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Influence of Cereal Rye Termination Timing on Residual Herbicide Efficacy in No-Till Corn

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Abstract

Field experiments were conducted in 2017-2018 and 2018-2019 at three locations in Indiana to assess weed suppression by cereal rye and residual herbicide premixes in no-till corn. Cereal rye biomass ranged from 540 to 3700 kg ha^{-1} when terminated in late April and early May. When cereal rye termination was delayed until corn planting in mid-May to mid-June, cereal rye biomass ranged from 1710 to 6200 kg ha^{-1}. Early-season weed biomass was suppressed 27 to 84% by cereal rye residue in three of five site-years. Early-season weed biomass reduction by a residual herbicide premix was similar whether applied to cereal rye or non-cover crop treatments in four of five site-years. In one site-year, weed biomass reduction by a residual herbicide premix was 16% greater when applied to cereal rye compared to non-cover crop ground. Weed biomass decreased by approximately 12% for every 1000 kg ha^{-1} of additional cereal rye or wheat biomass, and peak weed biomass suppression was estimated to occur at 8000 kg ha^{-1} of cover crop biomass. Corn yield was similar in all treatments in all but one site-year, when a 57% yield reduction from cereal rye was observed in 2018 due to corn stand reduction from cereal rye competition. Overall, cereal rye did not reduce residual herbicide efficacy regardless of herbicide application timing.

Keywords

Cover crop residue, herbicide application timing

Weed interference in corn was estimated to have caused $3.8 billion in yield loss annually from 2007 to 2013 in the United States and Canada [1]. Worldwide, 259 weed species have evolved resistance to at least one mode of action, and several species have developed resistance to multiple herbicide sites of action [2]. Since dependence on only one weed control method may lead to herbicide-resistant weed infestations, multiple strategies should be used to manage weeds and protect crop yields [3, 4]. Integrated weed management (IWM) strategies that reduce selection pressure for herbicide resistance include tillage, diversified crop rotations, biological controls, harvest weed seed destruction, and cover crops [5].

Common herbicide-resistant weeds in corn and soybean production in the Eastern Corn Belt include waterhemp (*Amaranthus tuberculatus* (Moq.) J. D. Sauer), horseweed (*Erigeron canadensis* L.), and giant ragweed (*Ambrosia trifida* L.). Herbicide resistance to at least two herbicide sites of action groups has been documented in all of these weeds [2]. Herbicide resistance to nine herbicide modes of action used in corn production has been reported among these species in the United States [2]. Glyphosate-resistant giant ragweed, horseweed, and waterhemp populations have been reported in corn across the Eastern Corn Belt, which increases the need for alternative weed management practices such as cover crops [2].

According to the USDA Census of Agriculture, cover cropped farmland increased from 10.3 to 15.4 million acres from 2012 to 2017 [6]. In Indiana from 2011 to 2018, cover cropped corn acres rose from 2 to 8% of total acres [7]. Rapid cover crop adoption occurred from 2011 to 2015 in Indiana, but acreage has decreased slightly since then. Total cover crop acreage in Indiana in 2018 was 400,000 acres or 4% of total farmland [7]. In a national survey of cover crop users, 69% of growers had observed improved control of herbicide-resistant weeds after using cereal rye as a cover crop, even though there is very little published research to support this result [8].

Diversification of crop rotations can contribute to summer annual and winter annual weed management [9-12]. Reference [13] showed that changes in weed density in diversified crop rotations were due primarily to changes in cultural and herbicide weed management strategies for each crop in the rotation. Integrating winter cover crops into summer crop rotations will alter weed management practices in summer annual crops. Attention to residual herbicide rotational intervals will be important for fall cover crop establishment. Weed suppression by cover crop biomass could allow growers to delay postemergence herbicide applications. Reference [14] demonstrated that cereal rye reduces the average size of horseweed (*Erigeron canadensis* L.) and decreases the variability in horseweed size, which could increase control by appropriately timed applications of foliar herbicides. Summer annual weed biomass suppression in corn has also been reported by others [15, 16]. The impacts of any cover crop in corn on the weed community are dependent the cover crop biomass and composition of the weed community. Reference [17] determined that common lambsquarters (*Chenopodium album* L.) and witchgrass (*Panicum capillare* L.) density were more sensitive than velvetleaf (*Abutilon theophrasti* Medik.) and dandelion to increasing amounts of cereal rye biomass. Reference [18] reported that a cereal rye cover crop in continuous no-till corn reduced weed species diversity compared to a no-cover crop control. Therefore, integrating cereal rye into crop rotations may result in overall weed seedbank reductions, but could also alter the composition of the weed community.

Above-ground cover crop biomass can prevent soil residual herbicides from reaching the soil upon application [19]. If adequate precipitation or irrigation is not received to wash the herbicide off of the residue, weed control may be reduced. Reference [20] observed that after a atrazine application to wheat residue, 40% of the applied atrazine had reached the soil, but after 50 mm of precipitation, over 90% of the herbicide was found in the soil. Reference [15] observed no difference in weed control when metolachlor was applied to wheat residue in Nebraska, and that at every rate of *S*-metolachlor, weed biomass and density decreased as wheat biomass increased from 0 to 6800 kg ha^{-1}, with 30 to 36 cm of precipitation within one month of herbicide application. Residual herbicides and cover crop residues appear to be compatible for overall weed control with proper management, even if some amount of residual herbicide is initially retained by the cover crop residue [15, 19- 22].

