Weed Science

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An Early-Killed Rye (*Secale cereale*) Cover Crop Has Potential for Weed Management in Edamame (*Glycine max*)

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Weed Management

Cite this article: Crawford LE, Williams MM, Wortman SE (2018) An Early-Killed Rye (*Secale cereale*) Cover Crop Has Potential for Weed Management in Edamame (*Glycine max*). Weed Sci. doi: 10.1017/wsc.2018.5

Received: 11 October 2017
Accepted: 11 January 2018

Associate Editor:
Timothy L. Grey, University of Georgia

Key words:
Crop emergence; integrated weed management; weed suppression

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Abstract

The potential role of fall-seeded cover crops for weed management in edamame [soybean, *Glycine max* (L.) Merr.] is unknown. Field experiments were conducted over three edamame growing seasons to (1) determine the extent to which cover crop–residue management systems influence edamame emergence while selectively suppressing weed density and biomass, and (2) determine whether cultivars differed in emergence in cover crop–residue management systems. Cover crop treatments included a winter-killed oilseed radish (*Raphanus sativus* L.), two canola (*Brassica napus* L.) treatments (early-killed and late-killed), two cereal rye (*Secale cereale* L.) treatments (early-killed and late-killed), and a bare-soil control. Two spring timings of a cover crop burndown application created the early-killed and late-killed treatments for canola and cereal rye. Twelve soybean cultivars were tested, including 11 edamame cultivars differing in seed size and a grain-type soybean control. Spring residue biomass in cover crop treatments ranged from 438 kg ha^{-1} for winter-killed radish to 9,003 kg ha^{-1} for late-killed cereal rye. Cultivars responded similarly to cover crop treatments, and with the exception of late-killed cereal rye, cover crop treatments resulted in similar crop emergence as the bare-soil control. While all cover crop treatments reduced weed biomass 6 wk after planting compared with the bare soil, winter-killed radish and both canola treatments increased weed density. Early-killed cereal rye has potential for weed management in edamame, as evidenced by the fact that the treatment did not interfere with planting or crop establishment, yet reduced weed density 20% and suppressed early-season weed growth 85%.

Introduction

Certain U.S. vegetable growers and processors are working toward producing edamame [soybean, *Glycine max* (L.) Merr.] on a commercial scale to address consumer demand for domestically grown product. Initially, weed interference was identified as a major obstacle to domestic production. Some herbicides have since been registered for use on edamame (Williams and Nelson 2014), and the vegetable industry now has nascent weed management systems in the crop (Williams 2015a). Further development of integrated weed management (IWM) systems are needed, particularly IWM systems that combat herbicide resistance by taking greater advantage of biological, cultural, and physical weed management tactics (Harker and O'Donovan 2013).

Several fall-seeded cover crops suppress weed density and biomass through biological (e.g., seed predation), chemical (e.g., allelopathy), and physical (e.g., light interception) mechanisms (Wortman et al. 2013). Cover crop residues have been examined for their weed management contributions in no-till grain-type soybean for decades (Liebl et al. 1992; Moore et al. 1994). Dense residues from cover crops such as cereal rye (*Secale cereale* L.) reduce preplant weed emergence and biomass in excess of 90% (Forcella 2013). Even low levels of certain residues, including cereal rye and oilseed radish (*Raphanus sativus* L.) provide early-season benefits to weed management (Moore et al. 1994; Ryan et al. 2011). However, cover crops can also lower soybean stand and yield by reducing available soil moisture or interfering with seedling establishment (Davis 2010; Forcella 2013). Moreover, dense cover crop residues can interfere with crop-planting equipment and reduce crop emergence (Forcella 2013).

Edamame are larger seeded than grain-type soybean and can exhibit low crop emergence (Duppong and Hatterman-Valenti 2005; Sánchez et al. 2005). Regardless of weed-suppressive benefits, cover crop residues would not be a viable management tactic if they further compromised edamame emergence. Currently, the potential role of fall-seeded cover crops for weed management in edamame is unknown. Therefore, the first objective of this study was to determine the extent to which cover crop–residue management systems influence edamame emergence while selectively suppressing weed density and biomass. Because seed size of edamame is not only larger

Table 1. Details of cover crop treatments and cultural practices in field trials near Urbana, IL across 2014–2016 edamame growing seasons.

