Weed Technology

www.cambridge.org/wet

Interseeded annual ryegrass, oilseed radish, and crimson clover tolerance to residual herbicides commonly used in corn

Aaron P Brooker[1], Christy L Sprague[2] and Karen A Renner[2]

[1]Graduate Research Assistant, Department of Plant, Soil and Microbial Sciences, Michigan State University, East Lansing, MI, USA and [2]Professor, Department of Plant, Soil and Microbial Sciences, Michigan State University, East Lansing, MI, USA

Research Article

Cite this article: Brooker AP, Sprague CL, Renner KA (2020) Interseeded annual ryegrass, oilseed radish, and crimson clover tolerance to residual herbicides commonly used in corn. Weed Technol. **34**: 35–41. doi: 10.1017/wet.2019.90

Received: 17 May 2019
Revised: 29 July 2019
Accepted: 12 September 2019
First published online: 24 September 2019

Associate Editor:
David Johnson, Corteva Agriscience

Nomenclature:
acetochlor; atrazine; bicyclopyrone; bromoxynil; clopyralid; dicamba + diflufenzopyr; dimethenamid-P; flumetsulam; fluthiacet; glyphosate; isoxaflutole; mesotrione; rimsulfuron; saflufenacil; *S*-metolachlor; topramezone; annual ryegrass, *Lolium perenne* L. spp. *multiflorum* (Lam.) Husnot; corn, *Zea mays* L., crimson clover, *Trifolium incarnatum* L.; oilseed radish, *Raphanus sativus* L.

Keywords:
cover crops; residual herbicides

Author for correspondence:
Christy Sprague, Professor, Department of Plant, Soil and Microbial Sciences, Michigan State University, 1066 Bogue Street, East Lansing, MI 48824. Email: sprague1@msu.edu

Abstract

Cover cropping is limited by seasonal constraints following corn harvest in the Upper Midwest of the United States. Grass, clover, and brassica cover crops can be interseeded in corn; however, this is problematic because cover crops must tolerate herbicide applications to manage weeds. The objective of this research was to determine the tolerance of broadcast interseeded annual ryegrass, oilseed radish, and crimson clover to PRE and POST residual herbicide applications in corn. From 2016 to 2018 field trials were conducted in Michigan to determine the tolerance of annual ryegrass, oilseed radish, and crimson clover to 13 PRE and 14 POST (applied to V2 corn) herbicides. Cover crops were interseeded into corn at the V3 and V6 stages. Greenhouse experiments to evaluate these species were also conducted from 2016 to 2018; PRE and POST herbicides were applied at 1×, 0.5×, and 0.25× (0.25× was PRE only) of field-application rates. Based on these results, annual ryegrass can be interseeded into V3 or V6 corn following a PRE application of atrazine, clopyralid, saflufenacil, bicyclopyrone, isoxaflutole, or mesotrione, or a POST application of atrazine, bromoxynil, or mesotrione. Oilseed radish can be interseeded into V3 or V6 corn following a PRE application of clopyralid, atrazine, *S*-metolachlor, bicyclopyrone, or isoxaflutole or at V6 following application of acetochlor, dimethenamid-P, or mesotrione. Oilseed radish can also be interseeded following POST application of atrazine (571 g ai ha^{-1}), bromoxynil, fluthiacet, acetochlor, mesotrione, dicamba + diflufenzopyr, or dimethenamid-P + topramezone. In greenhouse trials, crimson clover was tolerant to rimsulfuron, saflufenacil, and pyroxasulfone applied PRE. Annual ryegrass and oilseed radish can be interseeded into corn at the V3 and V6 stages, but special attention must be given to cover crop species selection and herbicide label restrictions when following herbicide applications in corn.

Introduction

Diverse crop rotations improve crop productivity by enhancing soil health and resource use efficiency (McDaniel et al. 2014; Tiemann et al. 2015). Cover crops diversify crop rotations; however, only about 2% of agricultural hectares are seeded with cover crops (USDA-NASS 2019). Cover crops can increase the diversity in corn and soybean (*Glycine max* L. Merr.) rotations but adding cover crops can be difficult. In the Upper Midwest of the United States, limited time is available to establish a cover crop following corn grain and soybean harvest in the fall. Although winter cereals can be seeded following harvest, cover crop establishment and growth can be limited by the short growing season (Baker and Griffis 2009).

Interseeding cover crops into corn during the early vegetative growth stage gives farmers an option to establish a cover crop in a grain corn rotation (CTIC 2017). Although interseeding is not a new practice, a variety of cover crops have been interseeded into corn, including annual ryegrass, crimson clover (Belfry and Van Eerd 2016; Curran et al. 2018; Grabber et al. 2014; Zhou et al. 2000), and oilseed radish (Belfry and Van Eerd 2016; Roth et al. 2015). Farmers reported that grasses are currently the best cover crop choice for interseeding (51%), followed by clovers (14%) and radish (10%) (CTIC 2017).

