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Effect of Crimson® NG Adjuvant on Glyphosate Efficacy in Corn

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Abstract

There is limited published data on the impact of the addition of Crimson® NG to glyphosate on weed control efficacy in corn under Ontario environmental conditions. Four field experiments were conducted at the University of Guelph, Ridgetown Campus, Ridgetown, Ontario during 2022 and 2023 with two water sources to evaluate weed control with glyphosate alone and in combination with Crimson® NG. Glyphosate was applied at rates of 900, 1029, or 1221 g ae ha^{-1}, with and without Crimson® NG at 1.0 and 2.5% v/v, using water with 56 ppm (Ridgetown) and 1600 ppm (Plattsville) hardness. Results showed that glyphosate at 900 g ae ha^{-1} controlled velvetleaf, Powell amaranth, common ragweed, common lambsquarters, barnyardgrass, and giant foxtail 97-100%, independent of water hardness. Neither increased glyphosate rates nor the addition of Crimson® NG significantly improved weed control. No corn injury was observed with all herbicide/adjuvant treatments evaluated. These findings confirm that glyphosate at 900 g ae ha^{-1} is highly effective for the control of common annual grass and broadleaf weeds. Weed control efficacy with glyphosate was not influenced by water source and there was no improvement in weed control efficacy from increasing the rate of glyphosate or from the addition of Crimson® NG.

Keywords: barnyardgrass, common lambsquarters, common ragweed, giant foxtail, Powell amaranth, velvetleaf

1. Introduction

Corn (*Zea mays* L.) is an important crop in Canada due to its productivity, versatility, and wide range of uses. Different types of corn (grain, silage, and pop) cater to various agricultural and consumer needs (Ranum et al., 2014; Erenstein et al., 2022; Ram et al., 2023). Corn has many uses in Canada, including food products (corn meal, corn syrup, corn starch, and corn oil), animal feed (grain and silage), biofuel (ethanol), and industrial products. Corn starch and other derivatives are used in manufacturing paper, textiles, pharmaceuticals, and biodegradable plastics (Ranum et al., 2014; García-Lara & Serna-Saldivar, 2019). Corn has a high yield and monetary returns per hectare making it a valuable crop for farmers; it has become one of the most valuable crops grown in Canada (Ranum et al., 2014; Baker, 2018). In addition, corn is a crucial component of a diverse crop rotation which contributes to soil health and productivity (Baker, 2018; Shah et al., 2021).

Most of the corn grown in Canada is produced in Ontario and Quebec. Ontario farmers annually seed around 800,000 hectares of grain corn, generating an approximate farm-gate value of $1.6 billion (Soltani et al., 2022; OMAFRA, 2023). Corn production supports economic growth, job creation, and sustainable agricultural practices. Effective weed control in corn production in Ontario can provide substantial benefits, including higher yields, increased profitability, improved crop quality, sustainable farming practices, optimized resource use, and long-term soil health. Investing in effective weed control is essential for the success and sustainability of corn production in the region. The economic return on investment in weed control in corn can be substantial; studies have shown that every dollar spent on weed control can return multiple dollars due to increased yield and quality (Soltani et al., 2016a).

Despite the evolution of glyphosate-resistant (GR) weeds due to the frequent use of glyphosate in GR crops, many farmers continue to rely on glyphosate (N-(Phosphonomethyl)glycine) ($C_3H_8NO_5P$) as a component of their weed control program due to its excellent weed control efficacy, wide margin of crop safety, absence of residues affecting future crop rotations, minimal environmental impact, and cost-effectiveness (Sikkema & Soltani, 2007; Beckie et al., 2014). Currently, over 95% of corn in Ontario is seeded to GR hybrids (Beckie et al., 2014). Glyphosate provides effective, broad-spectrum control of annual, biennial, and perennial grass and broadleaf weeds. Earlier research has shown that the addition of ammonium sulphate (AMS) to glyphosate, especially when applied at lower rates, can enhance weed control efficacy (Thelen et al., 1995; Hall et al., 2000; Pratt et al., 2003; Shaner et al., 2006; Nurse et al., 2008; Soltani et al., 2011, 2016b; Bastiani et al., 2021). AMS binds to cations (*e.g.*, calcium and magnesium) in hard water that could otherwise bind to glyphosate; the cation plus glyphosate complex is taken less readily by weeds resulting in reduced weed control efficacy (Thelen et al., 1995). AMS can also improve the absorption of glyphosate by weeds by affecting the leaf cuticle (Thelen et al., 1995; Pratt et al., 2003)

Crimson® NG is a new liquid premix of AMS and a proprietary blend of water conditioning, coupling, and antifoam agents marketed by Winfield Solutions, LLC (St. Paul, MN, USA) to enhance water conditioning and improve weed control efficacy with glyphosate (Winfield United, 2023). Crimson® NG contains 50.0% AMS and 50.0% other constituents (Anonymous, 2023). According to the manufacturer, Crimson® NG conditions hard water by chelating calcium and magnesium ions, which can otherwise reduce the effectiveness of certain herbicides (Winfield United, 2023). They suggest that by improving the solubility and uptake of active ingredients, the addition of Crimson® NG can lead to better absorption and translocation of herbicides within plants and help achieve more consistent and reliable weed control (Winfield United, 2023). Earlier research has shown that by addressing water hardness and ensuring the proper pH level, adjuvants can help maximize the effectiveness of herbicides and enhance the performance of crop protection products, which can lead to reduced application rates and fewer reapplications, ultimately saving costs (Nurse et al., 2008; Soltani et al., 2011, 2016b).

