Weed Technology

www.cambridge.org/wet

Research Article

Cite this article: Duenk E, Soltani N, Miller RT, Hooker DC, Robinson DE, Sikkema PH (2023) Effect of glufosinate rate and addition of ammonium sulfate on annual weed control in glyphosate/glufosinate/2,4-D–resistant soybean. Weed Technol. **37**: 141–146. doi: 10.1017/wet.2023.22

Received: 2 November 2022
Revised: 7 February 2023
Accepted: 11 March 2023
First published online: 5 April 2023

Associate Editor:
Aaron Hager, University of Illinois

Nomenclature:
Glyphosate; glufosinate; common ragweed; *Ambrosia artemisiifolia* L.; common lambsquarters; *Chenopodium album* L.; green foxtail; *Setaria viridis* (L.) P. Beauv.; velvetleaf; *Abutilon theophrasti* Medik.; soybean; *Glycine max* (L.) Merr.

Keywords:
Ammonium sulfate; biomass; density; glyphosate/glufosinate/2,4-D-resistant soybean; grain yield; postemergence herbicides

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

Effect of glufosinate rate and addition of ammonium sulfate on annual weed control in glyphosate/glufosinate/2,4-D–resistant soybean

Emily Duenk[1], Nader Soltani[2], Robert T. Miller[3], David C. Hooker[4], Darren E. Robinson[5] and Peter H. Sikkema[5]

[1]Graduate Student, University of Guelph Ridgetown Campus, Ridgetown, ON, Canada; [2]Adjunct Professor, University of Guelph Ridgetown Campus, Ridgetown, ON, Canada; [3]Regional Technical Services Manager, BASF Canada Inc., Mississauga, ON, Canada; [4]Associate Professor, University of Guelph Ridgetown Campus, Ridgetown, ON, Canada and [5]Professor, University of Guelph Ridgetown Campus, Ridgetown, ON, Canada

Abstract

The development of glufosinate-resistant soybean cultivars has created opportunities for use of glufosinate applied postemergence for weed control. Four field experiments were conducted in 2021 and 2022 to ascertain the effect of glufosinate rate and the addition of ammonium sulfate on annual weed control in glyphosate/glufosinate/2,4-D–resistant soybean. An increased glufosinate rate of 500 from 300 g ai ha^{-1} improved control of common ragweed, common lambsquarters, redroot pigweed, and foxtail species and resulted in decreased density and dry biomass of common lambsquarters and foxtail species. The addition of ammonium sulfate to glufosinate increased control of common lambsquarters, 2 and 8 wk after application (WAA), and of foxtail species, 2, 4, and 8 WAA, but did not improve control of common ragweed and redroot pigweed. Increasing the dose of glufosinate from 300 to 500 g ai ha^{-1} improves control of common ragweed, redroot pigweed, common lambsquarters, and foxtail species; however, the benefit of the addition of ammonium sulfate to glufosinate is weed species-specific.

Introduction

Weed interference can reduce soybean yield more than any other biotic factor (Oerke 2006). The extent of yield loss due to weeds is impacted by several factors including relative time of crop and weed emergence, weed species composition, weed density, weather, soil type, and soil nutrient levels. For instance, interference from high densities of common ragweed or common lambsquarters can diminish soybean yield by up to 70% and 75%, respectively (Weaver 2001). Generally, grass weeds are considered less competitive than broadleaf weeds; however, at high densities (>400 plants m^{-2}) green foxtail decreased soybean yield by 80% (Weaver 2001). The inclusion of an early postemergence (POST) herbicide such as glufosinate can be one component of a diversified weed management strategy to minimize soybean yield loss from weed-crop interference.

Glufosinate is a nonselective, POST-applied herbicide that offers broad-spectrum weed control. First commercialized in Canada in 1993, glufosinate blocks glutamine synthetase, an essential enzyme for nitrogen assimilation, metabolism, and photorespiration, creating the accumulation of reactive oxygen species (Takano et al. 2019; Takano and Dayan 2020). Driven by an immense accumulation of reactive oxygen species, glufosinate-induced phytotoxicity is rapid, causing cell death shortly after application (Takano et al. 2019). Only six weed species have evolved resistance to glufosinate, despite commercialization for almost 30 yr (Heap 2022). Weed control efficacy with glufosinate is influenced by weed species, weed height at application, time of day at application, weather, adjuvant, and glufosinate application rate (Coetzer et al. 2002; Steckel et al. 1997). In general, dicot species are more susceptible to glufosinate than monocot species (Takano et al. 2019). Common lambsquarters has reduced sensitivity to glufosinate that results in variable control compared to other broadleaf weeds (Steckel et al. 1997; Takano and Dayan 2020).

