Weed Technology 2017 31:503–513

Influence of Various Cover Crop Species on Winter and Summer Annual Weed Emergence in Soybean

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Field experiments were conducted in 2013, 2014, and 2015 in Columbia and Moberly, Missouri to determine the effects of cereal rye, Italian ryegrass, winter wheat, winter oat, crimson clover, Austrian winterpea, hairy vetch, oilseed radish, and cereal rye plus hairy vetch on winter and summer annual weed emergence in soybean. For comparison purposes, each experiment in each year included a Fall PRE, Spring PRE without residual, and Spring PRE residual herbicide programs. Cereal rye and cereal rye plus hairy vetch reduced winter annual weed emergence by 72 and 68%, respectively, but were not comparable to the Fall PRE which reduced winter annual weed emergence by 99%. The following spring, early-season waterhemp emergence was similar among treatments of cereal rye, cereal rye plus hairy vetch, and the Spring PRE residual herbicide program. In contrast, all cover crop species other than Italian ryegrass reduced late season waterhemp emergence between 21 and 40%, but were not comparable to the Spring PRE residual herbicide program, which reduced late season waterhemp emergence by 97%. All other summer annual weeds excluding waterhemp showed a similar response among cover crop and herbicide treatments. Overall, results from this experiment indicate that certain cover crops are able to suppress winter and summer annual weed emergence, but not to the extent of soil-applied residual herbicides.
Nomenclature: Austrian winter pea, *Pisum sativum* L.; cereal rye, *Secale cereale* L.; crimson clover, *Trifolium incarnatum* L.; hairy vetch, *Vicia villosa* Roth.; Italian ryegrass, *Lolium perenne* L. ssp. multiflorum (Lam.) Husnot; oat, *Avena sativa* L.; soybean, *Glycine max* (L.) Merr.; wheat, *Triticum aestivum* L.
Key words: Cover crops, pigweed, weed suppression.

In recent years, cover crop use has become increasingly common in the midwestern United States. Several species, such as Italian ryegrass, barley (*Hordeum vulgare* L.), winter oat, cereal rye, winter wheat, hairy vetch, and various clovers (*Trifolium* spp.) have been identified for their utility as cover crops and are being widely recommended (Johnson et al. 1998; Kuo et al. 1997; Teasdale and Mohler 1993; Weston 1990). Cover crops offer several agronomic benefits, such as reduced soil erosion, reduced water runoff, improved water infiltration, increased soil moisture retention, increased soil tilth, and increased organic carbon and nitrogen (Mallory et al. 1998; Sainju and Singh 1997; Teasdale 1996; Varco et al. 1999; Yenish et al. 1996). However, according to a recent United States Department of Agriculture survey (SARE 2014), farmers who plant cover crops ranked weed control as the fourth most important reason for adopting the practice. Although many studies have shown the agronomic benefits of cover crops in a corn and soybean rotation, there is still the need to quantify weed control following the termination of various winter annual cover crop species.

Cover crop residues have the ability to suppress weed growth by releasing allelopathic volatile chemicals into the weed rooting zone (Barnes and Putnam 1986; Burgos et al. 1999; Olofsdotter et al. 2002; White et al. 1989), changing microclimatic conditions, and creating a physical barrier (Ateh and Doll 1996; Collins et al. 2007; Reddy 2001; Teasdale et al 1991; Teasdale and Moehler 2000; Yenish et al. 1996). In addition, living cover crops can reduce weed density by directly competing with weeds and have a greater potential to suppress weed emergence and growth than cover crops that have been terminated prior to planting (Teasdale et al. 2007). Winter-hardy cover crop species are planted in the fall and remain alive until they are terminated the

DOI: 10.1017/wet.2017.23
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following spring prior to planting a cash crop of corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), or soybean. Under this scenario, the cover crop species will remain alive and will be in the most direct competition with winter annual weed species. Hayden et al. (2012) reported that cereal rye and hairy vetch reduced winter annual weed biomass by 95% to 98% and 71% to 91%, respectively. Previous research has also shown that cereal rye and winter wheat can reduce horseweed [*Conyza canadensis* (L.) Cronq.] emergence up to 90% and the use of a residual herbicide such as flumioxazin can provide additional control (Christenson et al. 2014; Davis et al. 2007). Thus, it is widely accepted that certain winter annual cover crop species can have a substantial suppressive impact on winter annual weeds.