Information is currently lacking on the effect of cover crops on late-season weed suppression in corn. Additionally, the effects of cereal rye on giant ragweed have not been reported. While several studies in the Eastern Corn Belt have reported early season weed suppression by cereal rye in corn, additional research is needed to evaluate the efficacy of various application timings of residual herbicides in cereal rye. The objective of this experiment was to evaluate the weed suppressive ability of cereal rye throughout the growing season, as well as the compatibility of residual herbicides with cereal rye in no-till corn. We hypothesize that cereal rye will reduce early-season weed biomass and density, but will not decrease late-season weed biomass and density but not late-season biomass or density. We also hypothesize that weed control by a residual herbicide premix will be similar in cereal rye and non-cover crop treatments.

1. Materials and Methods

1.1 Experimental Design

No-till corn field studies were conducted in 2017 through 2018 and 2018through 2019 at three locations in Indiana. The locations were Throckmorton Purdue Agricultural Center [TPAC, (8343 US-231, Lafayette, IN 47909) (40.29 N, -86.91 W)], Davis Purdue Agricultural Center [DPAC, (6230 N State Rd 1 Farmland, IN 47340) (40.26 N, -85.15 W)], and Southeast Purdue Agricultural Center [SEPAC, (4425 Country Rd 350 N Butlerville, IN 47223) (39.03 N, -85.53 W)]. Information regarding corn planting, herbicide applications, and data collections for all site-years is shown in Table 1. The experiment was a split-split-plot randomized complete block design. Main plots were cover crop treatment, which was fall-planted cereal rye or non-cover crop. Subplots were blocked within main plots and consisted of two termination timings, which were two weeks before corn planting (early) or at corn planting (at plant). Due to prolonged spring precipitation in 2019 that prevented field operations and corn planting, early terminations were made 5 to 6 weeks before corn planting. Sub-subplots were randomized within subplots and consisted of four herbicide strategies (Table 2).

Cereal rye (Elbon™, Cisco, Indianapolis, IN 46219) (103 kg ha^{-1}) was planted in the fall of 2017 and 2018 in one of the two main plots, with the other main plot left fallow until corn planting in the spring of the following year. The following spring, all plots were planted with SmartStax™ corn, (DKC62-08RIB, Dekalb®, St. Louis, MO 63118) spaced 76 cm apart in mid-May 2018. Due to wet weather in the spring of 2019, planting was delayed until early- to mid-June at TPAC and DPAC in 2019, and abandonment of the SEPAC location in 2019. Starter fertilizer at a rate of 34 kg N ha^{-1}, 45 kg N ha^{-1}, and 45 kg N ha^{-1} was applied at TPAC, DPAC, and SEPAC, respectively. A side dress fertilizer application of 28% UAN was made near the V6 growth stageat rates of 159 kg N ha^{-1}, 166 kg N ha^{-1}, and 183 kg N ha^{-1} at

TPAC, DPAC, and SEPAC, respectively.

Table 1. Calendar dates for each event at each site. Cereal rye was planted at 103 kg ha^{-1} and terminated the following spring using glyphosate. Two weed collections were made: one before the POST herbicide application which occurred 2 to 4 WAP and one before corn harvest[a,b,c]

	DPAC		SEPAC[c]	TPAC	
Event	2018	2019	2018	2018	2019
Cover crop planting	10/23/2017	10/22/2018	10/7/2017	10/4/2017	10/3/2018
Cover crop early termination	5/5/2018	5/6/2019	4/30/2018	4/26/2018	4/24/2019
Cover crop at-plant termination	5/19/2018	6/15/2019	5/14/2018	5/10/2018	6/12/2019
Corn planting	5/19/2018	6/15/2019	5/14/2018	5/10/2018	6/11/2019
Weed biomass collection 2-4 WAP	6/20/2018	7/12/2019	6/4/2018	6/15/2018	6/25/2019
POST herbicide application	6/20/2018	7/13/2019	6/5/2018	6/16/2018	6/25/2019
Weed biomass collection prior to corn harvest	-[b]	-[b]	9/23/2018	9/18/2018	10/4/2019

[a] Abbreviations: DPAC = Davis Purdue Agricultural Center (6230 N State Rd 1 Farmland, IN 47340) (40.26 N, -85.15 W), SEPAC = Southeast Purdue Agricultural Center (4425 Country Rd 350 N Butlerville, IN 47223) (39.03 N, -85.53 W), TPAC = Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909) (40.29 N, -86.91 W), CC = cover crop, POST = postemergence herbicide application.

[b] Weed biomass was not collected at DPAC in Fall 2018 and 2019 due to near complete weed control in all treatments.

[c] The experiment was not carried out at SEPAC in 2019 because of prolonged spring precipitation that led to excessive soil moisture, preventing corn planting at an ideal date.

Table 2. Herbicides applied for four different herbicide strategies. All herbicides were applied using a CO_2-pressurized backpack sprayer[a]

Herbicide strategy	At cover crop termination[b]		POST[c]	
	Active Ingredient	Rate	Active Ingredient	Rate
Reduced Herbicide	glyphosate[d]	1.54 kg ae ha^{-1}	dicamba[e]	0.14 kg ae ha^{-1}
			diflufenzopyr[e]	0.056 kg ai ha^{-1}
			glyphosate	1.54 kg ae ha^{-1}
Preplant residual	atrazine[f]	1.58 kg ai ha^{-1}	dicamba	0.14 kg ae ha^{-1}
	bicyclopyrone[f]	0.04 kg ai ha^{-1}	diflufenzopyr	0.056 kg ai ha^{-1}
	glyphosate	1.54 kg ae ha^{-1}	glyphosate	1.54 kg ae ha^{-1}
	mesotrione[f]	0.16 kg ai ha^{-1}		
	S-metolachlor[f]	1.43 kg ai ha^{-1}		
POST residual	glyphosate	1.54 kg ae ha^{-1}	atrazine[g]	1.82 kg ai ha^{-1}
			dicamba	0.14 kg ae ha^{-1}
			diflufenzopyr	0.056 kg ai ha^{-1}
			glyphosate	1.54 kg ae ha^{-1}
			S-metolachlor[g]	0.35 kg ai ha^{-1}
Preplant + POST residual	atrazine	1.58 kg ai ha^{-1}	atrazine	1.82 kg ai ha^{-1}
	bicyclopyrone	0.04 kg ai ha^{-1}	dicamba	0.14 kg ae ha^{-1}
	glyphosate	1.54 kg ae ha^{-1}	diflufenzopyr	0.056 kg ai ha^{-1}
	mesotrione	0.16 kg ai ha^{-1}	glyphosate	1.54 kg ae ha^{-1}
	S-metolachlor	1.43 kg ai ha^{-1}	S-metolachlor	0.35 kg ai ha^{-1}

