Weed Technology

www.cambridge.org/wet

Utilizing cover crops for weed suppression within buffer areas of 2,4-D-resistant soybean

Connor L. Hodgskiss[1], Bryan G. Young[2], Shalamar D. Armstrong[3] and William G. Johnson[2]

[1]Graduate Research Assistant, Department of Botany and Plant Pathology, Purdue University, West Lafayette, IN, USA; [2]Professor, Department of Botany and Plant Pathology, Purdue University, West Lafayette, IN, USA and [3]Professor, Department of Agronomy, Purdue University, West Lafayette, IN, USA

Research Article

Cite this article: Hodgskiss CL, Young BG, Armstrong SD, Johnson WG (2022) Utilizing cover crops for weed suppression within buffer areas of 2,4-D-resistant soybean. Weed Technol. **36**: 118–129. doi: 10.1017/wet.2021.84

Received: 6 May 2021
Revised: 20 July 2021
Accepted: 22 September 2021
First published online: 4 October 2021

Associate Editor:
Prashant Jha, Iowa State University

Nomenclature:
Giant ragweed; *Ambrosia trifida* L.; waterhemp; *Amaranthus tuberculatus* (Moq.) Sauer; cereal rye; *Secale cereale* L.; soybean; *Glycine max* (L.) Merr.

Keywords:
Termination timing

Author for correspondence:
William G. Johnson, Department of Botany and Plant Pathology, Purdue University, West Lafayette, IN 47907. Email: WGJ@purdue.edu

Abstract

Cover crops can be utilized to suppress weeds via direct competition for sunlight, water, and soil nutrients. Research was conducted to determine if cover crops can be used in label-mandated buffer areas in 2,4-D-resistant soybean cropping systems. Delaying termination of cover crops containing cereal rye to at or after soybean planting resulted in a 25 to more than 200 percentage point increase in cover crop biomass compared to a control treatment. Cover crops generally improved horseweed control when 2,4-D was not used. Cover crops reduced grass densities up to 54% at four of six site-years when termination was delayed to after soybean planting. Cover crops did not reduce giant ragweed densities. Cover crops reduced waterhemp densities by up to 45%. Cover crops terminated at or after planting were beneficial within buffer areas for control of grasses and waterhemp, but not giant ragweed. Yield reductions of 14% to 41% occurred when cover crop termination was delayed to after soybean planting at three of six site-years. Terminating the cover crops at planting time provided suppression of grasses and waterhemp within buffer areas and had similar yield to the highest-yielding treatment in five out of six site-years.

Introduction

Weeds are the most costly and damaging pest to crops in the United States (Oerke 2006). In recent years, herbicide-resistant weeds have made soybean [*Glycine max* (L.) Merr.] production more difficult. Currently the state of Indiana has 18 reported weed biotypes that are resistant to herbicides (Heap 2020). Using an integrated approach to manage weeds will be necessary as resistance issues continue to increase, with problematic weeds, such as waterhemp, now having resistance to five site-of-action groups (Evans et al. 2019). The failure of herbicides to control herbicide-resistant weeds has led to the development of genetically modified crops that are resistant to herbicides such as glyphosate, glufosinate, isoxaflutole, dicamba, and 2,4-D. Soybean varieties resistant to 2,4-D were commercialized in 2019, and it is anticipated that their acreage will grow rapidly due to high efficacy on glyphosate- and acetolactate synthase (ALS)-resistant broadleaf weed species, commonly found in soybean production.

The addition of 2,4-D to glufosinate has resulted in at least 94% control of both glyphosate-resistant and -susceptible waterhemp [*Amaranthus tuberculatus* (Moq.) Sauer] at heights up to 35 cm, demonstrating the usefulness of these Enlist E3® soybean varieties (Corteva Agrisciences, Indianapolis, IN), which confer resistance to both 2,4-D and glufosinate (Craigmyle et al. 2013). Glyphosate-resistant and 2,4-D-tolerant Palmer amaranth (*Amaranthus palmeri* S. Watson) was controlled better with glyphosate in combination with 2,4-D choline compared with 2,4-D amine or glyphosate alone, to which some Palmer amaranth biotypes have tolerance, demonstrating the benefit of Enlist E3® soybean for Palmer amaranth management (Spaunhorst and Johnson 2017). Chahal and Johnson (2012) and Kruger et al. (2010) documented that the addition of 2,4-D to glyphosate provided significant reductions in glyphosate-resistant horseweed [*Conyza canadensis* (L.) Cronquist] biomass, showing the advantage of using 2,4-D for horseweed control in soybean. Additionally, Robinson et al. (2012) observed that applications of 2,4-D in combination with glyphosate provided 97% control of several problematic weeds in soybean, including velvetleaf (*Abutilon theophrasti* Medik), waterhemp, giant ragweed (*Ambrosia trifida* L.), and common lambsquarters (*Chenopodium album* L.).

However, buffer areas, which do not receive postemergence (POST) applications of 2,4-D, are required for 2,4-D-resistant soybean. Buffer areas of 9 m in length between downwind sensitive areas and areas sprayed with 2,4-D are required by the label (Anonymous 2017). Managing Group 5 (ALS), 9 (glyphosate), and 14 (PPO)-resistant weeds in these buffer areas, where 2,4-D applications are not permitted, will be challenging. Cover crops may be a useful method of weed suppression within these buffer areas. Cover crops used with appropriate herbicide strategies to control weeds have been studied by a number of other researchers (Loux et al. 2017; Mock et al. 2012; Reeves et al. 2005; Yenish et al. 1996). Loux et al. (2017) reported that cover crops without herbicides provided only 14% control of waterhemp compared to 83% control with a preemergence (PRE) followed by POST herbicide programs averaged across sites. Reddy (2001) observed that cover crops used with a PRE-only herbicide resulted in lower cash crop yields compared to a no-cover crop conventional tillage system. However, when used in tandem with a POST herbicide application to control late-emerging weeds, negative impacts on yield were only observed when Italian ryegrass [*Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot] was used as a cover crop.

Davis et al. (2007) reported that a winter wheat (*Triticum aestivum* L.) cover crop provided similar horseweed suppression 4 mo after in-crop applications compared to suppression following a spring- or fall-applied residual herbicide across two years. Christenson (2015) reported that horseweed suppression with cereal rye (*Secale cereale* L.) was similar to that of all herbicide treatments. However, winter wheat and winter barley (*Hordeum vulgare* L.) were not as effective at suppressing horseweed. Cholette et al. (2018) reported correlations of cover crop ground cover and biomass with horseweed density (0.17 and 0.21, respectively) and biomass (0.30 and 0.40, respectively). Teasdale et al. (1991) also reported a correlation between cover crop biomass and weed density in Maryland of large crabgrass [*Digitaria sanguinalis* (L.) Scop.], goosegrass [*Eleusine indica* (L.) Gaertn.], stinkgrass [*Eragrostis cilianensis* (All.) Vign. ex Janchen], carpetweed (*Mollugo verticillata* L.), and common lambsquarters ($r^2 = 0.75$ at the 0.01 level). Weed suppression via cover crops can also reduce the selection pressure applied to weed species by reducing the number of weeds exposed to herbicide applications. Furthermore, cover crops are included in best management practices to reduce herbicide resistance, as described by Norsworthy et al. (2012).

When implementing cover crops in a production system, it is important to manage appropriately, as corn yield reductions up to 36% have occurred after a rye cover crop (Johnson et al. 1993). Creech et al. (2008) also observed 11% reductions in corn yield in Indiana when annual ryegrass (*Lolium multiflorum* Lam.) or winter wheat cover crops were used for winter annual weed control. Other researchers have reported increases in corn yield when legume species, such as white clover (*Trifolium repens* L.), red clover (*Trifolium pratense* L.), or barrel medic (*Medicago truncatula* Gaertn.), are used as cover crops in corn production (Hively and Cox 2001).

If cover crops are to be grown on a large number of acres, it is important that they be used in addition to other technologies, such as 2,4-D-resistant soybean. This research was conducted to determine if cover crops can be used to enhance weed control in label-mandated buffer areas in 2,4-D-resistant soybean. The effectiveness of three cover crops, terminated at three timings, with three different herbicide strategies, was evaluated for their impact on both weed control and soybean yield at three locations in Indiana.