In a corn and soybean production system, summer annual weeds are responsible for the majority of the economic losses because their lifecycles overlap with those of the planted crops. In the United States, crop production losses from weed interference are estimated to be as high as $33 billion annually (Pimentel et al. 2005). Therefore, the ability of cover crops to suppress summer annual weeds would be of great value in these systems. Webster et al. (2013) found that a cereal rye cover crop reduced Palmer amaranth (*Amaranthus palmeri* S. Wats) densities between cotton rows 40% to 88% in a strip tillage system, but the aggressive growth of Palmer amaranth within the cotton rows still prevented the cotton from producing lint. Similarly, cereal rye reduced total weed biomass from 60% to 90% in a three-year study where giant foxtail (*Setaria faberi* Herrm.), common lambsquarters (*Chenopodium album* L.), velvetleaf (*Abutilon theophrasti* Medik), and Pennsylvania smartweed (*Polygonum pensylvanicum* L.) were the main weeds present (Ateh and Doll 1996). Teasdale and Mohler (1993) concluded that the suppressive potential of a cover crop declines as the amount of residue decreases. The level of summer annual weed control that can be achieved with cover crops is largely dependent on the species due to the fact that some cover crops produce more biomass than others. Also, those cover crops that have a faster rate of decomposition will result in lower levels of summer annual weed control later in the season as opposed to ones that decompose more slowly (Teasdale et al. 2007).

Palmer amaranth control was less than 65% following cereal rye, winter wheat, crimson clover, hairy vetch, and cereal rye plus legume mixes; however, control increased to 87% or greater when acetochlor or fluometuron was applied in combination with these same species (Wiggins et al. 2016). Although a cover crop's ability to control summer annual weeds decreases throughout the growing season, adding a residual herbicide can provide additional late-season control.

Common waterhemp (*Amaranthus rudis* Sauer) is the most common and troublesome weed in Missouri, Illinois, and Iowa and is a significant problem in many other areas in the Midwest (Hager et al. 2000; Legleiter and Bradley 2008; Rosenbaum and Bradley 2013; Webster 2013). In addition, waterhemp can be extremely difficult to combat as a result of its extended period of emergence, rapid growth at high light intensities and temperatures, and prolific seed production (Hartzler et al. 1999; Massinga et al. 2003; Sauer 1957; Steckel et al. 2003). Waterhemp in Missouri, Iowa, and Illinois has evolved resistance to 5-enolpryuvylshikimate-3-phosphate synthase (EPSPS)-, protoporphyrinogen oxidase (PPO)-, 4-hydroxyphenylpyruvate dioxygenase (HPPD)-, photosystem II–, and acetolactate synthase (ALS)-inhibiting herbicides, and one population in Missouri is also resistant to the synthetic auxins (Heap 2015; Barlow et al. 2016; Schultz et al. 2015). Waterhemp with resistance to EPSPS, PPO, photosystem II, and ALS inhibitors has been documented in Kansas, and waterhemp with resistance to synthetic auxins and EPSPS-, HPPD-, and photosystem II–inhibiting herbicides has been documented in Nebraska (Bernards et al. 2012; Heap 2015; Shoup et al. 2003). Due to waterhemp populations that exhibit resistance to multiple sites of action and their inherent ability to display a prolonged germination period throughout the season (Horak and Loughin 2000; Sellers et al. 2003), currently one of the primary methods of waterhemp control in soybean production is through the application of PRE residual herbicides that act at multiple sites of action (Norsworthy et al. 2012).

To date, most of the research to determine the effects of cover crops on weed control has been conducted with only a few species, such as cereal rye and hairy vetch, and has often been done in organic-based systems where the use of herbicides for cover crop termination is prohibited. Additionally, there is little published research that shows the effects of cover crops on waterhemp emergence throughout the season. The objective of this research was to determine the effects of eight winter annual cover crop species on winter and summer annual weed emergence in soybean.

Materials and Methods

Site Description. Field experiments were conducted in 2013 and repeated in 2014 and 2015 in Boone County at the University of Missouri Bradford Research Center near Columbia, Missouri (38°53′53.22′′N, 92°22′14.42′′W) and in Randolph County near Moberly, Missouri (39°18′ 10.29′′N, 92°22′14.42′′W). Site selection was based on the presence of a variety of common summer annual grass and broadleaf weed species at the Columbia site and the presence of dense infestations of common waterhemp that exhibited resistance to glyphosate and ALS- and PPO-inhibiting herbicides at the Moberly site. The soil type at the Columbia site was a Mexico silt loam (fine, smectic, mesic Aeric Vertic Epiaqualfs) with 2.3% organic matter and a pH of 6.5 in 2013, 2.1% organic matter and a pH of 6.4 in 2014, and 2.2% organic matter and a pH of 6.3 in 2015. At the Moberly site, the soil was a Putnam silt loam (fine, smectitic, mesic Vertic Albaqualfs) with 2.2% organic matter and a pH of 6.3 in 2013, 1.9% organic matter and a pH of 6.3 in 2014, and 1.6% organic matter and a pH of 6.0 in 2015. Both sites were upland areas with a clay pan soil. Monthly rainfall totals and average monthly temperatures are presented in Table 1. The dates of major field operations are shown in Table 2. The experiment was conducted in a randomized complete block design with four replications of every treatment at the Columbia location and five replications of every treatment at the Moberly location. Individual plots measured 3 by 14 m in size.