[a] Abbreviations: POST = postermergence herbicide application.

[b] Cereal rye was either terminated two weeks before planting or at the time of corn planting. In 2019, corn planting was delayed due to wet weather, which also delayed the at-plant cereal rye termination.

[c] The POST application was made 2 to 4 weeks after corn planting at each site. For each site, all POST applications were made on the same day.

[d] Roundup Powermax®, Bayer, St. Louis, MO.

[e] Status®, BASF, Triangle Park, NC.

[f] Acuron®, Syntenta, Greensboro, NC.

[g] Bicep II Magnum®, Syngenta, Greensboro, NC.

The sub-subplots were herbicide strategies, and included two herbicide applications for all treatments: one applied at the termination of the cereal rye and winter annual weeds, and another applied as a post-emergence (POST) application 2 to 5 weeks after corn planting. The four different herbicide strategies were: 1) no residual, with no residual herbicides applied at termination or at POST, 2) preplant residual, with a residual herbicide premix applied at termination followed by a POST application with no residual herbicide, 3) POST residual, which consisted of a non-residual herbicide applied at termination, followed by a residual herbicide premix applied at POST, and 4)preplant + POST residual, with a residual herbicide premix included at both the termination application and at the POST application. Glyphosate (Roundup Powermax®, Bayer, St. Louis, MO 63141) was applied to all treatments at termination. Glyphosate + dicamba + diflufenzopyr (Status®, BASF, Triangle Park, NC 27560) were applied at the POST application. The residual herbicide premix applied at termination contained atrazine + S-metolachlor + mesotrione + bicyclopyrone (Acuron®, Syngenta, Wilmington, DE 19810). The residual herbicide premix applied at the POST application contained atrazine + *S*-metolachlor (Bicep II Magnum®, Syngenta, Triangle Park 27560). All herbicide applications were made with a CO_2-pressurized backpack sprayer using XR 110015 nozzles (TeeJet Technologies, Urbandale, IA 50322) for herbicide mixtures not containing dicamba. For treatments containing dicamba, TTI 11002 nozzles were used (TeeJet Technologies, Urbandale, IA 50322). A carrier volume of 140 L ha^{-1} was used to apply all herbicides.

1.2 Data Collection

Two weed biomass evaluations were made during the growing season at each site-year: early-season and late-season (Table 1). Predominant weed species at each site are shown in Table 3. For both early- and late-season evaluations, weeds from a 0.25 m^2 area in the front and back of the plot were collected. Cover crop biomass was collected at cover crop termination by removing above-ground biomass from a 0.25 m^2 area from each sub-subplot before termination (Table 4). All weed and cover crop biomass samples were oven-dried at 60 C for 48 hours before weighing.

Early-season weed biomass was evaluated for the dominant weed species at each site-year two to five weeks after corn planting which occurred just before the POST herbicide application. Biomass was summed over all species collected and is shown in Table 5. Summer annual grasses were evaluated at the site-years TPAC 2018, TPAC 2019, DPAC 2019, and SEPAC 2018. Giant ragweed was evaluated at TPAC in 2018 and 2019. Waterhemp was evaluated at DPAC in 2018 and 2019. Common cocklebur and morningglory species were evaluated at SEPAC in 2018.

Late-season weed biomass was evaluated in mid-September to early October. Weed biomass was collected and summed over all dominant weed species, and is shown in Table 6. Summer annual grasses were evaluated at TPAC in 2018 and 2019. Common cocklebur was evaluated at SEPAC in 2018. No late-season evaluations were made at DPAC in either year because high levels of weed control resulted in very few weeds in all plots.

The middle two corn rows of each sub-subplot were harvested with a plot combine once physiological maturity was reached (Table 7). Weight and grain moisture levels were recorded and standardized to 15.5% moisture.

Table 3. Weed species evaluated at each site[a,b]

Site	Common name	Scientific name
TPAC	giant ragweed	*Ambrosia trifida* L.
	barnyardgrass	*Echinochloa crus-galli (L.) P. Beauv.*
	fall panicum	*Panicum dichotomiflorumMichx.*
	giant foxtail	*SetariafaberiHerrm.*
	large crabgrass	*Digitariasanguinalis (L.) Scop.*
	yellow foxtail	*Setaria pumila (Poir.) Roem. &Schult.*
DPAC	waterhemp	*Amaranthus tuberculatus*
	barnyardgrass[b]	*Echinochloa crus-galli (L.) P. Beauv.*
	giant foxtail[b]	*SetariafaberiHerrm.*
	yellow foxtail[b]	*Setaria pumila (Poir.) Roem. &Schult.*
SEPAC	common cocklebur	*Xanthium strumarium*L.
	ivyleaf morningglory	*Ipomoea hederacea* Jacq.
	pitted morningglory	*Ipomoea lacunosa*L.
	barnyardgrass	*Echinochloa crus-galli (L.) P. Beauv.*
	fall panicum	*Panicum dichotomiflorumMichx.*
	giant foxtail	*SetariafaberiHerrm.*
	yellow foxtail	*Setaria pumila (Poir.) Roem. &Schult.*

[a] Abbreviations: DPAC = Davis Purdue Agricultural Center (6230 N State Rd 1 Farmland, IN 47340) (40.26 N, -85.15 W), SEPAC = Southeast Purdue Agricultural Center (4425 Country Rd 350 N Butlerville, IN 47223) (39.03 N, -85.53 W), TPAC = Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909) (40.29 N, -86.91 W) [b] Only present in 2019.

