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Annual Ryegrass Control in Corn With Glyphosate plus Residual Herbicides Applied Preplant in the Spring

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Abstract

Glyphosate needs to be partnered with other herbicides that have residual biological activity on ryegrass (*Lolium multiflorum* Lam.) to improve the efficacy and consistency of annual ryegrass control in corn. Five field experiments were conducted from 2019 to 2021 near Exeter, Ontario to evaluate various glyphosate tank mixes applied preplant (PP) in the spring in corn for the control of annual ryegrass seeded as a cover crop in the fall of the previous year (2018 to 2020). At 1 week after application (WAA), all glyphosate tank mixes evaluated provided minimal annual ryegrass control (14-28%). At 2 WAA, the addition of dimethenamid-p/saflufenacil to glyphosate improved annual ryegrass control from 55% to 68%; there was no improvement in annual ryegrass control with the other 14 tank mixes evaluated. At 3 WAA, the addition of dimethenamid-p/saflufenacil and mesotrione + rimsulfuron to glyphosate controlled annual ryegrass 91 and 90%, respectively. At 4 WAA, the addition of dimethenamid-p, dimethenamid-p/saflufenacil, mesotrione + rimsulfuron, *S*-metholachlor, or bicyclopyrone/mesotrione/*S*-metolachlor to glyphosate improved annual ryegrass control 7, 7, 10, 8, and 6%, respectively. At 6 WAA, the addition of pyroxasulfone, pyroxasulfone + atrazine, dimethenamid-p, dimethenamid-p/saflufenacil, mesotrione + rimsulfuron, *S*-metholachlor, atrazine/*S*-metolachlor, or bicyclopyrone/mesotrione/*S*-metolachlor to glyphosate improved annual ryegrass control 10, 9, 12, 10, 17, 13, 10, and 12%, respectively but the addition of all other herbicides to glyphosate did not improve annual ryegrass control. Density and biomass reductions of annual ryegrass with glyphosate tank mix evaluated generally followed a similar trend as the visible control. Annual ryegrass interference reduced corn yield by up to 83% compared to the non-treated control. The addition of a residual herbicide to glyphosate did not result in an improvement in the seed yield of corn. Among the glyphosate tank mixes evaluated glyphosate + mesotrione + rimsulfuron provided the most consistent control of annual ryegrass in corn.

Keywords: density, biomass, corn, visible control, yield, *Lolium multiflorum* Lam.

1. Introduction

Corn (*Zea mays* L.) is one of the most valuable agricultural crops grown in Canada (Molenhuis, 2018). Canada is the 11th top corn-producing country in the world and Ontario farmers grow nearly two-thirds of all corn produced in Canada (Molenhuis, 2018). Corn growers in Ontario seeded 890,000 hectares and produced nearly 9 million tonnes of corn with a farm gate value of approximately $1.8 billion in 2020 (OMAFRA, 2021). Nearly 60% of the grain corn produced is used for feed and the remaining 40% is used for various industrial uses (OMAFRA, 2021). Corn producers need to modify their crop production practices to improve soil health and reduce the ecological downturn associated with conventional corn production practices while maintaining their competitiveness in the global marketplace (Lu et al., 2000). Inclusion of fall-sown cover crops in cropping systems has been shown to enhance soil health by improving organic matter, water holding capacity, nutrient sequestration, nutrient availability, and soil structure and reducing nutrient leaching and soil erosion (Blanco-Canqui et al., 2015; Moore et al., 1994; Snapp et al., 2005; Teasdale et al., 2007; Thilakarathna et al., 2015). Cover crops have also been shown to suppress weeds and reduce weed seeds in the soil seedbank by providing a natural habitat for beneficial organisms that feed on weed seeds (Cholette et al., 2018; Clark, 2012; Moore et al., 1994; Teasdale, 1996; Teasdale et al., 2007). Additionally, some cover crops have been shown to exude allelopathic chemicals into the soil that reduced weed growth (Li et al., 2008; Weston, 1996). Leguminous cover crops can also fix nitrogen and decrease the need for synthetic nitrogen application in subsequent crops (Lu et al., 2000).