Cover crop treatment	Cultivar	Seeding rate	Seeding method	Planting date	Kill date[a]
		kg ha^{-1}			
Winter-killed radish	‘CCS-779’	6.7	Hand[b]	August 27, 2013 September 23, 2014 September 8, 2015	November 23, 2013 November 12, 2014 December 31, 2015
Early-killed canola	‘Kronos’	6.7	Hand[b]	August 27, 2013 September 23, 2014 September 8, 2015	April 17, 2014 April 17, 2015 April 5, 2016
Early-killed rye	‘HiRye 500’	161.4	Drill	September 11, 2013 September 25, 2014 September 25, 2015	April 17, 2014 April 17, 2015 April 5, 2016
Late-killed canola	‘Kronos’	6.7	Hand[b]	August 27, 2013 September 23, 2014 September 8, 2015	May 5, 2014 May 6, 2015 April 15, 2016
Late-killed rye	‘HiRye 500’	161.4	Drill	September 11, 2013 September 25, 2014 September 25, 2015	May 5, 2014 May 6, 2015 April 15, 2016

[a] For radish, winter-killed dates are based on first occurrence of four consecutive nighttime temperatures ≤3.9 C (Weil et al. 2009). For all other treatments, dates are when glyphosate was applied at a rate of 1,094 g ae ha^{-1}.

[b] Planted using an adjustable hand seeder followed by incorporation with a two-gang cultipacker.

than grain-type soybean, but also more variable among cultivars, the second objective was to determine whether cultivars differed in their emergence in cover crop–residue management systems.

Materials and Methods

Experimental Design

A field experiment was conducted at the University of Illinois Vegetable Crop Farm near Urbana, IL (40.076623 N, −88.239866 W), for edamame growing seasons in 2014 to 2016. Different fields were used each year. The soil was a Flanagan silt loam (fine, smectitic, mesic Aquic Argiudolls) with an average organic matter content of 3.4% and an average pH of 5.9. The previous crop of each field was grain-type soybean.

The experiment was a split-plot randomized complete block design with three replications. Main plots were assigned one of six fall-seeded cover crop–residue management systems, hereafter simply called “cover crop treatments,” including a bare-soil control. Cover crops were planted with hand and drill planters in late summer in 2013 to 2015, after the previous crop was harvested (Table 1). Cover crop treatments were selected to create a gradient of residues at planting and included one radish treatment (due to winterkill, a low-residue treatment), two canola (*Brassica napus* L.) treatments (i.e., early-killed and late-killed canola; medium-residue treatments), and two cereal rye treatments (early-killed and late-killed cereal rye; high-residue treatments; Table 1). Different timings of a burndown application with glyphosate (Roundup WeatherMax®, 1,094 g ae ha^{-1}, Monsanto, St Louis, MO) were used to create early-killed and late-killed treatments. Main plots measured 36 m^2. Subplot treatments were assigned one of 12 soybean cultivars and included 11 edamame cultivars and one grain-type soybean cultivar (Table 2). Selection of edamame cultivars was based on seed availability of the more commonly used cultivars among commercial growers in the United States. Each subplot consisted of one 2.5-m row of 64 crop seeds. There was an inadequate supply of edamame seed for the larger plots necessary for accurately measuring crop yield.

The entire study area was sprayed with a burndown application of glyphosate at 1,094 g ae ha^{-1} 1 wk before planting to kill emerged weeds; this application was in addition to the cover crop kill application in cereal rye and canola. All cultivar seeds were treated with mefenoxam (3.37 g per 100 kg seed) and fludioxonil (2.27 g per 100 kg seed; Apron Maxx, Syngenta Crop Protection, Greensboro, NC) fungicides before planting. Cultivars were direct seeded into cover crop treatments using a no-till cone planter on May 27, 2014, May 28, 2015, and May 23, 2016.