In previous research, residual herbicides reduced cover crop establishment and growth when the cover crops were seeded in late summer or fall. In Arkansas, PRE applications of atrazine, fluridone, and pyrithiobac reduced biomass of fall-seeded crimson clover by 30%, 30%, and 33%, respectively, and atrazine and fluridone reduced the biomass of fall-seeded rapeseed by 20% and 22%, respectively (Palhano et al. 2018). Oilseed radish that had been seeded 3 mo after imazethapyr application demonstrated up to 65% injury in Ontario, Canada (Yu et al. 2015). In Missouri, the biomass of fall-seeded annual ryegrass was reduced by 67% after pyroxasulfone application; other herbicides reduced establishment of crimson clover (Cornelius and Bradley 2017). In Pennsylvania, pyroxasulfone and *S*-metolachlor caused reductions of 80% and 86%, respectively, in the biomass of annual ryegrass interseeded

Table 1. Corn planting and cover crop interseeding dates for each site year from 2016 to 2018.

	Preemergence experiment		
Site year[a]	Corn planted	V3 interseeded	V6 interseeded
MSUAF 2016	May 17	June 3	June 22
MSUAF 2017	May 23	June 15	June 23
MSUAF 2018	June 4	June 21	July 15
SVREC 2018	May 9	June 5	June 19
Springport 2016	May 21	June 8	
Springport 2017	May 31	June 19	June 29
Springport 2018	May 26	June 14	June 21
	Postemergence experiment[b]		
Site year	Corn planted	V3 interseeded	V6 interseeded
MSUAF 2017	May 23	June 17	June 25
MSUAF 2018	May 8	June 1	June 15
SVREC 2018	May 9	June 5	June 19
Springport 2018	May 26	June 14	June 21

[a]Abbreviations: MSUAF, Michigan State University Agronomy Farm, East Lansing, Michigan; SVREC, Saginaw Valley Research and Extension Center, Richville, Michigan.
[b]Postemergence herbicides were applied on the same day of V3 interseeding, except at the MSUAF 2017 site year, where herbicides were applied 1 d prior to the V3 interseeding.

into corn at the V5 growth stage (Abendroth et al. 2011), and red clover biomass was reduced by up to 98% by mesotrione applications (Wallace et al. 2017).

The body of research on cover crop tolerance to herbicides is limited to a few cover crop species, soil types, and climatic regions, and very little research has been conducted for cover crops interseeded within zero to 5 wk following a residual herbicide application. Currently, there is no peer-reviewed information on the tolerance of cover crops interseeded into corn at V2 to V3 growth stages following POST herbicide applications. Research is needed to support recommendations on cover crop seeding timing in relation to herbicide application timing. The objectives of this research were to evaluate the effects of PRE- and POST-applied herbicides on annual ryegrass, crimson clover, and oilseed radish establishment when interseeded into corn at the V3 and V6 growth stages.

Materials and Methods

Field Experiments

Field experiments to study PRE herbicide applications were conducted in 2016, 2017, and 2018 at the Michigan State University Agronomy Farm (MSUAF) in East Lansing, Michigan (42.7107° N, 84.4714°W), at an on-farm location in Springport, Michigan (42.3564°N, 84.6889°W), and in 2018 only at the Saginaw Valley Research and Extension Center (SVREC) in Richville, Michigan (42.2998°N, 84.6975°W) for a total of 7 site-years (Table 1). POST herbicide field experiments were conducted in 2017 and 2018 at MSUAF and in 2018 in Springport and SVREC for a total of 4 site-years. Soils at MSUAF included a Conover loam (fine-loamy, mixed, active, mesic Aquic Hapludalfs) in 2016 and 2018 and a Riddles-Hillsdale sandy loam (fine-loamy, mixed, active, mesic Typic Hapludalfs; coarse-loamy, mixed, active, mesic Typic Hapludalfs) in 2017. Soils at SVREC were a Tappan-Londo loam (fine-loamy, mixed, active, calcareous, mesic Typic Epiaquolls; fine-loamy, mixed, semiactive, mesic Aeric Glossaqualfs). Soils at Springport were a Riddles sandy loam (fine-loamy, mixed, active, mesic Typic Hapludalfs) each year. At MSUAF, soil pH ranged from 5.6 to 6.2 and soil organic matter (SOM) ranged from 1.8% to 3.3%. Soil pH was 7.5 and SOM was 3.0% at SVREC. Springport soil pH ranged from 5.9 to 6.2, and SOM ranged from 1.6% to 1.8%. The experimental design for PRE and POST experiments was a strip-plot with four replications with cover crop species interseeded in strips of corn at both V3 and V6 stages with herbicides applied in strips perpendicular to cover crop planting.

Tillage at MSUAF included chisel plowing to a 20-cm depth in the fall and soil finishing to a 10-cm depth in the spring. A total of 187 kg N ha^{-1} was applied just prior to planting. At SVREC, a disc-ripper (Kuhn North America, Inc. Broadhead, WI) (20-cm depth) was used in the fall followed by use of a Triple K soil finisher (Kongskilde Agriculture, Albertslund,Denmark) (10-cm depth) in the spring. Prior to spring tillage 157 kg N ha^{-1} was applied. No-tillage was used at Springport and 193 kg N ha^{-1} was applied. Phosphorus and potassium were applied following soil test recommendations at all locations, and no insecticides or fungicides were applied. Glyphosate-resistant corn was planted in May or early June depending on the site year in 76-cm rows (Table 1). Corn maturity was 92 d at the MSUAF and SVREC sites, and between 96 and 99 d at the Springport sites. Seeding depths ranged from 3.8 to 5.0 cm and seeding rate was 79,000 seeds ha^{-1} at MSUAF and SVREC and 74,100 seeds ha^{-1} at Springport. Glyphosate was applied prior to corn planting and just prior to interseeding into corn at V3 and V6.