Materials and Methods

Site Description

Field trials were conducted at three locations in Indiana in 2018 and 2019 to evaluate weed suppression and the impact on yield provided by three cover crops, terminated at three different times, with three different herbicide strategies. Experiments were conducted at the Throckmorton Purdue Agricultural Center (TPAC), near Lafayette, IN (40.29°N, 86.91°W); the South East Purdue Agricultural Center (SEPAC), near Butlerville, IN (39.03°N, 85.53°W); and the Davis Purdue Agricultural Center (DPAC), near Farmland, IN (40.26°N, 85.16°W). The TPAC soil was primarily a Toronto-Millbrook complex that has historically been tilled. The soil at TPAC had an organic matter (OM) of 2.6% with a pH of 6.3 and a cation exchange capacity (CEC) of 10.6 meq 100 g^{-1}. The SEPAC location was predominantly a Cobbsfork silt loam that was poorly drained. The SEPAC soil had an OM of 1.7%, a pH of 6.1, and a CEC of 5.6 meq 100 g^{-1} and is in no-till management. The DPAC location primarily had a Pewamo silty clay loam that was also in no-till management. The DPAC soil had an OM of 3.6%, a pH of 6.0, and a CEC of 15.8 meq 100 g^{-1}.

Experimental Design and Herbicide Treatments

The experimental design was a split block with a factorial arrangement of treatments and four replications. The main blocks were the three cover crops, which included cereal rye, crimson clover (*Trifolium incarnatum* L.), and an 80:20 by weight mixture of the two that is hereinafter referred to as the mix. Crimson clover was seeded to provide a representative ground cover of winter annual broadleaf weeds and was used as a control treatment. Respective seeding rates for cereal rye, crimson clover, and the mix were 101 kg ha^{-1}, 20 kg ha^{-1}, and 78 kg ha^{-1}. Planting dates for cover crops can be found in Table 1.

Within each cover crop was a factorial treatment arrangement of three termination timings and three herbicide strategies to terminate the cover crops. The three termination timings that were implemented in this study were before soybean planting (BP), at soybean planting (ATP), and after soybean planting (AFP). Specific dates for these termination times in both years can be found in Table 1. The three herbicide strategies that were utilized in this experiment were glyphosate, a glyphosate in combination with 2,4-D, and a glyphosate plus 2,4-D, plus a residual herbicide. The residual herbicide changed with site and termination timing due to label restrictions and according to key weed species targeted at each location. The rates of each herbicide used can be found in Table 2. The glyphosate-only herbicide strategy was used to evaluate cover crop weed suppression within buffer areas, which are required by Enlist E3® soybean. These buffer areas are required to reduce off-target movement, which has become a concern as synthetic auxin-resistant soybean has been commercialized. The two herbicide strategies that utilize 2,4-D were used to simulate weed suppression across an entire field, or outside of buffer areas.

All herbicide applications were made using a 3-m CO_2-propelled backpack sprayer calibrated to deliver 140 L ha^{-1} at 143 kPa. Nozzles recommended by herbicide labels, AIXR 11015 (Teejet Technologies, Wheaton, IL), were used. The primary weed species at SEPAC were a wide variety of grasses and common waterhemp in 2019. At the TPAC location, giant ragweed, fall panicum (*Panicum dichotomiflorum* Michx.), and foxtail species (*Setaria* spp.) were the predominant weed species. The DPAC weed flora was primarily common waterhemp and a mix of grass species. Key species at each location are summarized in Table 3. A broadcast POST application was made after all cover crops had been terminated. The specific time of this broadcast POST application can be found in Table 1, and the herbicides used can be

Table 1. Date of cover crop planting, termination times, planting, POST application, and harvest at all three of the trial locations.[a,b]

	TPAC		SEPAC		DPAC	
	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2
Cover crop planted	26 Sep 2017	3 Oct 2018	22 Sep 2017	3 and 18 Oct 2018[c]	27 Oct 2017	22 Oct 2018
BP termination	26 Apr 2018	23 Apr 2019	30 Apr 2018	8 May 2019	5 May 2018	6 May 2019
Planting	10 May 2018	3 Jun 2019	14 May 2018	4 Jun 2019	17 May 2018	7 Jun 2019
AFP termination	23 May 2018	11 Jun 2019	29 May 2018	12 Jun 2019	2 Jun 2018	21 Jun 2019
Broadcast POST application	16 Jun 2018	26 Jun 2019	5 Jun 2018	9 Jul 2019	14 Jun 2018	13 Jul 2019
Harvest	24 Oct 2018	14 Oct 2019	25 Oct 2018	25 Nov 2019	22 Oct 2018	5 Nov 2019

[a] Abbreviations: AFP, after planting; BP, before planting; DPAC, Davis Purdue Agriculture Center (Farmland, IN); SEPAC, South East Purdue Agriculture Center (Butlerville, IN); TPAC, Throckmorton Purdue Agricultural Center (Lafayette, IN).

[b] The before-planting termination was much longer than originally intended due to adverse weather conditions in spring 2019 causing an extended delay in planting time.

[c] Cereal rye at SEPAC in 2019 was reseeded due to poor emergence, resulting in two cover crop planting dates.

Table 2. Herbicides used and rates that were applied for the three cover crop termination timings and the broadcast POST application.[a,b,c]

Site and timing	Active ingredient	Rate	Formulation	Manufacturer
		kg ha^{-1}		
Used at all sites for termination	Glyphosate + 2,4-D	1.12 + 1.08	Enlist Duo®	Corteva
Used at all sites for termination and broadcast POST	Glyphosate	1.28	Roundup Powermax®	Bayer
All TPAC terminations and broadcast POST at SEPAC and TPAC	Cloransulam-methyl	0.009/0.027/0.044 [a]	FirstRate®	Corteva
Residual at DPAC BP and ATP	Sulfentrazone + imazethapyr	0.32 + 0.065	Authority® Assist	FMC
Residual at SEPAC BP and ATP	Flumioxazin + chlorimuron-ethyl	0.085 + 0.029	Valor® XLT	Valent
Residual at DPAC and SEPAC AFP	Acetochlor	1.49	Warrant®	Bayer
Broadcast POST at DPAC	Fomesafen	0.2	Flexstar®	Syngenta
Broadcast POST at SEPAC (2019 only)	Glyphosate + fomesafen	1.13 + 0.24	Flexstar GT 3.5®	Syngenta

[a] Three different rates of cloransulam-methyl were used in this experiment. The 0.044 kg ha^{-1} was used at the two earliest terminations at TPAC, the 0.027 kg ha^{-1} rate was used as the broadcast POST application at SEPAC, and the 0.009 kg ha^{-1} rate was used at the late termination timing and the broadcast POST applications at TPAC. This was done to follow maximum use rates determined from the label.

[b] Fomesafen was added to the broadcast POST application in 2019 at the SEPAC location due to waterhemp being much more prevalent than in the previous year.

[c] Abbreviations: AFP, after planting; ATP, at planting; BP, before planting; DPAC, Davis Purdue Agriculture Center (Farmland, IN); SEPAC, South East Purdue Agriculture Center (Butlerville, IN); TPAC, Throckmorton Purdue Agricultural Center (Lafayette, IN).

found in Table 2. The broadcast POST application was sprayed when average weed height across all plots was 10 to 15 cm.

Data Collection

Just prior to the termination of cover crops, both cover crop and weed biomass were collected from a 0.25-m^2 quadrant in each plot. This was done to evaluate early-season weed suppression by the three different cover crops and to observe the increase in cover crop biomass as termination time was delayed. Soybean was planted at a rate of 350,000 seeds ha^{-1}; soybean planting dates can be found in Table 1. Prior POST application, densities of key weed species were recorded at each location. These densities were assessed from two quadrants in the front and back of each plot using either a 0.25-m^2 or 1-m^2 quadrant, which were averaged for a single value of plants m^{-2} for each plot. The plots were harvested using a small plot combine, and yields were adjusted to 13% moisture. The results reported in this article focus on weed densities prior to the broadcast POST application and are referred to as early summer weed densities.