Eight winter annual cover crops were planted into fields that had previously been in a corn-soybean rotation at the following seeding rates on September 11, 12, and 10 in 2012, 2013, and 2014, respectively: 'Roane' wheat at 135 kg ha^{-1}, cereal rye at 123 kg ha^{-1}, 'Marshall' Italian ryegrass at 28 kg ha^{-1}, oat at 78 kg ha^{-1}, crimson clover at 34 kg ha^{-1}, Austrian winter pea at 56 kg ha^{-1}, hairy vetch at 34 kg ha^{-1}, and 'Tillage Radish' (*Raphanus sativus* L.) at 9 kg ha^{-1}. A mix of cereal rye plus hairy vetch was also planted at 78 + 34 kg ha^{-1}. All cover crops were planted with a no-till drill (John Deere 750, Deere & Company, 1 John Deere Place, Moline, IL 61265) into fields that had previously been in soybean production. In order to compare the levels of winter and summer annual weed control provided by cover crops with the current levels of weed control that growers are accustomed to, three herbicide programs were evaluated on plots that did not have a cover crop planted. These consisted of 1) a fall treatment of glyphosate at 0.86 kg ha^{-1} plus 2,4-D ester at 0.56 kg ha^{-1} plus sulfentrazone at 0.122 kg ha^{-1} plus chlorimuron-ethyl at 0.0157 kg ha^{-1}, referred to as the fall herbicide program; 2) a spring PRE treatment of glyphosate at 1.72 kg ha^{-1} plus 2,4-D ester at 0.56 kg ha^{-1} plus sulfentrazone at 0.098 kg ha^{-1} plus cloransulam-methyl at 0.01 kg ha^{-1} followed by a POST treatment of fomesafen at 1.22 kg ha^{-1} plus *S*-metolachlor at 0.27 kg ha^{-1} applied at the V2/V3 growth stage, referred to as the spring PRE residual herbicide program; and 3) a spring PRE treatment of glyphosate at 1.72 kg ha^{-1} plus 2,4-D ester at 0.56 kg ha^{-1}, referred to as the spring PRE w/o residual herbicide program. Prior to soybean planting, all cover crops were terminated with glyphosate at 1.72 kg ha^{-1} plus 2,4-D ester at 0.56 kg ha^{-1}. The specific herbicide formulations utilized are listed in Table 3. Prior to termination, aboveground cover crop biomass within three 0.33-m^2 quadrats was harvested from each cover crop species. At each location and in all years, soybean 'MorSoy 3759N LL' with a glufosinate-resistance trait was seeded at 370,000 seeds ha^{-1} in rows spaced 76 cm apart into a no-tillage seedbed. All herbicide treatments were applied with a CO_2-pressurized backpack sprayer equipped with XR8002 flat-fan nozzle tips (TeeJet®, Spraying Systems Co, PO Box 7900, Wheaton, IL 60187) calibrated to deliver 140 L ha^{-1} at 117 kPa. Treatments were applied at a constant speed of 5 km hr^{-1}. A nontreated control that contained no herbicide application or cover crop was also included for comparison.

Treatment Evaluation and Data Collection. Each year, winter annual weed densities were determined by counting individual plants within two 0.5-m^2 quadrats in the same location in each plot just prior to the spring herbicide application. The predominant winter annual weeds evaluated in these experiments included henbit (*Lamium amplexicaule* L.), common chickweed [*Stellaria media* (L.) Vill.], and field pennycress (*Thlaspi arvense* L.). Summer

https://doi.org/10.1017/wet.2017.23 Published online by Cambridge University Press

Table 1. Monthly rainfall (mm) and average monthly temperatures (C), in comparison to the 30-yr average, in 2012 through 2015 at Bradford Research Center sites in Columbia and Moberly, Missouri.

