The resistance profile of the horseweed populations from each location was determined in greenhouse screenings. Horseweed seed was collected randomly from multiple plants at each location. Square transplanting flats (25 cm × 25 cm × 5 cm) were filled with potting mix (Berger Growing Media with sphagnum peat moss, perlite, wetting agent, dolomitic, and calcitic limestone) and were watered until the soil was completely saturated. Horseweed seeds (approximately 300) were sprinkled onto the soil surface. Approximately 0.3 mm of the potting mix was used to cover the seed on the soil surface. The trays remained in the greenhouse (16-h photoperiod with 26 C day and 17 C night temperatures) and were watered with approximately 20 ml of water daily. Once the seedlings had at least four leaves, 100 horseweed plants from each population were transplanted into individual circular pots 10 cm diam. When horseweed reached 10 cm in height, 40 horseweed plants from each population were sprayed with glyphosate (900 g ae ha⁻¹), and another 40 were sprayed with cloransulam-methyl (17.5 g ai ha⁻¹). The horseweed was sprayed in a spray chamber equipped with flat-fan nozzles calibrated to deliver 205 L ha⁻¹ at 2.6 km h⁻¹ and 280 kPa. Two untreated checks for every 10 horseweed plants were used as comparisons to conduct the visible control ratings. Visible control ratings were completed at 1, 3, and 5 WAA with a 0 to 100% scale; 0% represented no control, 100% represented complete necrosis (Canadian Weed Science Society 2018). The values in Table 2 represent the percentage of horseweed resistant to glyphosate and cloransulam-methyl at each location at 5 WAA. The seed was not collected at the Bothwell site, and therefore resistance screening was not conducted for this location.

Table 1. Year, location, soil characteristics, air temperature, and relative humidity at the time of treatment application, treatment spray date, and soybean seeding and emergence dates for four field trials conducted in southern Ontario in 2020 and 2021.

Year	Location	Soil characteristics						Weather at treatment application		Agronomic information		
		Texture	Sand	Silt	Clay	OM ^a	pH	Air temperature	Relative humidity	Treatment spray date	Soybean seedling date	Soybean emergence date
			%					C	%			
2020	Ridgetown	Sandy loam	75	17	7	1.9	7.1	23	93	May 26	June 5	June 11
2020	Moraviantown	Loamy sand	87	7	5	2.5	6.6	25	69	June 16	June 18	July 2
2021	Kintyre	Sandy loam	53	29	18	4.4	6.9	6	55	May 13	May 19	May 25
2021	Bothwell	Loamy sand	85	11	4	3.3	6.8	18	42	May 31	June 12	June 18

^aAbbreviations: OM, organic matter.

Table 2. Year, location, glyphosate-resistant (GR) horseweed size and density at the preplant treatment applications, and resistance profile at each location at 5 wk after application for four field trials conducted in southern Ontario in 2020 and 2021.

Year	Location	GR horseweed		Resistance	
		Size	Density	Glyphosate	Cloransulam-methyl
		cm	Plants m ⁻²	%	
2020	Ridgetown	8	386	100	99
2020	Moraviantown	8	111	92	100
2021	Kintyre	7	224	98	85
2021	Bothwell	8	65	–	–

A randomized complete block design was used in this study. There were four blocks within each trial. Each block had a weedy and weed-free control. The plots measured 2.25 m wide (equivalent to three soybean rows, 0.75 m apart) by 8 m in length. The treatments (Tables 3 and 4) were applied PP with a CO₂-pressurized backpack sprayer calibrated to 200 L ha⁻¹ at 240 kPa once the average horseweed height in each plot was approximately 10 cm. Glyphosate (900 g ae ha⁻¹) was applied to the weedy control, and glyphosate (900 g ae ha⁻¹) plus saflufenacil (25 g ai ha⁻¹) plus metribuzin (400 g ai ha⁻¹) plus the non-ionic surfactant Merge (1 L ha⁻¹) was applied to the weed-free control; both treatments were applied PP. A postemergence application of the premix glyphosate/dicamba (240/120 g ae ha⁻¹) was applied to the weed-free treatment. The entire experimental area was treated with a postemergence application of glyphosate (450 g ae ha⁻¹) to eliminate weeds not being studied.