Table 4. Cover crop biomass at early and at-plant terminations for each site-year [a,b,c]

Year	Site	Early	At-plant	P-value
		kg ha^{-1}		
2018	TPAC	1260 b	3400 a	<0.001
	DPAC	1120 b	1710 a	<0.001
	SEPAC	3700 b	7080 a	<0.001
2019	TPAC	1300 b	6200 a	<0.001
	DPAC	540 b	2130 a	<0.001
	SEPAC	-[d]	-[d]	

[a] Abbreviations: TPAC = Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909) (40.29 N, -86.91 W),DPAC = Davis Purdue Agricultural Center (6230 N State Rd 1 Farmland, IN 47340) (40.26 N, -85.15 W),SEPAC = Southeast Purdue Agricultural Center (4425 Country Rd 350 N Butlerville, IN 47223) (39.03 N, -85.53 W)

[b] Early termination was made two weeks before corn planting in 2019 and 4 to 5 weeks before corn planting in 2019. At-plant termination was made on the day of corn planting.

[c] Untransformed data are shown for clarity. Letters following values indicate statistical significance of log-transformed means within each year according to Tukey's HSD ($P \leq 0.05$).

[d] SEPAC 2019 was eliminated from the dataset as prolonged spring precipitation and wet soils prevented timely corn planting.

Table 5. Early-season weed biomass for each site-year at2 to 5 weeks after corn planting and just before the POST herbicide' application. Data were pooled over 1 to 7 dominant species depending on location[a,b]

			2018			2019		
Termination	Cover	Termination	TPAC[d]	DPAC[e]	SEPAC[f]	TPAC[d]	DPAC[e]	SEPAC[g]
			g m^{-2}					
Early	Pooled	Pooled	18.6 a	20.0	14.7 a	83.3 a	126.9 a	-
At-plant			4.5 b	17.9	2.4 b	2.7 b	20.3 b	-
		P-value	<0.001	0.177	<0.001	<0.001	<0.001	-
Pooled	None	Pooled	15.0	22.6	14.6 a	49.8 a	76.6	-
	Cereal rye		8.1	16.2	2.6 b	36.2 b	70.6	-
		P-value	0.605	0.269	0.005	0.023	0.453	-
Pooled	Pooled	gly	20.9 a	39.8 a	15.9 a	67.2 a	101.5 a	-
		gly + residual	2.2 b	0.0 b	1.2 b	16.8 b	45.7 b	-
		P-value	<0.001	<0.001	<0.001	<0.001	<0.001	-
Pooled	None	gly	27.5 a	45.2 a	27.4 a	76.6 a	106.3 a	-
		gly + residual	2.6 b	0.0 b	1.6 b	23.1 b	46.9 b	-
	Cereal rye	gly	14.3 a	33.4 a	4.4 b	61.8 a	96.6 a	-
		gly + residual	2.0 b	0.0 b	0.8 b	10.6 c	44.5 b	-
		P-value	0.009	0.025	0.018	0.025	0.002	-
Early	Pooled	gly	34.3 a	42.6	27.6 a	133.2 a	166.9 a	-
		gly + residual	3.0 c	0.0	1.7 bc	33.4 b	86.8 b	-
At-plant		gly	7.6 b	37.7	4.1 b	5.2 c	36.0 c	-
		gly + residual	1.5 c	0.0	0.8 c	0.3 d	4.6 d	-
		P-value	0.008	0.144	<0.001	<0.001	<0.001	-
Early	None	Pooled	24.5	24.2	24.7	96.8	128.4	-
	Cereal rye		12.8	24.8	4.6	67.8	125.3	-
At-plant	None		5.3	20.9	4.4	2.9	24.4	-
	Cereal rye		3.5	14.8	0.5	2.6	15.7	-
		P-value	0.959	0.385	0.686	0.536	0.518	-

Early	None	gly	45.2	48.6	47.3	147.9	164.9 a	-
		gly + residual	3.8	0.0	2.1	45.8	92.0 b	-
	Cereal rye	gly	23.3	36.7	8.1	120.6	169.0 a	-
		gly + residual	2.2	0.0	1.2	21.0	81.6 b	-
At-plant	None	gly	9.8	41.9	7.5	5.4	47.7 b	-
		gly + residual	1.3	0.0	1.3	0.5	1.9 d	-
	Cereal rye	gly	5.3	29.5	0.6	5.2	24.2 c	-
		gly + residual	1.7	0.0	0.3	0.1	7.3 d	-
		P-value	0.975	0.521	0.681	0.805	0.001	-

[a] Abbreviations: TPAC = Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909) (40.29 N, -86.91 W), DPAC = Davis Purdue Agricultural Center (6230 N State Rd 1 Farmland, IN 47340) (40.26 N, -85.15 W), SEPAC = Southeast Purdue Agricultural Center (4425 Country Rd 350 N Butlerville, IN 47223) (39.03 N, -85.53 W), gly = glyphosate.

[b] Letters following values denote statistical significance of log-transformed data in each column according to Tukey's HSD ($P \leq 0.05$). Untransformed data are shown for clarity.