Glufosinate-resistant soybean was developed in 2011; these cultivars have genes that code for the phosphinothricin acetyltransferase enzyme (*PAT* gene), which results in the rapid metabolism of glufosinate (Takano and Dayan 2020). The *PAT* gene has been stacked with other herbicide resistance traits to expand POST herbicide options, including traits that confer resistance to glyphosate, dicamba, and 2,4-D.

Ammonium sulfate (AMS) is commonly applied as an adjuvant with weak-acid herbicides (Devkota and Johnson 2016). Efficacy from glufosinate on difficult-to-control species is antagonized by cations present in hard water (Takano and Dayan 2020). Inclusion of AMS in the herbicide mixture can lessen the antagonistic effect (Thelen et al. 1995) by increasing herbicide absorption (Maschhoff et al. 2000). The addition of AMS to the carrier solution prior to adding glufosinate is often required for the control of velvetleaf independent of the concentration of hard water cations in solution (Pratt et al. 2003). Greenhouse experiments reported enhanced control of giant ragweed when AMS was mixed with glufosinate, but control of Palmer amaranth was not improved (Devkota and Johnson 2016). Experiments conducted in field corn in Ontario reported that inclusion of AMS with glufosinate enhanced the control of common lambsquarters but had no effect on other annual weeds evaluated (Soltani et al. 2011); the benefit of AMS is weed species–dependent (Devkota and Johnson 2016; Soltani et al. 2011). Further studies should be conducted in Ontario to determine the benefit of AMS and the appropriate rate of AMS for the control of problematic annual weeds in soybean. Furthermore, the cost of AMS has increased significantly in recent years. Ontario farmers can have substantial monetary gains by selectively using AMS depending on the weed species present.

New soybean cultivars possessing multiple herbicide resistance to glyphosate, glufosinate, and 2,4-D are now available in eastern Canada, which may reduce the evolution of herbicide-resistant weeds by increasing the POST herbicide options. Use of glufosinate as a POST herbicide in Ontario soybean has expanded in recent years for controlling glyphosate-resistant and multiple herbicide–resistant weeds. Few studies have been conducted in Ontario on the effect of glufosinate rates in combination with various rates of AMS for the control of troublesome weed species in glyphosate/glufosinate/2,4-D–resistant (GG2R) soybean. It is economically and environmentally important to determine the lowest effective dose of glufosinate and AMS for the control of problematic weeds in soybean under Ontario environmental conditions.

The objectives of this study were to ascertain the effect of the glufosinate rate and the addition of AMS at three rates for the control of problematic annual weeds in GG2R soybean. This study builds upon previous research on glufosinate rate and AMS by examining the weed species–specific response of common lambsquarters, common ragweed, redroot pigweed, and foxtail species under the environmental conditions of southwest Ontario, which has not yet been examined in the recent literature.

Methods and Materials

Four site-years of field experiments were conducted in Ontario: at the Huron Research Station near Exeter (43.32°N, 81.50°W) in 2021; the University of Guelph, Ridgetown Campus in Ridgetown (42.45°N, 81.88°W) in 2021 and 2022; and at the BASF Research Farm near London (42.87°N, 81.13°W) in 2022. Treatments were arranged in a randomized complete block design with four replications. Glufosinate was applied at two doses, 300 and 500 g ai ha^{-1}, mixed with four rates of AMS (0, 3.25, 6.50, and 13.00 L ha^{-1}) applied POST to GG2R soybean between the V2 and V4 stages, depending on site-year (Table 1). The 200 g L^{-1} formulation of glufosinate with a current field use rates of 300 and 500 g ai ha^{-1} (Liberty 200 SN; BASF Canada Inc., Mississauga, ON) was used in this study. Each replication contained a weed-free control that was maintained with *S*-metolachlor/metribuzin (1,943 g ai ha^{-1}; Boundary LQD; Syngenta Canada Inc., Guelph, ON) + imazethapyr (75 g ai ha^{-1}; Pursuit; BASF Canada Inc.) applied preemergence followed by a POST application of glyphosate (900 g ae ha^{-1}; Roundup WeatherMAX; Bayer Crop Science Inc., Calgary, AB). A second weed-free control was kept weed-free from the time of the POST application treatment and consisted of glyphosate (900 g ae ha^{-1}) applied POST. All weed-free treatments were hand-weeded as necessary to ensure they were absent of weeds. Herbicide treatments were sprayed between 9:00 and 11:00 AM to reduce the time-of-day application effect reported for glufosinate efficacy (Martinson et al. 2005; Montgomery et al. 2017; Takano and Dayan 2020).