Cover crop species included one species each of grass, legume, and brassica. Annual ryegrass ('Tillage Rootmax'), crimson clover, and oilseed radish ('Tillage') (Center Seeds, Sydney, OH, in 2016 and 2017 and LaCrosse Seed, LaCrosse, WI, in 2018) were broadcast interseeded into corn at V3 and V6 at 18, 18, and 9 kg ha^{-1}, respectively. At MSUAF and SVREC, cover crops were interseeded using a hand-spreader. At Springport, a 36-row vacuum-powered custom-built interseeder (Hasenick Brothers, LLC., Springport, MI) with drop tubes between corn rows was used to interseed. Interseeding dates varied by site year and occurred from mid-May to early July depending on the corn planting date and corn development stage (Table 1). Herbicides at all locations were applied using a custom-built tractor-mounted compressed air sprayer at 178 L ha^{-1} and 207 kPa with TeeJet AIXR11003 nozzles (TeeJet Technologies, Wheaton, IL). In the PRE experiment, herbicides were sprayed 1 to 2 days after corn planting in 3-m strips perpendicular to corn rows. At MSUAF and SVREC, cover crops were interseeded in 3-m (four corn rows) strips in the direction of corn planting resulting in 9-m^2 plots. At Springport, cover crops were interseeded in 27-m (36 corn rows) strips in the direction of corn planting resulting in 3×27-m^2 plots. In the POST experiment, herbicides were applied to corn at the V2 to V3 stage in the direction of corn planting. POST herbicides were applied on the same day as the V3 cover crop interseeding except in 2017 at MSUAF, when herbicides were applied 1 d prior to the V3 interseeding. Cover crops were interseeded perpendicular to corn rows at MSUAF and SVREC, and in the direction of corn rows at Springport. All herbicides examined in the PRE and POST experiments are listed in Table 2. A no-herbicide control was included for each cover crop species in both experiments. Plots were visually evaluated for cover crop stand reduction following corn harvest in October. Evaluations were carried out between the second and third corn rows of each plot at MSUAF and SVREC. At Springport, three to four evaluations were carried out along the entire length of each plot. Cover crop injury was evaluated as a percentage of stand reduction compared with the no-residual-herbicide control plots, which were given a value of 0% stand reduction.

https://doi.org/10.1017/wet.2019.90 Published online by Cambridge University Press

Table 2. PRE and POST herbicide common name, application timings, herbicide sites of action (SOA), and field use rates applied in the field and greenhouse experiments from 2016 to 2018.

Common name	Trade name	Application timing	SOA	Rate (g ai ha^{-1})
Flumetsulam	Python[a]	PRE	2	56
Rimsulfuron	Resolve SG[a]	PRE	2	22
Clopyralid	Stinger[a]	PRE	4	105
Atrazine	AAtrex[b]	PRE, POST (0.5×, 1×)[g]	5	1,120, 571, 1,120
Saflufenacil	Sharpen[c]	PRE	14	75
Acetochlor	Harness[d], Warrant[d]	PRE, POST	15	2,455, 1,262
Dimethenamid-P	Outlook[c]	PRE	15	942
Pyroxasulfone	Zidua[c]	PRE	15	179
S-metolachlor	Dual II Magnum[e]	PRE	15	1,424
Bicyclopyrone	comp. of Acuron[e]	PRE	27	50
Isoxaflutole	Balance Flexx[d]	PRE	27	105
Mesotrione	Callisto[e]	PRE, POST	27	210, 105
Bromoxynil	Buctril[d]	POST	6	421
Fluthiacet	Cadet[f]	POST	14	1.7
Tembotrione	Laudis[d]	POST	27	92
Topramezone	Armezon[c]	POST	27	18
Mesotrione + atrazine	–	POST (0.5×)[g]	27 + 5	105 + 285
Mesotrione + atrazine	–	POST (1×)[g]	27 + 5	105 + 509
Dicamba + diflufenzopyr	Status[c]	POST	4 + 19	140 + 56
Dimethenamid-P + topramezone	Armezon PRO[c]	POST	15 + 27	920 + 17
Thiencarbazone + tembotrione	Capreno[d]	POST	2 + 27	27 + 77
S-metolachlor + mesotrione + glyphosate	Halex GT[e]	POST	15 + 27 + 9	1,068 + 105 + 1,042

[a]Corteva Agriscience, Wilmington, DE, https://www.corteva.com
[b]Land O'Lakes, Inc., Arden Hills, MN, https://www.landolakesinc.com
[c]BASF Corporation, Florham Park, NJ, https://www.basf.com
[d]Bayer CropScience LP, St. Louis, MO, https://www.cropscience.bayer.com
[e]Syngenta International AG, Basel, Switzerland, https://www.syngenta.com
[f]FMC Corporation, Philadelphia, PA, http://www.fmc.com
[g]Applied at different field use rates as indicated.