Statistical Analysis

Correlations between cover crop biomass and weed biomass were done using SAS 9.4 PROC CORR procedure, and all other data were analyzed using the PROC GLIMMIX procedure in SAS 9.4 (SAS, Cary, NC). The densities and biomass collected were subjected to a log transformation to analyze data. However, for clarity purposes, untransformed data are presented. Analysis was similar to that described by Yang (2010) for balanced split-plot designs. Mean separations were identified using Tukey's honest significant difference (HSD) test with an alpha equal to 0.05. The three locations were analyzed separately due to differences in soil types and key weed species present. Orthogonal contrasts were conducted on specific factors of interest and are presented in the appropriate section.

Results and Discussion

Cover Crop and Weed Biomass prior to Cover Crop Termination

Termination timing and cover crop species influenced cover crop biomass. Two-way interactions occurred between cover crop and termination timing in both years at TPAC ($P = 0.0433$ and $P < 0.0001$, respectively) and in 2019 at SEPAC ($P = 0.0183$). In 2018, cover crop biomass was influenced by cover crop and termination timing at SEPAC ($P < 0.0001$ and $P < 0.0001$, respectively) and DPAC ($P = 0.0039$ and $P < 0.0001$, respectively). The control treatment resulted in half as much biomass as for cereal rye or the mix (Table 4). Terminating cover crops BP reduced cover crop biomass by one-half compared to later terminations. At both sites in 2019, cereal rye and the mix produced more biomass than the control treatment. At TPAC in 2019, delaying the termination of a

Table 3. Key weed species at each of the trial locations that were collected for biomass and recorded for density.[a,b]

TPAC	SEPAC	DPAC
Grasses[b]	Grasses	Grasses
Morningglory (*Ipomoea* spp.)	Morningglory	Morningglory
Giant ragweed (*Ambrosia trifida* L.)	Common ragweed (*Ambrosia artemisiifolia* L.)	Waterhemp
Common lambsquarters (*Chenopodium album* L.)	Common cocklebur (*Xanthium strumarium* L.)	
Velvetleaf (*Abutilon theophrasti* Medik.)	Waterhemp [*Amaranthus tuberculatus* (Moq.) Sauer)], 2019 only	

[a] Abbreviations: DPAC, Davis Purdue Agriculture Center (Farmland, IN); SEPAC, South East Purdue Agriculture Center (Butlerville, IN); TPAC, Throckmorton Purdue Agricultural Center (Lafayette, IN).

[b] Grass species and approximate composition at the two sites were as follows: at TPAC, large crabgrass (*Digitaria sanguinalis* L.) (2%), smooth crabgrass [*Digitaria ischaemum* (Schreb.) Schreb. ex Muhl.] (3%), fall panicum (*Panicum dichotomiflorum* Michx.) (15%), barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv] (17%), and foxtail species (*Setaria* spp.) (67%); at SEPAC, barnyardgrass (2%), large crabgrass (2%), annual bluegrass (*Poa annua* L.) (8%), fall panicum (34%), and foxtail species (54%); at DPAC, smooth crabgrass (1%), large crabgrass (4%), foxtail species (18%), barnyardgrass (32%), and fall panicum (45%).

Table 4. Influence of cover crop and termination timing on cover crop biomass prior to termination in the spring at three sites in Indiana.[a,b,c]

			Termination timing			
Site	Year	Cover crop	BP	ATP	AFP	Pooled
				kg ha^{-1}		
TPAC	2018	Crimson clover	488 c	1,346 bc	3,095 ab	1,643 b
		Cereal rye	3,358 a	5,127 a	6,281 a	4,922 a
		Mix	3,804 a	4,148 a	6,149 a	4,700 a
		Pooled	2,550 b	3,540 a	5,175 a	
	2019	Crimson clover	0 c	0 c	0 c	0 b
		Cereal rye	1,548 b	5,956 a	5,484 a	4,329 a
		Mix	1,631 b	6,327 a	5,682 a	4,547 a
		Pooled	1,060 b	4,094 a	3,722 a	
SEPAC	2018	Crimson clover	922	3,016	3,435	2,458 b
		Cereal rye	3,405	6,692	6,944	5,680 a
		Mix	3,597	5,751	7,293	5,509 a
		Pooled	2,614 b	5,238 a	5,829 a	—
	2019	Crimson clover	17 b	0 b	0 b	6 b
		Cereal rye	3,166 a	5,919 a	5,759 a	4,948 a
		Mix	3,111 a	6,669 a	6,747 a	5,509 a
		Pooled	2,614	5,238	5,829	
DPAC	2018	Crimson clover	0	60	200	87 b
		Cereal rye	1,470	3,076	4,420	2,989 a
		Mix	700	1,691	2,369	1,587 a
		Pooled	725 b	1,601 a	2,322 a	—

[a] Abbreviations: AFP, after planting; ATP, at planting; BP, before planting; DPAC, Davis Purdue Agriculture Center (Farmland, IN); SEPAC, South East Purdue Agriculture Center (Butlerville, IN); TPAC, Throckmorton Purdue Agricultural Center (Lafayette, IN).

[b] Data were log-transformed before analysis; however, untransformed mean values are presented based on the interpretation of the transformed data.

[c] Means followed by the same letter within site-year and pooled data are not different according to Tukey's HSD test ($P \leq 0.05$). No LSD letter separations are shown if the factor or interaction was not significant at the 0.05 level.

cereal rye or the mix to at or after soybean planting resulted in 70% more cover crop biomass compared to all other treatments.

Correlations between cover crop biomass and early-season weed biomass provided a Pearson correlation coefficient of 0.38 ($P < 0.0001$). As cover crop biomass increased, the mass and variability of the early-season weed biomass decreased (Figure 1). Using cover crops with cereal rye terminated at or after planting provided higher cover crop biomass compared to the earliest-terminated cover crops or the control treatment. The relationship indicated that the increase in cover crop biomass would be beneficial in reducing the variability of early-season weed suppression.

A two-way interaction between cover crop and termination timing affected the weed biomass prior to cover crop termination at DPAC in 2018 ($P < 0.0001$) and at both SEPAC and TPAC in 2019 ($P = 0.0122$ and $P < 0.0001$, respectively). Terminating the crimson clover control treatment after soybean planting resulted in the highest weed biomass (Table 5). In 2018, weed biomass at both SEPAC and TPAC was affected by termination timing ($P = 0.0186$ and $P = 0.0186$, respectively). Delaying termination from BP to after soybean planting reduced weed biomass by 33 and 50 percentage points, respectively, for TPAC and SEPAC. In 2018, the TPAC location weed biomass was also influenced by cover crop ($P < 0.0001$), with cereal rye and the mix reducing weed biomass by 98 and 91 percentage points, respectively, compared to the control treatment. Terminating the control treatment at or after soybean planting resulted in nearly double the weed biomass compared to treatments that utilized a cover crop that contained cereal rye at SEPAC and TPAC in 2019. Similarly, terminating cereal rye BP in 2019 at TPAC reduced weed biomass by at least 82 percentage points compared to all other treatments, except for the mix terminated before and at soybean planting. At SEPAC in 2019, terminating a cover crop containing cereal rye at any time reduced weed biomass by at least 79 percentage points compared to the crimson clover control treatment.

Delaying termination with cover crops containing cereal rye to at or after soybean planting resulted in a 25 percentage point increase in cover crop biomass compared to the control treatment. Weed biomass was variable, ranging from 6 to 2,436 kg ha^{-1}.

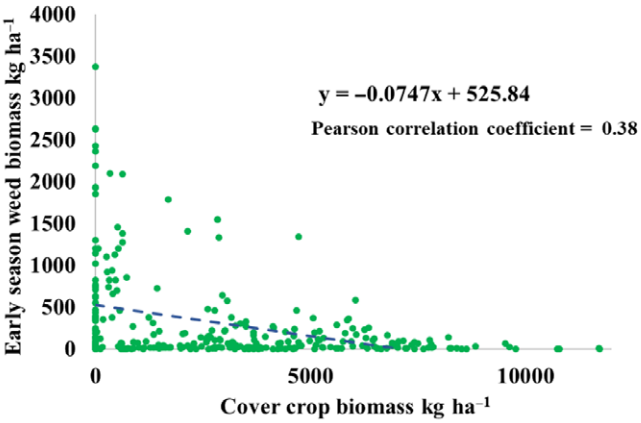

Figure 1. Correlation of early-season (April and May) weed biomass by cover crop biomass across three sites in Indiana in 2018 and 2019. Sites included the Throckmorton Purdue Agricultural Center (TPAC, Lafayette, IN), the South East Purdue Agricultural Center (SEPAC, Butlerville, IN), and the Davis Purdue Agriculture Center (DPAC, Farmland, IN).

