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Integrated weed management strategies with cereal rye mulch in processing vegetable legumes

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Abstract

Little is known about the potential benefits of cereal rye (*Secale cereale* L.) in combination with various weed management tactics in processing vegetable legume crops such as edamame, lima bean, and snap bean. Field experiments were conducted over 3 yr to determine the extent to which early-terminated rye (ETR) and integrated weed management (IWM) tactics, including pre- and post-emergence herbicides with (augmented) or without (standard) hand weeding, suppress weed density and biomass. Possible drawbacks on crop establishment and yield were also investigated. Early-terminated rye (cereal rye terminated 4 wk before vegetable crops planting; i.e., Feekes growth stage 8.00 to 9.00) reduced total weed biomass 53 and 73% compared with stale seedbed (SSB) in edamame and snap bean, respectively. In contrast, total weed density and biomass were increased by 67 and 39%, respectively, in lima bean under ETR compared with SSB treatment. Early-terminated rye did not influence edamame establishment or yield; however, snap and lima beans had reduced yield. Soil nitrate-nitrogen 4 wk after planting was negatively correlated with soil moisture in all vegetable legume crops tested. The application of pre- and post-emergence herbicides, particularly when followed by hand weeding, reduced weed density and biomass and improved yield in all crops, except snap bean, compared with weedy plots. Results show that ETR can serve as an important component of IWM in edamame.

1 | INTRODUCTION

Processing vegetable legumes, including edamame [*Glycine max* (L.) Merr.] (also known as vegetable soybean), lima bean (*Phaseolous lunatus* L.), and snap bean (*Phaseolus vulgaris* L.), are constituents of a dynamic market in the United States that contributes significantly to the national and local economy. For example, the growing popularity of edamame has resulted in its increased marketability in many countries, including the United States (Carson, Freeman, Zhou, Welbaum, & Reiter, 2011; Shockley, Dillon, & Woods, 2011; Soyfoods, 2019). More particularly, imports of frozen edamame in the United States were 25,000 tons in 2005, which is 15,000 tons more than in 2000. Edamame is one of the most consumed soy foods after soymilk, with a fourfold increase in consumption between 2000 and 2008 (Sams, Pantalone, Kopsell,

Abbreviations: DAP, days after planting; ETR, early-terminated rye; IWM, integrated weed management; SSB, stale seedbed

Zivanovic, & Deyton, 2012; Soyfoods, 2019). According to Zhang, Li, Chin, and Qi (2017), edamame consumption in the United States was about 25,000 tons in 2013. In addition, United Soybean Board forecasts indicate greater edamame increases compared with other soy products in the future (Shockley et al., 2011), with a premium average economic return threefold greater than grain-type soybean (Zhang, Li, & Liu, 2013). Lima bean and snap bean are even more important in the United States. According to the USDA National Agricultural Statistics Service (USDA National Agricultural Statistics Service, 2019), the average harvested areas in 2018 were 9,611 and 89,638 ha for all-purpose (i.e., canning, frozen, and fresh market beans) lima bean and snap bean, respectively, reflecting a production value of about $21 million and $363 million for lima and snap bean, respectively. Processing vegetable legumes also offers producers an opportunity to diversify traditional corn (*Zea mays* L.) and soybean rotations (De Bruin, Porter, & Jordan, 2005; McNaughton, Sikkema, & Robinson, 2004) and to satisfy consumer demand for domestically grown specialty vegetable crops (Sciarappa et al., 2007; Williams & Nelson, 2014).

Growers and processors identify weed interference as a major limitation to domestic production of processing vegetable legumes (Williams, 2015). Besides yield loss from weed competition (Aguyoh & Masiunas, 2003; Bailey, Wilson, & Hines, 2003), weeds can interfere with harvest operations through reductions of the raw product recovery by the harvesters. Processing cost increases due to crop contamination with foreign plant material also can result in reduced payment or crop rejection (Kee, Glancey, & Wootten, 1997; VanGessel, Monks, & Johnson, 2000).

Limited post-emergence herbicide options and underdeveloped IWM systems result in poor weed control in processing vegetable legumes, which rely heavily on mechanical weed control and occasional hand weeding (Fennimore & Doohan, 2008; Pornprom, Sukcharoenvipharat, & Sansiriphun, 2010; Williams & Nelson, 2014). However, rising labor costs due to lack of personnel or competition for labor increase production cost (Blank, 1998). Therefore, producer net returns will decline unless labor inputs can be reduced or replaced with other tools and technologies suitable for use in specialty crops (Fennimore & Doohan, 2008).

The use of cereal rye (*Secale cereale* L.) as a cover crop alone or in combination with various herbicide programs, tillage systems, or crop rotations has been long studied for weed management (Clark, 2007; Mirsky et al., 2013) in grain-type soybean and bean crops (Boydston & Williams, 2016; Hill, Renner, Sprague, & Davis, 2016; Liebl, Simmons, Wax, & Stoller, 1992; Reddy, 2001; Skarphol, Corey, & Meisinger, 1987). Weed emergence and biomass suppression (Crawford, Williams, & Wortman, 2018; Reddy et al., 2001), reduction of herbicide resistant weed selection (Dorn, Jossi, & van der Heijden, 2015), and soil moisture conservation (Munawar, Blevins, Frye, & Saul, 1990) or soil erosion control (Moyer & Blackshaw, 2009) are benefits of cereal rye inclusion in a cropping system.