[c] Herbicides were applied 5 to 6 weeks before collection in 2018, and 6 to 7 weeks before collection in 2019, due to prolonged wet weather that delayed corn planting. Residual herbicide premix contains atrazine, bicyclopyrone, mesotrione, and *S*-metolachlor.

[d] Weed species at TPAC in 2018 and 2019 include giant ragweed, barnyardgrass, fall panicum, giant foxtail, and yellow foxtail.

[e] In 2018, waterhemp was the only weed collected at DPAC. Barnyardgrass, giant foxtail, and yellow foxtail, and waterhemp were collected in 2019.

[f] Weed species collected at SEPAC in 2018 include barnyardgrass, common cocklebur giant foxtail, horseweed, morningglory spp. and yellow foxtail.

[g] SEPAC 2019 was eliminated from the data set as prolonged spring precipitation and excessive soil moisture prevented timely corn planting.

Table 6. Late-season weed biomass. Data were pooled over 1 to 4 species depending on location[a,b]

			2018		2019	
Termination	Cover Crop	Herbicide Strategy[c]	TPAC	SEPAC	TPAC	SEPAC[d]
			g m^{-2}			
Early	Pooled	Pooled	1.9	8.2 b	6.5 a	-
At-plant			1.0	87.4 a	1.3 b	-
		P-value	0.072	0.002	<0.001	-
Pooled	None	Pooled	1.7	8.8 b	4.1	-
	Cereal rye		1.2	87.2 a	3.7	-
		P-value	0.856	0.016	0.843	-
Pooled	Pooled	NR	4.6 a	57.9	7.3 a	-
		PRE-R	1.0 b	56.8	1.6 b	-
		POST-R	0.1 bc	20.6	6.6 a	-
		PRE-POST-R	0.1 c	56.4	0.0 c	-
		P-value	<0.001	0.733	<0.001	-
Early	None	Pooled	2.1	3.6	5.0	-
	Cereal rye		1.6	14.0	8.0	-
At-plant	None		1.3	13.2	2.5	-
	Cereal rye		0.7	160.8	0.1	-
		P-value	0.768	0.496	0.143	-
Early	Pooled	NR	5.4 a	7.9	10.3 a	-
		PRE-R	1.8 b	6.1	3.0 b	-
		POST-R	0.1 c	14.6	12.4 a	-
		PRE-POST-R	0.1 c	5.1	0.3 c	-
At-plant	Pooled	NR	3.7 ab	107.9	4.3 bc	-
		PRE-R	0.1 c	107.6	0.2 c	-
		POST-R	0.2 c	26.5	0.9 c	-
		PRE-POST-R	0.1 c	107.7	0.0 c	-
		P-value	<0.001	0.565	0.002	-

Pooled	None	NR	5.0	16.3	7.6	-
		PRE-R	1.5	4.4	2.3	-
		POST-R	0.1	12.4	5.1	-
		PRE-POST-R	0.1	2.2	0.0	-
	Cereal rye	NR	4.2	99.6	7.0	-
		PRE-R	0.4	109.3	0.9	-
		POST-R	0.1	28.7	8.2	-
		PRE-POST-R	0.0	110.5	0.1	-
		P value	0.699	0.741	0.528	-
Early	None	NR	5.2	1.1	6.8 a	-
		PRE-R	2.9	1.6	4.3 abc	-
		POST-R	0.0	8.5	8.4 a	-
		PRE-POST-R	0.2	2.4	0.5 bc	-
	Cereal rye	NR	5.6	13.8	13.7 a	-
		PRE-R	0.8	10.6	1.7 ab	-
		POST-R	0.1	20.7	16.4 a	-
		PRE-POST-R	0.0	7.8	0.1 bc	-
At-plant	None	NR	4.7	30.5	8.4 abc	-
		PRE-R	0.1	7.2	0.2 bc	-
		POST-R	0.2	16.3	1.8 bc	-
		PRE-POST-R	0.1	2.1	0.0 bc	-
	Cereal rye	NR	2.7	185.3	0.3 bc	-
		PRE-R	0.1	208.1	0.2 bc	-
		POST-R	0.1	36.4	0.0 c	-
		PRE-POST-R	0.0	213.3	0.0 bc	-
		P-value	0.647	0.550	0.026	-

[a] Abbreviations: TPAC = Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909) (40.29 N, -86.91 W), DPAC = Davis Purdue Agricultural Center (6230 N State Rd 1 Farmland, IN 47340) (40.26 N, -85.15 W), SEPAC = Southeast Purdue Agricultural Center (4425 Country Rd 350 N Butlerville, IN 47223) (39.03 N, -85.53 W), gly = glyphosate, residual = residual herbicide premix, NR = no residual, PP-R = preplant residual, POST-R = POST residual, PP-POST-R = preplant + POST residual.

[b] Weeds were not evaluated at DPAC due to scarcity of weeds. Untransformed means are shown in the table. Letters following values denote statistical significance of log-transformed means in each column, according to Tukey's HSD (*P*≤0.05).

[c] The residual herbicide premix is described in Table 2 and contains atrazine, bicyclopyrone, mesotrione, and *S*-metolachlor.

[d] SEPAC in 2019 was eliminated from the study, as prolonged spring precipitation and wet soils prevented timely corn planting.