Greenhouse Experiment

The effects of PRE and POST herbicides on cover crop biomass were also evaluated in a greenhouse. The evaluation consisted of a three-factor experiment arranged in a randomized complete block design with four replications and repeated two times. The three factors were cover crop species, herbicide active ingredient, and herbicide rate. The soil used for this experiment was a steam-sterilized, sandy loam field soil with a pH of 7.4 and 3% SOM collected near Charlotte, Michigan (42.5656°N, 84.8356°W). Square, 100-cm^2 × 13-cm depth pots were filled with soil and saturated with water. Sixteen seeds of a single cover crop species were seeded on the soil surface in each pot. A thin layer (<5 mm) of soil was applied over the cover crop seeds to avoid directly applying herbicides to the seeds. Herbicides were applied the same day as seeding using a single-nozzle pressurized air spray chamber (Allen Manufacturing, Midland, MI) at 178 L ha^{-1} and 207 kPa with a TeeJet 8001E nozzle. Each herbicide was applied at 1×, 0.5×, and 0.25× the field-use rates for the PRE experiment and 1× and 0.5× the field-use rates for the POST experiment. Reduced application rates were used to simulate herbicide degradation prior to cover crop seeding in the field. Following herbicide application, pots were surface watered using a light mist to ensure adequate moisture for germination without displacing seeds. For the remainder of the experiment, pots were individually subirrigated to reduce herbicide leaching and prevent movement to other pots. Cover crop species, seed source, and herbicides used were the same as those in the field studies. At 28 d after planting, the aboveground biomass of cover crops growing in each pot was harvested, dried at 27 C for at least 3 d, and weighed.

Statistical Analysis

Field experiment data were combined over site years and analyzed using the MIXED procedure in SAS 9.4 (SAS Institute Inc., Cary, NC). Cover crop species, interseeding timing, and herbicide were considered fixed effects; and replication, site-year, and replication within site-year were considered random effects. Analyses were conducted to determine differences in stand reduction for each herbicide by cover crop species combination. Comparisons of least square means at $P \leq 0.05$ were made if *F* tests were significant ($P \leq 0.05$) using the SAS pdmix800 macro (Saxton 1998).

Greenhouse experiment data were combined over the two experiment times for the PRE and POST experiments. Cover crop biomass data for the POST-applied herbicides were analyzed using the MIXED procedure in SAS 9.4. Cover crop species, herbicide, and herbicide rate were considered fixed effects. Experiment time and replication within experiment time were considered random effects. Analyses were conducted to determine differences in dry biomass comparing each herbicide × herbicide rate within each cover crop species with the no-herbicide control. Means were compared using the same methods as in the field experiment data. For the PRE-applied herbicides, biomass as a percent of the control was plotted against the application rates with the LL.3 three-parameter log-logistic model using the DRC package in R (R Core Team 2018) (Equation 1) to determine herbicide rates that would cause 10% and 50% biomass reduction. Ten percent biomass reduction was chosen as a level that a farmer may find acceptable. Fifty percent reduction was used to indicate an unacceptable amount of biomass reduction and herbicides that should not be used with certain cover crops. A three-parameter model provided the best fit for the number of rates used. For dose response curves that did not fit the LL.3 model, the three-parameter log-logistic Weibull model (Equation 2) was used. This occurred only for positive dose response curves, where biomass of herbicide treatments was similar to or more than the no-herbicide control. The effective dose (ED) function determined the point on the line where

https://doi.org/10.1017/wet.2019.90 Published online by Cambridge University Press

Table 3. Annual ryegrass and oilseed radish stand reduction (%) caused by PRE herbicides in the field experiment.

Herbicide	Site of action	Annual ryegrass[a]	Oilseed radish[b]	
		V3 + V6	V3	V6
		Stand reduction (%)[c]		
Flumetsulam	2	46*	74*	100*
Rimsulfuron	2	33*	73*	74*
Clopyralid	4	6	12	29
Atrazine	5	8	13	18
Saflufenacil	14	4	23	36*
Acetochlor	15	67*	44*	7
Dimethenamid-P	15	71*	28	6
Pyroxasulfone	15	86*	48*	41*
S-metolachlor	15	68*	27	9
Bicyclopyrone	27	7	6	16
Isoxaflutole	27	6	28	16
Mesotrione	27	17*	56*	15
No herbicide		0	0	0
±SEM[d]		(± 8)	(± 10)	(± 10)

[a]Annual ryegrass data are combined across site years and the V3 and V6 interseeding timings.
[b]Oilseed radish data were combined over site years.
[c]Treatment means followed by an asterisk (*) indicates significantly reduced cover crop stand compared with the no-herbicide control at α = 0.05 within each column using Fisher's least significant difference test.
[d]Standard error of the mean.

Table 4. Annual ryegrass and oilseed radish stand reduction (%) caused by POST herbicides in the field experiment.[a]

Treatment	Site of action	Annual ryegrass	Oilseed radish
		Stand reduction (%)[b]	
Atrazine (571 g ha^{-1})	5	14	20
Atrazine (1120 g ha^{-1})	5	12	34*
Bromoxynil	6	13	11
Fluthiacet	14	26*	19
Acetochlor	15	91*	24
Mesotrione	27	9	18
Tembotrione	27	60*	37*
Topramezone	27	76*	44*
Mesotrione + atrazine (285 g ha^{-1})	27 + 5	16	59*
Mesotrione + atrazine (509 g ha^{-1})	27 + 5	23*	60*
Dicamba + diflufenzopyr	4 + 19	48*	31
Dimethenamid-P + topramezone	15 + 27	76*	4
Thiencarbazone + tembotrione	2 + 27	87*	47*
S-metolachlor + mesotrione + glyphosate	15 + 27 + 9	92*	41*
No herbicide		0	0
±SEM[c]		(±9)	(±12)