Core Ideas

- Early-terminated rye (ETR) reduced weed biomass in edamame and snap bean.
- Weed management treatments suppressed weeds in all vegetable legumes.
- ETR did not compromise yield in edamame and enhanced product recovery.
- Effects of ETR on hand-weeding time varied among vegetable legumes.
- Negative soil moisture–nitrogen relationships were found in all vegetable legumes under ETR.

One of the key agronomic management decisions influencing the level of weed suppression provided by cereal rye is termination timing. It has been reported that late-terminated (i.e., early milk to hard dough growth stage or Feekes scale 10.54–11.3; cited in Large [1954]) compared with early-terminated cereal rye resulted in greater weed suppression due to the higher rye biomass production (Keene et al., 2017; Ruis et al., 2019). Cereal rye biomass increased from 37 to 100% when terminated 2 wk after early rye termination (Feekes scale, 9.50) (Keene et al., 2017; Mischler, Curran, Duiker, & Hyde, 2010; Nord, Ryan, Curran, Mortensen, & Mirsky, 2012). Nevertheless, yield reductions in grain–soybean (Forcella, 2013) and snap bean (Boydston & Williams, 2016) following crop planting into a thick and heavy cereal rye cover mulch, a result of late cereal rye termination (Keene et al., 2017; Ruis et al., 2019), have been observed. Yield reductions were attributed to low crop population establishment due to physical interference on seed placement in the soil, soil nitrogen (N) leaching (Cooper et al., 2017), or N immobilization (Liebman et al., 2018) caused by rye's high C/N ratio (Creamer, Bennett, & Stinner, 1997). In addition, delays on mechanical weed control, including hand weeding, and harvesting operations and final product processing of the vegetable cash crop due to the presence of foreign plant material have been reported due to the excessive production of cover crop residue (Bussan, Copas, & Drilias, 2008). Mowing and hand weeding operations in vegetable crops, including snap bean, required more time under mulch compared with a nonmulched control (Pfeiffer, Silva, & Colquhoun, 2015).

A major question to be addressed is whether early-terminated rye (ETR) can suppress weeds without compromising crop establishment. Crawford et al. (2018) demonstrated the potential of ETR use in edamame, as evidenced by weed growth suppression of 85% compared with a stale seedbed (SSB). The authors also reported minimal interference of ETR with planting or establishment of the crop. The objective of our research was to investigate the effects of ETR in combination with herbicide-based weed management programs augmented with hand-weeding on weed emergence and growth and crop emergence and yield in processing vegetable legume crops. We hypothesized (a) that ETR will suppress weeds compared with a SSB in edamame, lima bean, and snap bean; (b) that ETR will maintain crop yield and improve harvesting and hand-weeding operations; and (c) that ETR will enhance the effectiveness of the standard herbicide program augmented with hand-weeding.

2 | MATERIALS AND METHODS

2.1 | Site description and experimental setup

An experiment consisting of three field studies was conducted for three consecutive growing seasons from 2014 to 2017 at the University of Illinois, Vegetable Crop Farm, Urbana, IL (40.07662° N, 88.23986° W; 222 m asl). Studies were established on a Flanagan silt loam soil (fine, smactitic, mesic, Aquic Argiudolls type) containing 3.5% organic matter with a pH of 5.8. Each study, including one vegetable crop (edamame, lima bean, or snap bean), was arranged as a split-plot complete randomized block design with four replications. The main plot was a combination of ground cover treatments (i.e., ETR and SSB). Weed management treatments, assigned as subplots for each ground treatment, were (a) "standard," consisting of pre-emergence and post-emergence herbicides (herbicide details described below), and (b) "augmented," consisting of standard + hand-weeding and a weedy control. Main plot size was 9.2 m by 9.2 m, and each four-row strip subplot was 3.1 m by 9.2 m. A different field was used for each growing season. When precipitation for a prolonged period (~10–14 d) was less than 2–2.5 cm (Figure 1), water was supplemented through a linear irrigation system set to deliver 12.5 mm of water per irrigation event. The total amount of irrigation was 30, 37.5, and 37.5 mm for 2015, 2016, and 2017, respectively.

2.2 | Cereal rye cover crop and vegetable crops management

Prior to cereal rye planting, the experimental area was tilled with one pass of a disk harrow and of a field cultivator to a depth of 15 cm. Cereal rye variety Aroostook (King's Agriseeds Inc.) was seeded (1 Oct. 2014 for the 2015 growing season, 25 Sept. 2015 for 2016 growing season, and 28 Sept. 2016 for the 2017 growing season; Table 1) with a conventional grain drill in 10-cm-wide rows to a depth of 2 cm at a rate of 135 kg ha^{-1}. The experimental area, including SSB treatment, was sprayed with a burndown application of glyphosate at 1.094 kg a.e. ha^{-1} when rye was tillering (Feekes scale 3–4; cited in Large [1954]) to terminate cereal rye and to control emerged weeds (Table 1). Vegetable crops were direct seeded using a Monosem, four-row no-till planter in late May 2015 and 2016 or early in June 2017 (Table 1). Weeds emerged from the pre-existing weed seedbank each year.