However, cover crops containing cereal rye never had weed biomass that exceeded 177 kg ha^{-1}, while the control treatment terminated after soybean planting at TPAC in 2019 had weed biomass of 2,436 kg ha^{-1}. Utilizing cover crops containing cereal rye reduced early-season weed biomass at four of six sites. Additionally, at four of six site-years, a cover crop terminated at the later timing had similar weed biomass to earlier timings. Reductions of weed biomass by cereal rye of 91% and higher have previously been documented by Werle et al. (2018) in Nebraska. Caution should be used when delaying cover crop termination due to possible negative impacts on cash crop yield and the possibility of seed production by cover crops producing volunteers that compete with the cash crop for resources (Keene et al. 2017).

Early Summer Grass Densities prior to Broadcast POST

Grass control was evaluated at all six site-years. Delaying termination timing to after soybean planting reduced grass densities at all six site-years. Grass densities were reduced by cover crops at four out of six site-years. However, the amount by which grass densities were reduced was highly variable, ranging from 41 to 98 percentage points (Table 6). Three-way interactions between cover crop, termination timing, and herbicide strategy affected grass densities at both SEPAC ($P = 0.0019$) and DPAC ($P = 0.019$) in 2018 (Table 7).

In both 2018 and 2019, TPAC grass densities were affected by termination timing ($P = 0.0009$ and $P = 0.0001$, respectively). In 2018, TPAC grass densities were reduced by at least 54 percentage points when a cereal rye cover crop was utilized compared to crimson clover ($P = 0.0295$; Table 6). When terminated after soybean planting, grass densities were reduced by 71 percentage points in 2019 compared to when termination was BP and were reduced by 41 percentage points when terminated at soybean planting compared to BP in 2018. In 2019, DPAC grass densities were at least 87% lower when termination was delayed to at or after soybean planting compared to before planting ($P = 0.0128$). Contrasts were conducted to determine if a glyphosate-only herbicide strategy provided similar grass suppression to a glyphosate plus 2,4-D herbicide strategy. At five of six site-years, the glyphosate-alone herbicide strategy resulted in similar grass densities to the glyphosate in combination with 2,4-D within the cereal rye cover crop at a 0.05 level of significance, supporting that cover crops would be valuable

Table 5. Influence of cover crop and termination timing on weed biomass prior to cover crop termination in the spring at three sites in Indiana.[a,b,c,d,e]

			Termination timing			
Year	Site	Cover crop	BP	ATP	AFP	Pooled
				kg ha^{-1}		
TPAC	2018	Crimson clover	1,061	—[e]	761	911 a
		Cereal rye	17	—	22	20 c
		Mix	134	—	32	83 b
		Pooled	404 a	—	272 b	
	2019	Crimson clover	116 bc	1,563 a	2,436 a	1,372 a
		Cereal rye	15 d	82 bc	157 bc	85 c
		Mix	29 cd	118 bcd	160 b	102 b
		Pooled	53	588	918	
SEPAC	2018	Crimson clover	413	662	307	461
		Cereal rye	168	128	26	107
		Mix	168	177	45	130
		Pooled	250 a	323 a	126 b	—
	2019	Crimson clover	220 b	533 ab	576 a	443 a
		Cereal rye	21 c	46 c	15 c	27 b
		Mix	13 c	11 c	6 c	10 b
		Pooled	85	196	199	
DPAC	2018	Crimson clover	12 b	113 b	985 a	370
		Cereal rye	10 b	65 b	27 b	34
		Mix	40 b	21 b	102 b	54
		Pooled	20 a	66 b	372 c	

[a] Abbreviations: AFP, after planting; ATP, at planting; BP, before planting; DPAC, Davis Purdue Agriculture Center (Farmland, IN); SEPAC, South East Purdue Agriculture Center (Butlerville, IN); TPAC, Throckmorton Purdue Agricultural Center (Lafayette, IN).

[b] Data were log-transformed before analysis; however, untransformed mean values are presented based on the interpretation of the transformed data.

[c] Means followed by the same letter within site-year and pooled data are not different according to Tukey's HSD test ($P \leq 0.05$). No LSD letter separations are shown if the factor or interaction was not significant at the 0.05 level.

[d] Weeds that made up more than approximately 5% of the density combined for biomass measurements included the following: at TPAC, chickweed [*Stellaria media* (L.) Vill.] (50%), henbit (*Lamium amplexicaule* L.) (17%), giant ragweed (18%); at SEPAC, fall panicum (5%), cressleaf groundsel [*Packera glabella* (Poir.) C. Jeffrey] (6%), bittercrest (*Cardamine hirsuta* L.) (7%), horseweed (9%), field speedwell (*Veronica agrestis* L.) (15%), annual bluegrass (*Poa annua* L.) (30%); at DPAC, fall panicum (6%), field speedwell (11%), horseweed (28%), waterhemp (32%).

[e] Missing data from ATP timing at TPAC in 2018.

Table 6. Influence of cover crop, termination timing, and herbicide strategy on early summer grass density prior to a POST application at three sites in Indiana in 2018 and 2019.[a,b,c,d]

				Termination timing			
Site	Year	Herbicide strategy	Cover crop	BP	ATP	AFP	Pooled
				plants m^{-2}			
TPAC	2018	Gly	Crimson clover	32	18	21	24
			Cereal rye	9	26	2	12
			Mix	90	5	135	77
		Gly + 2,4-D	Crimson clover	32	38	9	26
			Cereal rye	23	10	4	12
			Mix	34	47	3	28
		Gly + 2,4-D + residual	Crimson clover	31	20	12	21
			Cereal rye	15	5	1	7
			Mix	19	4	10	11
		Pooled	Crimson clover	32	25	14	24 a
			Cereal rye	16	13	3	11 b
			Mix	47	19	49	38 ab
		Gly	Pooled	44	16	53	38
		Gly + 2,4-D		30	31	5	22
		Gly + 2,4-D + residual		22	9	8	13
		Pooled	Pooled	32 a	19 b	22 ab	
TPAC	2019	Gly	Crimson clover	32	12	11	18
			Cereal rye	38	20	8	22
			Mix	8	25	7	13
		Gly + 2,4-D	Crimson clover	34	9	1	14
			Cereal rye	39	11	3	17
			Mix	14	11	13	12
		Gly + 2,4-D + residual	Crimson clover	28	7	1	12
			Cereal rye	38	2	1	14
			Mix	20	4	31	18
		Pooled	Crimson clover	31	9	4	15
			Cereal rye	38	11	4	18
			Mix	14	13	17	14
		Gly	Pooled	26	19	9	18
		Gly + 2,4-D		29	10	5	15
		Gly + 2,4-D + residual		28	4	11	14
		Pooled	Pooled	28 a	11 b	8 b	
SEPAC	2018	Gly	Crimson clover	204 ab	162 a–c	0 c	122
			Cereal rye	79 ab	21 a–c	2 a–c	34
			Mix	11 a	15 ab	10 a–c	12
		Gly + 2,4-D	Crimson clover	205 ab	27 ab	1 a–c	78
			Cereal rye	48 ab	4 ab	0 a–c	17
			Mix	25 ab	2 ab	1 a–c	9
		Gly + 2,4-D + residual	Crimson clover	16 ab	1 ab	5 a–c	7
			Cereal rye	8 ab	16 a–c	0 a–c	8
			Mix	3 ab	1 bc	0 a–c	1
		Pooled	Crimson clover	142 a	63 bc	2 ef	69 a
			Cereal rye	79 ab	14 de	1 f	20 ab
			Mix	13 b–d	6 de	4 ef	8 b
		Gly	Pooled	98 a	66 ab	4 d	56 a
		Gly + 2,4-D		93 a	11 bc	1 d	35 a
		Gly + 2,4-D + residual		9 bc	6 cd	2 d	6 b
		Pooled	Pooled	67 a	28 b	2 c	
SEPAC	2019	Gly	Crimson clover	63	7	1	24 b
			Cereal rye	48	20	20	29 ab
			Mix	73	30	43	49 ab
		Gly + 2,4-D	Crimson clover	73	41	18	44 a
			Cereal rye	75	57	24	52 ab
			Mix	60	29	20	36 ab
		Gly + 2,4-D + residual	Crimson clover	25	36	39	33 ab
			Cereal rye	58	17	16	30 ab
			Mix	28	6	14	16 a
		Pooled	Crimson clover	54	28	19	34
			Cereal rye	48	31	20	37
			Mix	53	22	25	33
		Gly	Pooled	61 a	19 a	21 b	34 b
		Gly + 2,4-D		69 a	42 b	21 b	44 a
		Gly + 2,4-D + residual		37 a	19 b	23 b	26 b
		Pooled	Pooled	56 a	27 b	21 c	
DPAC	2018	Gly	Crimson clover	116 ab	125 a–e	0 c	80 a
			Cereal rye	11 a–g	10 b–g	0 e–g	7 b
			Mix	25 a–d	2 a–g	0 c–g	9 ab

