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Confirmation of glyphosate-resistant waterhemp (*Amaranthus tuberculatus*) in New York

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Abstract

Waterhemp has become a serious management challenge for New York (NY) field crop growers. Two putative glyphosate-resistant (GR) waterhemp populations (NY1 and NY2) were collected in 2023 from two soybean fields in Seneca County, NY. The objectives of this research were to (1) confirm and characterize the level of glyphosate resistance in waterhemp populations from NY relative to a known glyphosate-susceptible Nebraska (NE_SUS) population and (2) evaluate the efficacy of various postemergence (POST) herbicides for GR waterhemp control. Based on the shoot dry weight reductions (GR_{50} values) in a dose-response study, the NY1 and NY2 populations exhibited 5.6- to 8.3-fold resistance to glyphosate compared with the NE_SUS population. In a separate study, POST herbicides such as dicamba, glufosinate, lactofen, and 2,4-D applied alone or in a mixture with glyphosate or glufosinate had provided 89% to 99% control and ≥ 97% shoot dry weight reduction of NY1 and NY2 populations 21 days after treatment (DAT). Greater than 98% control of the NE_SUS population was achieved with tested POST herbicides, except mesotrione (62% control). Furthermore, atrazine, chlorimuron + thifensulfuron, and mesotrione were the least effective in controlling NY1 and NY2 populations (42% to 59% control and 50% to 67% shoot dry weight reductions, respectively). These results confirm the first report of GR waterhemp in NY. Growers should adopt effective alternative POST herbicides tested in this study to manage GR waterhemp.

Nomenclature: Atrazine; chlorimuron; dicamba; glufosinate; glyphosate; lactofen; mesotrione; thifensulfuron; 2,4-D; waterhemp, *Amaranthus tuberculatus* (L.)

Keywords: Glyphosate; soybean; New York

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Introduction

Waterhemp is one of the most troublesome summer annual broadleaf weed species in the pigweed family infesting agronomic crops across the midwestern United States (Hager et al. 2002; Steckel and Sprague 2004a). It is native to the central United States with a distribution ranging from Texas to Canada (Rosenbaum and Bradley 2013; Nordby et al. 2007). It is a dioecious (i.e., male and female flowers on separate plants) and C_4 plant with several unique characteristics, including an extended emergence window (May through September), rapid growth rate, and prolific seed production (Duff et al. 2009; Hartzler et al. 1999; Steckel et al. 2003). Waterhemp is a highly competitive weed and can cause significant crop grain yield losses. For instance, Hager et al. (2002) reported up to 43% grain yield losses in soybean [*Glycine max* (L.) Merr] when waterhemp plants were allowed to compete up to 10 weeks after soybean unifoliate expansion. Season-long competition of waterhemp plants reduced soybean yields by 37 to 44% (Steckel and Sprague 2004a). Similarly, season-long interference of waterhemp reduced corn (*Zea mays* L.) grain yield by 11 to 74% (Steckel and Sprague 2004b). Depending upon growing conditions and in the absence of crop competition, a single female waterhemp plant can produce >100,000 seeds. Waterhemp seeds remain viable in the soil for several years, resulting in large soil seedbanks (Hager et al. 1997; Nordby et al. 2007). In controlled seedbank burial studies, about 12% and 10% of the total waterhemp seedbank persisted after three and four years of burial, respectively (Buhler and Hartzler 2001; Nordby et al. 2007; Steckel et al. 2007).

Waterhemp is highly prone to evolve herbicide resistance (Heap 2024). Several waterhemp populations have been reported with resistance to seven different classes of herbicides, including inhibitors of acetolactate synthase (ALS), photosystem II (PSII), protoporphyrinogen oxidase (PPO), 4-hydroxyphenylpyruvate dioxygenase (HPPD), 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS), very long chain fatty acid (VLCFA), and synthetic auxins (Bernards et al. 2012; Guo et al. 2015; Hausman et al. 2011; Heap 2024; Patzoldt et al. 2003; Shoup et al. 2003; Zelaya and Owen 2005). Among all these reported cases, glyphosate resistance is quite common among waterhemp populations (Heap 2024). Since its first confirmed occurrence in Missouri in 2005, glyphosate-resistant (GR) waterhemp has been reported from 21 states in the U.S. and one province (Ontario) in Canada (Heap 2024). In addition, multiple herbicide resistance within waterhemp populations is also a significant concern (Heap 2024). For instance, five-way (resistance to ALS, EPSPS, PS II, PPO, and HPPD inhibitors) and six-way (resistance to ALS,