2.3 | Herbicide treatments

Immediately after planting of vegetable crops (Table 1), experimental plots designated to receive standard and augmented weed control treatments were sprayed with pre-emergence (i.e., S-metolachlor) and post-emergence herbicides (i.e., fomesafen, clethodim, bentazon, and imazamox) at recommended application rates in mixtures (Tables 1 and 2). Post-emergence herbicides were applied at the V2 to V3 growth stages of the vegetable legume crops and when the height of the emerged weeds was less than 10 cm (Table 1). All herbicide treatments were applied using a compressed-air pressurized backpack sprayer fitted with AI-11002S flat-fan nozzles (TeeJet Technologies) calibrated to deliver 187 L ha^{-1} at 275 kPa for pre- and post-emergence treatments.

2.4 | Data collection

Cereal rye biomass was evaluated immediately prior to its termination (4 wk before vegetable crop planting) (Table 1) by clipping all aboveground plant parts at the soil surface from one randomly selected 0.5-m^2 quadrat from each main plot. Plant material was dried at 60 °C for 72 h and weighed.

Three 2-cm-diameter soil cores per main plot were sampled at a 0- to 20-cm soil depth for determination of soil mineral N (NO_3^-–N and NH_4^+–N) at planting and 28 d after planting (DAP) for each vegetable crop and experimentation year. Soil samples were air dried at 70 °C for 48 h, prior to soil mineral N evaluation. Soil tests were conducted by A&L Great Lakes Laboratories, Inc.

In each main plot, three 2-cm-diameter soil cores were also collected from a depth of 0–20 cm the day before vegetable crop planting and at 28 DAP for soil moisture content determination. Soil cores from the same main plot