Control ratings were visually determined at 2, 4, and 8 WAA for each treatment based on the estimated percentage biomass reduction of horseweed relative to the weedy control within each block. The ratings were completed with a 0 to 100% scale; 0% represented no control, 100% represented complete necrosis (Canadian Weed Science Society 2018). At 8 WAA, two 0.25-m² quadrats were set randomly in each plot for density and biomass data collection. Density was determined by counting all GR horseweed in each quadrat. Biomass was determined by cutting each plant at the base of its stem, organized in bags labeled by treatment, and stored in a dryer to dry to steady moisture. Once dry, the samples were weighed to determine biomass.

Glyphosate/dicamba-resistant soybean (DKB10-20) was seeded 2 to 12 d after the PP treatment applications, at about

Table 3. Herbicides and surfactants used in this study conducted in southern Ontario, Canada in 2020 and 2021.

Common name	Trade name	Manufacturer
Herbicides		
Glufosinate ^a	Liberty	BASF Canada Inc., 100 Milverton Drive, Mississauga, ON
2,4-D ester	Ester 700	Nufarm Canada., 5101, 333 96 th Avenue NE, Calgary, AB
Dicamba	Xtendimax	Bayer CropScience Inc., 160 Quarry Park Boulevard SE, Calgary, AB
Halauxifen-methyl ^b	Elevore	Dow AgroSciences Canada Inc., 2400, 215 2nd Street SW, Calgary, AB
Saflufenacil ^c	Eragon LQ	BASF Canada Inc.
Metribuzin	Sencor 480SC	Bayer CropScience Inc.
Surfactants		
Non-ionic surfactant	Merge	BASF Canada Inc.
Methylated seed oil	MSO concentrate	Dow AgroSciences Canada Inc.

^aTwo treatments with glufosinate included 28% urea ammonium nitrate.

^bTreatments with halauxifen-methyl included the surfactant methylated seed oil (1.0% v/v).

^cTreatments with saflufenacil included the surfactant Merge (1.0 L ha⁻¹).

416,000 seeds ha⁻¹ to a 3.75-cm depth. Soybean injury was assessed 2 and 4 wk after emergence using a 0 to 100% scale, with 0% representing no soybean injury, and 100% complete soybean necrosis (Canadian Weed Science Society 2018). Once soybean reached harvest maturity, a plot combine harvested two soybean rows per plot; soybean yield and moisture content were recorded.

Statistical Analysis

PROC GLIMMIX in SAS 9.4 (SAS, Cary, NC) was utilized for the data analyses. Variances were organized as the fixed effects (treatment) and random effects (block, block-within-environment, and treatment-by-environment). Normality assumptions were met after conducting the Shapiro-Wilk test and reviewing residual plots. No treatment-by-environment interaction was detected, so the data were analyzed together. GR horseweed control 2, 4, and 8 WAA was analyzed using an arc-sine distribution with the link identity; soybean yield was analyzed using a normal distribution. GR horseweed density and biomass data were analyzed with a log-normal distribution with the link identity; the omega procedure was used to back-transform the treatment means from the log-scale format (M Edwards, Ontario Agricultural College

Table 4. Treatment means of glyphosate-resistant (GR) horseweed control 2, 4, and 8 wk after application (WAA), density, biomass, and soybean yield from four field trials conducted in southern Ontario, Canada in 2020 and 2021.^{a,b}