(*Continued*)

Table 6. (*Continued*)

Site	Year	Herbicide strategy	Cover crop	Termination timing			
				BP	ATP	AFP	Pooled
		Gly + 2,4-D	Crimson clover	103 a	6 a–g	2 a–g	44 ab
			Cereal rye	11 a–f	1 gf	0 g	4 b
			Mix	51 a–c	4 d–g	0 gf	18 ab
		Gly + 2,4-D + residual	Crimson clover	55 a–g	11 a–g	1 c–g	19 ab
			Cereal rye	23 a–g	3 gf	0 g	9 b
			Mix	8 a–g	1 gf	0 gf	3 b
		Pooled	Crimson clover	91	47	1	49
			Cereal rye	15	4	0	6
			Mix	28	2	0	10
		Gly	Pooled	50	46	0	32 a
		Gly + 2,4-D		55	3	1	21 b
		Gly + 2,4-D + residual		29	5	1	11 ab
		Pooled	Pooled	45 a	18 b	0 c	
DPAC	2019	Gly	Pooled	33	3	2	13 ab
		Gly + 2,4-D		47	6	1	19 a
		Gly + 2,4-D + residual		11	2	1	5 b
		Pooled	Pooled	30 a	4 b	1 b	

[a] Abbreviations: AFP, after planting; ATP, at planting; BP, before planting; DPAC, Davis Purdue Agriculture Center (Farmland, IN); SEPAC, South East Purdue Agriculture Center (Butlerville, IN); TPAC, Throckmorton Purdue Agricultural Center (Lafayette, IN).

[b] Data were log-transformed before analysis; however, untransformed mean values are presented based on the interpretation of the transformed data.

[c] Means followed by the same letter within site-year are not different according to Tukey's HSD test ($P \le 0.05$), unless pooled. No LSD letter separations are shown if the factor or interaction was not significant at the 0.05 level.

[d] Grass species and approximate composition at the three sites were as follows: at TPAC, large crabgrass (2%), smooth crabgrass (3%), fall panicum (15%), barnyardgrass (17%), foxtail species (67%); at DPAC, smooth crabgrass (1%), large crabgrass (4%), foxtail species (18%), barnyardgrass (32%), fall panicum (45%); at SEPAC, barnyardgrass (2%), large crabgrass (2%), annual bluegrass (8%), fall panicum (34%), foxtail species (54%).

for weed suppression within buffer areas where 2,4-D is not permitted.

Norsworthy et al. (2011) reported that a cereal rye cover crop provided 10 to 11 percentage points of additional goosegrass [*Eleusine indica* (L.) Gaertn.] control compared to fallow plots when glyphosate plus pyrithiobac was applied to one-leaf cotton (*Gossypium hirsutum* L.). Dhima et al. (2006) reported reductions in barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.] and bristly foxtail [*Setaria verticillata* (L.) P. Beauv.] in Greece due to winter cereal cover crop mulches and attributed this to allelopathy.

Our research showed that termination timing reduced grass densities, but we did not evaluate allelopathic effects. Few researchers have assessed the effects of cover crop and termination timing on grass densities. To reduce grass densities within buffer areas, delay termination of cover crops containing cereal rye to at or after soybean planting, as this provided over 41% reduction in three of six site-years in this research.

Early Summer Giant Ragweed Densities prior to Broadcast POST

Giant ragweed was evaluated at two of six site-years. Delaying cover crop termination to at or after soybean planting reduced giant ragweed densities by 54 and 78 percentage points, respectively, compared to the earliest termination time in 2019 ($P = 0.022$); however, termination did not influence giant ragweed densities in 2018 (Table 7). Cover crops did not affect giant ragweed densities in either year. Utilizing glyphosate in combination with 2,4-D and a residual herbicide provided 80 and 26 percentage points more control than glyphosate alone in 2018 ($P = 0.0073$) and 2019 ($P = 0.0018$), respectively. Previous research on the influence of cover crops and termination time on giant ragweed is minimal. Bruin et al. (2005) reported that cereal rye reduced giant ragweed biomass but not density at one site-year in Minnesota. However, the influence of herbicide strategies on giant ragweed has been reported by several researchers. Ganie and Jhala (2017) reported that 2,4-D in combination with glufosinate provided at least 81% control of giant ragweed compared to a nontreated control but was similar to glufosinate applied alone. The use of 2,4-D as an additional mode of action will allow for better POST weed management practices, as described by Norsworthy et al. (2012), as implementing multiple modes of action will likely extend the longevity of the 2,4-D-resistant technology.

Delaying termination of cover crops was beneficial in reducing giant ragweed densities in 2019. Termination timing did not influence giant ragweed densities in 2018. Giant ragweed densities in 2019 were reduced by later termination timings due to the delayed soybean planting as a result of a wet spring. The delay in soybean planting in 2019 allowed for giant ragweed to emerge without having to compete with a soybean crop or living cover crop for 5 wk between the first termination timing and the at-planting termination. Cover crops would not be effective for control of giant ragweed in buffer areas, as we report that herbicide strategies with 2,4-D were the only control method that reduced giant ragweed densities in both years. Contrasts conducted showed that the use of cereal rye provided similar suppression when terminated with glyphosate or glyphosate plus 2,4-D at a 0.05 level of significance. However, the use of a residual herbicide increased giant ragweed control.

Early Summer Waterhemp Densities prior to Broadcast POST

Waterhemp was evaluated at three of six site-years. Waterhemp densities at DPAC in 2018 and SEPAC in 2019 were affected by a herbicide strategy by termination timing interaction ($P = 0.0063$ and $P = 0.0002$, respectively; Table 8). Delaying termination to at or after planting and using glyphosate in combination with 2,4-D and a residual herbicide reduced waterhemp densities by at least 92% compared to glyphosate alone at the two earlier timings or glyphosate plus 2,4-D at the early timing at DPAC in 2018 (Table 8). At SEPAC, utilizing glyphosate plus 2,4-D plus a residual

Table 7. Influence of cover crop and termination timing on early summer giant ragweed density prior to application of a POST at the Throckmorton Purdue Agricultural Center, Lafayette, IN.[a,b,c]

				Termination timing			
Site	Year	Herbicide strategy	Cover crop	BP	ATP	AFP	Pooled
				plants m^{-2}			
TPAC	2018	Gly	Crimson clover	9	17	40	22
			Cereal rye	18	135	65	73
			Mix	64	7	88	53
		Gly + 2,4-D	Crimson clover	11	12	18	14
			Cereal rye	26	79	23	43
			Mix	19	50	14	28
		Gly + 2,4-D + residual	Crimson clover	2	10	18	10
			Cereal rye	6	18	3	9
			Mix	14	11	8	11
		Pooled	Crimson clover	7	13	25	15
			Cereal rye	18	77	30	41
			Mix	32	23	37	30
		Gly	Pooled	30	53	64	49 a
		Gly + 2,4-D		19	47	18	28 ab
		Gly + 2,4-D + residual		7	13	10	10 b
		Pooled	Pooled	19	38	31	
TPAC	2019	Gly	Crimson clover	246	148	71	155
			Cereal rye	292	127	32	150
			Mix	271	131	120	174
		Gly + 2,4-D	Crimson clover	260	201	45	168
			Cereal rye	251	98	17	122
			Mix	276	84	73	144
		Gly + 2,4-D + residual	Crimson clover	223	105	29	119
			Cereal rye	186	40	9	78
			Mix	265	111	101	159
		Pooled	Crimson clover	243	151	48	147
			Cereal rye	292	88	19	117
			Mix	271	108	98	159
		Gly	Pooled	270	135	74	160 a
		Gly + 2,4-D		262	127	45	145 ab
		Gly + 2,4-D + residual		224	85	46	118 b
		Pooled	Pooled	252 a	116 b	55 b	

[a] Abbreviations: AFP, after planting; ATP, at planting; BP, before planting; Gly, glyphosate.