Annual ryegrass (*Lolium multiflorum* Lam.), also known as Italian ryegrass, is a fast-growing cover crop that is suitable for cooler regions of the USA and Canada (Nandula et al., 2007). Annual ryegrass has very dense roots which allow it to sequester nitrogen and be very effective in breaking up compacted soils (Grant, 2018). Although annual ryegrass has many beneficial attributes for inclusion as a fall-sown cover crop in cropping systems in the USA and Canada, it has not been adopted by many growers mainly due to the difficulty of controlling it in the spring prior to seeding corn (Nandula, 2014). Effective control of annual ryegrass before seeding corn is crucial to eliminate early-season interference and subsequent corn yield losses. Earlier studies have reported as much as 49% corn seed yield losses when annual ryegrass was not controlled (Kobayashi et al., 1987; Nandula, 2014).

Earlier research has shown that glyphosate can be an effective herbicide for the control of annual ryegrass in Ontario; however, glyphosate alone does not provide consistent control of ryegrass prior to seeding corn (Soltani et al., 2020, 2021). Glyphosate needs to be partnered with other herbicides that have residual biological activity on ryegrass to improve the efficacy and consistency of annual ryegrass control in corn (Soltani et al., 2020, 2021). Currently registered preplant residual herbicides in Ontario that can be tank mixed with glyphosate for the control of annual ryegrass include atrazine/dicamba, atrazine + pendimethalin, pendimethalin, atrazine + isoxaflutole, atrazine, atrazine/mesotrione/*S*-metolachlor, atrazine/bicyclopyrone/mesotrione/*S*-metolachlor, pyroxasulfone + atrazine, pyroxasulfone, atrazine/*S*-metolachlor, dimethenamid-P/saflufenacil, dimethenamid-P, bicyclopyrone/mesotrione/*S*-metolachlor, *S*-metolachlor, and mesotrione + rimsulfuron (OMAFRA, 2022). Earlier studies have shown that the efficacy of glyphosate to control some weeds can be decreased when tank mixed with other herbicides (Flint & Barrett, 1989; Jordan et al., 2001; Wicks & Hanson, 1995). To our knowledge, no study has cumulatively compared the efficacy of glyphosate plus these residual herbicides for the control of annual ryegrass in corn under Ontario environmental conditions.

The purpose of this research was to evaluate the effect of various glyphosate tank mixes applied pre-plant (PP) in the spring for the control of annual ryegrass seeded as a cover crop in the fall of the previous year.

2. Materials and Methods

Five field experiments were established from 2019 to 2021 at Huron Research Station, University of Guelph [43.316305, -81.504763] near Exeter, Ontario. There was one trial in 2019 and two trials (separated in time and space each year) in 2020 and 2021. Trials were started in the fall of 2018, 2019, and 2020 when annual ryegrass was seeded after harvesting the previous crop and finished after corn harvest in the following year (2019, 2020, and 2021). Each experiment was designed as a randomized complete block design with four replications. Treatments evaluated were non-treated control (weedy), glyphosate, glyphosate + atrazine/dicamba, glyphosate + atrazine + pendimethalin, glyphosate + pendimethalin, glyphosate + atrazine + isoxaflutole, glyphosate + atrazine, glyphosate + atrazine/mesotrione/*S*-metolachlor, glyphosate + atrazine/bicyclopyrone/mesotrione/*S*-metolachlor, glyphosate + pyroxasulfone + atrazine, glyphosate + pyroxasulfone, glyphosate + atrazine/*S*-metolachlor, glyphosate + dimethenamid-P/saflufenacil, glyphosate + dimethenamid-P, glyphosate + bicyclopyrone/mesotrione/*S*-metolachlor, glyphosate + *S*-metolachlor, and glyphosate + mesotrione + rimsulfuron applied PP at the manufacturers' recommended rates. The rates and adjuvants used with each treatment are presented in Tables 3 and 4.