There is limited published data on the effect of Crimson® NG on weed control efficacy with glyphosate for the control of common annual grass and broadleaf weeds in corn under Ontario environmental conditions. Furthermore, the relative effect of increasing the glyphosate rate compared to adding Crimson® NG at the same cost has not been fully investigated. This data is imperative so Ontario corn producers can make science-based decisions to maximize weed control efficacy and corn yield while minimizing weed management costs. Crimson® NG may be a valuable tool for farmers and agronomists looking to optimize the efficacy of crop protection products by ensuring that the active ingredients in spray solutions work as effectively as possible, even in the presence of hard water.

This study was conducted to determine if weed control efficacy with glyphosate applied at 900 g ae ha^{-1} shows a greater improvement in weed control by adding Crimson® NG or increasing the rate of glyphosate with two water sources: Ridgetown, ON (56 ppm hardness) and Plattsville, ON (1600 ppm hardness).

2. Materials and Methods

This study consisted of four field experiments (3 in 2022 and 1 in 2023) conducted at the University of Guelph, Ridgetown Campus, Ridgetown, Ontario. Detailed information including soil characteristics, corn seeding and emergence dates, herbicide application dates, and weather conditions at herbicide application are presented in Table 1. Seedbed preparation included fall mouldboard plowing followed by two passes with a field cultivator with rolling basket harrows in the spring.

Table 1. Year, location, soil characteristics, corn seeding and emergence dates, herbicide application dates, and weather conditions at application for four experiments conducted in Ontario, Canada in 2022 and 2023

	Year	Location	Texture	Soil characteristics[a]					Seeding date	Emergence date	Application date	Application weather conditions		
				Sand	Silt	Clay	Organic matter	pH				Air temperature	Relative humidity	Wind speed
				-------------- % -------------								C	%	km h^{-1}
E1	2022	Ridgetown A	Clay Loam	30	31	39	4.7	7.2	May 12	May 19	June 15	26.6	81.0	7.8
E2	2022	Ridgetown B	Loam	26	36	38	4.1	7.3	May 13	May 20	June 17	24.2	57.1	6.9
E3	2022	Ridgetown C	Sandy loam	74	15	11	3.1	6.4	May 12	May 19	June 15	29.5	78.1	2.9
E4	2023	Ridgetown	Sandy loam	42	33	25	4.2	6.6	May 11	May 19	June 28	13.6	83.2	4.4

Note. [a] Soil cores were extracted to a depth of 15 cm and analyzed by A&L Canada Laboratories Inc. (2136 Jetstream Road, London, ON) to determine soil characteristics.

Experiments were established as a randomized complete block design with four replications. Treatment details are listed in Tables 2-5. Each plot was 3 m wide and 8 long and consisted of four corn rows spaced 0.75 m apart of GR ‘DKC39-97 RIB’/‘DKC 42-04RIB’ seeded at a rate of approximately 85,000 seeds ha^{-1}.

Herbicide treatments were applied postemergence when the weed canopy was approximately 10 cm in height (V2-4 corn growth stage) using a CO_2-pressurized backpack sprayer calibrated to deliver 200 L ha^{-1} aqueous solution at 240 kPa. The spray boom was 1.5 m wide with four ULD120-02 nozzles (Hypro, New Brighton, MN, USA) spaced 0.5 m apart producing a spray width of 2.0 m. Water hardness of the Ridgetown and Plattsville water sources was 56 and 1600 ppm, respectively.

Glyphosate was applied at 900, 1029, or 1221 g ae ha^{-1} and Crimson® NG was added at 1.0 or 2.5% v/v. In 2022, the cost of glyphosate was \$18.60 L^{-1} CAD and Crimson® NG was \$4.40 L^{-1} CAD. Based on these prices, glyphosate at 900 g ae ha^{-1} cost \$31.05 ha^{-1}; the addition of Crimson® NG at 1.0% v/v or increasing the rate of glyphosate to 1029 g ae ha^{-1} increased the cost identically to \$35.45 ha^{-1}. The addition of Crimson® NG at 2.5% v/v or increasing the rate of glyphosate to 1221 g ae ha^{-1} increased the cost identically to \$42.05 ha^{-1}. The rates of glyphosate used were chosen to determine if it was more cost-effective to add Crimson® NG or increase the glyphosate since the cost to the grower is identical.