Table 7. Corn yield at each site-year

Termination	Cover	Herbicide	2018			2019		
			TPAC	DPAC	SEPAC	TPAC	DPAC[d]	SEPAC[d]
			kg ha^{-1}					
Early	Pooled	Pooled	16517	12185	7523 a	13010 b	-	-
At-plant			16434	11866	6652 b	14822 a	-	-
		P-value	0.777	0.428	0.033	0.013	-	-
Pooled	None	Pooled	16876	11727	9831 a	13263	-	-
	Cereal rye		16076	12324	4245 b	14569	-	-
		P-value	0.051	0.250	<0.001	0.103	-	-
Pooled	Pooled	NR	16509	11377	6626	12725	-	-
		PRE-R	15921	12415	8282	15295	-	-
		POST-R	16678	11868	6866	11865	-	-
		PRE-POST-R	16795	12441	6576	15779	-	-
		P-value	0.067	0.061	0.679	<0.001	-	-

Early	None	Pooled	16899	11829	9825	12098	-	-
	Cereal rye		16853	11624	9836	14428	-	-
At-plant	None		16135	12540	5221	13922	-	-
	Cereal rye		16016	12108	3468	15215	-	-
		P-value	0.902	0.602	0.101	0.443	-	-
Early	Pooled	NR	16247	10933	6878	10577 b	-	-
		PRE-R	16169	12812	9235	15430 a	-	-
		POST-R	16657	12377	6986	10297 b	-	-
		PRE-POST-R	16996	12617	6994	15737 a	-	-
At-plant		NR	16771	11821	6373	14872 a	-	-
		PRE-R	15674	12019	7329	15161 a	-	-
		POST-R	16698	11358	6747	13433 a	-	-
		PRE-POST-R	16595	12266	6159	15821 a	-	-
		P-value	0.431	0.175	0.945	0.002	-	-
Pooled	None	NR	16838	11754	9040	11987	-	-
		PRE-R	16520	11483	12355	14602	-	-
		POST-R	17318	11641	9293	10595	-	-
		PRE-POST-R	16828	12028	8635	15869	-	-
	Cereal rye	NR	16179	11000	4211	13462	-	-
		PRE-R	15323	13348	4209	15988	-	-
		POST-R	16038	12094	4440	13134	-	-
		PRE-POST-R	16763	12854	4519	15690	-	-
		P value	0.269	0.384	0.596	0.373	-	-
Early	None	NR	16468	11458	8695	9716	-	-
		PRE-R	16768	11682	13455	14406	-	-
		POST-R	17751	12047	8487	8507	-	-
		PRE-POST-R	16610	12130	8662	15764	-	-
	Cereal rye	NR	16026	10408	9386	11439	-	-
		PRE-R	15570	13942	11254	16454	-	-
		POST-R	15563	12707	10099	12087	-	-
		PRE-POST-R	17381	13103	8607	15710	-	-
At-plant	None	NR	17208	12049	5061	14258	-	-
		PRE-R	16272	11284	5014	14799	-	-
		POST-R	16885	11235	5484	14684	-	-
		PRE-POST-R	17045	11926	5326	15973	-	-
	Cereal rye	NR	16333	11593	3361	15486	-	-
		PRE-R	15075	12754	3404	15523	-	-
		POST-R	16512	11480	3395	14182	-	-
		PRE-POST-R	16145	12605	3712	15670	-	-
		P-value	0.099	0.891	0.851	0.794	-	-

[a] Abbreviations: TPAC = Throckmorton Purdue Agricultural Center (8343 US-231, Lafayette, IN 47909) (40.29 N, -86.91 W), DPAC = Davis Purdue Agricultural Center (6230 N State Rd 1 Farmland, IN 47340) (40.26 N, -85.15 W), SEPAC = Southeast Purdue Agricultural Center (4425 Country Rd 350 N Butlerville, IN 47223) (39.03 N, -85.53 W), NR = no residual, PRE-R = preplant residual, POST-R = POST residual, PRE-POST-R = preplant + POST residual.

[b] To satisty statistical assumptions, data for SEPAC in 2018 were log-transformed. Untransformed data was analyzed for all other site-years. Untransformed data is shown for all site-years for clarity.

[c]Herbicide strategies are detailed in Table 2

[d]Data were compromised at DPAC in 2019, as the crop was damaged and improperly fertilized.

[e]SEPAC 2019 was eliminated from the dataset, since prolonged spring precipitation and wet soils prevented corn planting and other field operations.

1.3 Data analysis

Analysis of variance (ANOVA) was conducted using PROC GLIMMIX in SAS 9.4 (SAS, 100 SAS Campus Drive, Cary, NC 27513). Weed biomass and density data were log-transformed when appropriate to meet statistical assumptions. Untransformed data are shown in all tables and figures for clarity, while the statistical significance shown is of based on the log-transformed data to satisfy statistical assumptions. The variables termination timing and herbicide strategy were fixed effects, and cover crop treatment, as well as cover crop by replication and cover crop by replication by termination timing were set as random effects. A Satterthwaite denominator degree of freedom was utilized to produce an accurate approximation of F. Means were compared using Tukey's Honest Significant Difference (HSD) at a significance level of $\alpha = 0.05$. All site-years were analyzed individually due to significant site-year interactions.

2. Results and Discussion

2.1 Cereal Rye Biomass Before Termination

Termination timing was significant as a main effect in each site-year. Due to the late-October planting date at DPAC, cover crop biomass was not higher than 2200 kg ha^{-1} even in at-plant terminated plots. Delaying cereal rye termination until corn planting resulted in increased biomass for every site-year (Table 4).

In April and May of 2018, average monthly temperatures were 6.7 and 20 C, respectively. Compared to 30-year averages, April was 3 C cooler and May was 2.5 C warmer. Precipitation in April and May at all sites was within 2 cm of the 30-year average at all sites. Early terminations were performed two weeks before corn planting at all sites, and at-plant terminations were performed at corn planting. At the early termination timing in 2018, cereal rye biomass was 1260 kg ha^{-1} at TPAC, 1120 kg ha^{-1} at DPAC, and 3700 kg ha^{-1} at SEPAC. At-plant terminated cereal rye had higher biomass by 170% at TPAC, 53% at DPAC, and 91% at SEPAC compared to cereal rye biomass at the early termination (Table 4).