Table 1. Active ingredients, trade name, and manufacturer of herbicides used in preplant programs [a]

Active ingredient	Trade name	Manufacturer
Atrazine	Aatrex Liquid 480	Syngenta Canada Inc., Guelph, ON
Dicamba/atrazine	Marksman	BASF Canada, Mississauga, ON
Dimethenamid-P	Frontier MAX	BASF Canada, Mississauga, ON
Glyphosate	Roundup WeatherMax	Bayer CropScience Inc. Calgary, AB
Isoxaflutole	Converge Flexx Herbicide	Bayer CropScience Canada, Calgary, AB
Mesotrione	Callisto 480SC Herbicide	Syngenta Canada Inc., Guelph, ON
Pendimethalin	Prowl H_2O	BASF Canada, Mississauga, ON
Pyroxasulfone	Zidua SC	BASF Canada, Mississauga, ON
Rimsulfuron	Prism SG	Corteva Agriscience Canada Company, Chatham, ON
Saflufenacil/dimethenamid-P	Integrity	BASF Canada, Mississauga, ON
S-metolachlor	Dual Magnum II	Syngenta Canada Inc., Guelph, ON
S-metolachlor/atrazine	Primextra	Syngenta Canada Inc., Guelph, ON
S-metolachlor/mesotrione/atrazine	Lumax EZ Herbicide	Syngenta Canada Inc., Guelph, ON
S-metolachlor/mesotrione/bicyclopyrone	Acuron Flexi XR	Syngenta Canada Inc., Guelph, ON
S-metolachlor/mesotrione/bicyclopyrone/atrazine	Acuron XR	Syngenta Canada Inc., Guelph, ON

Note. [a] Specimen labels for each product and manufacturer contact information can be found at https://pr-rp.hc-sc.gc.ca/ls-re/index-eng.php

Experimental plots were 3 m wide and 10 m long. Annual ryegrass (Speare Seeds Limited, Harriston, Ontario) was seeded in rows spaced 18 cm apart (seeding rate of 22 kg ha^{-1}) after the previous crop was harvested. Herbicide treatments were applied prior to seeding corn; treatment dates are presented in Table 2. Glyphosate/glufosinate-resistant corn (‘DKC 42-60RIB’) was seeded approximately 5 cm deep from April to June of each year at the rate of approximately 86,000 seeds ha^{-1} in rows that were spaced 75 cm apart.

Table 2. Location, year, soil characteristics, herbicide application date, corn planting, emergence, and harvest dates for five field trials at the Huron Research Station, Exeter, ON (2019, 2020, and 2021)

Location	Year	Soil Characteristics [a]			Application date	Corn planting date	Corn emergence date	Corn harvest date
		Texture	Organic matter (%)	pH				
HRS-Range N3	2019	Clay Loam	3.5	7.9	May 11	June 4	June 11	October 29
HRS-Range N3	2020	Clay Loam	3.0	7.7	April 24	May 6	May 24	October 26
HRS-Range N4	2020	Clay Loam	3.3	7.8	May 5	May 6	May 24	October 26
HRS-Range N3	2021	Clay Loam	3.3	7.8	April 14	April 26	May 17	November 2
HRS-Range N4	2021	Clay Loam	3.3	7.8	April 26	April 26	May 17	November 2

Note. HRS: Huron Research Station.

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

Herbicides were applied preplant (when annual ryegrass was 20 cm or less) using a CO_2-pressurized backpack sprayer (delivery rate of 200 L ha^{-1} at a pressure of 240 kPa). The spray boom was 1.5 m long and had four ultra low drift (ULD 120-02, Pentair-Hypro, New Brighton, Minnesota) nozzles spaced 0.5 m apart, producing a spray width of 2.0 m.

Annual ryegrass control was assessed visually 1, 2, 3, 4, and 6 weeks after treatment application (WAA) using a scale of 0 to 100, with 0 representing no control and 100 representing total control. Annual ryegrass density and biomass were determined 4 WAA from two 0.25 m^2 quadrats placed between the corn rows. Annual ryegrass plants were counted (density) and clipped at the soil surface, placed in paper bags, dried at 60 ^oC, and then weighed (biomass). Grain corn yield (adjusted to 15.5% moisture) was determined at maturity by combining the middle two rows of each plot using a small plot combine.