[b] Data were log-transformed before analysis; however, untransformed mean values are presented based on the interpretation of the transformed data.

[c] Means followed by the same letter within year and factor are not different according to Tukey's HSD test ($P \leq 0.05$). No LSD letter separations are shown if the factor or interaction was not significant at the 0.05 level.

herbicide after soybean planting reduced waterhemp densities by at least 34% compared to all other treatments.

In 2018, DPAC waterhemp densities were reduced by 45% in cereal rye compared to the control treatment ($P = 0.0364$). However, in 2019, waterhemp densities at DPAC were only affected by termination time and herbicide strategy used ($P < 0.0001$ and $P < 0.0001$, respectively). Terminating at and after soybean planting reduced waterhemp densities by 65 and 93 percentage points, respectively, compared to the earliest timing. Additionally, using glyphosate in combination with 2,4-D and a residual herbicide reduced waterhemp densities by at least 93% compared to other herbicide strategies. Contrasts showed that cereal rye terminated with glyphosate alone only provided similar control as the glyphosate plus 2,4-D at DPAC in 2018 ($P = 0.1478$).

Steckel et al. (2003) evaluated waterhemp under various levels of shade and found that increased shade reduced waterhemp biomass and seed production, which would be beneficial in late-terminated cereal rye cover crops. Additionally, waterhemp under 99% shade had mortalities of 97% and 84%, respectively, in May and June. Hay et al. (2019) reported that appropriate herbicide strategies resulted in 97% control of *Amaranthus* species in Kansas grain sorghum [*Sorghum bicolor* (L.) Moench] across six site-years, while a winter wheat cover crop provided only a 50 percentage point reduction in pigweed density and biomass at three out of six site-years. Similar results were found in this study, as one of the two sites with established cover crops had reductions of 45 percentage points when a cereal rye cover crop was utilized compared to the control treatment. Cornelius and Bradley (2017) reported that cover crops reduced late-season waterhemp biomass from 21 to 40 percentage points, but this was less than the 97 percentage point reduction in late-season waterhemp emergence provided by a spring PRE residual herbicide. Norsworthy et al. (2011) reported that cover crops could provide control of Palmer amaranth in cotton ranging from 0% to 91% with no herbicide, while in combination with herbicides, they provided 94% or greater control of Palmer amaranth. Cover crops will be a useful integrated weed management practice to aid in controlling waterhemp but need to be used in tandem with appropriate herbicide programs to achieve acceptable levels of control that will minimize seed production.

Soybean Yield

Soybean yield at TPAC in 2018 was influenced by a three-way interaction between cover crop, termination timing, and herbicide strategy ($P = 0.008$). Delaying termination of cover crop to the latest timing resulted in a 16% reduction in soybean yield compared to the earlier timings at TPAC in 2018 (Table 9). In 2019, soybean

Table 8. Influence of cover crop, termination time, and herbicide strategy on early summer waterhemp density prior to a POST application at two sites in Indiana.[a,b,c]

				Termination timing			
Site	Year	Herbicide strategy	Cover crop	BP	ATP	AFP	Pooled
				plants m^{-2}			
SEPAC	2019	Gly	Crimson clover	253	440	714	469
			Cereal rye	740	357	279	458
			Mix	432	250	369	350
		Gly + 2,4-D	Crimson clover	204	224	390	273
			Cereal rye	300	269	205	258
			Mix	245	268	220	244
		Gly + 2,4-D + residual	Crimson clover	95	171	174	147
			Cereal rye	174	219	25	139
			Mix	87	150	38	91
		Pooled	Crimson clover	184	278	426	296
			Cereal rye	740	282	169	285
			Mix	254	222	209	228
		Gly	Pooled	475 a	349 ab	454 ab	426 a
		Gly + 2,4-D		249 ab	254 ab	272 ab	258 b
		Gly + 2,4-D + residual		119 b	180 b	79 c	126 c
		Pooled	Pooled	281 a	261 ab	268 b	
DPAC	2018	Gly	Crimson clover	135	62	2	66
			Cereal rye	85	24	0	36
			Mix	66	27	0	31
		Gly + 2,4-D	Crimson clover	115	20	2	54
			Cereal rye	77	1	0	26
			Mix	50	12	0	21
		Gly + 2,4-D + residual	Crimson clover	15	8	1	8
			Cereal rye	19	0	0	6
			Mix	7	2	0	3
		Pooled	Crimson clover	88	30	1	42 a
			Cereal rye	60	8	0	23 b
			Mix	41	13	0	18 ab
		Gly	Pooled	95 a	37 ab	1 de	44 a
		Gly + 2,4-D		81 a	11 b–d	0 c–e	32 a
		Gly + 2,4-D + residual		13 bc	3 c–e	0 e	5
		Pooled	Pooled	63 a	17 b	0 c	
DPAC	2019	Gly	Pooled	196	111	24	110 a
		Gly + 2,4-D		266	57	10	120 a
		Gly + 2,4-D + residual		21	3	1	8 b
		Pooled	Pooled	161 a	57 b	12 c	

[a] Abbreviations: AFP, after planting; ATP, at planting; BP, before planting; DPAC, Davis Purdue Agriculture Center (Farmland, IN); Gly, glyphosate; SEPAC, South East Purdue Agriculture Center (Butlerville, IN); TPAC, Throckmorton Purdue Agricultural Center (Lafayette, IN).

[b] Data were log-transformed before analysis; however, untransformed mean values are presented based on the interpretation of the transformed data.

[c] Means followed by the same letter within site-year and pooled data are not different according to Tukey's HSD test ($P \leq 0.05$). No LSD letter separations are shown if the factor or interaction was not significant at the 0.05 level.

yield at TPAC was 28% lower in the early-terminated control treatment compared to all other treatments ($P = 0.0311$). Lower soybean yields in early-terminated plots in 2019 are likely a result of delayed soybean planting due to high spring precipitation, resulting in higher weed pressure in those plots, as evaluated by collecting the POST weed biomass.

In 2018, soybean yield at SEPAC was influenced by termination timing ($P < 0.0001$). Delaying termination to at or after soybean planting reduced soybean yields by 14% to 41% compared to the earliest timing (Table 9). Producer interest in delaying termination timing of cover crops to plant into a living cover crop has increased in recent years (WG Johnson, personal observation). However, reductions in soybean yield up to 41% can occur when termination of a cover crop is delayed, as observed in this study in 2018. Previous reductions in cash crop yield due to cover crops has been observed (Eckert 1988; Liebl et al. 1992). Reddy (2001) reported yield reduction in soybean yield due to stand loss ranging from 2% to 20% when cover crops were terminated 2 to 3 wk prior to soybean planting. In response to yield reductions in 2018, nutrient analysis was conducted on cover crop biomass in 2019. We observed that carbon in the cover crop increased by at least 41% from the before-planting timing to termination timings at or after soybean planting (data not shown). Additionally, nitrogen taken up by the cover crop was higher at the TPAC location by at least 68 percentage points at the later termination timings (data not shown). Delayed cereal rye termination results in reproductive growth that leads to a wider carbon to nitrogen ratio in the cover crop biomass and less available nitrogen in the soil solution. Thus soil nitrogen immobilization is likely to occur, drastically reducing the portion of soil-derived nitrogen needed by the soybean for optimum production. In one of the six site-years, delayed termination increased soybean yield (DPAC in 2019); however, cover crops at this site were winter-killed. This research provides evidence that cover crops alone did not cause yield reductions; however, when used in combination with a delayed termination, they can result in yield reductions from 14% to 41%.