[a]Data are combined across site years and the V3 and V6 interseeding timings.
[b]Treatment means followed by an asterisk (*) significantly reduced cover crop stand compared with the no herbicide control within each column at α = 0.05 using Fisher's least significant difference test.
[c]Standard error of the mean.

a certain application rate resulted in 10% and 50% biomass reduction (R Core Team 2018; Ritz et al. 2015). For the LL.3 model, $f(x)$ = biomass reduction, x = herbicide rate, c = lower limit, b = slope of the curve, and e = rate at specified biomass reduction (i.e., 10% or 50%). For the Weibull model, $f(x)$ = biomass reduction, x = herbicide rate, b = slope of the curve, and e = rate at specified biomass reduction. We did not determine ED values for POST herbicides because only two rates were evaluated in the greenhouse.

$$f(x) = \frac{100 - c}{1 + \exp(b(\log(x) - \log(e)))} \quad [1]$$

$$f(x) = d(\exp(-\exp(b(\log(x) - e)))) \quad [2]$$

Results and Discussion

Annual Ryegrass

The time of annual ryegrass interseeding did not affect the response to herbicides in the PRE and POST field experiments (Tables 3 and 4); therefore, data were combined over the V3 and V6 interseeding timings. In the PRE field experiment, annual ryegrass stand was reduced by more than 60% after application of Group 15 herbicides (Mallory-Smith and Retzinger 2003) (Table 3). The Group 2 herbicides, flumetsulam and rimsulfuron, caused moderate stand reductions. In the greenhouse experiment, annual ryegrass biomass was reduced by 50% at rates less than field-use rates of acetochlor, dimethenamid-P, and pyroxasulfone (Table 5). Rimsulfuron, atrazine, *S*-metolachlor, and isoxaflutole when applied at rates less than the field-use rate resulted in a 10% reduction in annual ryegrass biomass (Table 5). Conversely, clopyralid, saflufenacil, and bicyclopyrone could be used at the field-use rates without significant biomass or stand reduction (Tables 3 and 5). In the POST field experiment, application of acetochlor, dimethenamid-P + topramezone, thiencarbazone + tembotrione, *S*-metolachlor + mesotrione + glyphosate, and topramezone reduced annual ryegrass stands by 75% or more (Table 4). Atrazine (571 and 1,120 g ha^{-1}), bromoxynil, mesotrione, and mesotrione + atrazine (285 g ha^{-1}) applications did not reduce annual ryegrass stand compared with the no-herbicide control. In the greenhouse experiment, only dimethenamid-P + topramezone and *S*-metolachlor + mesotrione + glyphosate reduced annual ryegrass biomass relative to the no-herbicide control at the 0.5× and 1× application rates, whereas acetochlor reduced annual ryegrass biomass at the 1× rate only (Table 6).

In both the field and greenhouse experiments, acetochlor, dimethenamid-P, pyroxasulfone, and *S*-metolachlor applications resulted in reduced annual ryegrass stand and biomass. Additionally, application of acetochlor and premixes containing Group 15 herbicides applied POST to V2 to V3 corn also resulted in losses of annual ryegrass stand and biomass. Group 15 herbicides control many grass-weed species (Shaner 2014), and pyroxasulfone is specifically noted for controlling annual ryegrass (Hulting et al. 2012); however, unlike our results, Wallace et al. (2017) reported that annual ryegrass could be interseeded in corn at the V5 stage following PRE application of dimethenamid-P or acetochlor. Wallace et al. (2017) also reported that annual ryegrass could be interseeded into V5 corn following PRE application of the Group 2 herbicide rimsulfuron. That result differs from our results in which the Group 2 herbicides flumetsulam and rimsulfuron caused intermediate reductions in annual ryegrass stand and biomass. It is not clear why these results differ, but climate and soil types may have resulted in differences. Mesotrione caused a 17% stand reduction in the field compared with the no-herbicide control; which may be acceptable if weeds are controlled (Table 3).

Oilseed Radish

In the PRE field experiment, the Group 2 herbicides flumetsulam and rimsulfuron caused the greatest reduction (>70%) in oilseed radish stand at both interseeding timings (Table 3). When oilseed radish was interseeded into corn at the V3 stage, applications of mesotrione, pyroxasulfone, and acetochlor also resulted in reduced stands, whereas at the V6 stage, pyroxasulfone and saflufenacil were the only other herbicides that caused a reduced stand compared with

https://doi.org/10.1017/wet.2019.90 Published online by Cambridge University Press

Table 5. PRE herbicide rates to cause 10% biomass reduction (BR_{10}) and 50% biomass reduction (BR_{50}) using Equations 1 and 2 in the text to annual ryegrass, oilseed radish, and crimson clover in the greenhouse from 2016 to 2018.