Weeds emerging in the experiment were from the naturally occurring soil seedbank. Aside from suppression provided by cover crop residues and crop interference, no other weed management tactic was applied after crop planting.

Data Collection

Aboveground plant residues were measured 3 d before cultivar planting by harvesting two 0.5-m^2 areas from each main plot. Weeds present before planting were included in the cover crop residue biomass sampling, because it was difficult to distinguish preplant weed biomass from cover crop biomass; however, weed occurrence was minimal at the sampling time, given it was early in the growing season and there had been at least one burndown application of glyphosate, even in the no-cover crop treatments. In each main plot, five 2.0-cm-diameter soil cores also were taken from a depth of 20 cm the day before edamame planting. Soil cores were composited by main plot, and soil moisture was determined gravimetrically.

The 100-seed mass and germination of cultivar seed lots were determined before planting. After planting, cultivar emergence was assessed daily across each subplot until all plants had at least one fully emerged trifoliate leaf. Weed emergence by species was assessed weekly in four randomly placed, permanent 0.25-m^2 quadrats within main plots until 6 wk after planting. Weed seedlings were immediately removed from the permanent quadrats after species emergence was assessed. At 6 wk after planting, total aboveground weed biomass of each main plot was sampled from 1-m^2 sampling areas. Weeds were sorted by species, dried to constant mass, and weighed. Because the objectives of this study focused on cultivar emergence and early-season weed density and biomass, the study was terminated 6 wk after planting. Growth

Table 2. Germplasm information for 1 soybean and 11 edamame cultivars used in each year of the study.

Soybean type	Cultivar	100-seed mass	Germination	Source
		g	%	
Grain-type	'Asgrow AG-3253'	18.8	97	Asgrow, St Louis, MO
Edamame	'AGS 292'	32.7	90	Washington State University, Pullman, WA
	'BeSweet 292'	30.4	92	Rupp Seeds, Wauseon, OH
	'Gardensoy 11'	22.4	92	University of Illinois, Urbana, IL
	'Gardensoy 42'	28.4	81	University of Illinois, Urbana, IL
	'IA 1010'	25.9	86	Iowa State University, Ames, IA
	'IA 2076'	23.6	90	Iowa State University, Ames, IA
	'Misono Green'	26.7	86	Snow Brand Seed USA, Portland, OR
	'Mojo Green'	23.8	85	Wannamaker Seeds, Saluda, NC
	'Sunrise'	24.9	83	Wannamaker Seeds, Saluda, NC
	'WSU 729'	24.5	91	Washington State University, Pullman, WA
	'WSU 910a'	28.5	88	Washington State University, Pullman, WA

responses beyond 6 wk after planting were at risk of being confounded by the single-row cultivar subplots.

Data Analysis

Data were analyzed with ANOVA in SAS (v. 9.4, SAS Institute, Cary, NC) using PROC MIXED. Data met assumptions of normality, equality of variance, and independence based on residual analysis (Hox 2002). Two ANOVA models were used. Cover crop treatment was the fixed effect in the ANOVA model used to analyze cover crop biomass, soil moisture, weed emergence, and weed biomass data. Both cover crop and cultivar were fixed effects in the ANOVA model used to analyze crop emergence data. Year and replicate nested within year were treated as random effects in both models after initial analysis, as a fixed effect revealed no significant or biologically meaningful interactions with treatment effects. Main effects and interactions (when appropriate) were examined. Treatment comparisons were made using a protected Tukey's means separation test at $\alpha = 0.05$.

Results and Discussion

Cover Crops

The goal of creating a gradient of cover crop residues was accomplished. Differences in residue biomass were observed among cover crop treatments before crop planting ($P < 0.001$). Few preplant weeds were observed at glyphosate application, as evidenced by the bare-soil control averaging 43 kg ha^{-1} of plant residue. Residue biomass in other cover crop treatments ranged from 438 kg ha^{-1} for winter-killed radish to 9,003 kg ha^{-1} for late-killed cereal rye (Table 3). Cover crop biomass levels were comparable with results reported in previous research in the upper Midwest (Davis 2010; Hill et al. 2016).