Month and location	Rainfall[a]					Temperature[a]				
	2012	2013	2014	2015	30 yr avg	2012	2013	2014	2015	30 yr avg
	mm					C				
Columbia										
January	26	61	23	24	56	1	1	−4	0	−1
February	55	98	35	36	63	3	1	−4	−4	2
March	113	84	31	39	81	14	4	5	8	8
April	171	188	210	84	114	14	12	13	14	14
May	25	249	78	144	138	21	18	19	19	18
June	39	52	129	192	132	24	23	23	24	24
July	18	62	37	213	115	29	24	23	25	26
August	49	48	75	80	114	25	24	25	23	25
September	46	62	156	29	109	20	22	19	20	21
October	68	72	259	–	85	13	14	14	–	14
November	25	37	34	–	105	8	6	4	–	8
December	42	43	56	–	64	4	−1	3	–	1
Moberly										
January	13	73	12	21	49	0.4	−1	−6	−2	−2
February	40	94	34	44	53	3	−1	−6	−5	0
March	126	81	17	59	75	13	1	3	6	6
April	126	231	156	65	104	13	10	12	14	13
May	77	167	64	119	131	20	17	18	19	18
June	57	82	141	299	130	23	22	23	22	22
July	36	36	92	223	122	28	23	22	25	25
August	9	32	120	73	106	24	23	24	23	24
September	141	57	64	20	110	18	21	19	22	19
October	113	100	203	–	84	12	13	13	–	13
November	57	58	38	–	74	7	4	3	–	6
December	37	34	45	–	60	3	−3	2	–	−0.4

[a] 30-yr averages (1981 to 2010) obtained from NCDC (2011).

annual weed emergence throughout the season was determined by counting all weeds within two 0.5-m^2 quadrats in the same location in each plot starting 2 wk after cover crop termination and continuing every 2 wk throughout the soybean growing season. The final count was conducted when soybean reached the R2 growth stage. After each count, glufosinate was applied at 0.41 kg ha^{-1} over the entire trial area to eliminate any emerged weeds that were present during the previous 2-wk period. As waterhemp was the predominant weed in all locations and all other summer annual weeds were inconsistent, the summer annual weed emergence data were separated into waterhemp and all summer annual weeds

Table 2. Dates of major field operations.

Field operation	Date of operation			
	2012	2013	2014	2015
Cover crop seeding date	Sep 11	Sep 12	Sep 10	—
Dates of herbicide application				—
Fall PRE herbicide program	Nov 14	Nov 19	Nov 20	—
Spring PRE residual herbicide program	—	Apr 15 fb[a] Jul 12	Apr 9 fb Jun 18	Apr 8 fb May 28
Spring PRE without residual herbicide program		Apr 25	May 2	Apr 23
Dates of cover crop termination		Apr 25	May 2	Apr 23
Soybean seeding date		Jun 12	May 21	May 4

[a] Abbreviation: fb, followed by.

Table 3. Sources of materials used in the experiment.

Herbicide[a]	Trade name	Formulation	Manufacturer	Address
Sulfentrazone + cloransulam	Authority First	0.7 WG	FMC Corporation	Philadelphia, PA
Sulfentrazone + chlorimuron	Authority XL	0.7 WG	FMC Corporation	Philadelphia, PA
Fomesafen + *S*-metolachlor	Prefix	5.92 L	Syngenta	Greensboro, NC
Glufosinate	Liberty	2.3 L	Bayer CropScience	Research Triangle Park, NC
Glyphosate	Roundup Powermax	4.5 L	Monsanto	St. Louis, MO
2,4-D ester	LO-VOL 4	4 L	Tenkoz, Inc	Alpharetta, GA
Ammonium sulfate	N-Pak AMS	3.4 L	Winfield Solutions	St. Paul, MN

[a] Abbreviations: WG, water-dispersible granule; L, liquid.

other than waterhemp. The other summer annual weeds present included giant foxtail (*Setaria faberi* Herrm.), giant ragweed (*Ambrosia trifida* L.), common cocklebur (*Xanthium strumarium* L.), and common ragweed (*Ambrosia artemisiifolia* L.). Emergence data were also separated into early- and late-season totals, which were differentiated by the total weed counts made before and after the POST application of fomesafen plus *S*-metolachlor in the spring PRE residual herbicide program.

Statistical Analysis. All data were analyzed using the PROC GLIMMIX procedure in SAS (version 9.3, SAS® Institute Inc, Cary, NC). Experimental locations and replications (nested within experimental locations) were considered random effects, and herbicide treatments and cover crop species were considered fixed effects. Considering year as a random effect in the model allows inferences about treatments over a wide range of environments (Blouin et al. 2011; Carmer et al. 1989). Individual treatment differences were detected using Fisher's protected LSD at $P \leq 0.05$.