Corn injury was visually evaluated 1 and 4 weeks after herbicide application (WAA) and weed control was visually evaluated 4 and 8 WAA on a scale of 0 (no injury/control) to 100% (complete necrosis/control). Corn was combined at harvest maturity with a small plot combine; seed moisture content and weight were recorded. Corn yield was adjusted to 15.5% seed moisture content prior to analysis.

Data were analyzed in SAS Studio v9.4, OnDemand for Academics (SAS Institute Inc., Cary, NC). The GLIMMIX procedure was used to construct mixed models and subject data to ANOVA. The fixed effect was herbicide treatment, and the random effects were environment (location-year combinations), block nested within environment, and environment-by-treatment interaction. Data were pooled across environments based on covariance analyses. The Pearson chi-square/DF and Shapiro-wilk statistics were used to evaluate model fitness and potential overdispersion of residuals, respectively. The distribution of studentized residuals across fixed and random effects was visually evaluated to confirm the assumptions of ANOVA. Visual estimates of weed control at 4 and 8 weeks after application (WAA), and corn grain moisture and yield at harvest, were analyzed using the Gaussian (identity link) distribution. Treatments with a mean and variance of zero were excluded from analyses and compared to individual treatment means using a t-test. Treatment means were compared using Tukey-Kramer's least significant difference. Orthogonal contrasts were completed to address specific questions. An alpha level of 0.05 was used for analyses.

3. Results and Discussion

Data were pooled and averaged over years and locations when there was no statistically significant interaction between year, location, and treatments (Tables 2-5). Weeds present at study sites included velvetleaf (*Abutilon theophrasti* L.), Powell amaranth (*Amaranthus powellii* S. Watson), common ragweed (*Ambrosia artemisiifolia* L.), common lambsquarters (*Chenopodium album* L.), barnyardgrass (*Echinochloa crus-gali* (L.) P. Beauv.), and giant foxtail (*Setaria faberi* R.A.W. Herrm).

3.1 Velvetleaf (ABUTH)

At 4 and 8 WAA, glyphosate (900 g ae ha^{-1}) with Ridgetown water (56 ppm water hardness) as the carrier controlled velvetleaf 98-99% (Table 2). Increasing the rate of glyphosate to 1029 or 1221 g ae ha^{-1} or the addition of Crimson® NG at 1.0 or 2.5% v/v did not improve velvetleaf control (Table 2).

Table 2. Control of velvetleaf (*Abitulon theophrasti* L.) and Powell amaranth (*Amaranthus powellii* S. Watson) 4 and 8 weeks after application (WAA) from four field trials conducted in southwestern Ontario, Canada in 2022 and 2023[a,b]

	Rate	ABUTH		AMAPO	
		4 WAA	8 WAA	4 WAA	8 WAA
	g ai ha^{-1} + % v/v	%			
Untreated control	-	0 c	0 c	0 c	0 b
Ridgetown water + glyphosate	900	98 ab	99 ab	99 ab	99 a
Ridgetown water + glyphosate + Crimson® NG	900 + 1.0	98 ab	99 ab	100 a	99 a
Ridgetown water + glyphosate	1029	99 ab	99 ab	100 a	99 a
Ridgetown water + glyphosate + Crimson® NG	900 + 2.5	99 ab	99 ab	99 a	99 a
Ridgetown water + glyphosate	1221	99 ab	99 a	100 a	99 a
Plattsville water + glyphosate	900	98 a	99 b	98 b	99 a
Plattsville water + glyphosate + Crimson® NG	900 + 1.0	98 b	99 ab	99 a	99 a
Plattsville water + glyphosate	1029	99 ab	99 ab	99 a	99 a
Plattsville water + glyphosate + Crimson® NG	900 + 2.5	99 ab	99 ab	99 a	99 a
Plattsville water + glyphosate	1221	99 ab	99 ab	99 a	99 a
Contrasts[c]					
Ridgetown water *vs.* Plattsville water		99 *vs.* 99 NS	99 *vs.* 99 *	100 *vs.* 99 *	99 *vs.* 99 NS
Glyphosate 900 g ha^{-1} *vs.* glyphosate 900 g ha^{-1} + Crimson® NG 1.0% v/v		98 *vs.* 98 NS	99 *vs.* 99 NS	99 *vs.* 100 *	99 *vs.* 99 *
Glyphosate 900 g ha^{-1} *vs.* glyphosate 900 g ha^{-1} + Crimson® NG 2.5% v/v		98 *vs.* 99 *	99 *vs.* 99 NS	99 *vs.* 99 *	99 *vs.* 99 *
Glyphosate 900 g ha^{-1} + Crimson® NG 1.0% v/v *vs.* glyphosate 900 g ha^{-1} + Crimson® NG 2.5% v/v		98 *vs.* 99 NS	99 *vs.* 99 NS	100 *vs.* 99 NS	99 *vs.* 99 NS
Glyphosate + Crimson® NG 1.0% v/v *vs.* glyphosate 1029 g ha^{-1}		98 *vs.* 99 NS	99 *vs.* 99 NS	100 *vs.* 100 NS	99 *vs.* 100 NS
Glyphosate + Crimson® NG 2.5% v/v *vs.* glyphosate 1221 g ha^{-1}		99 *vs.* 99 NS	99 *vs.* 99 NS	99 *vs.* 100 NS	99 *vs.* 99 NS

Note. [a] Abbreviations: NS: non-significant; WAA: weeks after application.