GG2R soybean was seeded approximately 4 cm deep at approximately 400,000 seeds ha^{-1} in rows spaced 75 cm apart. The plots near Exeter were 3 m wide (four soybean rows) and 10 m in length and 3 m wide × 8 m in length in Ridgetown and near London. Herbicides were sprayed using a carbon dioxide–pressurized backpack sprayer calibrated to deliver 200 L ha^{-1} solution at 240 kPa. The boom of the sprayer was outfitted with four ULD11002 spray nozzles (Pentair, New Brighton, MN) spaced 50 cm apart producing a spray width of 2.0 m. Hard water (1,600 ppm calcium carbonate) from a farm near Plattsville, ON, was used for the carrier spray solution to ascertain the benefit of AMS. Each site contained natural weed populations, and herbicide treatments were sprayed when weeds were approximately 10 cm tall. Additional trial information is presented in Table 1.

Soybean injury was evaluated visually using a scale of 0% to 100% (0% = no visible injury and 100% = complete necrosis) 1, 2, and 4 weeks after application (WAA). Weed control assessments by species were conducted 2, 4, and 8 WAA using a 0% to 100% scale (0% = no weed control and 100% = no weed presence). Regrowth of certain weeds was observed and taken into consideration during weed control assessments; regrowth indicated reduced weed control. Weed density and biomass for each weed species were collected 4 WAA from two randomly placed 0.25-m^2 quadrats in each plot. The weed species within each quadrat were counted (recorded as density) and cut aboveground, placed in labeled paper bags, and dried in a kiln at 60 C. Dry weed biomass was weighed and recorded as aboveground biomass. The center two rows of all plots were machine harvested at soybean harvest maturity; soybean yield and seed moisture content were recorded.

Statistical Analysis

All data were subjected to mixed model variance analysis using the GLIMMIX procedure with SAS software (version 9.4; SAS Institute Inc., Cary, NC). The fixed effect was herbicide treatment. Random effect consisted of environment, including location and year, and replication within the environment. All weed data were analyzed by weed species, and site-years were pooled by weed species present at each site. Residuals were plotted, and the Shapiro-Wilk statistic was used to determine whether data were normally distributed. Weed density and biomass data for all species were analyzed using a lognormal distribution to best meet the assumptions of the analysis. Transformed means were back-transformed for the presentation of results. The Tukey-Kramer test was used to compare means using a confidence level of $P = 0.05$. The nontreated control and weed-free controls were excluded from weed control and injury analysis due to no variance. Weed-free controls were excluded from weed density and biomass analysis. Nonorthogonal contrasts were performed to compare glufosinate rates of 300 and 500 g ai ha^{-1} across all treatments and to compare treatments containing only glufosinate to treatments including glufosinate + AMS.

Table 1. Year, location, soil characteristics, soybean planting, emergence and harvest dates, and herbicide application.[a]

		Soil characteristics			Soybean			Herbicide treatment application	
Year	Location	Texture	OM	pH	Planting date	Emergence date	Harvest date	Application date	Soybean development stage
			%						
2021	Exeter	Clay loam	2.9	7.6	May 14	May 22	November 2	June 14	V2
2021	Ridgetown	Clay loam	4.2	7.6	May 20	May 26	October 1	June 23	V4
2022	Ridgetown	Clay loam	5.5	6.6	May 24	May 31	October 6	June 28	V4
2022	London	Loam	3.3	6.7	June 15	June 22	October 11	July 14	V3

[a]Abbreviation: OM, organic matter.

Table 2. Effect of glufosinate rate and addition of ammonium sulfate on visible control of common lambsquarters after application, density, and dry biomass in glyphosate/glufosinate/2,4-D–resistant soybean.[a,c]