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EPSPS, PS II, PPO, HPPD inhibitors, and synthetic auxins) multiple herbicide-resistant (MHR) waterhemp populations have been reported in Illinois and Missouri, respectively (Evans et al. 2019; Shergill et al. 2018a). The rapid evolution and spread of MHR waterhemp populations further limits the number of alternative herbicide options available for their effective control (Bell et al. 2013; Faleco et al. 2022: Legleiter and Bradley 2008; Schultz et al. 2015; Singh et al. 2020).

Waterhemp populations were first observed in crop fields in 2014 in the central and western parts of New York state (Brown and Hunter 2019; Mike Stanyard, personal communication). Some of these populations were believed to have arrived via used farm equipment purchased from the Midwestern states (Hunter and Sosnoskie 2024). Currently, waterhemp populations are distributed across 20 counties in the NY state, infesting a large acreage of field and specialty crops, including corn (*Zea mays* L.), soybean (*Glycine max* [L.] Merr), alfalfa (*Medicago sativa*), snap beans (*Phaseolus spp.*), squashes (*Cucurbita spp.*), and dry beans (*Phaseolus spp.*), etc. (Marschner 2024). The majority of conventional field crop producers (mainly corn and soybean) in NY state rely on glyphosate applications in burndown (prior to crop seeding), in-season, and postharvest situations for season-long weed control (Mike Stanyard, personal observation). In recent years, waterhemp populations surviving glyphosate applications have become quite evident in NY soybean and corn fields. During the 2023 growing season, waterhemp control failures were observed in two separate soybean fields in Seneca County of central NY, following repeated applications of glyphosate at rates >1200 g ha^{-1}. In response to control failures, these waterhemp populations were collected from growers' fields to evaluate for suspected resistance to glyphosate. Furthermore, limited information exists on the effectiveness of alternative POST herbicides to control these putative GR waterhemp populations from NY state. Therefore, the main objectives of this research were to (1) confirm and characterize the level of glyphosate resistance in selected waterhemp populations and (2) investigate the efficacy of alternative POST herbicides to control these GR populations in NY.

Materials and Methods

Plant Materials. About 25 plants from two putative GR waterhemp populations surviving glyphosate application at 1260 g ha^{-1} were collected in late summer of 2023. The first field, referred to as NY1, was located near Seneca Falls, while the second field, referred to as NY2, was located near Junius. Both fields are in Seneca County, NY, approximately 15 km apart. Both fields were historically under corn-soybean rotations with repeated glyphosate use. To obtain seeds for the

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experiments, field-collected waterhemp plants from both NY1 and NY2 populations were separately grown in two separate greenhouses at Cornell University in Ithaca, NY, in 10-L pots and were allowed to mature during the fall of 2023. The first-generation seeds from both waterhemp populations harvested at maturity were used in subsequent greenhouse experiments. Furthermore, seeds of a previously known glyphosate-susceptible waterhemp population (NE_SUS) from a field site near Clay Center, Nebraska were used (Sarangi et al. 2015).

Glyphosate Dose-Response Experiments. Greenhouse experiments were conducted at the Guterman bioclimatic laboratory at Cornell University in Ithaca, NY, during spring of 2024. Seeds of the NY1, NY2, and NE_SUS waterhemp populations were planted, separately, on the surface of 54 by 34 by 6-cm germination flats filled with a Cornell greenhouse potting mixture (mixture of Canadian peat moss, vermiculite, perlite, dolomite lime, Jack's 10-5-10 media mix plus II and calcium sulfate). Waterhemp seedlings from each population were separately transplanted into 10-cm square plastic pots (Greenhouse Megastore, Danville, IL, USA) containing the same potting mixture as the germination trays. Experiments were set up in a randomized complete block (blocked by population) design with fifteen replications (one plant per pot = one replication) and repeated. Greenhouse conditions were set at 27/24 ± 3 C day/night temperatures with 16/8 h day/night photoperiods; the supplemental photoperiod was obtained with metal halide lamps (450 μmol m^{-2} s^{-1}). Young waterhemp seedlings (7- to 10-cm tall) from each population were sprayed with the isopropylamine salt of glyphosate (Durango™, Corteva Agrisciences, Indianapolis, IN) at doses of 0, 319, 638, 1276 (field-use rate, 1X), 2552, 5104, 10208, and 20416 g ha^{-1} combined with ammonium sulfate (AMS) at 2.0% (wt/v). Treatments were applied using a stationary cabinet spray chamber (Research Track Sprayer, De Vries Manufacturing, RR 1 Box184, Hollandale, MN) equipped with a flat-fan nozzle tip (TeeJet 8002XR, Spraying System Co., Wheaton, IL) calibrated to deliver 141 L ha^{-1} of spray solution at 276 kPa. All treated plants were returned to the greenhouse and watered daily to avoid moisture stress and maintain adequate growth. At 21 d after treatment (DAT), waterhemp plants were harvested at the soil level and dried at 65 C for 5 days to determine the aboveground shoot dry weight. The aboveground shoot dry weight reduction was calculated as percentage of the nontreated control.