[b] Within columns, means followed by the same letter are not significantly different according to Tukey's LSD (P > 0.05).

[c] *: single degree-of-freedom contrasts significant at P < 0.05.

Similarly, at 4 and 8 WAA, glyphosate (900 g ae ha^{-1}) with Plattsville water (1600 ppm water hardness) as the carrier controlled velvetleaf 98-99% (Table 2). Increasing the rate of glyphosate to 1029 or 1221 g ae ha^{-1} or adding Crimson® NG at 1.0 or 2.5% v/v did not improve velvetleaf control (Table 2).

Based on orthogonal contrasts there was no impact of water source on velvetleaf control at 4 WAA. There was no improvement velvetleaf control from the addition of Crimson® NG at 1.0 v/v to glyphosate at 4 and 8 WAA. There was no improvement velvetleaf control from the addition of Crimson® NG at 2.50 v/v to glyphosate at 8 WAA. In addition, there was no difference between the two concentrations of Crimson® NG (1.0 and 2.5% v/v) and there was no difference between the addition Crimson® NG or increasing the rate of glyphosate on velvetleaf control. There was a small improvement in velvetleaf control (1%) with the addition of Crimson® NG at 2.5% to glyphosate at 900 g ha^{-1} (Table 2).

These findings are consistent with other studies where the addition of other AMS adjuvants, such as Class Act® NG to glyphosate, provided no significant improvement in velvetleaf control in corn (Soltani et al., 2023). Other research showed that adding AMS to glyphosate at 450, 675, or 900 g ae ha^{-1} rarely enhanced velvetleaf control (Soltani et al., 2016b). Soltani et al. (2011) found no advantage to adding AMS to glyphosate (900 g ae ha^{-1}) for velvetleaf control in corn. Conversely, Pratt et al. (2003) reported up to a 70% improvement in velvetleaf control with AMS added to 280 g ae ha^{-1} glyphosate, although this is 31% of the lowest registered rate in Ontario. Nurse et al. (2008) and Young et al. (2003) indicated that AMS can enhance velvetleaf control with glyphosate rates under 450 g ae ha^{-1} (half the labelled rate). Hall et al. (2000) reported AMS (2.5 L ha^{-1}) with glyphosate at 125, 250, 500, or 1000 g ae ha^{-1} improves control regardless of water hardness.

3.2 Powell Amaranth (AMPO)

At 4 and 8 WAA, glyphosate (900 g ae ha^{-1}) using Ridgetown water (56 ppm water hardness) controlled Powell amaranth 99% (Table 2). Increasing the rate of glyphosate to 1029 or 1221 g ae ha^{-1} or the addition of Crimson® NG at 1.0 or 2.5% v/v did not improve Powell amaranth control (Table 2).

At 4 WAA, glyphosate (900 g ae ha^{-1}) using Plattsville water (1600 ppm water hardness) controlled Powell amaranth 98% (Table 2). Increasing the rate of glyphosate to 1029 or 1221 g ae ha^{-1} or adding Crimson® NG at 1.0 or 2.5% v/v improved Powell amaranth control 1% (Table 2). At 8 WAA, glyphosate (900 g ae ha^{-1}) using

Plattsville water (1600 ppm water hardness) controlled Powell amaranth 99% (Table 2). Increasing the rate of glyphosate to 1029 or 1221 g ae ha^{-1} or adding Crimson® NG at 1.0 or 2.5% v/v did not improve Powell amaranth control (Table 2).

Orthogonal contrasts showed that the lower water hardness resulted in slightly higher control of Powell amaranth at 4 WAA, but this effect was not observed at 8 WAA (Table 2). At 4 and 8 WAA, the addition of Crimson® NG at 1.0 or 2.5% v/v to glyphosate slightly improved Powell amaranth control (≤ 1%) compared to glyphosate alone (Table 2). There was no difference between the two concentrations of Crimson® NG (1.0 and 2.5% v/v) and there was no difference between the addition Crimson® NG or increasing the rate of glyphosate on Powell amaranth control (Table 2).