Haramoto and Pearce (2019) reported similar results in Kentucky as cover crop composition, termination timing, and herbicide interactions were variable in suppressing weeds over four site-years. Haramoto and Pearce (2019) demonstrated that

Table 9. Influence of cover crop, termination time and herbicide strategy on soybean yield at the at three sites in Indiana in 2018 and 2019.[a,b]

				Termination timing			
Site	Year	Herbicide strategy	Cover crop	BP	ATP	AFP	Pooled
				kg ha^{-1}			
TPAC	2018	Gly	Crimson clover	4,614 ab	4,282 a-c	4,573 ab	4,490
			Cereal rye	4,577 ab	4,955 a	3,013 cd	4,182
			Mix	4,548 a-c	3,449 a-d	3,761 a-d	3,919
		Gly + 2,4-D	Crimson clover	4,599 ab	4,577 ab	4,564 ab	4,580
			Cereal rye	4,801 a	4,592 ab	2,975 cd	4,123
			Mix	4,887 a	3,893 a-d	2,973 cd	3,918
		Gly + 2,4-D + residual	Crimson clover	4,685 a	4,281 a-c	4,370 a-c	4,446
			Cereal rye	4,451 a-c	4,400 a-c	3,140 b-d	3,997
			Mix	4,507 ab	3,884 a-d	2,711 cd	3,701
		Pooled	Crimson clover	4,633 a	4,380 a	4,503 a	4,505 a
			Cereal rye	4,577 a	4,649 a	3,043 b	4,101 ab
			Mix	4,648 a	3,742 ab	3,148 b	3,846 b
		Gly	Pooled	4,580	4,229	3,783	4,197
		Gly + 2,4-D		4,762	4,354	3,504	4,207
		Gly + 2,4-D + residual		4,548	4,188	3,407	4,048
		Pooled	Pooled	4,630 a	4,257 a	3,565 b	0
TPAC	2019	Gly	Crimson clover	3,083	4,917	4,427	4,143
			Cereal rye	4,036	4,644	4,787	4,489
			Mix	4,074	4,957	4,511	4,514
		Gly + 2,4-D	Crimson clover	2,920	4,837	4,636	4,131
			Cereal rye	4,264	4,745	4,742	4,584
			Mix	3,922	4,948	4,619	4,496
		Gly + 2,4-D + residual	Crimson clover	2,740	4,075	4,220	3,678
			Cereal rye	4,210	4,648	4,730	4,529
			Mix	4,110	4,529	4,539	4,393
		Pooled	Crimson clover	2,914 b	4,610 a	4,428 a	3,984 b
			Cereal rye	4,036 a	4,679 a	4,753 a	4,534 a
			Mix	4,036 a	4,811 a	4,556 a	4,468 a
		Gly	Pooled	3,731	4,839	4,575	4,382 a
		Gly + 2,4-D		3,702	4,843	4,665	4,404 a
		Gly + 2,4-D + residual		3,687	4,418	4,496	4,200 a
		Pooled	Pooled	3,707 b	4,700 a	4,579 a	
SEPAC	2018	Gly	Crimson clover	2,872	3,705	2,723	3,100
			Cereal rye	5,153	3,952	2,918	4,008
			Mix	4,359	3,437	2,312	3,369
		Gly + 2,4-D	Crimson clover	3,704	3,233	2,381	3,106
			Cereal rye	4,771	3,806	2,628	3,735
			Mix	4,476	3,699	3,013	3,729
		Gly + 2,4-D + residual	Crimson clover	3,736	3,348	1,739	2,941
			Cereal rye	4,284	3,720	2,082	3,362
			Mix	4,254	3,561	2,492	3,436
		Pooled	Crimson clover	3,437	3,429	2,281	3,049
			Cereal rye	5,153	3,826	2,543	3,702
			Mix	4,363	3,565	2,606	3,511
		Gly	Pooled	4,128	3,698	2,651	3,492
		Gly + 2,4-D		4,317	3,579	2,674	3,523
		Gly + 2,4-D + residual		4,091	3,543	2,104	3,246
		Pooled	Pooled	4,179 a	3,607 b	2,476 c	
SEPAC	2019	Gly	Crimson clover	2,238 ab	2,538 ab	2,685 ab	2,487
			Cereal rye	2,777 ab	2,943 a	3,278 a	2,999
			Mix	2,010 ab	1,777 ab	2,602 ab	2,130
		Gly + 2,4-D	Crimson clover	2,591 ab	892 b	2,710 ab	2,064
			Cereal rye	3,346 a	3,298 a	3,114 a	3,253
			Mix	1,972 ab	1,901 ab	2,481 ab	2,118
		Gly + 2,4-D + residual	Crimson clover	3,051 a	1,832 ab	2,654 ab	2,512
			Cereal rye	3,082 a	3,048 a	2,960 a	3,030
			Mix	1,625 ab	1,817 ab	2,451 ab	1,964
		Pooled	Crimson clover	2,626	1,754	2,683	2,354 b
			Cereal rye	2,777	3,096	3,117	3,094 a
			Mix	1,869	1,832	2,511	2,071 b
		Gly	Pooled	2,342	2,419	2,855	2,538
		Gly + 2,4-D		2,636	2,030	2,768	2,478
		Gly + 2,4-D + residual		2,586	2,232	2,688	2,502
		Pooled	Pooled	2,521	2,227	2,770	
DPAC	2018	Gly	Crimson clover	3,172	3,071	2,781	3,008 a
			Cereal rye	3,474	3,022	2,867	3,121 a
			Mix	3,294	3,348	3,005	3,216 a
		Gly + 2,4-D	Crimson clover	2,846	3,239	2,562	2,946 a

(*Continued*)

Table 9. (*Continued*)

				Termination timing			
Site	Year	Herbicide strategy	Cover crop	BP	ATP	AFP	Pooled
			Cereal rye	3,285	3,075	2,652	3,004 a
			Mix	3,705	3,536	3,079	3,440 a
		Gly + 2,4-D + residual	Crimson clover	3,113	3,385	2,640	2,988 a
			Cereal rye	3,083	2,971	2,325	2,793 a
			Mix	3,769	3,462	2,979	3,404 a
		Pooled	Crimson clover	3,044	3,232	2,674	3,011
			Cereal rye	3,281	3,023	2,614	2,973
			Mix	3,589	3,449	3,021	3,353
		Gly	Pooled	3,313	3,147	2,884	3,115
		Gly + 2,4-D		3,279	3,283	2,804	3,141
		Gly + 2,4-D + residual		3,322	3,273	2,647	3,058
		Pooled	Pooled	3,305 a	3,234 a	2,785 b	
DPAC	2019	Gly	Pooled	2,862	3,527	4,129	3,506
		Gly + 2,4-D		3,183	3,613	4,166	3,654
		Gly + 2,4-D + residual		3,260	3,910	3,915	3,695
		Pooled	Pooled	3,101 b	3,683 ab	4,070 a	

[a] Abbreviations: AFP, after planting; ATP, at planting; BP, before planting; DPAC, Davis Purdue Agriculture Center (Farmland, IN); Gly, glyphosate; SEPAC, South East Purdue Agriculture Center (Butlerville, IN); TPAC, Throckmorton Purdue Agricultural Center (Lafayette, IN).

[b] Means followed by the same letter within site-year and pooled data are not different according to Tukey's HSD test ($P \leq 0.05$). No LSD letter separations are shown if the factor or interaction was not significant at the 0.05 level.

residual herbicides are generally beneficial to use in cover crops to suppress weeds in summer annual cash crops. We provide additional evidence of the benefit of residual herbicides in cover crops and evaluate the effect of cover crops, termination timing, and herbicide strategy on a species level of three problematic broadleaf species and grasses as a whole. Cover crops were effective in reducing grass and waterhemp densities at more than one-half of the site-years. Termination timing and herbicide strategy were just as important as cover crops in reducing weed densities. Grass and waterhemp densities were reduced when termination was delayed to after planting at most of the site-years. In 2019, giant ragweed densities were reduced by 78 percentage points when termination was delayed to after soybean planting compared to before planting but were not reduced in 2018.