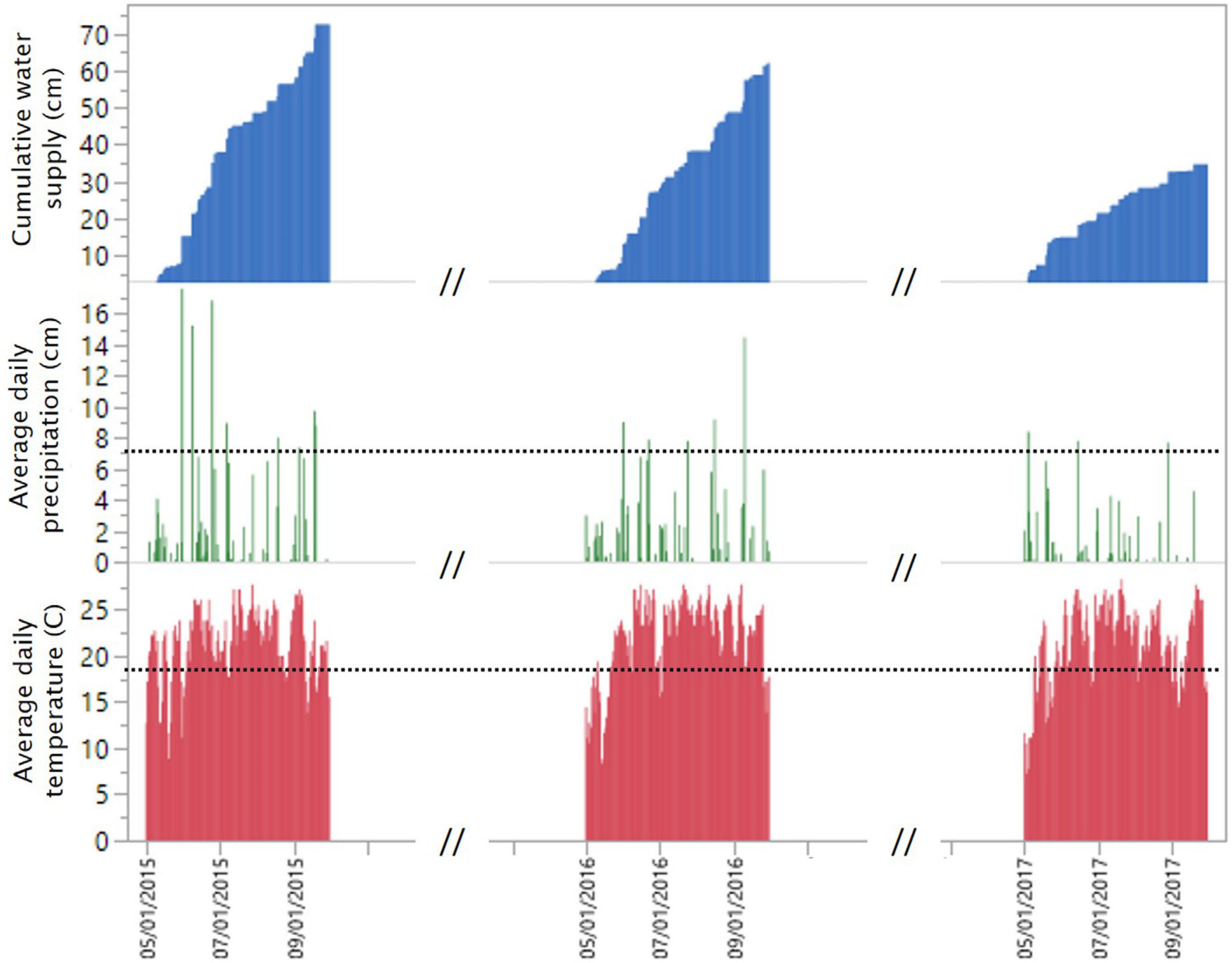

FIGURE 1 Cumulative water supply, average daily precipitation, and average daily temperature for 2015, 2016, and 2017 growing seasons near Urbana, IL. Dotted line depicts the average record of the last 30 yr for the corresponding growing seasons

were aggregated, and soil moisture was determined gravimetrically based on Equation 1.

$$\mathrm{GWC} = [(\text{wet soil weight} - \text{dry soil weight})/(\text{dry soil weight})] \times 100 \tag{1}$$

where GWC is gravimetric water content.

Average daily precipitation (cm) and average daily temperature (°C) data were obtained from a weather station located within 1 km of the experimental area (Illinois State Water Survey, Champaign). Average daily air temperatures at the field site were 21.5, 22.1, and 21.3 °C for the growing season of 2015, 2016, and 2017, respectively. Temperatures were warmer than the 30-yr average daily temperature (18.4 °C) for each year (Figure 1). The 2015 and 2016 growing seasons were characterized by higher and relatively evenly distributed daily precipitation compared with the 2017 season, which was characterized by a distinctively lower and more erratically distributed precipitation (Figure 1).

2.5 | Weed density and weed biomass

Total weed density and biomass of individual species were recorded from each weedy and standard treated edamame, lima bean, and snap bean subplot at 39 DAP and prior to harvest for each crop (55 DAP for edamame and snap bean; 92 DAP for lima bean) using one 0.5-m^2 quadrat per plot. The time needed for hand weeding in augmented subplots after post-emergence herbicide applications was recorded and expressed in h ha^{-1} person^{-1}. Finally, the aboveground weed biomass was collected within a randomly selected 0.5-m^2 quadrat 1–5 d before the vegetable crop harvest. Weed biomass was dried at 60 °C for 72 h and weighed.

TABLE 1 Field operations across three seasons of research on edamame, lima bean, and snap bean near Urbana, IL

Crop[a]	Cultivar	Seeding rate seeds ha^{-1}	Cereal rye planting	Cereal rye termination[b]	Vegetable crop planting	Pre-emergence herbicide	Post-emergence herbicide[b]	Hand weeding	Harvest
Edamame	Midori Giant	370,000	1 Oct. 2014	30 Apr. 2015	28 May 2015	29 May 2015	20 July 2015	1 July 2015	14 Aug. 2015
								13 July 2015	
								21 July 2015	
			25 Sept. 2015	15 Apr. 2016	23 May 2016	24 May 2016	21 June 2016	11 July 2016	11 Aug. 2016
								18 July 2016	
			28 Sept. 2016	17 Apr. 2017	2 June 2017	2 June 2017	27 June 2017	5 July 2017	23 Aug. 2017
								18 July 2017	
Lima bean	Eastland	235,000	1 Oct. 2014	30 Apr. 2015	28 May 2015	29 May 2015	20 July 2015	2 July 2015	30 Aug. 2017
								13 July 2015	
								21 July 2015	
			25 Sept. 2015	15 Apr. 2016	23 May 2016	24 May 2016	24 June 2016	11 July 2016	26 Aug. 2017
								18 July 2016	
			28 Sept. 2016	17 Apr. 2017	2 June 2017	2 June 2017	27 June 2017	5 July 2017	30 Aug. 2017
								18 July 2017	
Snap bean	Dominator	370,000	1 Oct. 2014	30 Apr. 2015	28 May 2015	29 May 2015	20 July 2015	1 July 2015	24 Aug. 2015
								13 July 2015	
								21 July 2015	
			25 Sept. 2015	15 Apr. 2016	23 May 2016	24 May 2016	24 June 2016	11 July 2016	19 Aug. 2016
								18 July 2016	
			28 Sept. 2016	17 Apr. 2017	2 June 2017	2 June 2017	27 July 2017	5 July 2017	26 Aug. 2017
								18 July 2017	

[a] Edamame seeds were produced by Wannamaker Seed Inc., lima bean seeds by Harris Seed, and snap bean seeds by Abbott & Cobb (Syngenta Vegetable Seeds).
[b] Glyphosate (1,094 g a.e. ha^{-1}) was applied 28 d (i.e., early-kill rye and maintain stale seedbed plots) prior to planting vegetable crops to secure a seedbed that was clean from weeds.