Other studies found that glyphosate (450 g ae ha^{-1}) controlled Powell amaranth at 89% at 4 WAA and 91% at 8 WAA; the addition of AMS adjuvants (Class Act® NG) improved control by 9 and 7%, respectively (Soltani et al., 2023). However, at higher doses (900 and 1350 g ae ha^{-1}), glyphosate controlled Powell amaranth at 98-99% with no significant improvement in Powell amaranth control from the addition of Class Act® NG (Soltani et al., 2023). Overall, adding Class Act® NG to glyphosate increased Powell amaranth control by 2% (Soltani et al., 2023). Research on other Amaranthus species has shown that redroot pigweed was effectively controlled (95-100%) by glyphosate, with or without 2% AMS, at doses of at least 450 g ae ha^{-1} (Guza et al., 2002; Krausz et al., 1996). Other studies demonstrated that adding AMS to glyphosate at 450, 675, or 900 g ae ha^{-1} did not enhance redroot pigweed control in corn (Soltani et al., 2016b). Soltani et al. (2011) also found no benefit from adding AMS (2.5 L ha^{-1}) to glyphosate (900 g ae ha^{-1}) for redroot pigweed control in corn. Mahoney et al. (2014) noted that AMS addition to glyphosate at 900 g ae ha^{-1} had minimal impact on redroot pigweed control regardless of water hardness. Nurse et al. (2008) observed better control of redroot pigweed at 2 WAA with AMS added to glyphosate at 225 g ae ha^{-1} (25% of Ontario's lowest label rate).

3.3 Common Ragweed (AMBEL)

At 4 and 8 WAA, glyphosate (900 g ae ha^{-1}) using Ridgetown water (56 ppm water hardness) controlled common ragweed 98% (Table 3). Increasing the rate of glyphosate to 1029 or 1221 g ae ha^{-1} or adding Crimson® NG at 1.0 or 2.5% v/v did not enhance common ragweed control (Table 3).

Table 3. Control of common ragweed (*Ambrosia artemisiifolia* L.) and common lambsquarters (*Chenopodium album* L.) 4 and 8 WAA from four field trials conducted in southwestern Ontario, Canada, in 2022 and 2023[a,b]

	Rate	AMBEL		CHEAL	
		4 WAA	8 WAA	4 WAA	8 WAA
	g ai ha^{-1} + % v/v	%			
Untreated control	-	0 c	0 b	0 b	0 b
Ridgetown water + glyphosate	900	98 ab	98 a	99 a	99 a
Ridgetown water + glyphosate + Crimson® NG	900 + 1.0	98 ab	99 a	99 a	99 a
Ridgetown water + glyphosate	1029	99 a	99 a	99 a	99 a
Ridgetown water + glyphosate + Crimson® NG	900 + 2.5	98 ab	99 a	99 a	99 a
Ridgetown water + glyphosate	1221	99 a	99 a	99 a	99 a
Plattsville water + glyphosate	900	97 b	98 a	98 a	97 a
Plattsville water + glyphosate + Crimson® NG	900 + 1.0	98 ab	99 a	99 a	99 a
Plattsville water + glyphosate	1029	98 ab	98 a	98 a	97 a
Plattsville water + glyphosate + Crimson® NG	900 + 2.5	98 ab	99 a	99 a	98 a
Plattsville water + glyphosate	1221	99 a	99 a	98 a	98 a
Contrasts[c]					
Ridgetown water *vs.* Plattsville water		98 *vs.* 98 NS	99 *vs.* 98 NS	99 *vs.* 98 NS	99 *vs.* 98 *
Glyphosate 900 g ha^{-1} *vs.* glyphosate 900 g ha^{-1} + Crimson® NG 1.0% v/v		97 *vs.* 98 NS	98 *vs.* 99 NS	97 *vs.* 99 NS	97 *vs.* 99 NS
Glyphosate 900 g ha^{-1} *vs.* glyphosate 900 g ha^{-1} + Crimson® NG 2.5% v/v		97 *vs.* 98 *	98 *vs.* 99 NS	97 *vs.* 99 NS	97 *vs.* 98 NS
Glyphosate 900 g ha^{-1} + Crimson® NG 1.0% v/v *vs.* glyphosate 900 g ha^{-1} + Crimson® NG 2.5% v/v		98 *vs.* 98 NS	99 *vs.* 99 NS	99 *vs.* 99 NS	99 *vs.* 98 NS
Glyphosate + Crimson® NG 1.0% v/v *vs.* glyphosate 1029 g ha^{-1}		98 *vs.* 98 NS	99 *vs.* 99 NS	99 *vs.* 99 NS	99 *vs.* 98 NS
Glyphosate + Crimson® NG 2.5% v/v *vs.* glyphosate 1221 g ha^{-1}		98 *vs.* 99 NS	99 *vs.* 99 NS	99 *vs.* 99 NS	98 *vs.* 98 NS

Note. [a] Abbreviations: NS: non-significant; WAA: weeks after application.

[b] Within columns, means followed by the same letter are not significantly different according to Tukey's LSD (P > 0.05).

[c] *: single degree-of-freedom contrasts significant at P < 0.05.