Cover crop treatments influenced soil moisture at the time of planting. Soil moisture of late-killed cereal rye was highest, followed by early-killed cereal rye. All other cover crop treatments were comparable in soil moisture with the bare-soil treatment (Table 3). This result suggests that cover crop growth during the fallow season did not deplete surface soil moisture reserves and that the greater surface residue provided by cereal rye served to reduce evaporative soil water loss between cover crop killing and planting. Elevated soil moisture in a cereal rye cover crop, relative to bare soil, is common in central Illinois but varies regionally with soil physical properties and weather (Davis 2010; Haramoto and Brainard 2012).

Table 3. Average decaying cover crop–residue biomass 3 d before planting and average gravimetric soil water content 1 d before planting in field trials near Urbana, IL, across 2014–2016 edamame growing seasons.[a]

Cover crop treatment	Residue biomass	Gravimetric soil water content
	kg ha^{-1}	%
Bare soil	43 d	16.0 c
Winter-killed radish	438 d	16.0 c
Early-killed canola	1,205 c	16.0 c
Early-killed rye	2,375 b	18.2 b
Late-killed canola	2,360 b	16.1 c
Late-killed rye	9,003 a	19.6 a

[a] Values followed by different letters are significantly different at $\alpha = 0.05$ based on a protected Tukey's means separation test.

Crop Emergence

Crop emergence varied with both cover crop treatment and cultivar ($P < 0.001$); however, there was no interaction ($P = 0.993$). Therefore, while emergence differed among cultivars, their responses to cover crop treatments were similar.

With one exception, cover crop treatments resulted in similar total crop emergence as the bare-soil control, which was 71.1% (Table 4). Crop emergence in the late-killed cereal rye treatment was only 38.5%. The late-killed cereal rye treatment could have lowered soybean emergence by several mechanisms. Poor seed to soil contact is a common problem when planting into high levels (≥6,000 kg ha^{-1}) of cover crop residues (Forcella 2013). Despite efforts to optimize planter performance in the present study, approximately 30% of crop seed in the late-killed cereal rye treatment was observed within cereal rye residue on the soil surface. The high level of residue in the late-killed cereal rye treatment (averaging 9,003 kg ha^{-1}) resulted in poor seed-to-soil

Table 4. Average crop emergence as influenced by cover crop treatment and cultivar 3 wk after planting in field trials near Urbana, IL, across 2014–2016 edamame growing seasons, with significance (P value) of main effects and their interaction included.

Factor	Level	Emergence[a]
		%
Cover crop	Bare soil	71.1 ab
	Winter-killed radish	74.5 a
	Early-killed canola	74.3 a
	Early-killed rye	66.5 b
	Late-killed canola	69.3 b
	Late-killed rye	38.5 c
	P value	<0.001
Cultivar	‘Asgrow AG-3253’	74.8 a
	‘AGS 292’	64.8 ab
	‘BeSweet 292’	64.7 ab
	‘Gardensoy 11’	68.4 ab
	‘Gardensoy 42’	60.1 b
	‘IA 1010’	71.1 ab
	‘IA 2076’	66.1 ab
	‘Misono Green’	61.0 b
	‘Mojo Green’	63.5 b
	‘Sunrise’	66.7 ab
	‘WSU 729’	71.1 ab
	‘WSU 910a’	56.1 b
	P value	<0.0001
Cover*cultivar	P value	0.993

[a] Within a response variable, values followed by different letters are significantly different at $\alpha = 0.05$ based on a protected Tukey’s means separation test.

contact and was likely the primary mechanism reducing crop emergence in that treatment. Similar cereal rye–residue planting interference has been observed in other crops, including cotton (*Gossypium hirsutum* L.) (Kornecki et al. 2009) and corn (*Zea mays* L.) (Lawley et al. 2011). Additional mechanisms by which cover crop residues reduce crop emergence include increased seed predation, reduced available light for seedling growth, increased allelopathic chemical concentrations in the seed zone, and physical interference (Forcella 2013; Moore et al. 1994; Wortman et al. 2013).