2.1 Statistical Analysis

Data were analyzed using the GLIMMIX procedure via SAS Studio v9.4, OnDemand for Academics (SAS Institute, Cary, NC). Variance was partitioned into the fixed effect of herbicide treatment and the random effects of environment (location-year combinations), block nested within environment, and the environment-by-treatment interaction. Annual ryegrass control at 1, 2, 3, 4, and 6 WAA were analyzed using the beta distribution and complementary log-log link. The weedy control was assigned a value of 0% and was therefore excluded from the analysis due to zero variance. Annual ryegrass density and biomass were analyzed using the lognormal distribution with identity link; treatment means were analyzed and compared on the log scale. Corn yield was analyzed using a normal distribution with identity link. The weedy control was included for the analysis of density, biomass, and corn yield data. The Pearson chi-square/degrees of freedom ratio and Shapiro-wilk statistic were used to determine model fitness and avoid potential overdispersion for all parameters. Studentized residual plots were used to confirm homogeneity of variance and normal probability plots were used to verify the assumptions of normality. Density and biomass data were back transformed using the omega method (M. Edwards, Ontario Agricultural College Statistician, University of Guelph, personal communication). Mean estimates were separated using Tukey-Kramer Least Significant Difference (LSD) at an alpha level of 0.05. Density and biomass treatment means were compared to the weed-free control using P-values generated via the Least Squares Means output.

3. Results and Discussion

3.1 Visible Control

At 1 WAA, glyphosate controlled annual ryegrass 20%; there was no improvement in annual ryegrass control with the addition of atrazine/dicamba, atrazine + pendimethalin, pendimethalin, atrazine + isoxaflutole, atrazine, atrazine/mesotrione/*S*-metolachlor, atrazine/bicyclopyrone/mesotrione/*S*-metolachlor, pyroxasulfone + atrazine, pyroxasulfone, atrazine/*S*-metolachlor, dimethenamid-P/saflufenacil, dimethenamid-P, bicyclopyrone/mesotrione/*S*-metolachlor, *S*-metolachlor, or mesotrione + rimsulfuron (Table 3).

Table 3. Annual ryegrass control 1, 2, 3, 4, and 6 weeks after application of glyphosate plus residual herbicide tank-mixtures applied preplant to corn from five experiments conducted near Exeter, ON, Canada (2019, 2020, and 2021)

Herbicide treatment	Rate (g ae or ai ha^{-1})	Visible control (%) [a, c]				
		1 WAA	2 WAA	3 WAA	4 WAA	6 WAA
Non-treated control	-	0	0	0	0	0
Glyphosate	1350	20 abcde	55 bcd	81 cdef	88 def	82 e
Glyphosate + atrazine/dicamba	1350 + 966/488	17 bcde	48 cd	73 fg	83 f	82 e
Glyphosate + atrazine + pendimethalin	1350 + 1680 + 1530	14 e	45 d	69 g	82 f	82 e
Glyphosate + pendimethalin	1350 + 1680	18 bcde	53 bcd	79 def	85 ef	83 e
Glyphosate + atrazine + isoxaflutole	1350 + 105 + 1063	15 de	48 cd	73 fg	84 ef	86 de
Glyphosate + atrazine	1350 + 1490	17 bcde	54 bcd	78 efg	89 def	89 cde
Glyphosate + atrazine/mesotrione/*S*-metolachlor	1350 + 526/140/1400	17 bcde	51 bcd	78 efg	89 def	89 cde
Glyphosate + atrazine/bicyclopyrone/mesotrione/*S*-metolachlor	1350 + 589/35/140/1262	15 cde	49 cd	76 efg	88 def	89 cde
Glyphosate + pyroxasulfone + atrazine	1350 + 150 + 1490	15 cde	51 bcd	77 efg	88 def	91 bcd
Glyphosate + pyroxasulfone	1350 + 150	20 bcde	60 abc	83 bcde	92 bcd	92 bcd
Glyphosate + atrazine/*S*-metolachlor	1350 + 1280/1600	17 bcde	51 bcd	77 efg	90 cde	92 bcd
Glyphosate + dimethenamid-P/saflufenacil	1350 + 660/75	28 a	68 a	91 a	95 bc	92 bcd
Glyphosate + dimethenamid-P	1350 + 693	21 abcd	60 abc	88 abc	95 bc	94 bc
Glyphosate + bicyclopyrone/mesotrione/*S*-metolachlor	1350 + 35/141/1268	21 ab	61 abc	87 abcd	94 bc	94 bc
Glyphosate + *S*-metolachlor	1350 + 1600	22 ab	63 ab	89 abc	96 ab	95 b
Glyphosate + mesotrione + rimsulfuron[b]	1350 + 15 + 144	19 bcde	58 abc	90 ab	98 a	99 a

Note. [a] Means followed by the same letter within a column are not significantly different according to Tukey-Kramer LSD (P > 0.05).