		Visible control[b]				
Treatment	Rate	2 WAA	4 WAA	8 WAA	Density	Dry biomass
	g ai ha^{-1} or L ha^{-1}		%		plants m^{-2}	g m^{-2}
Nontreated control	–	0	0	0	82 b	64.5 e
Weed-free control	–	100	100	100	0	0
Glufosinate	300	54 d	39 c	38 d	66 ab	48.5 cde
Glufosinate + AMS	300 + 3.25	56 d	40 c	38 d	62 ab	46.3 bcde
Glufosinate + AMS	300 + 6.50	63 cd	45 bc	43 bcd	57 ab	46.4 abcd
Glufosinate + AMS	300 + 13.00	57 d	38 c	39 cd	75 ab	61.3 de
Glufosinate	500	67 bc	58 ab	48 bcd	60 ab	34.5 abcd
Glufosinate + AMS	500 + 3.25	69 abc	58 ab	49 bc	51 ab	18.7 abc
Glufosinate + AMS	500 + 6.50	77 a	67 a	60 a	54 a	11.7 a
Glufosinate + AMS	500 + 13.00	76 ab	65 a	53 ab	47 ab	21.4 ab
Contrasts						
Glufosinate 300 g ai ha^{-1} vs. glufosinate 500 g ai ha^{-1}		57 vs. 72*	40 vs. 62*	40 vs. 52*	64 vs. 52*	47.9 vs. 19.3*
Glufosinate vs. glufosinate + AMS		60 vs. 66*	48 vs. 52	43 vs. 47*	63 vs. 57	40.5 vs. 30.2

[a]Abbreviations: AMS, ammonium sulfate; WAA, weeks after application.
[b]Means within the column followed by the same lowercase letter are not statistically different according to the Tukey-Kramer multiple range test ($P < 0.05$).
[c]An asterisk (*) indicates significant difference ($P < 0.05$).

Results and Discussion

Soybean Injury

Glufosinate applied alone and with AMS caused minimal GG2R soybean injury (<2%), data not presented.

Common Lambsquarters

Glufosinate applied at 300 g ai ha^{-1} controlled common lambsquarters by 38% to 54% at 2, 4, and 8 WAA; the inclusion of AMS with glufosinate had no effect on common lambsquarters control (Table 2). Glufosinate applied at 500 g ai ha^{-1} provided 48% to 67% control of common lambsquarters at 2, 4, and 8 WAA; the addition of AMS at 6.50 L ha^{-1} enhanced common lambsquarters control by 10% at 2 WAA and by 12% 8 WAA. These data are consistent with former research reporting substandard control of common lambsquarters with glufosinate alone and with AMS (Bethke et al. 2013; Fluttert et al. 2022; Steckel et al. 1997). Glufosinate applied at 300 and 500 g ai ha^{-1} decreased common lambsquarters density by 20% and 27%, respectively. No further reduction in common lambsquarters density was observed with the inclusion of AMS. Glufosinate applied at 300 and 500 g ai ha^{-1} decreased common lambsquarters biomass by 25% and 47%, respectively. There was no further decrease in dry biomass with the inclusion of AMS in the mixture. Common lambsquarters control was enhanced by 15%, 22%, and 12% at 2, 4, and 8 WAA, respectively, when the glufosinate dose was increased from 300 to 500 g ai ha^{-1}, based on nonorthogonal contrasts. Additionally, common lambsquarters density and dry biomass decreased by 12 plants m^{-2} and dry biomass by 28.6 g m^{-2}. AMS mixed with glufosinate enhanced the control of common lambsquarters by 6% and 4% at 2 and 8 WAA, respectively. There was no improvement in control of common lambsquarters at 4 WAA when AMS was included with glufosinate and there was no further decrease in common lambsquarters density or dry biomass. Pline et al. (2000) observed that the inclusion of AMS with glufosinate had no effect on common lambsquarters control. In contrast, Soltani et al. (2011) reported improved common lambsquarters control of 5% with the inclusion of AMS with glufosinate in field corn 8 WAA.

Common Ragweed

Glufosinate applied at 300 g ai ha^{-1} controlled common ragweed by 83% to 91% at 2, 4, and 8 WAA, and control was similar with the addition of AMS (Table 3). Glufosinate applied at 500 g ai ha^{-1} provided 94% to 96% control of common ragweed at 2, 4, and 8 WAA; the inclusion of the AMS did not provide increased control of common ragweed. All glufosinate applications reduced common ragweed density and dry biomass compared to the

https://doi.org/10.1017/wet.2023.22 Published online by Cambridge University Press

Table 3. Effect of glufosinate rate and the addition of ammonium sulfate on visible control of common ragweed after application, density, and dry biomass in glyphosate/glufosinate/2,4-D–resistant soybean.[a,c]