Similarly, at 4 and 8 WAA, glyphosate (900 g ae ha^{-1}) using Plattsville water (1600 ppm water hardness) controlled common ragweed 97-98% (Table 3). At 4 WAA, increasing the rate of glyphosate to 1221 g ae ha^{-1} improved common ragweed control 2% (Table 3).

At 8 WAA, increasing the rate of glyphosate to 1029 or 1221 g ae ha^{-1} or adding Crimson® NG at 1.0 or 2.5% v/v did not improve common ragweed control (Table 3).

Orthogonal contrasts showed no significant difference in common ragweed control between water sources (Ridgetown *vs.* Plattsville). At 4 WAA, the addition of Crimson® NG at 1.0% v/v did not improve common ragweed control; in contrast, the addition of Crimson® NG at 2.5% v/v improved common ragweed control 1%. At 4 and 8 WAA, there was no difference between the two concentrations of Crimson® NG (1.0 and 2.5% v/v) and there was no difference between the addition Crimson® NG or increasing the rate of glyphosate on common ragweed control (Table 3).

Other studies found that glyphosate (450 g ae ha^{-1}) controlled common ragweed at 81% at 4 WAA and 80% at 8 WAA, with other AMS additives (Class Act® NG) improving control by 7-8% (Soltani et al., 2023). Higher doses (900 and 1350 g ae ha^{-1}) controlled common ragweed at 90-95%, with no additional benefit from Class Act® NG (Soltani et al., 2023). Overall, Class Act® NG improved control by 4% at 4 WAA but had no effect at 8 WAA (Soltani et al., 2023). Similar findings were observed in other research where glyphosate at 450, 675, and 900 g ae ha^{-1} controlled common ragweed at rates of 80-97%, 85-99%, and 86-99%, respectively. The addition of AMS (2.5 L ha^{-1}) did not significantly enhance common ragweed control in corn (Soltani et al., 2016b). Another study indicated no improvement from adding AMS (2.5 L ha^{-1}) to glyphosate (900 g ae ha^{-1}) for common ragweed control in corn (Soltani et al., 2011).

3.4 Common Lambsquarters (CHEAL)

At 4 and 8 WAA, glyphosate (900 g ae ha^{-1}) using Ridgetown water (56 ppm water hardness) or Plattsville water (1600 ppm water hardness) controlled common lambsquarters 97-99% (Table 3). Increasing the rate of glyphosate to 1029 or 1221 g ae ha^{-1} or adding Crimson® NG at 1.0 or 2.5% v/v did not improve common lambsquarters control (Table 3).

At 4 WAA, orthogonal contrasts showed no difference in the control of common lambsquarters between the water sources (Ridgetown *vs.* Plattsville); however, control was reduced 1% with the Plattsville water at 8 WAA (Table 3). The addition of Crimson® NG to glyphosate did not improve the control of common lambsquarters. At 4 and 8 WAA, there was no difference between the two concentrations of Crimson® NG (1.0 and 2.5% v/v) and there was no difference between the addition Crimson® NG or increasing the rate of glyphosate on common lambsquarters control (Table 3).

In previous studies, glyphosate (450 g ae ha^{-1}) controlled common lambsquarters 77% at 4 WAA and 70% at 8 WAA; adding Class Act® NG improved control by 14% at 4 WAA and 20% at 8 WAA (Soltani et al., 2023). Adding Class Act® NG to glyphosate (900 g ae ha^{-1}) improved control by 6% at 4 WAA and 5% at 8 WAA, while there was no improvement at 1350 g ae ha^{-1} (Soltani et al., 2023). Based on that study, Class Act® NG enhanced common lambsquarters control by 6% at 4 WAA and 7% at 8 WAA across all glyphosate rates (Soltani et al., 2023). Other research showed that glyphosate applied at 450, 675, and 900 g ae ha^{-1} controlled common lambsquarters 91-99, 93-100, and 94-100%, respectively, with no improvement from the addition of AMS (Soltani et al., 2016b). Another study found no improvement with AMS (2.5 L ha^{-1}) added to glyphosate (900 g ae ha^{-1}) for common lambsquarters control in corn (Soltani et al., 2011). Nurse et al. (2008) reported that the addition of AMS (2%) to glyphosate improved common lambsquarters control when applied at rates below 450 g ae ha^{-1} but not above.

3.5 Barnyardgrass (ECHCG)

At 4 and 8 WAA, glyphosate (900 g ae ha^{-1}) using Ridgetown water (56 ppm water hardness) or Plattsville water (1600 ppm water hardness) controlled barnyardgrass 97-98% (Table 4). Increasing the rate of glyphosate to 1029 or 1221 g ae ha^{-1} or adding Crimson® NG at 1.0 or 2.5% v/v did not improve barnyardgrass control (Table 4).