[b] Treatment included Agral 90 (Syngenta Canada Inc., Guelph, ON) (0.2% v/v).

[c] Abbreviations: WAA; weeks after application.

At 2 WAA, glyphosate controlled annual ryegrass 55%. The addition of dimethenamid-P/saflufenacil to glyphosate improved annual ryegrass control to 68%; however, the addition of all other herbicides to glyphosate did not provide a significant improvement in the control of annual ryegrass in corn (Table 3). Soltani et al. (2021)

reported that glyphosate (900 g ae ha^{-1}) and glyphosate (900 g ae ha^{-1}) + rimsulfuron (15 g ai ha^{-1}) controlled annual ryegrass 69 and 77%, respectively at 2 WAA.

At 3 WAA, glyphosate controlled annual ryegrass 81%; the addition of dimethenamid-p/saflufenacil or mesotrione + rimsulfuron to glyphosate improved annual ryegrass control to 91 and 90%, respectively. The addition of all other residual herbicides to glyphosate did improve annual ryegrass control (Table 3).

At 4 WAA, glyphosate controlled annual ryegrass 88%. The tank mixes of glyphosate plus dimethenamid-P/saflufenacil, dimethenamid-P, bicyclopyrone/mesotrione/*S*-metolachlor, *S*-metolachlor or mesotrione + rimsulfuron controlled annual ryegrass 95, 95, 94, 96, and 98%, respectively; there was no improvement in annual ryegrass control with the other glyphosate tank mixes evaluated (Table 3).

At 6 WAA, glyphosate controlled annual ryegrass 82%; the addition of pyroxasulfone + atrazine, pyroxasulfone, atrazine/*S*-metolachlor, dimethenamid-P/saflufenacil, dimethenamid-P, bicyclopyrone/mesotrione/*S*-metolachlor, *S*-metolachlor or mesotrione + rimsulfuron improved annual ryegrass control to 91 to 99%. Glyphosate + mesotrione + rimsulfuron provided greater control of annual ryegrass than all other glyphosate tank mixes evaluated (Table 3). Soltani et al. (2021) reported that glyphosate (900 g ae ha^{-1}) and glyphosate (900 g ae ha^{-1}) + rimsulfuron (15 g ai ha^{-1}) controlled annual ryegrass 80 and 98%, respectively at 6 WAA.

Earlier research has shown that a high dose of glyphosate (1350 g ae ha^{-1}) controlled annual ryegrass 27, 61, 77, 72, and 68% at 1, 2, 3, 4, and 6 WAA in corn, respectively (Soltani et al., 2020). The tank mixes of a high dose of glyphosate (1350 ae ha^{-1}) with clethodim (30 g ai ha^{-1}), fluazifop-p-butyl (125 g ai ha^{-1}), quizalofop-p-ethyl (36 g ai ha^{-1}), sethoxydim (150 g ai ha^{-1}) or saflufenacil (25 g ai ha^{-1}) controlled annual ryegrass 75, 74, 79, 80, and 75%, respectively at 6 WAA (Soltani et al., 2020). In another study, Soltani et al. (2021) reported that glyphosate (900 ae ha^{-1}) controlled annual ryegrass 80% 6 WAA, the addition of foramsulfuron (35 g ai ha^{-1}), nicosulfuron (25 g ai ha^{-1}), or nicosulfuron/rimsulfuron (30 g ai ha^{-1}) improved control to 94, 95, and 98%, respectively at 6 WAA, Nandula et al. (2007) found 91 to 94% control of annual ryegrass (15-20 cm tall at application) with glyphosate at 840 and 1620 g ae ha^{-1}. Jordan et al. (2001) reported 84% annual ryegrass control with glyphosate (560 g ae ha^{-1}). Other research has shown reduced annual ryegrass control (84 *vs.* 59%) with glyphosate plus cyanazine (a triazine herbicide) compared to glyphosate alone (Jordan et al., 2001). Stritzke (1992) reported > 90% control of annual ryegrass with sethoxydim in corn.