Treatment	Rate	Visible control[b]			Density	Dry biomass
		2 WAA	4 WAA	8 WAA		
	g ai ha^{-1} or L ha^{-1}	———%———			plants m^{-2}	g m^{-2}
Nontreated control	–	0	0	0	30 b	50.8 b
Weed-free control	–	100	100	100	0	0
Glufosinate	300	91 a	88 ab	83 cd	1 a	0.3 a
Glufosinate + AMS	300 + 3.25	89 a	85 b	77 d	2 a	0.2 a
Glufosinate + AMS	300 + 6.50	92 a	92 ab	85 abcd	2 a	0.2 a
Glufosinate + AMS	300 + 13.00	93 a	89 ab	85 bcd	3 a	0.3 a
Glufosinate	500	96 a	96 a	94 ab	0 a	0.0 a
Glufosinate + AMS	500 + 3.25	94 a	96 a	90 abc	1 a	0.1 a
Glufosinate + AMS	500 + 6.50	97 a	94 ab	91 abc	0 a	0.0 a
Glufosinate + AMS	500 + 13.00	97 a	97 a	95 a	1 a	0.0 a
Contrasts						
Glufosinate 300 g ai ha^{-1} vs. glufosinate 500 g ai ha^{-1}		91 vs. 96*	88 vs. 96*	83 vs. 92*	2 vs. 0*	0.2 vs. 0.0
Glufosinate vs. glufosinate + AMS		94 vs. 94	92 vs. 92	87 vs. 87	1 vs. 1	0.1 vs. 0.1

[a]Abbreviations: AMS, ammonium sulfate; vs, versus; WAA, weeks after application.
[b]Means within the column followed by the same lowercase letter are not statistically different according to the Tukey-Kramer multiple range test ($P < 0.05$).
[c]An asterisk (*) indicates significant difference ($P < 0.05$).

Table 4. Effect of glufosinate rate and the addition of AMS on visible control of redroot pigweed after application, density, and dry biomass in glyphosate/glufosinate/2,4-D–resistant soybean.[a]

Treatment	Rate	Visible control[b,c]			Density	Dry biomass
		2 WAA	4 WAA	8 WAA		
	g ai ha^{-1} or L ha^{-1}	———%———			plants m^{-2}	g m^{-2}
Nontreated control	–	0	0	0	20 b	45.1 b
Weed-free control	–	100	100	100	0	0
Glufosinate	300	85 a	87 a	89 a	5 ab	0.5 ab
Glufosinate + AMS	300 + 3.25	90 a	88 a	83 a	10 ab	1.7 ab
Glufosinate + AMS	300 + 6.50	90 a	91 a	87 a	6 ab	0.9 ab
Glufosinate + AMS	300 + 13.00	94 a	95 a	91 a	6 ab	0.8 ab
Glufosinate	500	93 a	94 a	92 a	2 a	0.1 a
Glufosinate + AMS	500 + 3.25	92 a	92 a	88 a	8 ab	3.4 ab
Glufosinate + AMS	500 + 6.50	96 a	93 a	90 a	10 ab	1.2 ab
Glufosinate + AMS	500 + 13.00	96 a	96 a	92 a	4 a	0.1 a
Contrasts						
Glufosinate 300 g ai ha^{-1} vs. glufosinate 500 g ai ha^{-1}		89 vs. 94*	90 vs. 94*	87 vs. 91*	7 vs. 7	1.0 vs. 1.2
Glufosinate vs. glufosinate + AMS		89 vs. 93	90 vs. 92	90 vs. 88	4 vs. 8	0.3 vs. 1.5

[a]Abbreviations: AMS, ammonium sulfate; vs, versus; WAA, weeks after application.
[b]Means within the column followed by the same lowercase letter are not statistically different according to the Tukey-Kramer multiple range test ($P < 0.05$).
[c]An Asterisk (*) indicates significant difference ($P < 0.05$).

nontreated control. Research conducted by Pline et al. (2000) observed excellent control of common ragweed with glufosinate. Nonorthogonal contrasts indicate that increasing glufosinate rate from 300 to 500 g ai ha^{-1} increased common ragweed control by 5% to 9% at 2, 4, and 8 WAA, and decreased common ragweed density. AMS mixtures with glufosinate did not affect common ragweed control, density, or biomass.

Redroot Pigweed

Glufosinate applied at 300 and 500 g ai ha^{-1} controlled redroot pigweed by 85% to 89% and by 92% to 94% at 2, 4, and 8 WAA, respectively; the higher rate of glufosinate did not result in improved redroot pigweed control (Table 4). Redroot pigweed control was the same when AMS was added to either rate of glufosinate. Pline et al. (2000) reported ≥95% control of redroot pigweed with glufosinate at similar doses, which is consistent with this research. Glufosinate applied at 300 and 500 g ai ha^{-1} decreased redroot pigweed density by 75% and 90%, respectively, at 4 WAA; there was no further density reduction with the addition of AMS. Glufosinate applied at 300 and 500 g ai ha^{-1} decreased redroot pigweed dry biomass by 99% and 99.8%, respectively; no further reduction in dry biomass was observed with the addition of AMS. Nonorthogonal contrasts indicate that the higher rate of glufosinate (500 g ai ha^{-1}) provided enhanced redroot pigweed control by 5, 4, and 4 percentage points at 2, 4, and 8 WAA, respectively. The redroot pigweed density and biomass were similar at both glufosinate doses. Based on nonorthogonal contrasts, the inclusion of AMS with glufosinate had no effect on redroot pigweed control, density, or dry biomass. Soltani

https://doi.org/10.1017/wet.2023.22 Published online by Cambridge University Press