Four edamame cultivars, specifically ‘Gardensoy 42,’ ‘Misono Green,’ ‘Mojo Green,’ and ‘WSU 910a,’ had lower emergence than the grain-type cultivar, ‘Asgrow AG-3253’ (Table 4). Edamame emergence as low as 35% is not uncommon in field trials (Duppong and Hatterman-Valenti 2005; Sánchez et al. 2005; Williams 2015b). In the present study, edamame emergence ranged from 56.1% to 71.1% when averaged across all cover crop treatments (Table 4). Weather conditions were favorable after planting and may have accounted for the higher crop emergence than in previous edamame research. For instance, spring air temperatures were well above the minimum 12 C needed for soybean germination, and precipitation was above the 30-yr average, indicating cold stress, drought stress, and soil crusting were unlikely during crop germination and emergence (Figure 1).

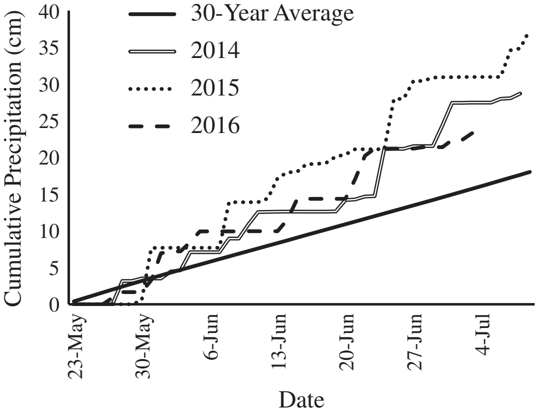

Figure 1. Cumulative daily precipitation by year, including the 30-yr average, from planting until the end of the experiment.

Weed Density

Predominant weed species included common lambsquarters (*Chenopodium album* L.), common purslane (*Portulaca oleracea* L.), common waterhemp [*Amaranthus rudis* (Moq.) J. D. Sauer], Palmer amaranth (*Amaranthus palmeri* S. Watson), and velvetleaf (*Abutilon theophrasti* Medik.). To minimize misidentification of newly emerged seedlings, *A. rudis* and *A. palmeri* were combined into an “*Amaranthus* species” group. In addition, a few other species were infrequently observed (Table 5). *Portulaca oleracea* accounted for 79% to 89% of emerged weeds in cover crop treatments with one exception; in the late-killed cereal rye treatment, *P. oleracea* accounted for only 52% of emerged weeds (Table 5).

Total weed density varied across cover crop treatments. Weed density in cover crop treatments, ranked low to high, were late-killed cereal rye < early-killed cereal rye < bare soil < winter-killed radish < early-killed canola < late-killed canola (Table 5). The bare-soil treatment had an average weed density of 96.0 weeds m^{-2}. Weed densities in the winter-killed radish, early-killed canola, and late-killed canola treatments were an average of 17.4, 50.2, and 74.8 weeds m^{-2} higher, respectively. There are several possible explanations for the higher weed emergence in the winter-killed radish and the two canola treatments compared with the bare-soil treatment. Although there were no significant soil moisture differences between radish, canola, and bare-soil treatments at crop planting, soil moisture is dynamic, and there may have been other times (not sampled) when soil moisture was more favorable for weed emergence in the radish and canola treatments compared with the bare-soil treatment. Haramoto and Brainard (2012) report that nonincorporated oat (*Avena sativa* L.) cover crop residues can increase soil moisture relative to incorporated oat residues. Surface residues of radish and canola may have increased water infiltration and reduced evaporation from the soil surface, thereby conserving soil moisture relative to the bare-soil treatment and favoring weed seed germination.