Herbicide	Site of action	Field use rate	Annual ryegrass		Oilseed radish		Crimson clover	
			BR_{10}	BR_{50}	BR_{10}	BR_{50}	BR_{10}	BR_{50}
		g ai ha^{-1}	% of field use rate[a]					
Flumetsulam	2	56	>100	>100	18.3	>100	0.05	>100
Rimsulfuron	2	22	74.0	>100	>100	>100	89.3	>100
Clopyralid	4	105	>100	>100	>100	>100	13.9	77.4
Atrazine	5	1,120	24.6	>100	20.0	86.1	1.9	7.7
Saflufenacil	14	75	>100	>100	0.04	>100	86.3	>100
Acetochlor	15	2,455	5.0	11.4	96.0	>100	0.3	7.8
Dimethenamid-P	15	942	3.0	9.3	0.01	>100	18.6	55.5
Pyroxasulfone	15	179	15.5	28.1	79.9	>100	88.5	>100
S-metolachlor	15	1,424	0.8	>100	>100	>100	1.7	24.2
Bicyclopyrone	27	50	>100	>100	>100	>100	0.01	>100
Isoxaflutole	27	105	79.6	>100	0.9	>100	81.0	93.8
Mesotrione	27	210	>100	>100	19.3	91.4	0.01	>100

[a]Rate of herbicide sprayed as a fraction of the field use rate.

Table 6. Annual ryegrass, oilseed radish, and crimson clover aboveground biomass reduction caused by postemergence (POST) herbicides in the greenhouse.

Herbicide	Site of action	Rate[a]	Annual ryegrass	Oilseed radish	Crimson clover
			Aboveground biomass (g pot^{-1})[b]		
Atrazine (571 g ha^{-1})	5	0.5	0.49	1.25	0.23
		1	0.55	1.31	0.17*
Atrazine (1,120 g ha^{-1})	5	0.5	0.45	1.08	0.14*
		1	0.62	1.30	0.09*
Bromoxynil	6	0.5	0.71	1.45	0.36
		1	0.62	1.29	0.46
Fluthiacet	14	0.5	0.77	1.34	0.36
		1	0.73	1.42	0.49
Acetochlor	15	0.5	0.38	1.28	0.49
		1	0.30*	1.36	0.48
Mesotrione	27	0.5	0.59	1.14	0.39
		1	0.51	1.12	0.29
Tembotrione	27	0.5	0.52	1.28	0.43
		1	0.51	1.19	0.31
Topramezone	27	0.5	0.56	1.30	0.39
		1	0.67	1.50	0.42
Mesotrione + atrazine (285 g ha^{-1})	27 + 5	0.5	0.57	0.86	0.38
		1	0.67	1.23	0.42
Mesotrione + atrazine(509 g ha^{-1})	27 + 5	0.5	0.68	1.12	0.37
		1	0.49	1.17	0.37
Dicamba + diflufenzopyr	4 + 19	0.5	0.58	1.03	0.21
		1	0.35	1.27	0.14*
Dimethenamid-P + topramezone	15 + 27	0.5	0.31*	1.45	0.28
		1	0.24*	1.21	0.14*
Thiencarbazone + tembotrione	2 + 27	0.5	0.47	1.35	0.28
		1	0.55	1.04	0.23
S-metolachlor + mesotrione + glyphosate	15 + 27 + 9	0.5	0.15*	1.26	0.22
		1	0.11*	1.13	0.11*
No herbicide			0.63	1.56	0.34
±SEM[c]			(±0.20)	(±0.83)	(±0.14)

[a]Rate of herbicide sprayed as a fraction of the 1× rate.
[b]Treatment means followed by an asterisk (*) indicates significantly reduced cover crop biomass compared with the no-herbicide control within each column at $\alpha = 0.05$ using Fisher's least significant difference test.
[c]Standard error of the mean.

the no-herbicide control. In the greenhouse study, atrazine and mesotrione were the only PRE herbicides that caused a 50% reduction in oilseed radish biomass at rates that were less than field-use rates (Table 5). Herbicides applied PRE that reduced oilseed radish biomass by 10% at rates lower than field-use rates included atrazine, mesotrione, isoxaflutole, acetochlor, dimethenamid-P, flumetsulam, saflufenacil, and pyroxasulfone (Table 5). In the POST field experiment, the time of interseeding did not affect oilseed radish response to herbicides applied POST to V2 to V3 corn; therefore, data were combined over interseeding timings (Table 4). Applications of atrazine (1,120 g ha^{-1}), tembotrione, topramezone, mesotrione + atrazine (571 and 1,120 g ha^{-1}), thiencarbazone + tembotrione, and *S*-metolachlor + mesotrione + glyphosate all resulted in unacceptable oilseed radish stands. In the greenhouse study, none of the herbicides applied POST resulted in reduced oilseed radish biomass compared with the no-herbicide control (Table 6); however, slight

https://doi.org/10.1017/wet.2019.90 Published online by Cambridge University Press

bleaching symptoms (<10%) were observed when any of the Group 27 herbicides (mesotrione, tembotrione, or topramezone) were applied (data not shown).