Effectiveness of Alternative POST Herbicides. Greenhouse experiments were conducted at the Guterman greenhouse facility at Cornell University in Ithaca, NY, during spring of 2024 and repeated to evaluate the effectiveness of alternative POST herbicides for control of GR common

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waterhemp populations from NY. Seedlings from NY1, NY2, and NE_SUS common waterhemp populations were grown in germination trays and then transplanted in 10 cm squared pots containing Cornell potting mixture as previously described. A randomized complete block design was used with 15 replications (one plant per pot) for each selected POST herbicide and population combination. A total of nine POST herbicides (Table 1) were evaluated in this study. A nontreated control for each population was included for treatment comparison. The selected POST herbicides were applied at their field-use rates for corn and/or soybean. Herbicide application procedures and plant growth conditions were similar to those described in the glyphosate dose–response experiments. All selected POST herbicides were applied to 8- to 10-cm-tall common waterhemp plants. Percent visual control and shoot dry weights of each common waterhemp population were determined at 21 DAT. For each population, shoot dry weights were expressed as a percentage of the nontreated control.

Statistical Analyses. Data from both experiments were checked for ANOVA assumptions using the Shapiro-Wilk and Levene tests with the UNIVARIATE and GLM procedures, respectively, in SAS software (SAS 9.3 version) and all data met ANOVA assumptions. Data were subjected to ANOVA using the MIXED procedure in SAS software to test the significance of fixed effects (population, treatment i.e. glyphosate dose or alternative POST herbicide, and their interactions). Random effects in the model were experiment run and replications nested within experimental runs. For both studies, data were combined across experimental runs due to nonsignificant experimental run by treatment interactions (P = 0.235 for glyphosate dose response experiment; P = 0.412 for alternative POST herbicide experiment). Shoot dry weights (% of nontreated) of each common waterhemp population from the dose-response study were regressed against glyphosate doses using a three-parameter log-logistic model (Ritz et al. 2015):

$$y = [\frac{d}{1} + exp\ \{b(log x - log e)\}] \qquad (1)$$

Where *y* is the shoot dry weight reduction (% of nontreated), *d* is the maximum shoot dry weight, *e* is the glyphosate dose required for 50% reduction in shoot dry weights (referred to as GR_{50} values, respectively), *x* is the glyphosate dose, and *b* represents the slope of each curve. The Akaike information criterion was used to select the nonlinear three-parameter model. A lack-of-fit test (P = 0.247) indicated that the selected nonlinear model accurately described the shoot dry weight response of each common waterhemp population (Ritz et al. 2015). All nonlinear regression parameter estimates, standard errors, and GR_{90} values (glyphosate dose required for

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90% reduction in shoot dry weights) were determined by using the *drc* package in R software (Ritz et al. 2015). On the basis of GR_{50} values, the resistance index (referred as R/S ratio) for each NY common waterhemp population was estimated by dividing the GR_{50} value for each NY GR common waterhemp population by the GR_{50} value of the NE_SUS population. For effectiveness of alternative POST herbicides, the data on percent visual control and shoot dry weights (% of nontreated) were arcsine-transformed before analysis to improve homogeneity of variance and normality of residuals. Nontransformed means are presented in tables based on the interpretations of the transformed data. Means were separated using Fisher's protected LSD test at a = 0.05.