The high weed density in the canola treatment was surprising, because a meta-analysis on *Brassica* cover crops such as canola found that incorporated *Brassica* residues produce allelochemicals that suppress weed emergence, but the effects were variable across environments and were short-lived (Haramoto and Gallandt 2004). Given that canola residues in the present study were not incorporated and that weed density was not measured until several weeks after canola cover crop termination, it is unlikely

Table 5. Effect of cover crop treatment on average total weed density, species-specific weed density, and total weed biomass in field trials near Urbana, IL, across 2014–2016 edamame growing seasons.[a]

Cover crop treatment	Total weed density	Species-specific weed density[b]						Total weed biomass
		POROL	AMARA	ABUTH	CHEAL	GRASS	OTHER	
	——————————No. m^{-2}——————————							kg ha^{-1}
Bare soil	96.0 d	85.8 c	2.0 d	0.8 b	0.2 c	1.8 b	5.4 c	1,554 a
Winter-killed radish	113.4 c	92.3 c	11.2 a	1.0 b	0.6 b	1.8 b	6.4 bc	1,164 b
Early-killed canola	146.2 b	124.6 b	9.1 b	1.8 a	0.4 bc	2.2 b	8.1 b	983 b
Early-killed rye	77.7 e	61.2 d	5.0 c	1.2 b	0.2 c	2.2 b	7.8 bc	226 d
Late-killed canola	170.8 a	146.3 a	5.0 c	0.9 b	1.0 a	4.4 a	13.1 a	548 c
Late-killed rye	7.3 f	3.8 e	1.0 d	0.0 c	0.4 bc	0.4 c	1.7 d	104 d

[a] Within a column, means followed by different letters are significantly different at $\alpha = 0.05$ based on a protected Tukey's means separation test.

[b] Species abbreviations: ABUTH, velvetleaf (*Abutilon theophrasti* Medik.); AMARA, *Amaranthus* spp., including common waterhemp [*Amaranthus rudis* (Moq.) J. D. Sauer], and Palmer amaranth (*Amaranthus palmeri* S. Watson); CHEAL, common lambsquarters (*Chenopodium album* L.); GRASS includes all grass species; OTHER includes infrequent observations of carpetweed (*Mollugo verticillata* L.), dandelion (*Taraxacum officinale* F. H. Wigg), horseweed (*Erigeron canadensis* L.), kochia [*Bassia scoparia* (L.) A. J. Scott], and Venice mallow (*Hibiscus trionum* L.); POROL, common purslane (*Portulaca oleracea* L.).

allelopathy would have been observed, even if it had played a role in this study. Soil nitrogen also could affect weed density results. Decomposing cereal rye residues typically reduce soil nitrogen availability, which suppresses weed emergence (Hill et al. 2016). However, radish residues, which may also reduce soil nitrogen availability, have shown mixed effects on weed emergence. Hill et al. (2016) reported that decomposing radish residues suppressed weed emergence, but Belfrey et al. (2017) and Lawley et al. (2012) reported that, under certain conditions, radish residues, on the surface or incorporated into the soil, stimulated early spring (January to March) emergence of common chickweed [*Stellaria media* (L.) Vill.], *C. album*, common ragweed (*Ambrosia artemisiifolia* L.), and redroot pigweed (*Amaranthus retroflexus* L.). Both Belfrey et al. (2017) and Lawley et al. (2012) hypothesized the stimulatory effect of radish on weed emergence was due to the higher soil nitrate levels relative to the control treatment. Lawley et al. (2012) found that soil nitrate levels in the radish treatments were more than three times higher than the nitrate levels in the control treatment. Perhaps soil nitrate released from decomposing winter-killed radish residues in the present study contributed to increased weed emergence relative to bare soil.

Cover crop treatments that stimulate in-crop weed emergence would be problematic, in part because herbicide efficacy declines with weed density under certain conditions. Myers et al. (2005) reported that crop and weed plants with more biomass can interfere with herbicide coverage, potentially blocking herbicide delivery to small plants. As such, positive correlations have been observed between weed density and herbicide failure (Scursoni et al. 2007). Moreover, positive relationships between soybean yield loss and weed density are well documented (Zimdahl 2004).