Results and Discussion

Winter Annual Weed Density Prior to Planting. Several cover crop species provided a significant reduction in winter annual weed emergence (Figure 1). The cover crop species evaluated in this research reduced winter annual weed emergence between 23% and 72% relative to the nontreated control. By comparison, the fall herbicide program provided a 99% reduction in winter annual weed emergence, which was greater than that provided by any cover crop. Cereal rye and cereal rye plus hairy

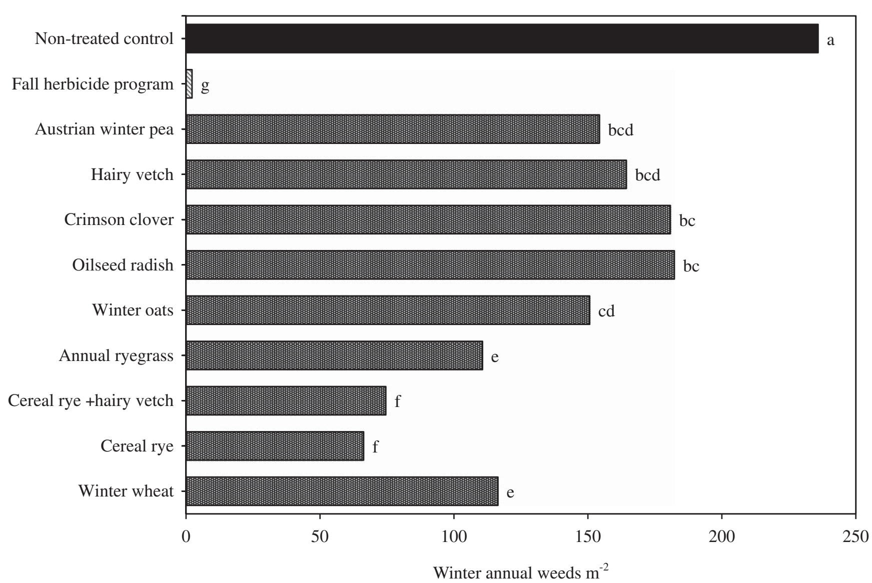

Figure 1. Influence of cover crops and herbicide treatments on total winter annual weed density across eight site-years in Missouri.

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vetch provided greater reductions (68% to 72%) in winter annual weed emergence than any other cover crop species evaluated. The ability of cereal rye or cereal rye plus legume mixes to reduce winter annual weed emergence has been reported elsewhere (Hayden et al. 2012; Teasdale et al. 2007; Teasdale and Moehler 1993). Hayden et al. (2012) reported up to an 89% reduction in winter annual weed emergence with a cereal rye plus hairy vetch cover crop mix. Living cereal rye is known to exude phytotoxic allelopathic compounds that are broadly defined as benzoxazinones, but more specifically dihydroxy-1,4(2*H*)-benzoxazin-3-one (DIBOA) and its breakdown product 2(3*H*)-benzoxazolinone (BOA) (Barnes et al. 1987).

Relative to cereal rye and cereal rye plus hairy vetch, Italian ryegrass and winter wheat provided the next highest level of winter annual weed reduction at 53% and 50%, respectively. Austrian pea, hairy vetch, crimson clover, oilseed radish, and winter oat all provided similar levels of winter annual weed reduction, which ranged from 23% to 36%. The lower suppressive potential observed from leguminous compared to cereal grain cover crops is consistent with results from Putnam and Duke (1978), who reported that leguminous cover crops produce allelopathic compounds in much smaller amounts than do cereal grains. Winter oat and oilseed radish were not able to overwinter in these experiments (Table 4), which explains why winter annual weed density was higher in these treatments compared to the other species evaluated. However, both species reduced winter annual weed emergence compared to the nontreated control; more than likely due to direct competition with fall-emerging winter annual weed species. In addition, *Brassica* species like oilseed radish are known to produce glucosinolates that are released once plant tissue begins to decompose (Brown and Morra 1996). Therefore, in climates where oilseed radish is not able to overwinter, its greatest potential for weed suppression may not be fully realized because decomposition occurs at a time when there is little or no weed emergence. In this research, we attribute the higher level of winter annual weed suppression with cereal rye, winter wheat, and Italian ryegrass compared to Austrian winter pea, hairy vetch, crimson clover, oilseed radish, and winter oats to the following factors: faster emergence and growth, better winter hardiness, greater percent ground cover, and most likely higher levels of allelopathic compounds like benzoxazinones.