TABLE 2 Herbicide programs for weed control in vegetable legume crops during the experimental period near Urbana, IL

Crop	Herbicide treatment	Application rate kg ai ha^{-1}	Trade name
Edamame	S-metolachlor fb[a]	1.79 fb	Dual magnum fb
	fomesafen + clethodim	0.421 + 0.102	Reflex + Select Max
Lima bean	S-metolachlor fb	1.79 fb	Dual magnum
	bentazon + imazamox + clethodim	0.262 + 0.035 + 0.102	Basagran + Raptor + Select Max
Snap bean	S-metolachlor fb	1.79 fb	Dual Magnum fb
	bentazon + clethodim	0.262 + 0.102	Basagran + Select Max
Adjuvants	crop oil concentrate	1% of the spray volume	

[a] fb, Followed by.

2.6 | Crop density and harvest

Density of each vegetable crop was assessed by counting plants in two 1-m sections of the middle two rows at two random locations in each subplot when all plants had reached one fully emerged true leaf (~18 DAP) and at harvest. Harvest date of each crop was based on crop development in the augmented treatment. Vegetable crops were harvested using an Oxbo BH100 harvester (Oxbo International), and yields were expressed as t ha^{-1}. Percentage of crop marketable pod mass to total harvested mass (hereafter called "recovery") was determined.

2.7 | Data analysis

An ANOVA considering year of experimentation with cereal rye cover crop and weed management treatments as fixed effects was conducted initially separately for each crop. No significant interactions ($P = .786$) between year and cover crop and/or weed management treatments were observed. Therefore, data for cereal rye biomass, crop density, crop yield, weed density, total weed biomass, soil moisture, and soil mineral N (i.e., NO_3^-–N and NH_4^+–N) were pooled across years for each crop separately and analyzed using ANOVA, with year and replication as random effects. Cover crop treatments, weed management treatments, and their interaction were considered fixed effects. Logarithmic transformations based on natural logs were performed on NO_3^-–N data. Means were separated using Fisher's protected LSD at a significance level of .05. Data were analyzed by JMP (v. 14.1 Pro, SAS Institute). A bivariate analysis was adopted to explore the correlation and linear relationships between soil moisture and soil mineral N at 28 DAP.

3 | RESULTS AND DISCUSSION

3.1 | Site-specific effects

Average ETR biomass production across years was 2,940 kg ha^{-1}. Similar results were reported by Crawford et al. (2018), who recorded an average ETR biomass production equal to 2,375 kg ha^{-1} over three growing seasons.

Soil moisture content in ETR was 15% higher than SSB at planting and at 28 DAP for every vegetable legume crop tested (data not shown). Crawford et al. (2018) reported similar results when soil moisture in ETR treatment was compared with SSB at planting and suggested that cover crop growth did not deplete soil moisture content. In support of these findings, Baldwin and Creamer (2006) stated that cover crop residue left on the soil surface conserves soil moisture content by reducing evaporation from the surface and by increasing water infiltration.

Soil nitrate-N (NO_3^-–N) content was lower ($P < .05$) in ETR compared with SSB for all legume vegetables except edamame at 28 DAP. In particular, NO_3^-–N in ETR treatment was 50 and 60% lower compared with NO_3^-–N in SSB for snap bean and lima bean, respectively.

The most common weed species across experimentation years were common purslane (*Portulaca oleracea* L.), carpetweed (*Mollugo verticillate* L.), barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv], and crabgrass [*Digitaria sanguinalis* (L.) Scop], with average density 18.4, 7.6, 3.7, and 1.9 plants m^{-2}, respectively. Weed species accounting for less than 5% of the total weed flora were Palmer amaranth (*Amaranthus palmeri* S. Watson), waterhemp [*A. tuberculatus* (Moq.) J. D. Sauer.], dandelion (*Taraxacum officinale* F. H. Wigg.), velvetleaf (*Abuthilon theoprasti* Medik.), horseweed (*Erigeron canadensis* L.), and prickly sida (*Sida spinosa* L.).

3.2 | Cereal rye and weed management tactics

Cereal rye cover crop and weed management treatments independently affected weed density and weed biomass, as evidenced by the lack of interaction between ground cover and weed management treatments. The suppression of the late-emerging summer weeds by the cereal rye attenuated due to decomposition of its residues following the termination of the cereal rye (Haramoto & Pearce,

TABLE 3 Effect of cereal rye cover crop and weed management treatments on total weed density and total weed biomass at 39 and 55 d after planting (DAP) for edamame and snap bean and at 39 and 92 DAP for lima bean near Urbana, IL