Table 5. Effect of glufosinate rate and the addition of AMS on visible control of foxtail species after application, density, and dry biomass in glyphosate/glufosinate/2,4-D–resistant soybean.[a,c]

Treatment	Rate	Visible control[b]			Density	Dry biomass
		2 WAA	4 WAA	8 WAA		
	g ai ha^{-1} or L ha^{-1}	-%-			plants m^{-2}	g m^{-2}
Nontreated control	–	0	0	0	68 b	54.0 b
Weed-free control	–	100	100	100	0	0
Glufosinate	300	85 c	70 d	78 c	17 a	2.0 a
Glufosinate + AMS	300 + 3.25	90 bc	79 bc	84 abc	10 a	0.6 a
Glufosinate + AMS	300 + 6.50	91 ab	74 dc	81 bc	21 a	2.3 a
Glufosinate + AMS	300 + 13.00	92 ab	79 bc	84 abc	16 a	2.3 a
Glufosinate	500	93 ab	84 ab	87 ab	15 a	1.6 a
Glufosinate + AMS	500 + 3.25	96 a	86 ab	87 ab	5 a	0.2 a
Glufosinate + AMS	500 + 6.50	95 ab	85 ab	90 a	7 a	0.4 a
Glufosinate + AMS	500 + 13.00	96 a	88 a	87 ab	9 a	0.7 a
Contrasts						
Glufosinate 300 g ai ha^{-1} vs. glufosinate 500 g ai ha^{-1}		90 vs. 95*	76 vs. 88*	82 vs. 88*	15 vs. 8*	1.7 vs. 0.6*
Glufosinate vs. glufosinate + AMS		89 vs. 94*	77 vs. 82*	82 vs. 86*	16 vs. 10	1.8 vs. 1.0

[a]Abbreviations: AMS, ammonium sulfate; vs, versus; WAA, weeks after application.
[b]Means within the column followed by the same lowercase letter are not statistically different according to the Tukey-Kramer multiple range test ($P < 0.05$).
[c]An asterisk (*) indicates significant difference ($P < 0.05$).

Table 6. Effect of glufosinate rate and the addition of AMS on glyphosate/glufosinate/2,4-D–resistant soybean yield.[a]

Treatment	Rate	Soybean yield[b]
	g ai ha^{-1} or L ha^{-1}	kg ha^{-1}
Nontreated control	–	2,400 c
Season-long weed-free control	–	3,600 a
Weed-free from POST application	–	3,500 ab
Glufosinate	300	3,200 b
Glufosinate + AMS	300 + 3.25	3,300 ab
Glufosinate + AMS	300 + 6.50	3,300 ab
Glufosinate + AMS	300 + 13.00	3,200 ab
Glufosinate	500	3,300 ab
Glufosinate + AMS	500 + 3.25	3,400 ab
Glufosinate + AMS	500 + 6.50	3,300 ab
Glufosinate + AMS	500 + 13.00	3,400 ab
Contrasts		
Glufosinate 300 g ai ha^{-1} vs. glufosinate 500 g ai ha^{-1}		3,200 vs. 3,400
Glufosinate vs. glufosinate + AMS		3,200 vs. 3,300

[a]Abbreviations: AMS, ammonium sulfate; POST, postemergence.
[b]Means within the column followed by the same lowercase letter are not statistically different according to the Tukey-Kramer multiple range test ($P < 0.05$).

et al. (2011) also observed no improvement in redroot pigweed control or decrease in dry biomass when AMS at 2.5 L ha^{-1} was included with glufosinate at 400 g ai ha^{-1}.