Results and Discussion

Glyphosate Dose Response. Results from the dose-response studies highlighted that two waterhemp populations (NY1 and NY2) from Seneca County, NY, were resistant to glyphosate (Table 2). The glyphosate dose that reduced shoot dry weights by 50% (GR_{50} values) for the NY1 and NY2 populations ranged from 1,685 to 2,502 g ha^{-1}, which was significantly higher (based on 95% CI) than that of the NE_SUS population (299 g ha^{-1}). Based on GR_{50} values, the NY1 and NY2 populations were 5.6-fold to 8.3-fold resistant to glyphosate, as compared with the NE_SUS population (Table 2; Figure 1). All tested plants of both NY1 and NY2 populations revealed a uniform glyphosate resistance trait as indicated by survival (although stunted) of both populations at 1X and 2X rates. Furthermore, the estimated glyphosate dose (GR_{90} values) that reduced 90% shoot dry weights of the NY1 and NY2 populations ranged from 18,672 to 23,630 g ha^{-1}, which was greater than that of the NE_SUS population (2,957 g ha^{-1}), as well as the field-use rate (1,276 g ha^{-1}). Based on the GR_{90} values, the NY1 and NY2 waterhemp populations were 6.3-fold to 7.9-fold more resistant to glyphosate than the NE_SUS population (Table 2; Figure 1).

Previous research reported a variable level of glyphosate resistance in waterhemp populations across several U.S. states. For instance, Singh et al. (2020) reported a high level resistance (17-fold) to glyphosate in a waterhemp population from Texas as compared with a susceptible population. Similarly, Legleiter and Bradley (2008) reported 19-fold resistance to glyphosate in a waterhemp population from Missouri. Sarangi et al. (2015) found 3- to 39-fold resistance to glyphosate in different waterhemp accessions originating from Nebraska. Our results are consistent with Smith and Hallett (2006), who previously reported up to 9-fold resistance to glyphosate in waterhemp accessions collected from Illinois, Iowa, and Missouri. More recently, GR waterhemp populations have also been identified in Idaho and in Ontario, Canada (Adjesiwor

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2022; Heap 2024). The majority of these previously reported GR waterhemp populations were identified from glyphosate-resistant crops, where glyphosate use was frequently used. The glyphosate use patterns were similar in NY, where soybean and corn producers rely heavily on glyphosate for in-season weed control with less reliance on PRE applied residual herbicides.

Effectiveness of Alternative POST Herbicides. Waterhemp populations differed in their response to herbicides as evident from the visual control (P<0.0001) and shoot dry weight reduction (P<0.0001). The glyphosate-sensitive population NE_SUS was controlled ≥ 98% with the labeled rates of all tested herbicides, except for mesotrione, which provided only 62% control 21 days after treatment (Table 3). Unsatisfactory control with meostrione further points toward potential HPPD-inhibitor resistance as well in this population. The evolution of HPPD-inhibitor-resistant waterhemp has already been confirmed in Iowa, Illinois, Nebraska, and North Carolina (Heap 2024; McMullan and Green 2011; Oliveira et al. 2017; Shergill et al. 2018b).

The GR waterhemp populations from New York (NY1 and NY2) responded similarly to herbicides in this study. Both NY1 and NY2 populations were controlled ≥97% with 2,4-D, dicamba, glufosinate, and the 2,4-D + glufosinate mixture. Although 2,4-D and glufosinate applied alone were as effective as 2,4-D + glufosinate in controlling the GR waterhemp, herbicide mixtures can greatly minimize the chances of selection for herbicide resistance (Aulakh et al. 2016; Benoit et al.2019b; Jhala et al. 2017; Kumar et al. 2023; Willemse et al. 2021). With lactofen, the average waterhemp control was 86 and 99% for the NY1 and NY2 populations, respectively. Aulakh et al. (2016) reported 98% or higher control of 10- to 20-cm tall common waterhemp with two different lactofen formulations. Lactofen and glufosinate have also been found very effective on Palmer amaranth, a closely related pigweed species (Aulakh et al. 2021; Kumar et al. 2023).

With the labeled rates of atrazine, chlorimuron + thifensulfuron, or mesotrione, both NY1 and NY2 populations were controlled < 60% indicating a high probability of multiple resistance to ALS-, HPPD-, and PSII-inhibitor herbicides. Waterhemp biotypes resistant to atrazine, chlorimuron, and mesotrione are already reported from Illinois, Iowa, and North Carolina (Heap 2024). Furthermore, waterhemp biotypes cross-resistant to mesotrione, tembotrione, and topramezone have been reported from Illinois, and Nebraska (McMullan and Green 2011; Oliveira et al. 2017).