	Edamame			Lima bean			Snap bean		
	Weed density		Weed biomass	Weed density		Weed biomass	Weed density		Weed biomass
Treatment	39 DAP	55 DAP		39 DAP	92 DAP		39 DAP	55 DAP	
	plants m^{-2}		g m^{-2}	plants m^{-2}		g m^{-2}	plants m^{-2}		g m^{-2}
ETR	21.6a	17.8a	27.2b	26.0a	26.4a	146.7a	25.1a	32.5a	31.8b
SSB	21.7a	12.6a	57.7a	17.8a	8.8b	105.3a	34.2a	36.2a	117.0a
Augmented	0b	0b	0b	0b	0b	0b	0b	0b	0b
Standard	2.4b	2.2b	7.1b	6.6b	6.5b	24.2b	5.8b	11b	21.7b
Weedy	40.9a	28.2a	77.8a	31.1a	28.6a	227.7a	53.4a	57.7a	187.1a

Note. ETR, early-terminated rye; SSB, stale seedbed. Means followed by the same letter within a column for cover crop or weed management are not significantly different according to Fisher's protected LSD at $P < .05$.

2019). Early-terminated rye residue may have resulted in short-lived weed suppression due to low biomass production relative to later killed residues (Webster, Scully, Grey, & Culpepper, 2013). Consequently, the results of the cover crop on weeds and vegetable legume crops are presented and discussed separately from weed management treatments.

3.3 | Effects of early-terminated rye on weeds in processing legume vegetable crops

Early-terminated rye suppressed weed growth in edamame. Averaged across weed management treatments and years, ETR reduced (P = .05) weed biomass by 53% compared with SSB but did not affect weed density in edamame (Table 3). Crawford et al. (2018) also reported weed biomass reductions up to 85% when 11 edamame biotypes were grown in ETR. Weed biomass is positively related to seed production in many species, including Palmer amaranth (Korres, Norsworthy, & Mauromoustakos, 2019), waterhemp (McLachlan, Murphy, Tollenaar, Weise, & Swanton, 1995), barnyardgrass (Pannwitt, Westerman, De Mol, & Gerowitt, 2019), and velvetleaf (Hartzler & Battles, 2001). The long-term influence of ETR on soil seedbank contributions merits study. According to Mirsky, Gallandt, Mortensen, Curran, and Shumway (2010), practices that prevent weed seed rain contribute to long-term weed suppression.

Weed density in ETR at 92 DAP (26.4 plants m^{-2}) was higher (P = .0002) than weed density in SSB (8.8 plants m^{-2}) in lima bean (Table 3). The greater soil moisture content in ETR, compared with SSB, in combination with poor lima bean establishment (Table 4) may have resulted in higher weed seed germination and establishment (Cardwell, 1984; Crawford et al., 2018). Teasdale and Mohler (1993) stated that light transmittance and daily soil temperature reductions by cereal rye residues can cause a reduction in weed emergence, but maintenance of soil moisture under a cover crop over time can favor weed emergence. Weed biomass was unaffected (P = .967) by ETR in comparison with SSB (Table 3).

Like edamame, ETR suppressed weed growth in snap bean. Early-terminated rye reduced total weed biomass (P = .0001) 73% compared with SSB in snap bean (Table 3). Total weed density in snap bean was not different (P = .648) between ETR (32.5 plants m^{-2}) and SSB (36.2 plants m^{-2}) (Table 3). Weed biomass suppression by ETR in snap bean is of particular interest because of the poor competitive ability of *Phaseolus* beans against weeds (Liebman, Corson, Rowe, & Halteman, 1995; Soltani et al., 2017).

TABLE 4 Effect of cereal rye cover crop on processing vegetable legume crop densities planted near Urbana, IL

Treatment	Crop density					
	Edamame		Lima bean		Snap bean	
	18 DAP	Harvest	18 DAP	Harvest	18 DAP	Harvest
	plants m^{-2}					
ETR	27.7b	27.4a	12.7b	13.6b	29.2b	28.9b
SSB	30.2a	28.4a	20.4a	17.3a	39.3a	31.6a

Note. ETR, early-terminated rye; SSB, stale seedbed. Means followed by the same letter within a column are not significantly different according to Fisher's protected LSD at $P < .05$.

TABLE 5 Effect of cereal rye cover crop and weed management treatments on processing vegetable legume crop yield and recovery, near Urbana, IL

Treatment	Edamame		Lima bean		Snap bean	
	Yield	Recovery[a]	Yield	Recovery	Yield	Recovery
	t ha^{-1}	%	t ha^{-1}	%	t ha^{-1}	%
ETR	6.7a	0.826a	2.5b	0.916a	3.6b	0.800b
SSB	7.0a	0.804b	5.3a	0.897b	9.7a	0.854a
Augmented	7.2a	0.822a	4.3a	0.912a	7.0a	0.835a
Standard	7.0ab	0.816a	4.3a	0.906a	7.0a	0.833a
Weedy	6.5b	0.816a	3.3b	0.902a	5.9a	0.808a

Note. ETR, early-terminated rye; SSB, stale seedbed. Means followed by the same letter within a column for cover crop or weed management are not significantly different according to Fisher's protected LSD at $P < .05$.

[a] Recovery is defined as the percentage of the marketable product over the total fresh biomass harvested.