Waterhemp Emergence. Cereal rye reduced early-season waterhemp emergence by 35% relative to that of the nontreated control, which is similar to the levels of reduction provided by the spring PRE residual and fall herbicide programs, which both reduced early-season waterhemp emergence by 26% (Figure 2). It is expected that a higher reduction of waterhemp emergence would typically occur with a spring PRE residual treatment, but since these applications were made in early- to mid-April and soybean planting didn't take place until May to June

Table 4. Aboveground biomass (kg ha^{-1}) and height (cm) of cover crop species at the time of termination in Columbia and Moberly, Missouri.

	Columbia								Moberly			
	Dry weight				Height				Dry weight		Height	
Species	2013	2014a [a]	2014b	2015	2013	2014a	2014b	2015	2014	2015	2014	2015
	kg ha^{-1}				cm				kg ha^{-1}		cm	
Wheat	1,431	1,845	1,152	804	20–28	25–32	18–24	25–30	1,056	2,253	20–30	20–30
Cereal rye	2,892	2,445	1,941	1,149	55–60	48–54	50–55	35–50	1,386	3,930	65–75	40–55
Italian ryegrass	1,179	873	384	768	15–20	8–12	5–8	18–24	282	2,232	15–25	25–34
Winter oat	612	102	96	0	10–15	5–10	4–6	0	0	0	0	0
Crimson clover	318	339	348	1,074	12–18	8–12	10–15	28–34	0	534	0	20–25
Hairy vetch	1,356	1,527	270	165	12–16	25–35	5–9	15–25	6	1,566	5–8	20–30
Cereal rye/ Hairy vetch	2,481	2,712	1,554	3,015	50–60/ 20–30	65–75/ 22–32	40–50/ 15–20	45–60/ 20–26	1,839	5,040	75–85/ 8–15	45–55/ 14–21
Austrian winter pea	915	273	81	0	15–22	10–15	5–8	0	0	66	0	12–17
Oilseed radish	0	0	0	0	25–32	0	0	0	0	0	0	0

[a] Two separate trials were conducted in Columbia in 2014, designated with the letters *a* and *b*.

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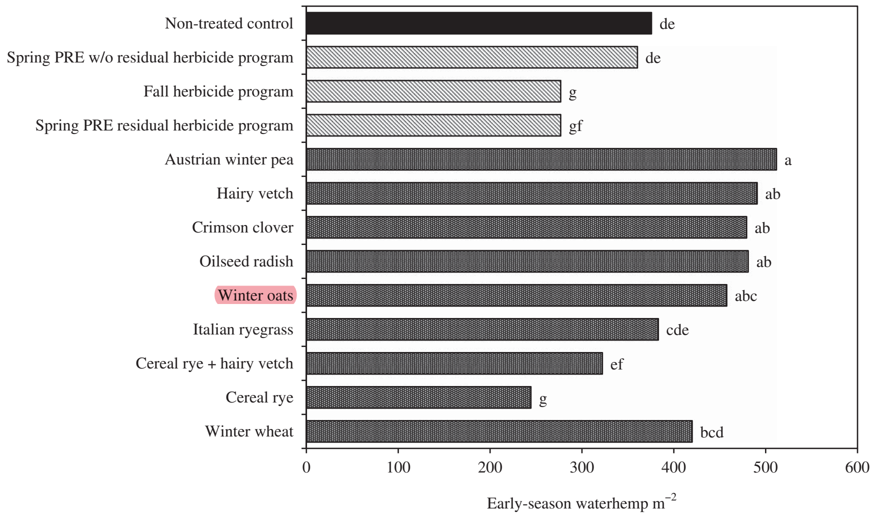

Figure 2. Influence of cover crops and herbicide treatments on early-season waterhemp emergence across eight site-years in Missouri.

(Table 2), this level of control is not unusual. For example, Meyer et al. (2016) observed less than 40% control of waterhemp 5 wk after treatment with several PRE residual herbicides commonly utilized in soybean. All other cover crop species did not reduce early season waterhemp emergence relative to the nontreated control. In fact, Austrian winter pea, hairy vetch, crimson clover, oilseed radish, and winter oat increased early season waterhemp emergence by 36%, 31%, 28%, 28%, and 22%, respectively. Legume cover crops such as Austrian winter pea, hairy vetch, and crimson clover biologically fix atmospheric nitrogen that subsequently becomes available during residue decomposition (Sainju and Singh 1997; Varco et al. 1999). Thus, the increased waterhemp emergence in these cover crop treatments is likely because of greater soil nitrogen availability. As previously reported, oilseed radish and winter oat did not overwinter, which resulted in less residue on the soil surface to impede waterhemp emergence (Table 4), resulting in higher densities of waterhemp. In addition, the nontreated control had more ground cover as a result of dense winter annual weed cover (236 g m^{-2}) in comparison to oilseed radish and winter oat (Table 4).