Consistent with visual control ratings, shoot dry weight reduction 21 DAT revealed similar differences among alternative POST herbicides within and across waterhemp populations (Table

3). For instance, all POST herbicides reduced shoot dry weights (% of nontreated) of the NE_SUS population by 97 to 100%, except for mesotrione (67%). Consistent with visual control ratings, the highest shoot dry weight reductions (90 to 100%) of NY1 and NY2 waterhemp populations were achieved with dicamba, glufosinate, lactofen, 2,4-D alone or in mixture with glyphosate or glufosinate. Compared with the NE_SUS population, the shoot dry weight reductions of NY1 and NY2 populations were significantly lower with POST applied atrazine (52 to 59%), chlorimuron + thifensulfuron (63 to 67%), and mesotrione (50 to 54%) at 21 DAT (Table 3).

Multiple herbicide-resistant amaranths are perceived to be a major production constraint in North America (Aulakh et al. 2021, 2024; Benoit et al. 2019a; Jhala et al. 2017; Khort and Sprague 2017; Kumar et al. 2023; Schryver et al 2017; Tranel 2021; Vyn et al. 2006). Waterhemp has evolved resistance to seven herbicide sites-of-action in the United States (Bernards et al. 2012; Bobadilla et al. 2021; Evans et al. 2019; Faleco et al. 2022; Heap 2024; Oliveira et al. 2018; Sarangi et al. 2015; Shergill et al. 2018a; Thinglum et al. 2011; Vennapusa et al. 2018). Recently, a waterhemp biotype resistant to six herbicide SOAs (Groups 2, 4, 5, 9, 14, and 27) has been confirmed in Missouri, with 16% of individual plants possessing genes for six-way resistance (Shergill et al. 2018b).

In this study, NE_SUS, NY1, and NY2 populations were controlled 86 to 99% with the labeled rates of 2,4-D, dicamba, glufosinate, or lactofen herbicide applied alone. This indicates that an array of effective postemergence herbicide sites of action exists, particularly for the management of these GR populations. However, a reduced sensitivity to atrazine and chlorimuron + thifensulfuron in NY1 and NY2 and to mesotrione in NE_SUS, NY1, and NY2 populations was observed. This is not surprising because ALS, EPSPS, PS II- inhibitor herbicide-resistant waterhemp populations have been widely reported in the US (Heap 2024). Waterhemp populations with confirmed resistance to 2, 4-D, dicamba, and lactofen (Benoit et al. 2019a; Heap 2024; Shergill et al. 2018a) and reduced sensitivity to dicamba and glufosinate have also been reported elsewhere (Hamberg et al. 2023).

Practical Implications. This research confirms the first report of GR waterhemp populations in New York. In addition, results highlight the possibility of ALS-, HPPD- and PSII inhibitors-resistance in GR waterhemp populations (multiple-resistance) that further need to be investigated in a whole plant dose-response study. Future studies will investigate the physiological, molecular, or genetic basis of glyphosate resistance, inheritance pattern, and associated fitness penalty (if any)

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in GR waterhemp populations (NY1 and NY2) from New York. Nonetheless, confirmation of GR waterhemp populations poses a serious concern for producers in New York and in the northeastern U.S. Producers should make all possible efforts to adopt best management practices to manage GR waterhemp populations (Norsworthy et al. 2012). Among POST herbicides, 2,4-D alone or with glyphosate or glufosinate, dicamba, glufosinate, and lactofen provided effective control of GR waterhemp populations from New York (NY1 and NY2), with responses to these herbicides equivalent to the susceptible population (NE_SUS). Growers can utilize these herbicides for effective control of tested GR waterhemp populations (NY1 and NY2) in a corn-soybean rotation. Multi-location field trials are currently in progress across New York to investigate various soil-applied PRE herbicides alone or with POST herbicides for control of GR waterhemp populations in corn and soybean. Combining PRE and POST emergence herbicides with diverse sites-of action has often provided season-long control of herbicide-resistant weeds (Aulakh et al. 2012, 2013; Benoit et al. 2019b; Jhala et al. 2017; Khort and Sprague 2017). Employing the stacked gene herbicide-resistant technologies in tandem with ecological weed management tactics such as cover cropping, implementing a competitive crop rotation, tillage, and harvest weed seed control (HWSC) techniques are mandatory for managing GR waterhemp and preventing its further spread.