3.4 | Weed response to weed management tactics

Augmented and standard weed management treatments reduced ($P \leq .0001$) weed density and weed biomass compared with the weedy control in all vegetable legume crops (Table 3). A cereal rye cover crop alone often is inadequate for managing weeds (De Bruin et al., 2005; Peachey, William, & Mallory-Smith, 2004; Walters & Young, 2010). This was confirmed in the case of lima bean because weed density was higher in the presence of ETR compared with SSB (Table 3). Therefore, the incorporation of various weed management tactics is of vital importance.

3.5 | Response of processing legume vegetable crops to early-terminated rye

Early-terminated rye compromised edamame establishment at 18 DAP compared with SSB; however, no differences (P = .257) in crop stand were observed at harvest (Table 4). A cereal rye cover crop has been reported to reduce crop stands, especially at early crop stages, because of interference with seed germination from cold soils, excessive soil water content, and release of phytotoxins from decomposing residue (Forcella, 2013; Kumar, Brainard, & Bellinder, 2009; Reddy, 2001; Teasdale, Brandsaeter, Calegari, & Skora Neto, 2007).

No differences were recorded on crop yield (P = .108) between ETR and SSB (Table 5). Liebl et al. (1992) reported that yield of grain soybean in ETR was higher than late-terminated rye and competitive with soybean in corn stubble.

Higher product recovery (P = .047) was recorded for ETR compared with SSB (Table 5). Early-terminated rye did not reduce hand-weeding time compared with SSB. Consistent with Crawford et al. (2018), ETR can be used in edamame as a component of IWM without compromising crop yield.

Early-terminated rye compromised lima bean establishment and lima bean yield. By 18 DAP, lima bean density in ETR was 62% of SSB and remained low at harvest (Table 4). The same reasons mentioned above for edamame could have contributed in the lower lima bean stand in ETR. In addition, lima bean yield in ETR was reduced by 52% compared with SSB (Table 5). Crawford et al. (2018) suggested that cover crop residues would not be a viable management tactic if crop emergence is compromised, which appears to hold true for lima bean.

Higher product recovery (P = .01) in ETR was recorded for lima bean, potentially improving mechanical harvest (Kee et al., 1997; VanGessel et al., 2000). However, compared with SSB, ETR extended (P = .0001) the time required for hand-weeding by 32.8 h ha^{-1} (i.e., 79.7 vs. 46.9 h ha^{-1} for ETR and SSB, respectively). Such an outcome may not be economical given the growing costs of labor (Fennimore & Doohan, 2008).