Caution should be used when delaying cover crop termination due to potential reductions in cash crop yield. We show that cereal rye with termination delayed to at or after planting would be beneficial within buffer areas for control of grass and waterhemp densities. However, yield reductions of up to 41% were observed when cover crop termination was delayed to after soybean planting. Use of cover crops within buffer areas, mandated by 2,4-D herbicide labels, has not previously been evaluated. We show that cover crops will be useful in suppressing grass and waterhemp densities within buffer areas but will not be effective in suppressing giant ragweed.

Residual herbicides along with 2,4-D should be used with cover crops whenever possible and can reduce the number of weeds exposed to POST applications of glyphosate and 2,4-D (Dewerff et al. 2015). We showed that the addition of 2,4-D and/or a residual provided 60 percentage points more control of horseweed and at least 26 percentage points more control of giant ragweed compared to glyphosate alone. Early summer weed biomass supports the assessments of reduced weed densities, as early summer weed biomass was also reduced by 36 percentage points compared to early termination of glyphosate or glyphosate plus 2,4-D when termination was delayed to after planting and glyphosate was used in combination with 2,4-D and a residual herbicide (data not shown).

Future research on weed control with cover crops should focus on the impact on soybean yield when terminated near or after planting in various environments. Additionally, interactions between cover crop and residual herbicide strategies used will have important implications when managing for problematic herbicide-resistant weed species.

Acknowledgments. This research received no specific grant from any funding agency or the commercial or not-for-profit sectors. No conflicts of interest have been declared.

References

Anonymous (2017) Enlist One herbicide label. Dow AgroSciences Publication Number 010-02341. Indianapolis, IN: DowAgrosciences.

Bruin JL De, Porter PM, Jordan NR (2005) Use of a rye cover crop following corn in rotation with soybean in the upper Midwest. Agron J 97:587–598

Chahal GS, Johnson WG (2012) Influence of glyphosate or glufosinate combinations with growth regulator herbicides and other agrochemicals in controlling glyphosate-resistant weeds. Weed Technol 26:638–643

Cholette TB, Soltani N, Hooker DC, Robinson DE, Sikkema PH (2018) Suppression of glyphosate-resistant Canada fleabane (*Conyza canadensis*) in corn with cover crops seeded after wheat harvest the previous year. Weed Technol 32:244–250

Christenson, AM (2015) Cover crops for horseweed (*Conyza canadensis*) control before and during a soybean crop. M.S. thesis, Kansas State University. 43 p

Cornelius CD, Bradley KW (2017) Influence of various cover crop species on winter and summer annual weed emergence in soybean. Weed Technol 31:503–513

Craigmyle BD, Ellis JM, Bradley KW (2013) Influence of weed height and glufosinate plus 2,4-D combinations on weed control in soybean with resistance to 2,4-D. Weed Technol 27:271–280

Creech JE, Ferris VR, Faghihi J, Westphal A, Santini JB, Johnson WG (2008) Influence of winter annual weed management and crop rotation on soybean cyst nematode (*Heterodera glycines*) and winter annual weeds. Weed Sci 56:103–111

Davis VM, Gibson KD, Bauman TT, Weller SC, Johnson WG (2007) Influence of weed management practices and crop rotation on glyphosate-resistant horseweed population dynamics and crop yield. Weed Sci 55:508–516

Dewerff RP, Conley SP, Colquhoun JB, Davis VM (2015) Weed control in soybean as influenced by residual herbicide use and glyphosate-application timing following different planting dates. Weed Technol 29:71–81

Dhima KV, Vasilakoglou IB, Eleftherohorinos IG, Lithourgidis AS (2006) Allelopathic potential of winter cereals and their cover crop mulch effect on grass weed suppression and corn development. Crop Sci 46:345–352

Eckert DJ (1988) Rye cover crops for no-tillage corn and soybean production. J Prod Agric 1:207–210

Evans CM, Strom SA, Riechers DE, Davis AS, Tranel PJ, Hager AG (2019) Characterization of a waterhemp (*Amaranthus tuberculatus*) population from Illinois resistant to herbicides from five site-of-action groups. Weed Technol 33:400–410

Ganie ZA, Jhala AJ (2017) Interaction of 2, 4-D or dicamba with glufosinate for control of glyphosate-resistant giant ragweed (*Ambrosia trifida* L.) in glufosinate-resistant maize (*Zea mays*). Front Plant Sci 8:1–10

Haramoto ER, Pearce R (2019) Cover crop termination treatment impacts weed suppression potential. Weed Sci 67:91–102

Hay A, Marshall M, Anita J, Dallas E, Hay MM, Dille JA, Peterson DE (2019) Management of pigweed (*Amaranthus* spp.) in grain sorghum with integrated strategies. Weed Technol 33:701–709

Heap I (2020) The international survey of herbicide resistant weeds. http://www.weedscience.org/. Accessed February 8, 2020

Hively WD, Cox WJ (2001) Interseeding cover crops into soybean and subsequent corn yields. Agron J 93:308–313

Johnson GA, Defelice MS, Helsel ZR (1993) Cover crop management and weed control in corn (*Zea mays*). Weed Technol 7:425–430

Keene CL, Curran WS, Wallace JM, Ryan MR, Mirsky SB, VanGessel MJ, Barbercheck ME (2017) Cover crop termination timing is critical in organic rotational no-till systems. Org Agric Agroecol 109:272–282

Kruger GR, Davis VM, Weller SC, Johnson WG (2010) Control of horseweed (*Conyza canadensis*) with growth regulator herbicides. Weed Technol 24:425–429

Liebl R, Simmons FW, Wax LM, Stoller EW (1992) Effect of rye (*Secale cereale*) mulch on weed control and soil moisture in soybean (*Glycine max*). Weed Technol 6:838–846

Loux MM, Dobbels AF, Bradley KW, Johnson WG, Young BG, Spaunhorst DJ, Norsworthy JK, Palhano M, Steckel LE (2017) Influence of cover crops on management of amaranthus species in glyphosate- and glufosinate-resistant soybean. Weed Technol 31:487–495

Mock VA, Creech JE, Ferris VR, Faghihi J, Westphal A, Santini JB, Johnson WG (2012) Influence of winter annual weed management and crop rotation on soybean cyst nematode (*Heterodera glycines*) and winter annual weeds: years four and five. Weed Sci 60: 634–640

Norsworthy JK, McClelland M, Griffith G, Bangarwa SK, Still J (2011) Evaluation of cereal and brassicaceae cover crops in conservation-tillage, enhanced, glyphosate-resistant cotton. Weed Technol 25:6–13

Norsworthy JK, Ward SM, Shaw DR, Llewellyn RS, Nichols RL, Webster TM, Bradley KW, Frisvold G, Powles SB, Burgos NR, Witt WW, Barrett M (2012) Reducing the risks of herbicide resistance: best management practices and recommendations. Weed Sci 60:31–62

Oerke EC (2006) Crop losses to pests. J Agric Sci 144:31–43

Reddy KN (2001) Effects of cereal and legume cover crop residues on weeds, yield, and net return in soybean (*Glycine max*). Weed Technol 15: 660–668

Reeves DW, Price AJ, Patterson MG (2005) Evaluation of three winter cereals for weed control in conservation-tillage non-transgenic cotton. Weed Technol 19:731–736

Robinson AP, Simpson DM, Johnson WG (2012) Summer annual weed control with 2, 4-D and glyphosate. Weed Technol 26:657–660

Spaunhorst DJ, Johnson WG (2017) Variable tolerance among palmer amaranth (*Amaranthus palmeri*) biotypes to glyphosate, 2,4-D amine, and premix formulation of glyphosate plus 2, 4-D choline (Enlist Duo®) herbicide. Weed Sci 65:787–797

Steckel LE, Sprague CL, Hager AG, Simmons FW, Bollero GA (2003) Effects of shading on common waterhemp (*Amaranthus rudis*) growth and development. Weed Sci 51:898–903

Teasdale JR, Beste CE, Potts WE (1991) Response of weeds to tillage and cover crop residue. Weed Sci 39:195–199

Werle R, Burr C, Blanco-Canqui H (2018) Cereal rye cover crop suppresses winter annual weeds. Can J Plant Sci 98:498–500

Yang RC (2010) Towards understanding and use of mixed-model analysis of agricultural experiments. Can J Plant Sci 90:605–627

Yenish JP, Worsham AD, York AC (1996) Cover crops for herbicide replacement in no-tillage corn (*Zea mays*). Weed Technol 10:815–821