Foxtail Species

Glufosinate applied at 300 g ai ha^{-1} controlled foxtail species by 70% to 85% at 2, 4, and 8 WAA; foxtail species control was enhanced with the inclusion of AMS at 6.50 and 13 L ha^{-1} at 2 WAA and with the inclusion of ammonium sulfate at 3.25 and 13 L ha^{-1} at 4 WAA. The inclusion of AMS with glufosinate had no effect on foxtail species control 8 WAA (Table 5). Glufosinate at 500 g ai ha^{-1} controlled foxtail species by 84% to 93% at 2, 4, and 8 WAA. Foxtail species control was not enhanced with the inclusion of AMS. Glufosinate applied at 300 and 500 g ai ha^{-1} reduced foxtail species density by 75% and 78% and dry biomass by 96% and 97%, respectively. The inclusion of AMS had no effect on the density and dry biomass of foxtail species. Based on nonorthogonal contrasts, elevating the dose of glufosinate from 300 to 500 g ai ha^{-1} improved foxtail control by 5 to 12 percentage points and reduced foxtail density by 7 plants m^{-2} and foxtail dry biomass by 1.1 g m^{-2}. Nonorthogonal contrasts show that the inclusion of AMS with glufosinate improved foxtail species control by up to 5%. Past research has shown greater glufosinate efficacy when co-applied with AMS for control of giant foxtail (Maschhoff et al. 2000). In contrast, Soltani et al. (2011) found no improvement in the efficacy, dry biomass, or density of foxtail species when AMS was added to glufosinate.

Soybean Yield

Interference from annual weeds reduced soybean yield by 34% in this study (Table 6). Weed interference with glufosinate applied at 300 g ai ha^{-1} reduced soybean yield by 11% in comparison with the season-long weed-free control (highest-yielding treatment). Reduced weed interference with all other glufosinate treatments resulted in soybean yield that was similar to the season-long weed-free control. Soybean yield in the season-long weed-free control and the weed-free control from the time of the POST application was similar.

This research demonstrates grass and broadleaf control in response to glufosinate dose and AMS, and that AMS rate is species-specific when using hard water as the carrier source. Based on contrasts, increasing the glufosinate dose from 300 to 500 g ai ha^{-1} improved control of common lambsquarters, common ragweed, redroot pigweed, and foxtail species at all evaluation dates. Additionally, raising the dose of glufosinate to 500 g ai ha^{-1} reduced the density and dry biomass of common lambsquarters and foxtail species and reduced common ragweed density. The inclusion of AMS with glufosinate enhanced common lambsquarters control at 2 and 8 WAA, and foxtail species control at 2, 4, and 8 WAA. The inclusion of AMS with glufosinate did not enhance the control of redroot pigweed or common ragweed. These results from 4 site-years in Ontario fields are consistent with other laboratory and field research. Maschhoff et al. (2000) reported that AMS improved control from glufosinate on some weed species by enhancing the absorption of glufosinate. Pline et al. (2000) observed increased control of common milkweed when AMS was added to glufosinate, but no increase in control of the annual weeds was evaluated. Steckel et al. (1997) reported differing sensitivity among weed species to glufosinate, with control being determined by glufosinate rate and the size of weeds when glufosinate is applied; the optimal rate of glufosinate was dependent on the species present and weed height at application. Our research indicates based on contrasts, that raising the dose of glufosinate from 300 to 500 g ai ha^{-1} results in enhanced control of common lambsquarters, common ragweed, redroot pigweed, and foxtail species, and the inclusion of AMS with glufosinate results in enhanced control of common lambsquarters and foxtail species. Ontario soybean producers who use glufosinate-resistant traits should apply glufosinate at 500 g ai ha^{-1} and should add AMS depending on the weed species present. In general, common lambsquarters control was poor with all glufosinate treatments, which is consistent with previous research (Bethke et al. 2013; Fluttert et al. 2022; Steckel et al. 1997). Growers should avoid the use of glufosinate if common lambsquarters is the target weed. Glufosinate efficacy may be improved when used as a POST herbicide in a two-pass weed control system because the size and density of weeds at the time of application is greatly reduced (Davis et al. 2010). Applications of glufosinate in this study were applied to an average of 10-cm weeds. Soybean growers applying glufosinate may find improved control, especially of common lambsquarters, compared to this study if applied to 5-cm weeds and less-dense weed populations.