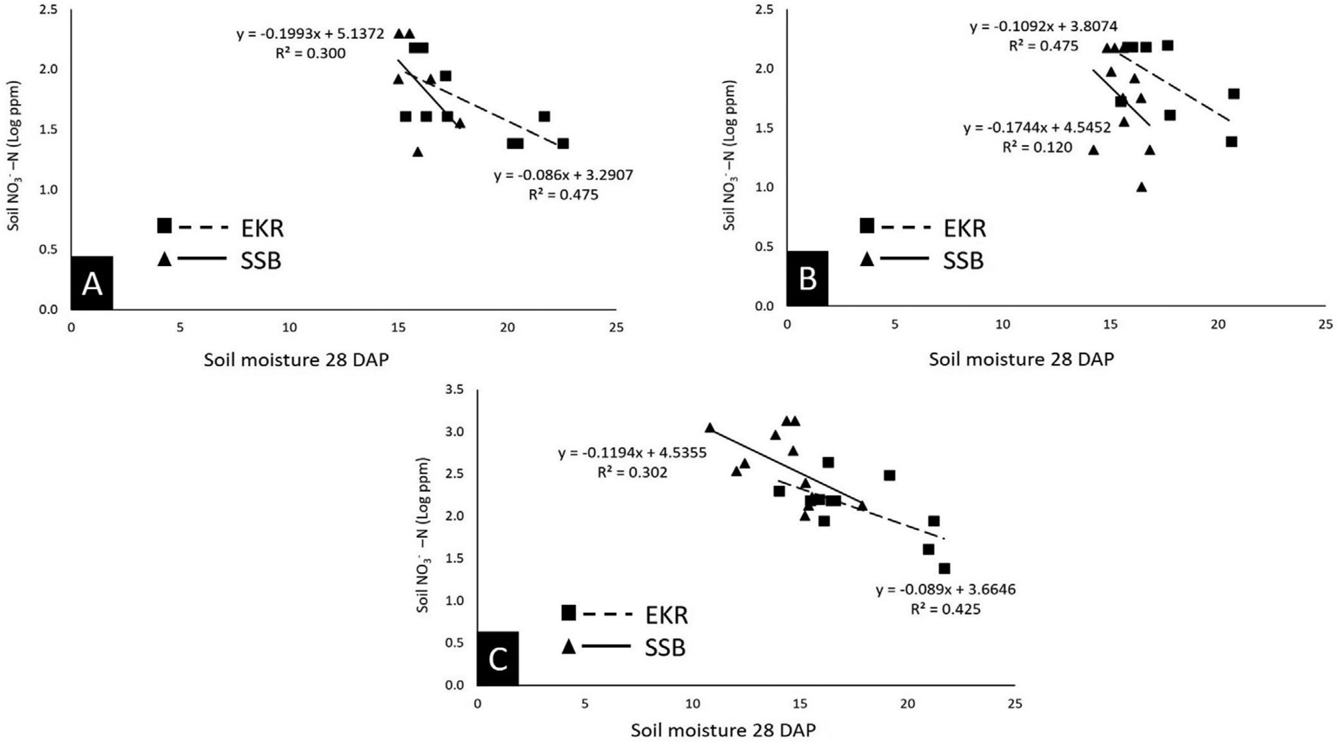

FIGURE 2 Relationship between soil moisture content and soil NO_3^-–N 28 d after planting (DAP) for early-terminated cereal rye (ETR) and stale seedbed (SSB) for (A) edamame, (B) lima bean, and (C) snap bean near Urbana, IL

Early-terminated rye reduced (P = .0001) snap bean establishment compared with SSB (Table 4). The difference in crop stand between ETR and SSB attenuated at harvest.

Compared with SSB, snap bean yield in ETR was reduced by 62.5% (P = .0001) (Table 5). Snap bean yield in ETR was likely limited by soil N rather than weed competition because snap bean is a poor N fixer (Hardarson & Zapata, 1984; Lindemann & Glover, 2003). Under ETR, soil NO_3^-–N, one of the major plant N sources, was reduced by 50% compared with SSB. Moreover, soil NO_3^-–N losses could have been affected by soil moisture content (Brennan & Smith, 2017); ETR soil moisture was 15% higher than SSB.

Snap bean recovery in ETR was reduced by 6% (P = .0004) (Table 5). Hand-weeding in ETR was 41.9 h ha^{-1}, compared with 27.8 h ha^{-1} in SSB. Similar values were recorded by Neto et al. (2003). Once crop establishment and yield can be secured through carefully designed agronomic decisions such as crop fertilization, ETR can be a useful tool for weed suppression in snap bean.

3.6 | Effects of ground cover treatments on soil nitrate

Nitrogen uptake or N immobilization by cereal rye cover crop, especially during the early growth stages of the crop, results in nitrate leaching reductions (Balkcom et al., 2007; Cooper et al., 2017). However, our results indicate a negative relationship between soil moisture and NO_3^-–N content at 28 DAP (Figure 2). This trend, which is particularly clear in ETR in edamame and snap bean, can be intensified at low soil NO_3^-–N content (Brennan & Smith, 2017).

Nitrogen loss from the legume rhizosphere can negatively affect the early growth of poor N fixers such as common bean (Hardarson & Zapata, 1984; Lindemann & Glover, 2003). Hartwig and Ammon (2002) reported that certain legumes tend to use soil N, if it is available, rather than fixing their own. In addition, as reported by Smeltekop, Clay, and Clay (2002), medic (*Medicago scutellata* Mill cv. Sava) took up significant amounts of fertilizer N when it was present with no N fixation occurring. From an agronomic perspective, loss of NO_3^-–N through leaching from the crop root zone represents a loss of a resource required for crop production. Therefore, the addition of chemical N fertilizer increases the cost of crop production and could affect legume nodulation and N fixation (Hartwig & Ammon, 2002). Further research is required to quantify the long-term effects of ETR on soil N dynamics and naturally occurring weed flora in relation to suitable fertilization schemes for lima bean and snap bean.

3.7 | Effect of weed management treatments on crop yield

Weed management systems are essential for protecting yield of vegetable legume crops. Use of augmented and standard weed management treatments avoided yield losses of 8–23% (Table 4). Similar results were recorded by Blackshaw and Molnar (2008); Brainard, Bellinder, Hahn, and Shah (2008); Williams (2015); Wilson (2005); and Reddy (2001) with pre- and post-emergence herbicides in soybean, dry bean, and snap bean. More particularly, yield improvements of 19–37% in grain–soybean (Reddy, 2001), 24–44% in edamame (Williams, 2015), and >96% in dry bean (Blackshaw & Molnar, 2008; Wilson, 2005) were observed in herbicide-treated plots compared with a non-treated control.

Yield between augmented and standard treatments did not significantly differ (Table 5). Similar crop yields reflected the effectiveness of herbicides programs adopted in this research (Table 5). However, weed biomass in the standard treatment could have contributed to soil seedbank inputs.

4 | CONCLUSIONS

Early-terminated rye can play a crucial role in edamame IWM, as evidenced by acceptable crop establishment, weed suppression, and maintaining crop yield. Use of ETR in lima bean and snap bean must first overcome issues of crop establishment and yield. Product recovery improved with ETR in edamame and lima bean but not in snap bean. Low amounts of soil NO_3^-–N at 28 DAP likely compromised yield of lima bean and snap bean. Weed suppression was improved by the use of pre- and post-emergence herbicides, particularly when followed by hand weeding. In addition, weed management improved yields compared with nontreated weedy check, although no differences were detected between augmented and standard weed management.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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