Oilseed radish can be interseeded into corn at the V3 or V6 growth stages following PRE application of clopyralid, *S*-metolachlor, or bicyclopyrone. In the field experiments, atrazine and isoxaflutole also did not reduce oilseed radish stand, but when these herbicides were applied in the greenhouse experiment closer to oilseed radish seeding, at least 10% biomass reduction occurred. Atrazine has been used for decades in Michigan, and research has shown that atrazine degrades rapidly in soils where it has been frequently applied (Mueller et al. 2017). Additionally, isoxaflutole degradation is accelerated in biologically active soils (Taylor-Lovell et al. 2002). Greenhouse soils in this experiment were sterilized, so degradation was likely slowed. Delaying oilseed radish interseeding until corn is at the V6 growth stage may reduce injury and biomass reduction if acetochlor, dimethenamid-P, or mesotrione are applied. In this experiment, there was variability in oilseed radish injury following a saflufenacil application, with more injury occurring at V6 compared with V3; Yu et al. (2015) found that fall-seeded oilseed radish was not injured by saflufenacil + dimethenamid-P. Seeding oilseed radish at either V3 or V6 following an application of saflufenacil likely causes some stand reduction, but this may be acceptable if weeds are controlled. Oilseed radish can be interseeded into V3 or V6 corn following POST applications of atrazine (571 g ha^{-1}), bromoxynil, fluthiacet, acetochlor, mesotrione, dicamba + diflufenzopyr, and dimethenamid-P + topramezone. Oilseed radish has not been used frequently in other interseeding research; however, research in Missouri where cover crops were seeded in September following PRE and POST applications of flumetsulam, isoxaflutole, rimsulfuron, and topramezone showed they could cause stand loss and biomass reduction of greater than 30% (Cornelius and Bradley 2017), so these herbicides also have the potential to cause injury and stand reduction in an interseeded system.

Crimson Clover

Crimson clover emergence in the field studies was very poor because it was intolerant of dry conditions following broadcast interseeding in all experimental site-years, so no data are presented. In the greenhouse experiment, PRE application of clopyralid, atrazine, acetochlor, dimethenamid-P, *S*-metolachlor, and isoxaflutole caused a 50% biomass reduction at less than 1× field-use rates (Table 5). POST application of atrazine (1,120 g ha^{-1}) at 1× and 0.5× caused crimson clover biomass to be reduced by as much as 66% relative to the no-herbicide control (Table 6). Dicamba + diflufenzopyr, dimethenamid-P + topramezone, and *S*-metolachlor + mesotrione + glyphosate application also resulted in reduced crimson clover biomass, but at the 1× rate only (Table 6).

Other researchers have shown successful establishment of crimson clover when it has been drill-interseeded in corn (Abdin et al. 1998; Belfry and Van Eerd 2016; Curran et al. 2018); therefore, the results of the greenhouse experiment could be useful in drill-interseeded systems where crimson clover may have better establishment. Our greenhouse experiment results suggest that crimson clover may be interseeded following PRE application of rimsulfuron, saflufenacil, and pyroxasulfone, and POST application of bromoxynil, fluthiacet, tembotrione, and topramezone. Conflicting results between the tolerance of crimson clover in the PRE and POST experiments with acetochlor and mesotrione suggest that crimson clover tolerance with these two herbicides should be further examined. These greenhouse results can be used to provide a starting point for further examination of interseeded crimson clover tolerance to PRE and POST herbicide applications.

Based on these results, annual ryegrass, crimson clover, and oilseed radish can be interseeded into corn following PRE and POST applications of herbicides with residual activity; however, cover crop species and herbicide combinations should be chosen to prevent cover crop injury, biomass reduction, and stand loss. Additional herbicide label restrictions need to be followed if cover crops will be used for feed or forage. Herbicide activity and cover crop performance may differ between conventional till and no-till management practices. These combinations will be selected based on the weeds that need to be managed and the goals of establishing a cover crop. Annual ryegrass can be interseeded into corn at the V3 or V6 growth stages following PRE application of atrazine, clopyralid, saflufenacil, bicyclopyrone, isoxaflutole, or mesotrione, and POST application of atrazine, bromoxynil, or mesotrione. Oilseed radish can be interseeded into corn at the V3 or V6 growth stage following PRE application of clopyralid, atrazine, *S*-metolachlor, bicyclopyrone, or isoxaflutole and following POST application of acetochlor, dimethenamid-P, or mesotrione at V6. Oilseed radish can also be interseeded into V3 or V6 corn following POST application of atrazine (571 g ha^{-1}), bromoxynil, fluthiacet, acetochlor, mesotrione, dicamba + diflufenzopyr, or dimethenamid-P + topramezone. Oilseed radish should not be interseeded following PRE application of flumetsulam or POST application of atrazine (1,120 g ha^{-1}) or mixtures containing atrazine. Crimson clover did not establish in this experiment and we do not recommend this species for broadcast interseeding; however, our greenhouse results suggest that crimson clover could be successfully interseeded following PRE application of rimsulfuron, saflufenacil, or pyroxasulfone, and POST application of bromoxynil, fluthiacet, tembotrione, or topramezone. Crimson clover should not be interseeded following PRE application of atrazine, *S*-metolachlor, or acetochlor, or POST application of atrazine (1,120 g ha^{-1}). Additional in-field research should be conducted to confirm these results. Annual ryegrass and oilseed radish can be interseeded in a mixture following PRE application of clopyralid or bicyclopyrone, and POST application of bromoxynil or mesotrione. Additionally, this mixture could be interseeded following PRE application of atrazine or isoxaflutole and POST application of atrazine (571 g ha^{-1}), but some stand reduction is expected. Farmers must consider weed control and cover crop goals when making these decisions, and some level of cover crop injury may be acceptable to achieve optimal weed control.

Acknowledgments. The Michigan Corn Marketing Program and Michigan State University's Project GREEEN provided funding for this project. No conflicts of interest have been declared. We thank Gary Powell and Brian Stiles for technical expertise and assistance with plot planting and maintenance. We also thank Center Seeds for donation of cover crop seeds used in the project in 2016 and 2017.