Treatment ^c	Rate	GR horseweed control			Density ^d	Biomass ^d	Soybean yield
		2 WAA	4 WAA	8 WAA			
	g ai/ae ha ⁻¹	%			No. plants m ⁻²	g m ⁻²	kg ha ⁻¹
Weedy control	–	0	0	0	276 e	156 d	2,150 a
Weed-free control	–	100	100	100	0	0	2,600 a
Glufosinate	500	65 c	66 c	63 b	149 de	105 cd	2,290 a
Glufosinate	1,000	76 abc	77 bc	73 b	120 cd	61 bc	2,540 a
Glufosinate + 100 L water + 100 L UAN	500	65 c	68 c	63 b	146 cde	119 cd	2,330 a
Glufosinate + 200 L UAN	500	72 bc	73 c	71 b	64 bcd	71 c	2,800 a
Glufosinate + halauxifen-methyl ^e	500 + 5	64 c	72 c	68 b	201 cde	93 c	2,480 a
Glufosinate + 2,4-D ester	500 + 528	76 abc	79 bc	74 b	98 cd	75 c	2,110 a
Glufosinate + saflufenacil ^f	500 + 25	76 abc	81 abc	79 ab	65 abc	68 bc	2,230 a
Glufosinate + metribuzin	500 + 400	87 a	88 ab	91 a	11 a	21 ab	2,750 a
Glufosinate + dicamba	500 + 600	84 ab	92 a	93 a	19 ab	12 a	3,160 a

^aLetters next to control means in a column (a–f) that differ from one another are statistically significant based on Tukey-Kramer's LSD ($P = 0.05$).

^bAbbreviation: UAN, 28% urea ammonium nitrate.

^cEach treatment included 900 g ae ha⁻¹ of glyphosate.

^dDensity and biomass were collected 8 WAA.

^eTreatments with halauxifen-methyl included the surfactant methylated seed oil (1.0% v/v).

^fTreatments with saflufenacil included the surfactant Merge (1.0 L ha⁻¹).

Statistician, University of Guelph, personal communication). The Tukey-Kramer's multiple-range test ($P = 0.05$) was used for the treatment means separation. The coefficient of variation (CV) was calculated for each least square mean to determine the consistency of the data.

Results and Discussion

Soybean Injury

Soybean injury was $\leq 10\%$ at all sites in 2020 and 2021 (data not presented).

Glyphosate-Resistant Horseweed Control

Glufosinate (500 g ai ha⁻¹) controlled GR horseweed 65%, 66%, and 63% at 2, 4, and 8 WAA, respectively, and did not reduce density or biomass relative to the weedy control (Table 4). Eubank et al. (2008) observed up to 96% control of 25- to 30-cm-tall GR horseweed with glufosinate (470 g ae ha⁻¹) at 4 WAA; air temperature and relative humidity at the time of application was 27 °C and 53%, respectively. The high level of control in this study could be attributed to the high air temperature and low GR horseweed density (22 plants m⁻²) at the time of application (Eubank et al. 2008). Byker et al. (2013a) observed 35% to 91% control of GR horseweed up to 11 cm tall and up to a 96% reduction in GR horseweed biomass at 4 WAA with glufosinate (500 g ai ha⁻¹) applied PP in soybean.

GR horseweed control was not improved when the rate of glufosinate was increased from 500 to 1,000 g ai ha⁻¹ or when glufosinate was applied with 28% UAN (50% or 100%) as the carrier solution (Table 4). Reports of increased herbicidal activity and injury on weed species have been reported when nitrogen fertilizer is added (Anonymous 2011); however, some studies have found this to be species-specific (Fielding and Stoller 1990). Complete control of 15-cm-tall horseweed was reported with glufosinate (494 g ha⁻¹) plus a 1:1 ratio mixture of water and 28% UAN (total carrier volume of 187 L ha⁻¹) and 28% UAN (187 L ha⁻¹) in a growth-room study (M Cowbrough, personal communication).

In the current study, there was no improvement in GR horseweed control when 28% UAN was used as the herbicide carrier.

There was no benefit of adding halauxifen-methyl to glufosinate for the control of GR horseweed, and there was no reduction in density or biomass relative to glufosinate (500 g ai ha⁻¹). Previous research also reported no improvement in GR horseweed control from the addition of halauxifen-methyl to other herbicides applied PP to soybean (Zimmer et al. 2018).