Table 4. Control of barnyardgrass (*Echinochloa crus-gali* (L.) P. Beauv.) and giant foxtail (*Setaria faberi* Herm.) 4 and 8 WAA from four field trials conducted in southwestern Ontario, Canada in 2022 and 2023[a,b]

	Rate	ECHCG		SETFA	
		4 WAA	8 WAA	4 WAA	8 WAA
	g ai ha^{-1} + % v/v	%			
Untreated control	-	0 c	0 b	0	0
Ridgetown water + glyphosate	900	98 ab	98 a	100	100
Ridgetown water + glyphosate + Crimson® NG	900 + 1.0	99 ab	98 a	100	100
Ridgetown water + glyphosate	1029	99 ab	98 a	100	100
Ridgetown water + glyphosate + Crimson® NG	900 + 2.5	99 ab	98 a	100	100
Ridgetown water + glyphosate	1221	99 a	99 a	100	100
Plattsville water + glyphosate	900	98 b	97 a	100	100
Plattsville water + glyphosate + Crimson® NG	900 + 1.0	98 ab	98 a	100	100
Plattsville water + glyphosate	1029	99 ab	98 a	100	100
Plattsville water + glyphosate + Crimson® NG	900 + 2.5	99 ab	98 a	100	100
Plattsville water + glyphosate	1221	98 ab	98 a	100	100
Contrasts[c]					
Ridgetown water *vs.* Plattsville water		99 *vs.* 98 NS	98 *vs.* 98 NS	-	-
Glyphosate 900 g ha^{-1} *vs.* glyphosate 900 g ha^{-1} + Crimson® NG 1.0% v/v		98 *vs.* 98 NS	98 *vs.* 98 *	-	-
Glyphosate 900 g ha^{-1} *vs.* glyphosate 900 g ha^{-1} + Crimson® NG 2.5% v/v		98 *vs.* 99 *	98 *vs.* 98 NS	-	-
Glyphosate 900 g ha^{-1} + Crimson® NG 1.0% v/v *vs.* glyphosate 900 g ha^{-1} + Crimson® NG 2.5% v/v		98 *vs.* 99 NS	98 *vs.* 98 NS	-	-
Glyphosate + Crimson® NG 1.0% v/v *vs.* glyphosate 1029 g ha^{-1}		98 *vs.* 99 NS	98 *vs.* 98 NS	-	-
Glyphosate + Crimson® NG 2.5% v/v *vs.* glyphosate 1221 g ha^{-1}		99 *vs.* 99 NS	98 *vs.* 98 NS	-	-

Note. [a] Abbreviations: NS: non-significant; WAA: weeks after application.

[b] Within columns, means followed by the same letter are not significantly different according to Tukey's LSD (P > 0.05).

[c] *: single degree-of-freedom contrasts significant at P < 0.05.

Orthogonal contrasts revealed no significant differences in barnyardgrass control between the water sources used (Ridgetown *vs.* Plattsville). At 4 WAA, the addition of Crimson® NG at 1.0% v/v to glyphosate did not improve barnyardgrass control; in contrast, the addition of Crimson® NG at 2.50% v/v to glyphosate improved barnyardgrass control 1%. At 8 WAA, the addition of Crimson® NG at 1.0% v/v to glyphosate improved barnyardgrass control; in contrast, the addition of Crimson® NG at 2.50% v/v to glyphosate did not improve barnyardgrass control. At 4 and 8 WAA, there was no difference between the two concentrations of Crimson® NG (1.0 and 2.5% v/v) and there was no difference between the addition Crimson® NG or increasing the rate of glyphosate on barnyardgrass control (Table 4).

The results align with other studies where glyphosate at 450 g ae ha^{-1} controlled barnyardgrass by 85% at 4 WAA and 82% at 8 WAA; the addition of Class Act® NG enhanced control 7% at 4 WAA (Soltani et al., 2023). At 900 g ae ha^{-1}, glyphosate controlled barnyardgrass 91% at 4 WAA and 89% at 8 WAA; there was a 4% improvement in barnyardgrass control with Class Act® NG at 4 WAA (Soltani et al., 2023). At 1350 g ae ha^{-1} glyphosate controlled barnyardgrass 95% control at 4 WAA and 93% at 8 WAA, the addition of Class Act® NG improved control 3% at 4 WAA but had no effect at 8 WAA (Soltani et al., 2023). Similar findings were reported in other research, with glyphosate at 450, 675, and 900 g ae ha^{-1} controlling barnyardgrass at rates of 90-98, 95-100, and 97-100%, respectively (Soltani et al., 2016b) and the addition of AMS (2.5 L ha^{-1}) did not enhance barnyardgrass control in corn (Soltani et al., 2016b; Soltani et al., 2011).

3.6 Giant Foxtail (SETFA)

At 4 and 8 WAA, glyphosate (900 g ae ha^{-1}) using Ridgetown water (56 ppm water hardness) or Plattsville water (1600 ppm water hardness) provided 100% control of giant foxtail (Table 5). Increasing the rate of glyphosate to 1029 or 1221 g ae ha^{-1} or adding Crimson® NG at 1.0 or 2.5% v/v did not have any impact on giant foxtail control (Table 4).