Practical Implications

Currently, glufosinate-resistance is being stacked alongside other herbicide-resistant soybean traits, including glyphosate, 2,4-D, and dicamba. Glyphosate/glufosinate/2,4-D–resistant (GG2R) soybean cultivars provide growers with additional POST herbicide options for improved weed control and introduce more diversity into weed management programs. Glufosinate can be applied POST for the control of problematic weeds in GG2R soybean. With the rise of herbicide cost in recent years, some growers may be seeking to decrease production costs by reducing the rate of glufosinate applications. Based on this research, the high label rate of 500 g ai ha^{-1} should be used for more consistent control of most annual weeds in Ontario. This rate was found to provide improved control of all species evaluated including common lambsquarters, common ragweed, redroot pigweed, and foxtail species, compared to the low label rate of 300 g ai ha^{-1}. With the use of hard water as the carrier solution, the benefit of adding AMS to glufosinate is weed species-specific. The inclusion of AMS with glufosinate can enhance control of common lambsquarters and foxtail species. The inclusion of AMS with glufosinate does not enhance the control of redroot pigweed or common ragweed. Glufosinate plus AMS applied at 6.5 L ha^{-1} was adequate to improve control of common lambsquarters 8 WAA, and higher rates of AMS are unnecessary. Input costs can be reduced by eliminating the inclusion of AMS with glufosinate in fields with weeds such as common ragweed and redroot pigweed. Results demonstrate that adequate control of common lambsquarters is not achieved with glufosinate regardless of the rate or the addition of AMS, and its use should be avoided if common lambsquarters is the target weed species.

Acknowledgments. This research was funded in part by BASF Canada, Grain Farmers of Ontario (GFO), and the Ontario Agri-Food Innovation Alliance. No other conflicts of interest have been declared.

References

Bethke RK, Molin WT, Sprague C, Penner D (2013) Evaluation of the interaction between glyphosate and glufosinate. Weed Sci 61:41–47

Coetzer E, Al-Khatib K, Peterson DE (2002) Glufosinate efficacy on *Amaranthus* species in glufosinate-resistant soybean (*Glycine max*). Weed Technol 16:326–331

Davis VM, Kruger GR, Young BG, Johnson WG (2010) Fall and spring preplant herbicide applications influence spring emergence of glyphosate-resistant Canada fleabane (*Conyza canadensis*). Weed Technol 24:11–19

Devkota P, Johnson WG (2016) Glufosinate efficacy as influenced by carrier water pH, hardness, foliar fertilizer, and ammonium sulfate. Weed Technol 30:848–859

Fluttert JC, Soltani N, Galla M, Hooker DC, Robinson DE, Sikkema PH (2022) Interaction between 4-hydroxyphenylpyruvate dioxygenase-inhibiting and reactive oxygen species-generating herbicides for control of annual weed species in corn. Weed Sci 70:423–435

Heap I (2022) The international survey of herbicide-resistant weeds. www.weedscience.org. Accessed: April 6, 2022

Martinson KB, Durgan BR, Gunsolus JL, Sothern RB (2005) Time of day of application effect on glyphosate and glufosinate efficacy. Crop Manag Res 4:1–7

Maschhoff JR, Hart SE, Baldwin JL (2000) Effect of ammonium sulfate on the efficacy, absorption, and translocation of glufosinate. Weed Sci 48:2–6

Montgomery GB, Treadway JA, Reeves JL, Steckle LE (2017) Effect of time of day of application of 2,4-D, dicamba, glufosinate, paraquat, and saflufenacil on horseweed (*Conyza canadensis*) control. Weed Technol 31:550–556

Oerke EC (2006) Crop losses to pests. J Agr Sci 144:31–43

Pline WA, Hatzios KK, Hagood ES (2000) Weed and herbicide-resistant soybean (*Glycine max*) response to glufosinate and glyphosate plus ammonium sulfate and pelargonic acid. Weed Technol 14:667–674

Pratt D, Kells JJ, Penner D (2003) Substitutes for ammonium sulfate as additives with glyphosate and glufosinate. Weed Technol 17:576–581

Soltani N, Nurse RE, Robinson D, Sikkema PH (2011) Effect of ammonium sulfate and water hardness on glyphosate and glufosinate activity in corn. Can J Plant Sci 99:437–443

Steckel GJ, Wax LM, Simmons FW, Phillips WH II (1997) Glufosinate efficacy on annual weeds is influenced by rate and growth stage. Weed Technol 11:484–488

Takano HK, Beffa R, Preston C, Westra P, Dayan FE (2019) Reactive oxygen species trigger the fast action of glufosinate. Planta 249:1837–1849

Takano HK, Dayan FE (2020) Glufosinate-ammonium: a review of the current state of knowledge. Pest Manag Sci 76:3911–3925

Thelen KD, Jackson EP, Penner D (1995) The basis for the hard water antagonism of glyphosate activity. Weed Sci 43:541–548

Weaver SE (2001) Impact of lamb's-quarters, common ragweed and green foxtail on yield of corn and soybean in Ontario. Can J Plant Sci 81:821–828