There was no benefit of adding 2,4-D ester to glufosinate for the control of GR horseweed, and there was no reduction in density or biomass relative to glufosinate (500 g ai ha⁻¹). In contrast to the present study, Eubank et al. (2008) observed that glufosinate (470 g ai ha⁻¹) plus 2,4-D (840 g ae ha⁻¹), applied PP to soybean, controlled 25- to 30-cm-tall GR horseweed 97% at 4 WAA and reduced GR horseweed density by a minimum of 99%. Chahal and Johnson (2012) reported 100% control of 3- to 4-cm-tall GR horseweed with glufosinate (530 g ai ha⁻¹) plus 2,4-D (560 g ae ha⁻¹) at 3 WAA in a greenhouse experiment.

There was no benefit of mixing saflufenacil with glufosinate for the control of GR horseweed and no reduction in biomass; however, there was a 30% reduction in GR horseweed density relative to glufosinate (500 g ai ha⁻¹). In contrast to this study, Budd et al. (2016a) observed 93% control of up to 14-cm-tall GR horseweed with glufosinate (500 g ai ha⁻¹) plus saflufenacil (25 g ai ha⁻¹) plus glyphosate (900 g ae ha⁻¹) applied PP to soybean 8 WAA; GR horseweed density and biomass were reduced 96% and 89%, respectively. Waggoner et al. (2011) reported 83% GR horseweed control with glufosinate (450 g ai ha⁻¹) plus saflufenacil (25 g ai ha⁻¹) applied PP in cotton approximately 4 WAA, similar to the current study, and a 90% reduction in density.

There was a benefit of adding metribuzin to glufosinate for the control of GR horseweed, and there was a reduction in GR horseweed density and biomass relative to glufosinate (500 g ai ha⁻¹). When metribuzin was tank-mixed with glufosinate, GR horseweed control improved 22%, 22%, and 28% at 2, 4, and 8 WAA and further reduced density and biomass 50% and 54%, respectively, compared to glufosinate (500 g ai ha⁻¹). Eubank et al. (2008) reported slightly higher GR horseweed control of 93% to 96% control with

glufosinate (470 g ai ha⁻¹) plus metribuzin (420 g ai ha⁻¹) at 4 WAA; GR horseweed density was reduced up to 99%, similar to this study. Loux and Johnson (2014) suggest that glufosinate plus metribuzin is an efficacious PP option to control GR horseweed in the spring.

There was a benefit of adding dicamba to glufosinate for the control of GR horseweed, and there was a reduction in GR horseweed density and biomass relative to glufosinate (500 g ai ha⁻¹). When dicamba was mixed with glufosinate, GR horseweed control improved by 19%, 26%, and 30% at 2, 4, and 8 WAA, respectively, and further reduced density and biomass 47% and 60%, respectively, compared to glufosinate (500 g ai ha⁻¹). Similarly, Eubank et al. (2008) reported 90% to 96% GR horseweed control with glufosinate (470 g ai ha⁻¹) plus dicamba (280 g ae ha⁻¹) applied PP in soybean 4 WAA and a minimum density reduction of 86%. In cotton, glufosinate (470 g ae ha⁻¹) plus dicamba (280 g ae ha⁻¹) applied PP controlled GR horseweed 90% at 8 WAA, similar to this study, and reduced density 79%, which was lower than the 93% density reduction in the present study (Steckel et al. 2006). Although there was a benefit of adding dicamba to glufosinate for the control of GR horseweed, it is not recommended to tank-mix glufosinate with dicamba (Anonymous 2018), as the ammonium ions in glufosinate can enhance dicamba volatility and subsequent off-target movement (Castner et al. 2020).

Glyphosate-Resistant Horseweed Consistency in Control

GR horseweed consistency of control was indicated by the CV. A lower CV indicates greater consistency in control (Shechtman 2013). The consistency of GR horseweed control at 2, 4, and 8 WAA was improved from the addition of all herbicide tankmix partners to glufosinate, when the rate of glufosinate was increased, and when 28% UAN was used as the carrier solution, as indicated by the lower CV values relative to glufosinate (500 g ai ha⁻¹) (Table 5). Glufosinate plus dicamba or metribuzin consistently reduced the CV more than the other treatments, indicating improved consistency of GR horseweed control. Similarly, Budd et al. (2016b) reported improved consistency in GR horseweed control when metribuzin (400 g ai ha⁻¹) was added to glyphosate (900 g ae ha⁻¹) plus saflufenacil (25 g ai ha⁻¹).