Table 5. Corn grain moisture and yield at harvest from four field trials conducted in southwestern Ontario, Canada in 2022 and 2023[a,b]

	Rate	Grain moisture	Grain yield
	g ai ha^{-1} + % v/v	%	t ha^{-1}
Untreated control	-	15.5 a	4.3 b
Ridgetown water + glyphosate	900	15.4 a	10.0 a
Ridgetown water + glyphosate + Crimson® NG	900 + 1.0	15.3 a	10.2 a
Ridgetown water + glyphosate	1029	15.4 a	10.5 a
Ridgetown water + glyphosate + Crimson® NG	900 + 2.5	15.4 a	10.3 a
Ridgetown water + glyphosate	1221	15.3 a	10.2 a
Plattsville water + glyphosate	900	15.4 a	10.0 a
Plattsville water + glyphosate + Crimson® NG	900 + 1.0	15.3 a	10.2 a
Plattsville water + glyphosate	1029	15.3 a	10.2 a
Plattsville water + glyphosate + Crimson® NG	900 + 2.5	15.3 a	10.2 a
Plattsville water + glyphosate	1221	15.3 a	10.1 a
Contrasts[c]			
Ridgetown water *vs.* Plattsville water		15.4 *vs.* 15.4 NS	10.3 *vs.* 10.1 NS
Glyphosate 900 g ha^{-1} *vs.* glyphosate 900 g ha^{-1} + Crimson® NG 1.0% v/v		15.5 *vs.* 15.3 NS	10.0 *vs.* 10.2 NS
Glyphosate 900 g ha^{-1} *vs.* glyphosate 900 g ha^{-1} + Crimson® NG 2.5% v/v		15.5 *vs.* 15.4 NS	10.0 *vs.* 10.2 NS
Glyphosate 900 g ha^{-1} + Crimson® NG 1.0% v/v *vs.* glyphosate 900 g ha^{-1} + Crimson® NG 2.5% v/v		15.3 *vs.* 15.4 NS	10.2 *vs.* 10.2 NS
Glyphosate + Crimson® NG 1.0% v/v *vs.* glyphosate 1029 g ha^{-1}		15.3 *vs.* 15.4 NS	10.2 *vs.* 10.3 NS
Glyphosate + Crimson® NG 2.5% v/v *vs.* glyphosate 1221 g ha^{-1}		15.4 *vs.* 15.3 NS	10.2 *vs.* 10.1 NS

Note. [a] Abbreviations: NS: non-significant.

[b] Within columns, means followed by the same letter are not significantly different according to Tukey's LSD (P > 0.05).

[c] *: single degree-of-freedom contrasts significant at P < 0.05.

These findings align with previous research on foxtail species. In other studies, glyphosate controlled green foxtail, 88% at 450 g ae ha^{-1} and 98% at 1350 g ae ha^{-1} at 4 WAA (Soltani et al., 2023). There was no benefit from adding Class Act® NG to glyphosate at any rate or time point (Soltani et al., 2023). In another study, glyphosate at 450, 675, and 900 g ae ha^{-1} controlled green foxtail 91-100, 96-100, and 97-100%, respectively, adding AMS (2.5 L ha^{-1}) did not enhance green foxtail control in corn (Soltani et al., 2016b). Similarly, another study reported no added benefit from combining AMS (2.5 L ha^{-1}) to glyphosate (900 g ae ha^{-1}) for green foxtail control in corn (Soltani et al., 2011).

3.7 Corn Injury and Yield

There was no effect from the herbicide/adjuvant treatments evaluated on corn injury (data not presented), seed moisture content, or seed yield (Table 5). The absence of corn injury or yield impact is consistent with other studies, which have shown minimal, to no, corn injury from glyphosate applied alone or co-applied with AMS or AMS-containing adjuvants at various rates, different water hardness (Nurse et al., 2008; Soltani et al., 2011, 2016b, 2023).

4. Conclusions

In conclusion, this research demonstrates that applying glyphosate at 900 g ae ha^{-1} effectively controls common annual broadleaf and grass weeds including velvetleaf, Powell amaranth, common ragweed, common lambsquarters, barnyardgrass, and giant foxtail, with control ranging from 97 to 99%, regardless of water hardness (56 ppm and 1600 ppm). Increasing the glyphosate rate or adding Crimson® NG at 1.0% and 2.5% v/v did not enhance weed control appreciably (≤ 1%) for any of the evaluated weed species. Furthermore, there was no visible corn injury and there was no effect on corn seed moisture content or yield. These results reaffirm the robust effectiveness of glyphosate alone, with or without Crimson® NG adjuvant, under different water hardness conditions, underscoring its reliability as an option for controlling velvetleaf, Powell amaranth, common ragweed, common lambsquarters, barnyardgrass, and giant foxtail in corn production.

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