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Table 1. List of alternative POST herbicides tested for controlling glyphosate-resistant and glyphosate-susceptible waterhemp populations in a greenhouse study at Cornell University, Ithaca, NY[a]

Herbicide	Trade name	Rate	Manufacturer	Site of action
		g ai or ae ha^{-1}		
Atrazine [b]	AAtrex	1120	Syngenta Company	Inhibition of PS II
Dicamba	Banvel	560	BASF	Synthetic auxin
Chlorimuron + thifensulfuron [b]	Synchrony	5.6 + 1.8	Corteva Agriscience	Inhibition of ALS
Mesotrione [b]	Callisto	105	Syngenta Company	Inhibition of HPPD
Glufosinate [c]	Liberty	656	BASF	Inhibition of GS
Lactofen[1]	Cobra	219	Valent USA	Inhibition of PPO
2,4-D	Enlist ONE	1070	Corteva Agriscience	Synthetic auxin
2,4-D + glyphosate [c]	Enlist One + Durango	1070 + 1280	Corteva Agriscience	Synthetic auxin + Inhibition of EPSPS
2,4-D + glufosinate [c]	Enlist One + Liberty	1070 + 656	Corteva Agriscience & BASF	Synthetic auxin + Inhibition of EPSPS

[a] Abbreviations: ALS, acetolactate synthase; EPSPS, 5-enolpyruvylshikimate-3-phosphate synthase; GSI, glutathione synthetase; HPPD, 4-hydroxyphenylpyruvate dioxygenase; PPO, Protoporphyrinogen oxidase; PS, photosystem.

[b] Crop oil concentrate (COC) at 1% v/v was included.

[c] Ammonium sulfate (AMS) at 2% wt/v was included.

Table 2. Regression parameter estimates of the 3-parameter log-logistic equation fitted to the shoot dry weight (% of nontreated) of glyphosate-resistant and -susceptible waterhemp populations from New York (NY1 and NY2) and Nebraska (NE_SUS), respectively, at 21 days after treatment (DAT) with various glyphosate doses in a greenhouse study at Cornell University, Ithaca, NY.

	Parameter estimates (± SE) [b]					
Population [a]	*d*	*b*	GR_{50}	95% CI	R/S [c]	GR_{90}
NY1	100 (3.8)	1.1 (0.1)	2502	1885–3120	8.3	18,672
NY2	99 (4.2)	0.8 (0.1)	1685	1134–2237	5.6	23,630
NE_SUS	100 (4.3)	0.9 (0.1)	299	188–410	-	2957

[a] Abbreviations: NY1 and NY2 are putative glyphosate-resistant waterhemp populations collected from two separate soybean fields in 2023 growing season from Seneca County, NY; NE_SUS is known glyphosate susceptible waterhemp population collected from a field site near Clay Center, Nebraska.

[b] Parameter *d* is the upper limit, *b* is the slope of each curve, and GR_{50} is the effective dose (g ha^{-1}) of glyphosate required for 50% shoot dry weight reduction (% of nontreated) for each waterhemp population; CI, confidence interval.

[c] R/S is the ratio of GR_{50} values of each putative glyphosate-resistant population relative to that of GR_{50} value of a susceptible population, SE, standard error.

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Table 3. Percent visual control and shoot dry weight reduction (% of nontreated) of glyphosate-resistant and -susceptible waterhemp populations from New York State (NY1 and NY2) and Nebraska (NE_SUS) with various POST herbicides at their labelled field-use rates 21 days after treatment (DAT) at Cornell University, Ithaca, NY[1].