References

Abendroth LJ, Elmore RW, Boyer MJ, Marlay SK (2011) Corn growth and development. Ames: Iowa State University Extension Publication PMR 1009

Abdin O, Coulman BE, Cloutier D, Faris MA, Zhou X, Smith DL (1998) Yield and yield components of corn interseeded with cover crops. Agron J 90:63–68

Baker JM, Griffis TJ (2009) Evaluating the potential use of winter cover crops in corn soybean systems for sustainable co-production of food and fuel. Agric For Meteorol 149:2120–2132

Belfry KD, Van Eerd LL (2016) Establishment and impact of cover crops intersown into corn. Crop Sci 56:1245–1256

[CTIC] Conservation Technology Information Center (2017) Report of the 2016–2017 national cover crop survey. West Lafayette, IN: Conservation Technology Information Center, Sustainable Agriculture Research and Education Program, and the American Seed Trade Association. https://www.ctic.org/files/2017CTIC_CoverCropReport-FINAL. Accessed: January 28, 2019

Cornelius CD, Bradley KW (2017) Carryover of common corn and soybean herbicides to various cover crop species. Weed Technol 31:21–31

Curran WS, Hoover RJ, Mirsky SB, Roth GW, Ryan MR, Ackroyd VJ, Wallace JM, Dempsey MA, Pelzer CJ (2018) Evaluation of cover crops drill interseeded into corn across the Mid-Atlantic region. Agron J 110:435–443

Grabber JH, Jokela WE, Lauer JG (2014) Soil nitrogen and forage yields of corn grown with clover or grass companion crops and manure. Agron J 106:952–961

Hulting AG, Dauer JT, Hinds-Cook B, Curtis D, Koepke-Hill RM, Mallory-Smith C (2012) Management of Italian ryegrass (*Lolium perenne* spp. *multiflorum*) in Western Oregon with preemergence applications of pyroxasulfone in winter wheat. Weed Technol 26:230–235

Mallory-Smith CA, Retzinger EJ (2003) Revised classification of herbicides by site of action for weed resistance management strategies. Weed Technol 17:605–619

McDaniel MD, Tiemann LK, Grandy AS (2014) Does agricultural crop diversity enhance soil microbial biomass and organic matter dynamics? A meta-analysis. Ecol Applic 24:560–570

Mueller TC, Parker ET, Steckel L, Clay SA, Owen MDK, Curran WS, Currie R, Scott R, Sprague C, Stephenson DO, Miller DK, Prostko EP, Grichar WJ, Martin J, Kruz LJ, *et al.* (2017) Enhanced atrazine degradation is widespread across the United States. Pest Manag Sci 73:1953–1961

Palhano MG, Norsworthy JK, Barber T (2018) Sensitivity and likelihood of residual herbicide carryover to cover crops. Weed Technol 32:236–243

R Core Team (2018) R: A Language and Environment for Statistical Computing. Vienna, Austria: R Foundation for Statistical Computing. https://www.R-project.org/. Accessed: January 8, 2019

Ritz C, Baty F, Streibig JC, Gerhard D (2015) Dose-response analysis using R. PLOS ONE 10(12). e0146021

Roth G, Curran W, Wallace J, Ryan M, Mirsky S (2015) Cover crop interseeder: improving the success in corn. Beltsville, MD: USDA-ARS Sustainable Agricultural Systems Laboratory. https://extension.psu.edu/cover-crop-interseeder-improving-the-success-in-corn. Accessed: January 28, 2019

Saxton AM (1998) A macro for converting mean separation output to letter groupings in Proc Mixed. Pages 1243–1246 *in* Proceedings of the 23rd SAS Users Group International. Nashville, TN: SAS Users Group International.

Shaner DL (2014) Herbicide Handbook, 10th Edition. Lawrence, KS: Weed Science Society of America.

Taylor-Lovell S, Sims GK, Was LM (2002) Effects of moisture, temperature, and biological activity on the degradation of isoxaflutole in soil. J Agric Food Chem 50:5626–5633

Tiemann LK, Grandy AS, Atkinson EE, Marin-Spiotta E, McDaniel MD (2015) Crop rotational diversity enhances belowground communities and functions in an agroecosystem. Ecol Lett 18:761–771

[USDA-NASS] United States Department of Agriculture National Agricultural Statistics Service (2019) 2017 United States Summary and State Data. Volume 1. Geographic Area Series. Part 51. http://www.agcensus.usda.gov/Publications/2012/Full_Report/Volume_1,_Chapter_1_US/usv1.txt. Accessed: July 13, 2019

Wallace JM, Curran WS, Mirsky SB, Ryan MR (2017) Tolerance of interseeded annual ryegrass and red clover cover crops to residual herbicides in Mid-Atlantic corn cropping systems. Weed Technol 31:641–650

Yu L, Van Eerd LL, O'Halloran I, Sikkema PH, Robinson DE (2015) Response of four fall-seeded cover crops to residues of selected herbicides. Crop Prot 75:11–17

Zhou X, Madramootoo CA, MacKenzie AF, Kaluli JW, Smith DL (2000) Corn yield and fertilizer N recovery in water-table-controlled corn-rye-grass systems. Eur J Agron 12:83–92