3.2 Density

Glyphosate reduced annual ryegrass density by 63% compared to the non-treated control. Glyphosate + atrazine/dicamba, atrazine + pendimethalin, pendimethalin, atrazine + isoxaflutole, atrazine, atrazine/mesotrione/*S*-metolachlor, atrazine/bicyclopyrone/mesotrione/*S*-metolachlor, pyroxasulfone + atrazine, pyroxasulfone, atrazine/*S*-metolachlor, dimethenamid-P/saflufenacil, dimethenamid-P, bicyclopyrone/mesotrione/*S*-metolachlor, or *S*-metolachlor reduced annual ryegrass density 55 to 84%; however, this reduction in density was similar to glyphosate applied alone. The addition of mesotrione + rimsulfuron to glyphosate was the only treatment among herbicides evaluated that decreased annual ryegrass density greater than glyphosate alone (92 *vs.* 63%) (Table 4). In a study by Soltani et al. (2021), glyphosate reduced annual ryegrass density 73%; glyphosate + foramsulfuron, nicosulfuron, rimsulfuron, or nicosulfuron/rimsulfuron reduced annual ryegrass density by 88 to 94%.

Table 4. Annual ryegrass density and biomass 4 weeks after application and corn grain yield with glyphosate plus residual herbicide tank-mixtures applied preplant to corn from five experiments conducted near Exeter, ON, Canada (2019, 2020, and 2021)

Herbicide treatment	Rate (g ae or ai ha^{-1})	Density [a] (Plants m^{-2})	Biomass (g m^{-2})	Yield (kg ha^{-1})
Non-treated control	-	170 e	251 g	2,260 b
Glyphosate	1350	63 bcd	39 bcdef	12,980 a
Glyphosate + atrazine/dicamba	1350 + 966/488	77 de	51 f	12,460 a
Glyphosate + atrazine + pendimethalin	1350 + 1680 + 1530	70 d	55 ef	11,810 a
Glyphosate + pendimethalin	1350 + 1680	57 cd	47 ef	12,310 a
Glyphosate + atrazine + isoxaflutole	1350 + 105 + 1063	53 cd	38 def	12,310 a
Glyphosate + atrazine	1350 + 1490	47 bcd	28 bcdef	12,800 a
Glyphosate + atrazine/mesotrione/*S*-metolachlor	1350 + 526/140/1400	52 bcd	31 bcdef	12,480 a
Glyphosate + atrazine/bicyclopyrone/mesotrione/*S*-metolachlor	1350 + 589/35/140/1262	59 bcd	38 cdef	13,040 a
Glyphosate + pyroxasulfone + atrazine	1350 + 150 + 1490	58 cd	38 def	13,520 a
Glyphosate + pyroxasulfone	1350 + 150	49 abcd	36 abcde	13,350 a
Glyphosate + atrazine/*S*-metolachlor	1350 + 1280/1600	45 cd	23 bcdef	12,710 a
Glyphosate + dimethenamid-P/saflufenacil	1350 + 660/75	30 abc	18 abcd	11,900 a
Glyphosate + dimethenamid-P	1350 + 693	29 abc	14 abc	12,930 a
Glyphosate + bicyclopyrone/mesotrione/*S*-metolachlor	1350 + 35/141/1268	27 abc	15 abcd	12,750 a
Glyphosate + *S*-metolachlor	1350 + 1600	27 ab	13 ab	12,230 a
Glyphosate + mesotrione + rimsulfuron [b]	1350 + 15 + 144	14 a	7 a	13,240 a

Note. [a] Means followed by the same letter within a column are not significantly different according to Tukey-Kramer LSD ($P > 0.05$).

[b] Treatment included Agral 90 (Syngenta Canada Inc., Guelph, ON) (0.2% v/v).