In 2019, spring precipitation was 4.5 to 7 cm above average through April and May at all sites. Average temperatures at all sites were within 1.5 C of 30-year averages. Early terminations were made 5 to 7 weeks before the at-plant terminations, due to the prolonged wet soil conditions that prevented field operations and corn planting. Cereal rye biomass at the early termination was 1300 kg ha^{-1} at TPAC and 540 kg ha^{-1} at DPAC. When terminated at corn planting, cereal rye biomass was 377% higher at TPAC and 294% higher at DPAC. Cereal rye biomass was not collected at SEPAC due to flooding and wet soils that prevented timely corn planting and other field operations.

Higher amounts of cereal rye biomass in at-plant terminations in 2019 compared to 2018 occurred because of delayed corn planting and later cover crop termination in 2019 relative to 2018. The lower biomass at DPAC was due to cereal rye planting that occurred on October 22nd and October 23rd, at least two weeks later than TPAC and SEPAC in both 2017 and 2018 (Table 1).

The cereal rye biomass at DPAC is comparable to biomass reported by [23] in Illinois, with similar planting and termination dates. At TPAC and SEPAC, cereal rye biomass in this experiment is similar to previously published studies with similar planting and termination dates [24-26]. Large differences in biomass were also observed from year to year, which is similar to other studies by [24-27]. Previous studies have shown no difference in cereal rye biomass from seeding rates of 56 to 210 kg ha^{-1} in Indiana, Illinois, Kentucky, Maryland, and Pennsylvania [26, 28].

The degree of weed suppression by cereal rye is dependent on the weed species that comprise the community and the cover crop biomass. Cereal rye biomass at 2200 kg ha^{-1}has been shown to reduce large crabgrass density by 49%, ivyleaf morningglory by 28%, and waterhemp by 41% compared to non-cover cropped plots [29]. Reference [17] evaluated weed suppression thresholds at varying levels of cover crop residue and found that common lambsquarters was suppressed 98% by cereal rye at 2000 kg ha^{-1}, witchgrass was suppressed 58% by 8500 kg ha^{-1}, and velvetleaf was suppressed 26% by 17000 kg ha^{-1}. Weed species that have a light requirement for germination are much more likely to be suppressed by cover crop residues than weed species without a light requirement [17].

A scatter plot of wheat and cereal rye cover crop biomass and weed biomass data from several studies, including the data from this manuscript, is shown in Figure 1. Cereal rye biomass in these previously published experiments ranged from 500 kg ha^{-1} to 9000 kg ha^{-1}, and weed biomass suppression was correlated with cereal rye biomass at termination, with a correlation coefficient of R = 0.57. Weed biomass decreased by approximately 12% for every 1000 kg ha^{-1} of additional cereal rye or wheat biomass, and peak weed biomass suppression was estimated to occur at 8000 kg ha^{-1} of cover crop biomass.

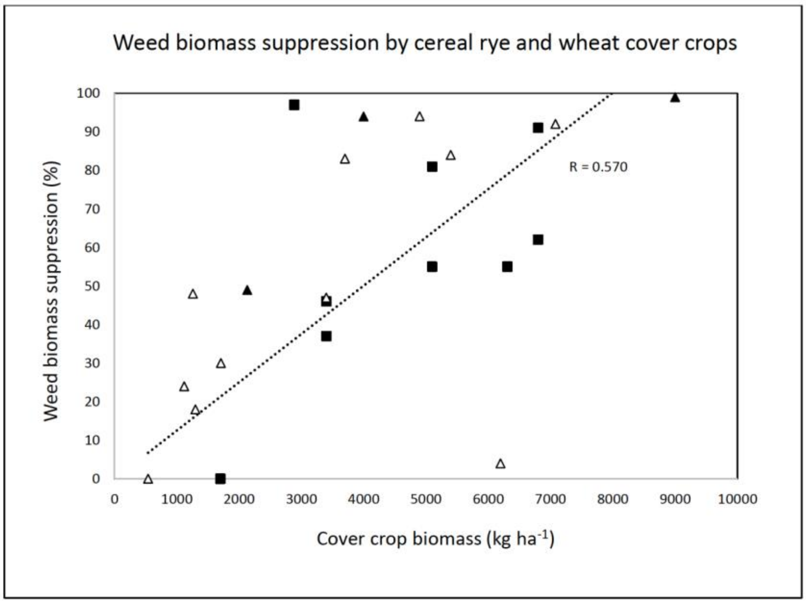

Figure 1. Weed biomass suppression by cereal rye and wheat cover crop residues in multiple studies. Data were taken from six studies and this study and plotted. Data were subjected to a regression analysis to determine an R value. Triangles represent data taken from studies carried out in Illinois, Indiana, and Michigan while square data points represent data taken from Nebraska. Unfilled symbols represent data taken from the research reported on in this manuscript, while filled symbols represent data taken from previously published research [15, 16, 28, 34, 35].

2.2 Early-Season Weed Biomass

Weed biomass collected two to five weeks after corn planting and before the POST herbicide application is shown in Table 5. In 2018, the interval between termination and biomass collection was between 35 and 48 days for early terminations and between 20 and 36 days for at-plant terminations. In 2019, the interval between termination and biomass collection was between 62 and 67 days for early terminations and between 13 and 27 days for at-plant terminations (Table 1). This prolonged period between the early termination and evaluation in 2019 allowed more weed emergence and growth, and for the residual herbicides to degrade after application. Since newly emerged weeds and weeds that had survived the application of the termination herbicide were collected, weed biomass from early terminated plots was greater in 2019 than 2018.

