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Enhancing winter rye termination by mixing glyphosate with other herbicides using water or UAN as the carrier

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Abstract

Herbicides are often used to terminate cover crops. Producers would like to use herbicides that work quickly, are effective, and do not increase the risk of selecting herbicide-resistant weeds. Eight experiments were conducted to determine whether mixing glyphosate (900 g a.e. ha^{-1}) with rimsulfuron (15 g a.i. ha^{-1}), mesotrione (100 g a.i. ha^{-1}), or rimsulfuron + mesotrione enhances winter rye control and to ascertain whether using urea ammonium nitrate (UAN) as the herbicide carrier improves and accelerates herbicide efficacy. Winter rye control was assessed 1, 2, 3, and 4 wk after application (WAA) and biomass was measured 4 WAA. The addition of rimsulfuron, mesotrione, or rimsulfuron + mesotrione to glyphosate did not enhance winter rye control. Similarly, using UAN as the herbicide carrier did not improve or accelerate herbicide efficacy. Glyphosate alone provided the greatest level of winter rye control. The addition of rimsulfuron, mesotrione, or rimsulfuron + mesotrione to glyphosate did not increase the level or speed of control. However, mixing glyphosate with rimsulfuron, mesotrione, or rimsulfuron + mesotrione adds other modes of action without compromising winter rye control.

Introduction

Many farmers have adopted the use of cover crops to protect soil from erosion caused by water and wind, increase soil organic matter, fix carbon, and capture nitrogen, among other benefits (Oelke et al. 1990). One of the most popular cover crop species is winter rye (*Secale cereale* L.) because it is tolerant to harsh winter conditions, produces aboveground biomass, and can suppress weed growth through competition and allelopathy (Clark 2007).

The impact of a winter rye cover crop on the yield of a subsequent cash crop has been variable. A negative impact on corn growth has been reported (Brennan et al. 2013; Kaspar et al. 2007; Wagger 1989), possibly due to a reduction in nitrogen availability since winter rye plays a role in nitrogen cycling. A living winter rye cover crop may reduce nitrate leaching due to nitrogen scavenging and a dead rye cover crop can immobilize nitrogen during decomposition (Kaspar et al. 2012; Vaughan and Evanylo 1998). With a carbon-to-nitrogen ratio of approximately 37:1, nitrogen immobilization from a winter rye cover crop may reduce nitrogen availability for the following crop, thereby affecting yield (Brennan et al. 2013; Wagger 1989). The timing of winter rye termination may play a role in whether winter rye will negatively affect the subsequent corn crop.

Terminating rye 14 d before planting did not cause corn yield reduction over 8 yr in Michigan; however, because of the high C:N ratio of rye, temporary nitrogen immobilization could occur following cover crop incorporation (Snapp and Surapur 2018). Delayed winter rye termination relative to corn planting resulted in greater soil nitrogen uptake and immobilization by the cover crop possibly reducing nitrogen availability for corn (Kaspar et al. 2007; Wagger 1989). Similarly, Acharya et al. (2022) observed that delaying rye termination to 6 or 12 d after planting resulted in a higher rye C:N ratio and nitrogen uptake, which were associated with 4.5% to 11.0% corn yield loss compared with termination at 17 d before planting. Acharya et al. (2022) also noted that shading of corn seedlings from the rye canopy and a higher incidence of corn root diseases were linked to delayed rye termination. This highlights the fact that corn yield loss linked to planting green practices may have multiple causes and reinforces the need for rapid and effective tools for rye termination. Glyphosate is a widely used herbicide due to its high efficacy; broad-spectrum weed control of annuals, biennials, and perennials; low mammalian toxicity; and limited environmental impacts (Duke and Powles 2008). Glyphosate can effectively terminate winter rye and is widely recommended for the termination of this cover crop (OSU 2018; Stahl and Sackett Eberhart 2018; Werle et al. 2017). However, due to its widespread use, intense selection pressure for the evolution of resistance in weeds has ensued; 57 weed species have evolved resistance to glyphosate to date (Duke 2018; Heap 2023). Glyphosate is a relatively slow-acting herbicide; visible effects can take 10 to 14 d to appear (Duke 1988), which results in prolonged competition between winter rye and a subsequent corn crop. Such competitive effects include direct shading from the rye canopy (Acharya et al. 2022) and alteration of light quality through a reduction in the red-to-far-red ratio, which would impact corn seedlings (Page et al. 2010). Therefore, it is important to identify glyphosate mixtures that provide rapid and effective winter rye termination and reduce the selection pressure for glyphosate resistance.