3.3 Biomass

Glyphosate reduced annual ryegrass density by 84% compared to the non-treated control. Glyphosate + atrazine/dicamba, atrazine + pendimethalin, pendimethalin, atrazine + isoxaflutole, atrazine, atrazine/mesotrione/*S*-metolachlor, atrazine/bicyclopyrone/mesotrione/*S*-metolachlor, pyroxasulfone + atrazine, pyroxasulfone, atrazine/*S*-metolachlor, dimethenamid-P/saflufenacil, dimethenamid-P, bicyclopyrone/mesotrione/*S*-metolachlor, or *S*-metolachlor reduced annual ryegrass biomass 78 to 95%. Glyphosate + mesotrione + rimsulfuron decreased annual ryegrass biomass by 97% (Table 4). In a study by Soltani et al. (2021) glyphosate reduced annual ryegrass biomass by 94%; glyphosate + foramsulfuron, nicosulfuron, rimsulfuron, or nicosulfuron/rimsulfuron reduced annual ryegrass density by 99-100%. In other studies, glyphosate (1350 g ae ha^{-1}) decreased annual ryegrass biomass by 96% compared to the weedy control at 4 WAA (Soltani et al. 2020). Additionally, the tank mix of glyphosate (1350 ae ha^{-1}) with saflufenacil (25 g ai ha^{-1}) reduced annual ryegrass biomass by 96% compared to the control at 4 WAA (Soltani et al., 2020).

3.4 Yield

Annual ryegrass interference reduced corn seed grain yield up to 83% in this study (highest yielding treatment compared to the weedy non-treated control); there was no difference in corn yield among the herbicide treatments evaluated (Table 4). In earlier studies, Soltani et al. (2020) and Soltani et al. (2021) reported that reduced annual ryegrass interference with glyphosate increased corn yield by 61 and 86%, respectively. Nandula (2014) found a 49% yield loss in corn when annual ryegrass was present at a biomass of 98,322 kg ha^{-1}. Annual ryegrass control with tank mixes of glyphosate (1350 ae ha^{-1}) with the Group 1 herbicides increased corn yield by as much as 66%; the tank mix of glyphosate (1350 ae ha^{-1}) with saflufenacil (25 g ai ha^{-1}) increased corn yield by 69% compared to the weedy control (Soltani et al., 2020). Annual ryegrass control with tank mixes of glyphosate (900 ae ha^{-1}) with the Group 2 herbicides increased corn yield by as much as 105% compared to the weedy non-treated control (Soltani et al., 2021).

4. Conclusions

At 1 WAA, there was minimal control of annual ryegrass (14 to 28%) with the herbicide treatments evaluated. At 2 WAA, only the addition of dimethenamid-p/saflufenacil to glyphosate improved annual ryegrass control by 13%; the other tank mixes provided no added benefit compared to the glyphosate applied alone. At 3 WAA, the addition of dimethenamid-p/saflufenacil and mesotrione + rimsulfuron to glyphosate improved annual ryegrass control by 9 to 10% compared to the glyphosate alone but the addition of all other herbicide tank mixes provided no added benefit for the control of annual ryegrass. At 4 WAA, the addition of dimethenamid-p/saflufenacil, dimethenamid-p, bicyclopyrone/mesotrione/*S*-metolachlor, *S*-metholachlor, or mesotrione + rimsulfuron to glyphosate improved annual ryegrass control 6 to 10% compared to glyphosate alone. At 6 WAA, the addition of pyroxasulfone + atrazine, pyroxasulfone, atrazine/*S*-metolachlor, dimethenamid-p/saflufenacil, dimethenamid-p, bicyclopyrone/mesotrione/*S*-metolachlor, *S*-metholachlor, or mesotrione + rimsulfuron to glyphosate improved annual ryegrass control 9 to 17%. Glyphosate + mesotrione + rimsulfuron reduced annual ryegrass density and biomass by 63 and 84%, respectively. Annual ryegrass interference reduced corn yield up to 83% compared to the nontreated control. The addition of all other herbicide treatments evaluated to glyphosate did not provide any significant improvement in the seed yield of corn. Among the glyphosate tank mixes evaluated, glyphosate + mesotrione + rimsulfuron provided the most consistent control of annual ryegrass in corn.

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