Both cereal rye treatments suppressed weed density relative to bare soil. The weed densities in the early-killed and late-killed cereal rye treatments were 18.3 and 88.7 weeds m^{-2} lower, respectively, than the bare-soil treatment. There are several possible reasons for lower weed density in cereal rye treatments. The late-killed cereal rye treatment had three times or more greater surface residue than all other cover crop treatments. Several studies report a negative relationship between residue biomass and weed emergence (Price et al. 2016; Ryan et al. 2011). However, the amount of residue at crop planting does not fully account for differences in weed emergence among cover crop treatments in the present study; early-killed cereal rye and late-killed canola had similar biomass before crop planting, yet very different weed densities. The cereal rye treatments resulted in a thick, generally uniform, residue mat. In contrast, canola treatments resulted in standing stems and scattered leaves that decomposed quickly. Differences in residue pattern and persistence may have accounted for some of the differences in weed densities. Additionally, cereal rye is well known for suppressing a variety of summer annual weeds (DeVore et al. 2013; Mehring et al. 2016; Moore et al. 1994), and allelochemicals are often implicated in weed suppression. Another potential factor limiting weed emergence in the cereal rye treatments could be the low soil nitrogen resulting from the decomposing cereal rye biomass. Cereal rye residues have a high carbon to nitrogen ratio, which can reduce soil nitrogen and emergence of nitrophilic species (Hill et al. 2016).

Midseason Weed Biomass

All cover crop treatments reduced weed biomass relative to the bare-soil treatment, which averaged 1,554 kg ha^{-1}. Weed biomass, ranked low to high, was late-killed cereal rye = early-killed cereal rye < late-killed canola < early-killed canola = winter-killed radish < bare soil (Table 5). Radish and canola treatments, despite having higher weed densities than bare soil, exhibited a strong suppressive effect on weed growth. Cereal rye treatments had the lowest weed density (77.7 and 7.3 weeds m^{-2}, early- and late-killed, respectively) and resulted in the lowest weed biomass 6 wk after planting (226 and 104 kg ha^{-1}, early- and late-killed, respectively).

Recent studies report that as cereal rye residues increase, *Amaranthus* species control increases (Price et al. 2016; Ryan et al. 2011). Several *Amaranthus* species, including *A. rudis* and *A. palmeri*, are especially problematic for producers, because they have high fecundity and herbicide resistance is becoming more common. Ryan et al. (2011) found a negative relationship between cereal rye–residue levels and biomass of smooth pigweed (*Amaranthus hybridus* L.) and *A. retroflexus*, but the relationship was not linear at low cereal rye–residue levels. Price et al. (2016) found that the use of cover crops reduced herbicide-resistant *A. palmeri* populations relative to winter-fallow systems. Price et al. (2016) also reported a negative relationship between cover crop–residue biomass and *A. palmeri* survival. Ryan et al. (2011) reported giant foxtail (*Setaria* *faberi* Herrm.) and *Amaranthus* species emergence was completely suppressed at cereal rye–residue levels above 15,000 kg ha^{-1}, which is considerably higher than residue levels in the present research.

Only one cover crop treatment in this study appeared to have potential for weed management in edamame. The early-killed cereal rye treatment was the best candidate for edamame production, because it provided measurable weed suppression without compromising crop emergence. Terminating cereal rye in early- to mid-April, 6 to 7 wk before edamame planting, limited cereal rye residue to 2,375 kg ha^{-1}, yet still provided a 20% reduction in weed density and an 85% reduction in weed biomass without any loss of crop emergence relative to the bare-soil control. Additional research is needed on coupling the early-killed cereal rye cover crop with other weed management tactics, including in-crop weed management using additional chemical, cultural, and physical control tactics.

Acknowledgments. The authors wish to thank Jim Moody, Nick Hausman, Michael Douglas, and the many undergraduate students who helped conduct the field experiment. No conflicts of interest have been declared.