Despite the low CV values for all treatments relative to glufosinate (500 g ai ha⁻¹), the CV values in this study were fairly high (Table 5). Glufosinate is most efficacious when applied at warm air temperatures (Kumaratilake and Preston 2005) and when relative humidity is high (Coetzer et al. 2001). Steckel et al. (2006) reported inconsistent control of GR horseweed when applied when temperatures were cold. In the present study, PP applications were applied when the air temperature and relative humidity were 6 to 25 °C and 42% to 93%, respectively (Table 5). At some locations, particularly the Kintyre location, conditions were not optimal at the time of application, which could have contributed to the higher CV values reported in the present study. Because glufosinate is a contact herbicide, thorough spray coverage is essential to achieve acceptable weed control (Anonymous 2011). Previous research reported poor weed control with glufosinate when applied to high weed densities (Steckel et al. 1997; Tharp and Kells 2002). The high GR horseweed densities, especially at the Ridgetown and Kintyre locations, could have contributed to the higher CV values in the present study.

Soybean Yield

Soybean yield was reduced 450 kg ha⁻¹ from GR horseweed interference relative to the weed-free control (Table 4). All herbicide

Table 5. The consistency of glyphosate-resistant (GR) horseweed control 2, 4, and 8 wk after application (WAA) with dicamba-based mixtures from four field trials conducted in southern Ontario, Canada in 2020 and 2021.^a

Treatment ^b	Rate g ai/ae ha ⁻¹	Consistency of GR horseweed control		
		2 WAA	4 WAA	8 WAA
		%		
Glufosinate	500	72.5	49.5	60.5
Glufosinate	1,000	63.5	43.6	53.7
Glufosinate + 100 L water + 100 L UAN	500	72.1	47.9	59.9
Glufosinate + 200 L UAN	500	67.8	46.3	56.1
Glufosinate + halauxifen-methyl ^c	500 + 5	71.8	45.7	56.0
Glufosinate + 2,4-D ester	500 + 528	63.3	42.3	52.9
Glufosinate + saflufenacil ^d	500 + 25	64.2	42.7	51.6
Glufosinate + metribuzin	500 + 400	56.0	38.4	43.7
Glufosinate + dicamba	500 + 600	58.2	36.7	42.4

^aAbbreviation: UAN, 28% urea ammonium nitrate.

^bEach treatment included 900 g ae ha⁻¹ of glyphosate.

^cTreatments with halauxifen-methyl included the surfactant methylated seed oil (1.0% v/v).

^dTreatments with saflufenacil included the surfactant Merge (1.0 L ha⁻¹).

treatments had similar soybean yields. Eubank et al. (2008) reported soybean yields comparable to the present study with glufosinate-based mixtures. In contrast, Quinn et al. (2021) reported that interference from GR horseweed reduced soybean yield in the weedy control by 1500 kg ha⁻¹ relative to the weed-free control.

This study concludes that GR horseweed control was not improved by increasing the rate of glufosinate from 500 to 1,000 g ai ha⁻¹, and there was no benefit from using 28% UAN (50% or 100%) as the carrier solution. In addition, GR horseweed control was not improved with glufosinate plus halauxifen-methyl, 2,4-D ester, or saflufenacil. In contrast, adding dicamba or metribuzin to glufosinate improved GR horseweed control and reduced GR horseweed density and biomass compared to glufosinate (500 g ai ha⁻¹). However, mixing glufosinate with dicamba is not recommended, because it may enhance dicamba volatility and subsequent off-target movement. There was an improvement in the consistency of GR horseweed control for all treatments 2, 4, and 8 WAA compared to glufosinate alone. This study concludes that the addition of metribuzin to glufosinate improves the level and consistency of GR horseweed control.

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