One way to achieve effective winter rye termination without relying solely on glyphosate would be to co-apply glyphosate with other herbicides. The co-application of glyphosate with other herbicides may result in faster termination of the winter rye cover crop. Rimsulfuron is an acetolactate synthase inhibitor (sulfonylurea) that controls many annual and perennial grass species as well as many dicots (Green and Green 1993). In corn, rimsulfuron applied early postemergence (POST) controlled winter rye by 46% to 62% depending on the year (Wilson et al. 2010), demonstrating its activity on this species. The co-application of rimsulfuron with glyphosate on annual ryegrass (*Lolium multiflorum* Lam.) resulted in a more rapid time to 80% visible control and a synergistic decrease in plant density (Soltani et al. 2021). Therefore, the co-application of rimsulfuron and glyphosate may result in improved winter rye control.

Mesotrione is a 4-hydroxyphenylpyruvate dioxygenase (HPPD) inhibitor that is primarily used to control broadleaf weeds in corn crops (Armel et al. 2003) with some activity on some grass species (Soltani et al. 2012). While there is no information on the activity of mesotrione applied POST for winter rye control, it does cause injury to winter wheat in the form of leaf bleaching (Soltani et al. 2011), which is characteristic of its mode of action (Lee et al. 1998). Although the activity of mesotrione applied POST in grass species can be limited, its effectiveness can be increased when applied in a mixture with glyphosate. For example, mesotrione provided 25% control of giant foxtail (*Setaria faberi* Herm.), but the addition of glyphosate improved control to more than 65% (Armel et al. 2003). While mixtures of HPPD inhibitors with sulfonylureas can be antagonistic the interaction is specific to weed species and herbicide (Kaastra et al. 2008; Schuster et al. 2007). The mixture of mesotrione and rimsulfuron is commercially available as Destra IS (Anonymous 2021), and the label specifies the control of many grass species applied POST. Schuster et al. (2007) reported that the co-application of rimsulfuron with mesotrione had no adverse effects on the control of green foxtail [*Setaria viridis* (L.) P. Beauv.]. Therefore, it is of interest to assess whether rimsulfuron or mesotrione could be used in combination with each other, or with glyphosate, to improve and accelerate the termination of winter rye compared to the use of glyphosate alone.

The application of herbicides with a nitrogen source allows farmers to optimize efficiency and reduce production costs. Moreover, the addition of nitrogen in the form of 28% urea ammonium nitrate (UAN) can enhance crop injury and weed control efficacy through increased leaf absorption (Bunting et al. 2004; Fielding and Stoller 1990; Koger et al. 2007; Miller et al. 1999). Winter wheat foliar injury following the application of thifensulfuron-methyl/tribenuron-methyl plus MCPA amine increased by 11 percentage points when 28% UAN was used as the carrier solution (Cowbrough and Sikkema 2012). Similarly, 28% UAN increased the visible injury caused by bispyribac to barnyardgrass 1.2-fold to 1.9-fold (Koger et al. 2007). It is of interest to determine whether the use of UAN as the carrier solution increases the rate of mortality of winter rye termination while also applying nitrogen for the subsequent corn crop. This would be beneficial to farmers due to an increase in overall operational efficiency.

The objectives of this research were to determine whether rimsulfuron, mesotrione, or a combination of the two, co-applied with glyphosate enhances winter rye termination, and to ascertain whether the use of UAN as the herbicide carrier improves and accelerates winter rye termination.

Materials and Methods

Field experiments were conducted in 2021 and 2022 in Ontario, Canada, at four University of Guelph locations: Elora Research Station, Woodstock Research Station, Huron Research Station, and Ridgetown Campus (Table 1). Soil textural classes at these sites ranged from sandy loam to silty clay loam with a pH of 6.7 to 7.9 (Table 2). Each experiment was arranged in a randomized complete block design with four replications and included 12 treatments as listed in Table 3. Plots measured 3 m wide by 10 m long.

Winter rye ('AC Hazlet'; SeCan Association, Ottawa, ON) was planted at a rate of 66 kg ha^{-1} during the latter part of October to early November in the previous year (Table 1) using a no-till drill (Model 750; John Deere, Ankeny, IA). The herbicide treatments were applied with a push-type small plot sprayer (Model EXD; R&D Sprayers, Opelousa, LA) calibrated to deliver 200 L ha^{-1} of spray mixture at 207 kPa using compressed medical air (Linde Canada Inc., Mississauga, ON) at a speed of 3.6 km h^{-1}. The spray boom was 2.5 m wide and fitted with six nozzles (TeeJet AIXR11002; Spraying Systems Co., Glendale Heights, IL) spaced 50 cm apart producing a spray width of 3 m. An untreated control with no herbicide was included in each replicate. The dates of winter rye seeding and emergence, the dates of herbicide application, and the stage and height of winter rye at the time of application are presented in Table 1. Water or 28% UAN at 200 L ha^{-1} of spray solution was used as the herbicide carrier.