Weed biomass was suppressed by cereal rye three of five site-years (Table 5). Weed biomass was reduced more by residual herbicides than by cereal rye in all site-years, expect at SEPAC in 2018, where weed biomass in cereal rye treatments was similar to weed biomass in glyphosate plus residual treatments. The difference of weed suppression by cereal rye between locations and years has also been observed by [12, 24, 25], who all observed weed suppression in some site-years, but not others. While cereal rye seeding rate remained consistent throughout this experiment, increasing the rate would probably have resulted in lower weed biomass, as [26] and [30] reported increased weed suppression by increasing cereal rye seeding rate from 90 to 270 kg ha^{-1}, even though seeding rate above 90 kg ha^{-1} did not influence cover crop biomass.

Weed biomass reduction in glyphosate plus residual treatments was similar in cereal rye and non-cover crop plots four of five site-years, and different at TPAC in 2019, where weed biomass was lower in cereal rye. These results corroborate findings from previously published studies that have shown that residual herbicides can be integrated with cover crops without losing herbicide efficacy when cereal rye biomass is below 7000 kg ha^{-1} [15, 19, 21]

2.3 Late-Season Weed Biomass

Weed biomass in mid-September to early October was only evaluated at three site-years: TPAC 2018, SEPAC 2018, and TPAC 2019 (Table 6). Complete weed control was observed at DPAC in both years after the POST herbicide application, and therefore biomass was not evaluated.

The lowest weed biomass was observed in POST residual and PRE plus POST residual treatments in both termination timings, as well as PRE residual in at-plant terminations. Grass biomass was 78 to 98% lower in plots where any residual herbicide had been applied, regardless of termination timing, compared to the no residual treatments. In 2019, a three-way interaction between termination timing, herbicide strategy, and cover crop was significant. The highest weed biomass was observed in early terminated plots that did not receive the residual herbicide premix at termination. The higher weed biomass was probably due to the dense weed canopy in early terminated plots at the POST herbicide application, which intercepted herbicide and prevented a uniform distribution of residual herbicide applied with the POST herbicide treatment [19]. Previously published research has not evaluated late-season weed biomass in corn; however, other experiments performed in soybean production have demonstrated increased pre-harvest weed control by cover crops [31, 32].

2.4 Corn Yield

At TPAC in 2018, no significant differences in corn yield were observed and yield on average was 16400 kg ha^{-1} (Table 7). In 2019, a herbicide strategy by termination timing interaction was observed. Because of prolonged spring precipitation, and the prolonged gap between the early cereal rye termination and corn planting in 2019, weeds competed with and shaded corn prior to the POST application in early terminated treatments without a residual herbicide premix. This stunted the corn and delayed canopy closure at TPAC in 2019 in those treatments. Treatments that involved early termination without a residual herbicide averaged 10300 to 10500 kg ha^{-1}, while all other treatments ranged from 13400 to 15800 kg ha^{-1}. The highest yields were treatments that included a residual herbicide at termination and treatments that were terminated at corn planting.

At DPAC in 2018, no significant differences were observed in corn yield, and yield averaged 12000 kg ha^{-1}. In 2019, the side-dress application of fertilizer was improperly applied, and only half of the plots received fertilizer. Additionally, trampling and feeding damage from deer prevented accurate analysis.

At SEPAC in 2018, no interactions were significant, but termination timing and cover crop were significant. Corn yield at SEPAC without a cover crop was 9800 kg ha^{-1}, while a cereal rye cover crop reduced corn grain yield to 4300 kg ha^{-1}. Corn yield reduction was likely due to both cereal rye shading and physical suppression in the spring and early summer, and common cocklebur competition in the fall. The cereal rye residue at SEPAC delayed the corn canopy, which then allowed common cocklebur plants that emerged after the POST application to be more competitive with the corn.

The similarity in corn yield at DPAC and TPAC in 2018 in cereal rye and non-cover croptreatments is supported by a meta-analysis by [33] from published studies across the US and eastern Canada. In the meta-analysis, corn yield was shown to be generally unaffected by grass cover crops, as long as nitrogen fertilizer is applied.

Corn yield loss from cereal rye at SEPAC in 2018 may have been caused by shading and physical suppression from the cereal rye, since cereal rye biomass was larger at SEPAC in 2018 than other site-years. The amount of nitrogen fertilizer applied at SEPAC also may not have been sufficient to overcome the low nitrogen levels in cereal rye treatments, compared to the non-cover crop treatments. Additionally, a low soil organic matter content of 1.7% and high amounts of cover crop residue at SEPAC may have slowed nitrogen mineralization by soil microbes compared to TPAC and DPAC.

A residual herbicide premix applied at termination resulted in greater weed biomass suppression than cereal rye, and weed biomass reduction by a residual herbicide premix applied at termination was observed at every site-year. The variability of weed suppression by a cereal rye cover crop should caution growers to not rely solely on postemergence herbicides and cover crops for weed control, as reduced weed densities as a result of a cover crop were infrequently observed. Furthermore, early-season weed control by residual herbicides was not reduced by a cereal rye cover crop. Cereal rye alone did not suppress late-emerging summer annual weeds. Residual herbicides applied at cover crop termination and at POST did control late-emerging summer annual weeds. Residual herbicides are still a valuable tool for weed management in no-till corn cover crop systems, and still provide weed control when applied to living cover crops and cover crop residue. For this reason, it is important for cover crop growers to use residual herbicides in an IWM system. Terminating cereal rye at corn planting only decreased corn yield at SEPAC, however growers should be wary of delaying termination and should closely monitor cereal rye biomass well before corn planting, as yield loss may be substantial.

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Nomenclature

Cereal rye, *Secale cereale* L.; corn, *Zea mays* L.

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