Italian ryegrass, winter wheat, cereal rye plus hairy vetch, and the spring PRE w/o residual herbicide program each resulted in early-season waterhemp emergence similar to that seen in the nontreated control.

In the case of late-season waterhemp emergence, cereal rye provided a 40% reduction, but neither cereal rye nor any other winter cover crop was comparable to the spring PRE residual herbicide program, which provided a 97% reduction in late-season waterhemp emergence (Figure 3). Although cereal rye provided some reduction in late-season waterhemp emergence, its effect was statistically similar to that of all other cover crops except Italian ryegrass. Compared to the residual herbicide treatments, cereal rye exhibited a similar level of waterhemp suppression early in the soybean growing season, but the suppressive potential decreased as the season progressed. These results are similar to those described by Webster et al. (2013), who showed that Palmer amaranth densities increased by 43% from early June to late July within plots that contained a cereal rye cover crop.

Summer Annual Weed Emergence Excluding Waterhemp. Overall the trends in emergence of other summer annual weeds were similar to that observed with waterhemp (Figures 4 and 5). Cereal rye and cereal rye plus hairy vetch reduced early-season summer annual weed emergence by 41% and 24%, respectively, which was similar to the effect of the spring PRE residual and fall herbicide programs. In contrast to waterhemp emergence, the only cover crop that increased summer annual weed emergence compared to the nontreated control was Austrian winter pea, which increased early-season summer annual weed emergence by 22%. This may be due to a nitrogen contribution from the cover crops, as explained previously. Italian ryegrass, winter oat, oilseed radish, crimson clover, and hairy vetch all resulted in early-season summer annual weed

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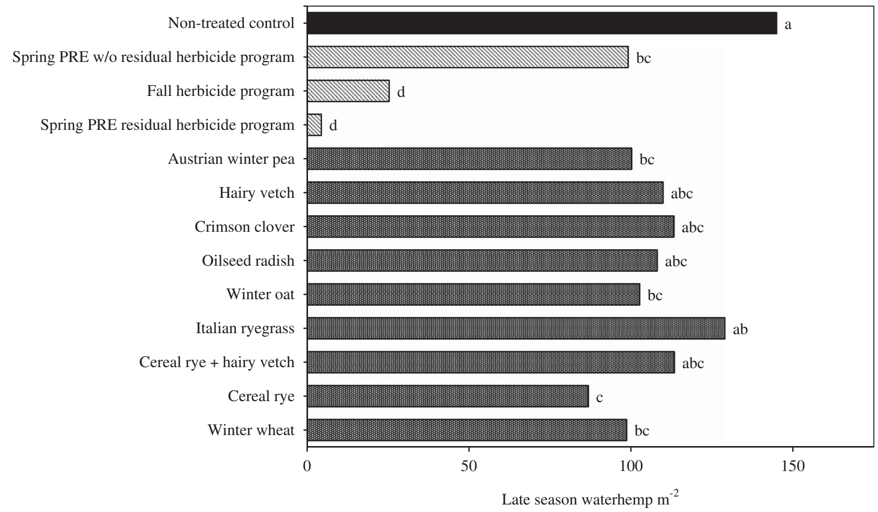

Figure 3. Influence of cover crops and herbicide treatments on late-season waterhemp emergence across eight site-years in Missouri.

emergence similar to that of the nontreated control. Much like what was observed with waterhemp, late-season summer annual weed emergence was reduced by 42% in response to cereal rye, but did not compare to the spring PRE residual herbicide program, which reduced late-season summer annual weed emergence by 93%. Winter wheat, cereal rye plus hairy vetch, Italian ryegrass, winter oat, oilseed radish, crimson clover, and hairy vetch each resulted in late-season summer annual weed emergence that was similar to that seen with the nontreated control.

These results indicate that cereal rye, Italian ryegrass, winter wheat, winter oat, crimson clover, Austrian winter pea, hairy vetch, oilseed radish, and cereal rye plus hairy vetch are each able to provide some degree of winter annual weed suppression, but that only certain cover crop species, such as cereal rye or cereal rye plus legume mixes, are able to provide reductions in early-season summer annual weed emergence similar to those seen with the residual herbicide programs. In addition, no cover crops were able to reduce late season weed emergence to the same degree as a residual herbicide program. This may be due to the lower levels of cover crop biomass accumulated in this study (Table 4) compared to those seen in other studies where cover crop