Winter rye control was assessed 1, 2, 3, and 4 wk after application (WAA) using a scale of 0% to 100%, where 0% represented no effect (complete plant survival) and 100% indicated complete winter rye necrosis. At 4 WAA, the total dry biomass (alive and dead material) of winter rye was determined by harvesting the winter rye within two 0.25-m^2 quadrats per plot centered over two rye rows near the middle of each plot; the winter rye was cut at the soil surface, placed in paper bags, and dried at 60 C until a constant weight was attained and then biomass was recorded.

Data were subjected to variance analysis using the GLIMMIX procedure with SAS software (version 9.4; SAS Institute, Cary, NC). An alpha value was set at 0.05 to determine differences among treatments. Site-years were redefined as environments (env) for the analysis. An initial mixed model analysis was conducted to evaluate env-by-treatment interactions for all parameters. The random effects included env, replication within env, and env-by-treatment; the fixed effect was herbicide treatment. No site-by-treatment interaction was present, so the data were pooled for analysis. To confirm that the assumptions of the

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Table 1. Experiment data.[a]

Location	Year	Rye planting date	Rye emergence date	Rye stage at termination	Rye height at termination	Date terminated	Biomass harvest
				Zadoks	cm		
Elora 1	2021	October 14	October 21	Z 31	24–35	May 6	May 31
Woodstock 1	2021	October 14	November 2	Z 31	33–43	May 6	June 1
Huron 1	2021	September 29	October 14	Z 21	18–24	April 26	May 25
Huron 2	2021	September 29	October 14	Z 31	30–41	May 6	June 1
Elora 2	2022	October 18	November 2	Z 31	15–20	May 10	June 7
Woodstock 2	2022	October 20	November 7	Z 31	15–18	May 9	June 6
Ridgetown 1	2022	October 14	October 22	Z 21	10–15	May 5	June 2
Ridgetown 2	2022	October 14	October 22	Z 31	20–25	May 11	June 9

[a]Data in the table are based on eight experiments conducted at four University of Guelph research locations in southwestern Ontario in 2021 and 2022.

Table 2. Soil characteristics.[a–c]

Location	Textural class	Sand	Silt	Clay	OM	pH	CEC
		———	———	%	———		meq 100 g^{-1}
Elora	Silt loam	31	50	19	4.2	7.4	16.6
Woodstock	Silt loam	40	43	17	4.8	7.7	22.3
Huron	Silty clay loam	17	46	37	3.5	7.9	32.7
Ridgetown	Sandy loam	46	27	27	5.5	6.7	16.0

[a]Abbreviations: CEC, cation exchange capacity; OM, organic matter.
[b]Soil characteristics were measured in the top 15 cm.
[c]Trials were conducted at four University of Guelph research locations in southwestern Ontario, in 2021 and 2022.

variance analyses were met, UNIVARIATE procedure with SAS software produced the Shapiro-Wilk statistic to test for normality, and studentized residuals were plotted to test for normality of residuals and assumptions for variance. Winter rye control ratings were analyzed using a normal distribution, and a lognormal distribution was specified within the GLIMMIX procedure for winter rye biomass. Herbicide mixtures with water as the carrier was analyzed using Colby's equation (Flint et al. 1988) for two-way herbicide (Equation 1) and three-way herbicide interactions (Equation 2) as follows:

$$E_1 = (X + Y) - (XY/100) \quad [1]$$

$$E_2 = (X + Y + Z) - (XY + XZ + YZ)/100 + (XYZ/10{,}000) \quad [2]$$

where E_1 represents the expected level of winter rye control when two herbicides are applied in a mixture; E_2 represents the expected level of winter rye control when three herbicides are applied in a mixture; and variables *X*, *Y*, and *Z* represent the level of winter rye control provided by each herbicide applied individually. The calculated E_n values were tested for antagonism, additivity, or synergism of herbicide combinations through a transformation of data to logarithms followed by significance tests of two by two or three by three contrasts in the form of $\mu_{ij} - \mu_{i0} - \mu_{0j} + \mu_{00}$ or $\mu_{ijk} - \mu_{i0} - \mu_{0j} - \mu_{0k} + \mu_{000}$ concerning the log-transformed data (Flint et al. 1988). Synergism was implied if I_{ij} or $I_{ijk} < 0$, antagonism was implied if I_{ij} or $I_{ijk} > 0$, and additivity was implied if I_{ij} or $I_{ijk} = 0$ (Flint et al. 1988). A *t*-test was used to detect significant deviations from zero at $P < 0.05$. Together, the sign and probability levels determined whether antagonism, additivity, or synergism occurred.