Herbicide	Rate	NE_SUS		NY1		NY2		NE_SUS		NY1		NY2	
	g ai or ae ha^{-1}	% control[4]						% of nontreated[4]					
Atrazine[1]	1120	99	aA	46	bBC	42	bC	100	aA	59	bB	52	bB
Dicamba	560	99	aA	99	aA	99	aA	100	aA	100	aA	97	aA
Chlorimuron thifensulfuron[2]	+5.6 + 1.8	98	aA	58	bB	59	bB	96	aA	67	bB	63	bB
Mesotrione[2]	105	62	bA	43	bB	49	bAB	67	bA	54	bA	50	bA
Glufosinate[3]	656	99	aA	99	aA	99	aA	100	aA	100	aA	100	aA
Lactofen[2]	219	99	aA	89	aA	99	aA	99	aA	90	aA	99	aA
2,4-D	1070	99	aA	99	aA	97	aA	100	aA	99	aA	96	aA
2,4-D glyphosate[3]	+1070 + 1280	99	aA	97	aA	98	aA	97	aA	95	aA	97	aA
2,4-D glufosinate[3]	+1070 + 656	99	aA	99	aA	99	aA	97	aA	100	aA	99	aA

[1]Abbreviations: NY1 and NY2 are putative glyphosate-resistant waterhemp populations collected from two separate soybean fields in the 2023 growing season from Seneca County, NY; NE_SUS is known glyphosate susceptible common waterhemp population collected from a field site near Clay Center, Nebraska.
[2]Crop oil concentrate (COC) at 1% v/v was included.
[3]Ammonium sulfate (AMS) at 2% wt/v was included.
[4]For percent control or shoot dry weight, means for a waterhemp population within a column followed by similar lowercase letters are not significantly different based on Fisher's protected LSD test at $P < 0.05$; means for an herbicide within a row followed by similar uppercase letters are not significantly different based on Fisher's protected LSD test at $P < 0.05$.

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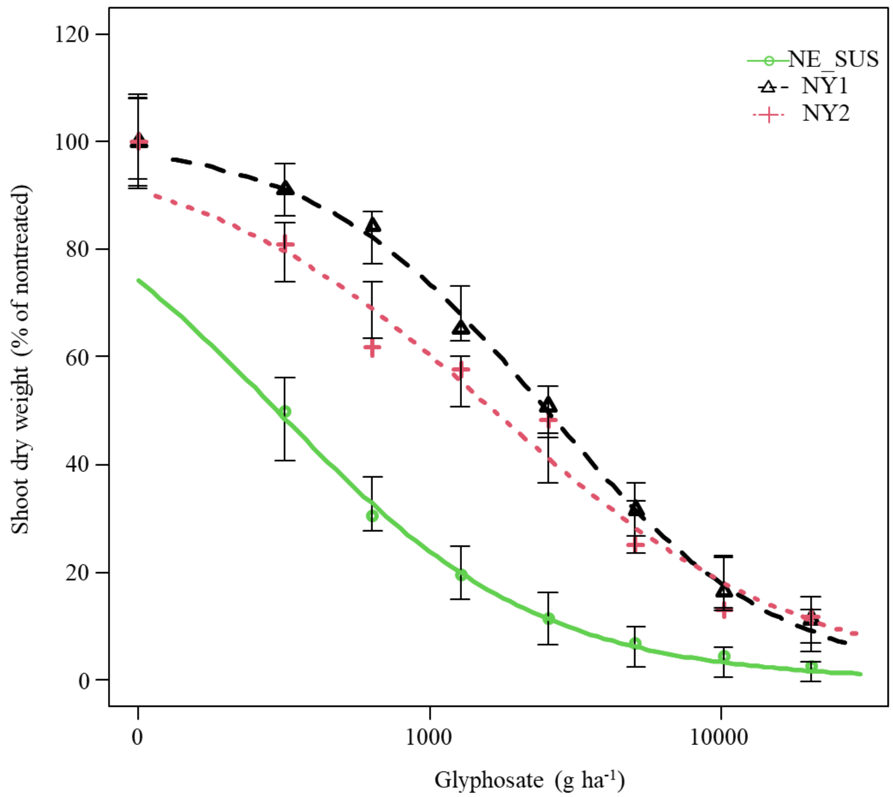

Figure 1. Shoot dry weight response (% of nontreated) of glyphosate-resistant (NY1 and NY2) and glyphosate-susceptible (NE_ SUS) waterhemp populations treated with various doses of glyphosate at 21 days after treatment (DAT) in a greenhouse study conducted at Cornell University Guterman bioclimatic laboratory in Ithaca, NY. Symbols indicate actual values of shoot dry weights (% of nontreated), and lines indicate predicted values of shoot dry weights (% of nontreated) obtained from the three-parameter log-logistic model. Vertical bars indicate model-based standard errors (plus and minus) of the predicted mean.

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