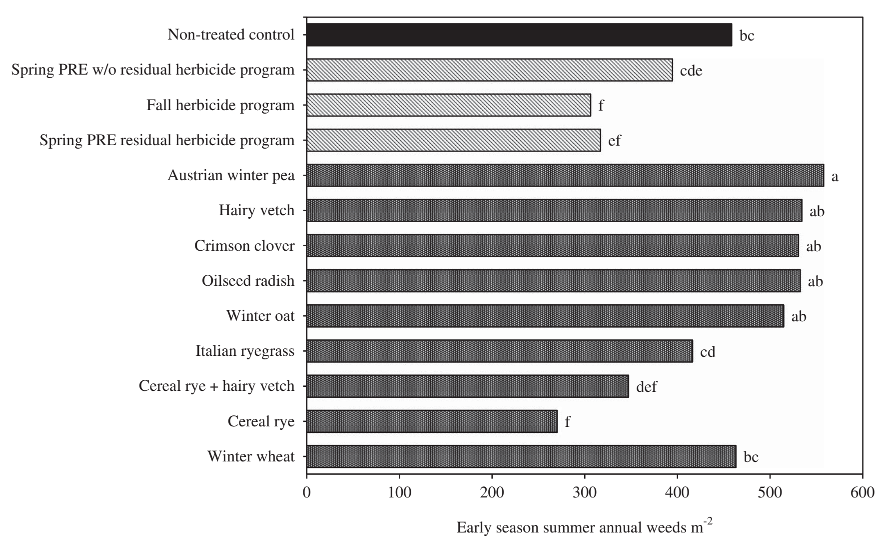

Figure 4. Influence of cover crops and herbicide treatments on early-season summer annual weed emergence, excluding waterhemp, across eight site-years in Missouri.

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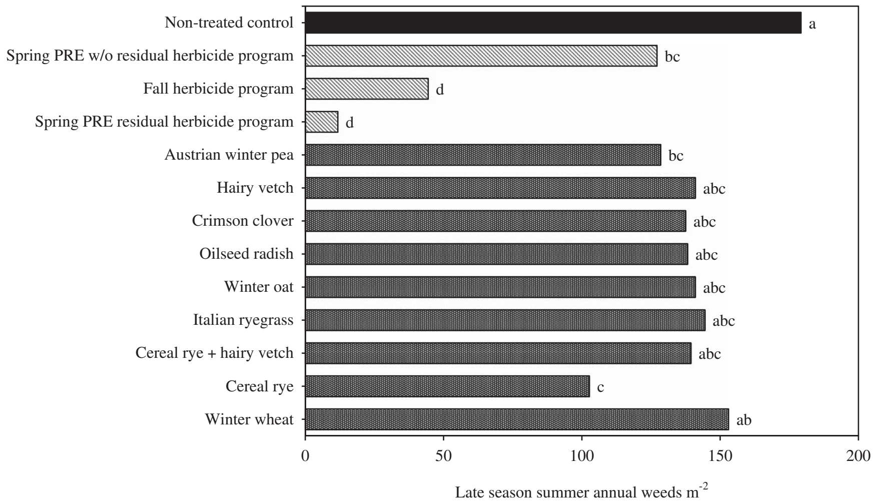

Figure 5. Influence of cover crops and herbicide treatments on late-season summer annual weed emergence, excluding waterhemp, across eight site-years in Missouri.

termination occurred later in the season, closer to cash crop planting, and/or was conducted using a roller-crimper (Ateh and Doll 1996; Mirsky et al. 2011; Reddy 2001; Webster et al. 2013). However, this research was conducted to determine how cover crops might fit in current soybean production systems without major modifications, and the levels of cover crop biomass reported here are consistent with those reported in similar studies recently conducted in Tennessee (Wiggins et al. 2016; Wiggins et al. 2015). Teasdale and Moehler (1993, 2000) reported that residue from cereal rye decomposes more slowly than residue from leguminous cover crops such as hairy vetch. Therefore, the longer persistence of weed suppression observed with cereal rye may be at least partially due to a higher persistence of residue into the soybean growing season compared with that observed with other cover crop species. Cereal rye also provided some degree of late-season waterhemp and other summer annual weed suppression, but there is a need for the integration of additional management strategies to combat late season weed flushes. These results are also consistent with those reported by Smith et al. (2011), who showed that 9000 $kg\,ha^{-1}$ of cover crop biomass is needed for substantial reduction in summer annual weed emergence. Additional research is also needed to determine the response of summer annual weeds to high-residue cover crops in combination with a residual herbicide program.

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Received July 12, 2016, and approved March 11, 2017.

Associate Editor for this paper: Aaron Hager, University of Illinois.