Results and Discussion

Herbicides with Water as the Carrier

Glyphosate, with water as the carrier, controlled winter rye by 40% at 1 WAA; control improved to 88%, 97%, and 99% at 2, 3, and 4 WAA, respectively, and winter rye biomass was reduced by 61% at 4 WAA. Rimsulfuron provided only 4% visible winter rye control at 1 WAA, which increased to 33% to 57% at 2 to 4 WAA; rimsulfuron reduced winter rye biomass by 54% at 4 WAA. Mesotrione did not provide any visible winter rye control at 1 to 4 WAA and did not reduce biomass. The mixture of rimsulfuron and mesotrione controlled winter rye similar to rimsulfuron alone at 1, 2, and 3 WAA, and it did not reduce winter rye biomass. The co-application of rimsulfuron and mesotrione resulted in an antagonistic reduction in winter rye control at 3 and 4 WAA, and an antagonistic increase in winter rye biomass. Adding rimsulfuron, mesotrione, or rimsulfuron + mesotrione to glyphosate did not improve winter rye control and did not decrease winter rye biomass compared to glyphosate applied alone. The mixture of glyphosate + rimsulfuron was antagonistic for winter rye at 1, 2, 3, and 4 WAA and biomass at 4 WAA. The mixture of glyphosate + mesotrione was antagonistic for the control of winter rye at 3 WAA and biomass at 4 WAA. The mixture of glyphosate + rimsulfuron + mesotrione was antagonistic for winter rye control at 1,2, 3, and 4 WAA; biomass reduction was additive.

Herbicides with UAN as the Carrier

The use of 28% UAN as the herbicide carrier compared to water as the carrier did not improve the control of winter rye with glyphosate, glyphosate + rimsulfuron, glyphosate + mesotrione, or glyphosate + rimsulfuron + mesotrione at 1, 2, 3, and 4 WAA, nor did it affect the biomass of winter rye at 4 WAA, with the

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Table 3. Winter rye control 1, 2, 3, and 4 wk after application and biomass 4 wk after application.[a–g]

			Control									
			1 WAA		2 WAA		3 WAA		4 WAA		Biomass	
Treatment	Rate	Herbicide carrier	Obs	Exp	Obs	Exp	Obs	Exp	Obs	Exp	Obs	Exp
	g ai ha^{-1}		%								g m^{-2}	
Untreated control											264 a	
Glyphosate	900	Water	40 a		88 a		97 a		99 a		103 cd	
Rimsulfuron	15	Water	4 b		33 b		57 b		56 b		122 b-d	
Mesotrione	100	Water	0 b		0 c		0 d		0 d		148 a-d	
Rimsulfuron + mesotrione	15 + 100	Water	3 b	4	30 b	33	53 b	57*	50 c	56*	250 ab	68*
Glyphosate + rimsulfuron	900 + 15	Water	40 a	42*	86 a	92*	97 a	99*	99 a	100*	121 b-d	48*
Glyphosate + mesotrione	900 + 100	Water	37 a	40	85 a	88	96 a	97*	98 a	99	171 a-c	58*
Glyphosate + rimsulfuron + mesotrione	900 + 15 + 100	Water	37 a	42*	83 a	92*	96 a	99*	98 a	100*	105 cd	27
Glyphosate	900	UAN	40 a		85 a		98 a		100 a		119 b-d	
Glyphosate + rimsulfuron	900 + 15	UAN	40 a		86 a		98 a		100 a		158 a-d	
Glyphosate + mesotrione	900 + 100	UAN	40 a		83 a		97 a		100 a		81 d	
Glyphosate + rimsulfuron + mesotrione	900 + 15 + 100	UAN	39 a		85 a		96 a		99 a		85 cd	
Contrasts			P-value									
Glyphosate vs all other treatments containing glyphosate			0.8452		0.1470		0.9682		0.9616		0.4334	
Water vs UAN for all glyphosate-containing treatments			0.7648		0.6101		0.3094		0.0552		0.5582	