References

Belfrey KD, Trueman C, Vyn RJ, Loewen SA, Van Eerd LL (2017) Winter cover crops on processing tomato yield, quality, pest pressure, nitrogen availability, and profit margins. PLoS ONE 12. doi:10.1371/pone0180500

Davis A (2010) Cover-crop roller-crimper contributes to weed management in no-till soybean. Weed Sci 58:300–309

DeVore JD, Norsworthy JK, Brye KR (2013) Influence of deep tillage, a rye cover crop, and various soybean production systems on Palmer amaranth emergence in soybean. Weed Technol 27:263–270

Duppong LM, Hatterman-Valenti H (2005) Yield and quality of vegetable soybean cultivars for production in North Dakota. HortTechnology 15:896–900

Forcella F (2013) Short- and full-season soybean in stale seedbeds versus rolled-crimped winter rye mulch. Renew Agri Food Syst 29:92–99

Haramoto ER, Brainard DC (2012) Strip tillage and oat cover crops increase soil moisture and influence N mineralization patterns in cabbage. HortScience 47:1596–1602

Haramoto ER, Gallandt ER (2004) Brassica cover cropping for weed management: a review. Renew Agri Food Syst 19:187–198

Harker KN, O'Donovan JT (2013) Recent weed control, weed management, and integrated weed management. Weed Technol 27:1–11

Hill EC, Renner KA, Sprague CL, Davis AS (2016) Cover crop impact on weed dynamics in an organic dry bean system. Weed Sci 64:261–275

Hox JJ (2002) Multilevel Analysis: Techniques And Application. 1st ed. Mahwah, NJ: Erlbaum. Pp 22–26

Kornecki TS, Raper RL, Arriaga FJ, Schwab EB, Bergtold JS (2009) Impact of rye rolling direction and different no-till row cleaners on cotton emergence and yield. Am Soc Agr Biol Eng 52:383–391

Lawley YE, Teasdale JR, Weil RR (2012) The mechanism for weed suppression by a forage radish cover crop. Agron J 104:205–214

Lawley YE, Weil RR, Teasdale JR (2011) Forage radish cover crop suppresses winter annual weeds in fall and before corn planting. Agron J 103:137–144

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

Mehring GH, Stenger JE, Hatterman-Valenti HM (2016) Weed control with cover crops in irrigated potatoes. Agronomy 6:3

Moore MJ, Gillespie TJ, Swanton CJ (1994) Effect of cover crop mulches on weed emergence, weed biomass, and soybean (*Glycine max*) development. Weed Technol 8:512–518

Myers MW, Curran WS, Vangessel MJ, Majek BA, Scott BA, Mortensen DA, Calvin DD, Karsten HD, Roth GW (2005) The effect of weed density and application timing on weed control and corn grain yield. Weed Technol 19:102–107

Price AJ, Monks CD, Culpepper AS, Duzy LM, Kelton JA, Marshall MW, Steckel LE, Sosnoskie LM, Nichols RL (2016) High-residue cover crops alone or with strategic tillage to manage glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) in southeastern cotton (*Gossypium hirsutum*). J Soil and Water Conserv 71:1–11

Ryan MR, Mirsky SB, Mortensen DA, Teasdale JR, Curran WS (2011) Potential synergistic effects of cereal rye biomass and soybean planting density on weed suppression. Weed Sci 59:238–246

Sánchez E, Kelley K, Butler L (2005) Edamame production as influenced by seedling emergence and plant population. HortTechnology 15: 672–676

Scursoni JA, Forcella F, Gunsolus J (2007) Weed escapes and delayed weed emergence in glyphosate-resistant soybean. Crop Prot 26: 212–218

Weil R, White C, Lawley Y (2009) Forage Radish: New Multi-purpose Cover Crop for the Mid-Atlantic. College Park, MD: University of Maryland Cooperative Extension. 6 p

Williams MM (2015a) Managing weeds in commercial edamame production: current options and implications. Weed Sci 63:954–961

Williams MM (2015b) Phenomorphological characterization of vegetable soybean germplasm lines for commercial production. Crop Sci 55: 1274–1279

Williams MM, Nelson RL (2014) Vegetable soybean tolerance to bentazon, fomesafen, imazamox, linuron, and sulfentrazone. Weed Technol 28: 601–607

Wortman SE, Francis CA, Bernards MA, Blankenship EE, Lindquist JL (2013) Mechanical termination of diverse cover crop mixtures for improved weed suppression in organic cropping systems. Weed Sci 61:162–170

Zimdahl RL (2004) Weed-Crop Competition: A Review. Oxford, UK: Blackwell. Pp 57–75