[a]Abbreviations: Exp, expected; Obs, observed; UAN, urea ammonium nitrate.
[b]Means followed by the same letter within a column are not significantly different according to the Tukey-Kramer test ($P < 0.05$).
[c]Data were collected from eight experiments conducted at four University of Guelph locations in southwestern Ontario in 2021 and 2022.
[d]All data were pooled for all locations and years. Data presented in the table have been back-transformed to the original scale.
[e]Dry weights of winter rye were recorded at 4 WAA.
[f]Expected responses are based on Colby's equations: $E_1 = (X+Y) - (X*Y/100)$ and $E_2 = (X+Y+Z) - (XY+XZ+YZ)/100 + (XYZ/10{,}000)$.
[g]Expected values followed by an asterisk (*) indicate significant ($P = 0.05$) deviation from additive effect.

exception that the biomass of winter rye was numerically lower with glyphosate + mesotrione with UAN as the carrier (Table 3).

Glyphosate controlled winter rye by 99% at 4 WAA; however, glyphosate is a slow-acting herbicide and only 40% control was observed at 1 WAA (Table 3). This is consistent with previous reports of glyphosate providing relatively low levels of control 1 WAA on weeds such as velvetleaf (*Abutilon theophrasti* Medic), common ragweed (*Ambrosia artemisiifolia* L.), and fall-planted winter cereals, but control increased to ≥80% at 2 WAA (Soltani et al. 2010; Walsh et al. 2014).

Rimsulfuron provided control of winter rye that ranged between 4% and 57% (Table 3). This poor level of control is consistent with the observations made by Wilson et al. (2010). The mixture of glyphosate + rimsulfuron resulted in an antagonistic interaction, with observed visible control values less than expected and higher biomass (Table 3). This is in contrast with the results reported by Soltani et al. (2021) who observed a higher level of control with rimsulfuron alone and determined the rimsulfuron + glyphosate mixture accelerated visible control and synergistically reduced density compared to each herbicide alone. Similarly, the mixture of glyphosate + mesotrione or glyphosate + rimsulfuron + mesotrione did not improve winter rye termination and there was an additive or antagonistic action. The addition of mesotrione to sulfonylureas can reduce grass control. For example, co-application of mesotrione or mesotrione + atrazine with rimsulfuron, nicosulfuron, or foramsulfuron reduced the control of green foxtail, yellow foxtail [*Setaria pumila* (Poir.) Roem. & Schult.], and shattercane [*Sorghum bicolor* (L.) Moench.] (Schuster et al. 2007, 2008).

Although it is widely reported that the use of UAN as a herbicide carrier can increase the foliar uptake of herbicides and increase weed control efficacy (Bunting et al. 2004; Fielding and Stoller 1990; Koger et al. 2007; Miller et al. 1999), there was no increase in efficacy with UAN as the herbicide carrier in this study. This could be due to winter rye having glaucous leaves covered with epicuticular wax (Laskoś et al. 2022; Shepherd and Wynne Griffiths 2006) that reduces herbicide absorption compared to plants with a thinner layer of epicuticular wax (Baker and Hunt 1981).

Although the addition of rimsulfuron, mesotrione, or rimsulfuron + mesotrione to glyphosate did not result in increased or more rapid winter rye termination, it also did not reduce the control level. This study concludes that the aforementioned herbicides can be co-applied with glyphosate to help reduce the selection pressure for glyphosate resistance, expand the spectrum of weed control, and provide residual control of some annual grass and broadleaf weeds.

Practical Implications

There is limited information on the benefit of co-applying glyphosate with rimsulfuron, mesotrione, or a combination of the two, for winter rye termination. Additionally, there is limited information regarding the use of UAN as the herbicide carrier on the speed and level of winter rye termination. Results show that there was no benefit of mixing glyphosate with rimsulfuron, mesotrione, or rimsulfuron + mesotrione for winter rye termination. In addition, the use of water or UAN as the herbicide carrier resulted in similar winter rye termination. The use of UAN as the herbicide carrier could provide growers with the opportunity to apply nitrogen at the same time as herbicide application, which would improve operational efficiencies. This will reduce possible corn nitrogen deficiencies due to delayed winter rye termination, decrease the number of passes across the field, decrease labor costs, and decrease the potential for soil compaction. However, there are concerns that the application of UAN as a carrier applied to the rye leaf surface without a urease inhibitor or incorporation could result in considerable nitrogen losses through volatilization (Keller and

Mengel 1986). Ultimately, glyphosate mixtures with rimsulfuron, mesotrione, or rimsulfuron + mesotrione for winter rye termination would increase the spectrum of weed control, provide residual control of certain annual grass and broadleaf species, and reduce the selection pressure for the evolution of herbicide-resistant weeds.

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