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Managing Weeds in Commercial Edamame Production: Current Options and Implications

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Edamame, a specialty food-grade soybean popular among health-conscious consumers, is growing in popularity worldwide. Despite a well-developed soybean industry, most edamame consumed in the United States is imported from Asia. Considerable interest exists in growing edamame domestically; however, weed interference is a major problem, and until recently, only a single herbicide was registered for use on the crop. The objectives of this work were (1) to compare effectiveness of weed management treatments that utilize herbicides currently registered for use on edamame or that may be registered in the near future, (2) to determine the significance of edamame cultivar on performance of these treatments, and (3) to identify potential relationships between the crop and weed. Ten different weed management treatments were tested in three edamame cultivars over a 3-yr period. All weed management treatments increased marketable pod yield relative to the nontreated control, but only treatments with saflufenacil or *S*-metolachlor combinations were comparable to the hand-weeded weed-free treatment. Of the treatments studied, *S*-metolachlor followed by imazamox was among the greatest yielding, had the least weed density and biomass, and did not reduce crop population density. Also, cultivars differed in their weed-suppressive ability. Path analysis indicated certain relationships were consistent across cultivars, such as weed population density having a direct negative association with crop biomass; however, other edamame–weed interactions were not identical across cultivars. Although more improvements are needed, the vegetable industry is beginning to have nascent weed management options in edamame, which will likely reduce reliance on hand weeding and result in crop-production costs that are more competitive in the global market.
Nomenclature: Imazamox; *S*-metolachlor; saflufenacil; edamame, *Glycine max* (L.) Merr.
Key words: Competitive cultivars, hand weeding, immature soybean seed, minor crop, vegetable soybean.

Soybean is the leading oilseed crop worldwide, with global production averaging 252 million Mt in recent years (Food and Agricultural Organization of the United Nations [FAOSTAT] 2014). Soybean is grown on ~30 million ha in the United States, producing a crop valued at some $40 billion (National Agriculture Statistics Service [NASS] 2014). As such, considerable time, energy, and expense are invested in improving soybean production, including weed management, in both public and private sectors. In stark contrast, vegetable-type soybean (also known as edamame) production has been nearly nonexistent in the United States until recently.

Edamame is a specialty food-grade soybean harvested at an immature seed stage (i.e., R6, full seed) and promoted for its health benefits. Edamame differs from grain-type soybean in large part because cultivars have been selected to produce large seeds with a sweet, nutty flavor and other sensory and nutritional characteristics (Shurtleff and Aoyagi 2009). Edamame consumption is on the rise globally, particularly in the United States, where it is becoming more available in supermarkets and restaurants (Mimura et al. 2007). Despite a well-developed grain-type soybean industry in the United States, a majority of edamame consumed in the country is imported from Asia, particularly China (Dong et al. 2014).

Producing edamame in the United States is far from a novel idea. In the late 1920s, edamame cultivars were collected by the U.S. Department of Agriculture from China, Korea, and Japan (Morse 1930), which were subsequently tested by several state agricultural experiment stations (Morse 1937). During World War II, several canned edamame products were marketed and some 44 cultivars were released in the United States (Shurtleff and Aoyagi 2009). In the 1980s, more Americans were introduced to edamame through several Rodale Press publications, including research on edamame production (Haas et al. 1982). Commercial edamame production was documented late in the 20th century in the midwest (Anonymous 1990), but never reached a level to satisfy domestic demand at

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the time (Shurtleff and Aoyagi 2009). A few federal and state researchers have released a small number of edamame cultivars in the last two decades (e.g. Iowa State University, University of Illinois, etc.); however, additional cultivar improvement is needed and research on production practices has been minimal. Fueled in part by increasing consumer interest in the product itself and in domestically grown products in particular, certain vegetable processors have initiated edamame production in the United States.

Vegetable processors identify weed interference as a major limitation to domestic production of edamame on a commercial scale (author, personal observation). Several reasons may account for this obstacle, including the fact that few herbicides have been registered for use on edamame in the United States. Despite numerous herbicides from multiple chemical families being available for use on grain-type soybean, including within-plant traits conferring tolerance to nonselective herbicides, criteria for registering products on edamame are different (IR-4 Project 2012). As of 2009, clethodim was the only herbicide with a federal label for use on edamame in the United States. Since then, fomesafen, imazamox, linuron, *S*-metolachlor, and trifluralin have been registered (Williams and Nelson 2014). Currently, weed management in edamame is characterized by use of crop rotation, rotary hoeing, interrow cultivation, minimal herbicide use, and extensive hand weeding.

Aside from limited herbicide options, perhaps the crop could be improved to enhance its competitive ability with weeds. For instance, edamame cultivars are often plagued with poor crop establishment (Sánchez et al. 2005), nonuniform crop canopy (Rao et al. 2002), and susceptibility to certain insect pests (McPherson et al. 2008; Rao et al. 2002). Hand weeding is a major component of weed management in China, the largest edamame producer (Q. Zhang, personal communication). Although domestic vegetable processors also rely on hand weeding, labor costs can exceed \$1,200 ha^{-1} (D. McMillan, personal communication). Such high production costs threaten specialty crop production in the United States because of the economic disadvantage relative to countries where labor costs are low (Fennimore and Doohan 2008).

In order to grow the fledgling production of edamame in the United States, there is a critical need to develop immediate, if not initially rudimentary, weed management systems for edamame. Such systems almost certainly would utilize the limited herbicides available for use in the crop. These systems not only need to be tested with regards to agronomic performance metrics (e.g., weed control, crop yield, etc.), but also in terms of the potential role of additional cultural, mechanical, and biotic tactics. For instance, variability in grain-type soybean cultivar competitive ability has had implications to weed management for decades (Jordan 1992; Monks and Oliver 1988). Can the same be said of edamame? Therefore, the objectives of this study were (1) to compare effectiveness of weed management treatments that utilize herbicides currently registered for use on edamame or that may be registered in the near future; (2) to determine the significance of edamame cultivar on performance of these treatments, and in order to develop incipient knowledge of edamame competitiveness, (3) to identify potential relationships between the crop and weeds.

Materials and Methods

Site Characteristics. Experiments were conducted in 3 yr at the University of Illinois Vegetable Crop Farm near Urbana, IL (40.07°N, 88.23°W). Experiments were located in a different field each year. The previous crop was grain-type soybean. The soil was a Flanagan silt loam (fine, smectitic, mesic Aquic Argiudoll) averaging 3.7% organic matter and pH of 5.7. The field was prepared for planting with one pass each of a disc harrow and field cultivator, leaving a seedbed free of weed plants and minimal surface residue. Planting dates were May 20, May 15, and May 23 of 2011, 2012, and 2013, respectively. Rainfall was occasionally supplemented with sprinkler irrigation to facilitate plant growth during abnormally dry periods (Figure 1A).

Experimental Methodology. The experimental design was split plot with four replications. Main-plot treatments consisted of three edamame cultivars ('Butterbean', 'IA1010', and 'Gardensoy 43') planted in blocks of 4 rows spaced 76 cm apart and 76 m in length. Crop seeding rate was 260,000 seeds ha^{-1}. Cultivars were chosen because an adequate amount of seed could be obtained. Subplot treatments consisted of 10 weed management treatments randomly assigned to four-row, 6.1-m-long subplots, separated by a 1.5-m alley. Weed management treatments were chosen to reflect potential use of herbicides that were registered for use on edamame at the initiation of this research (clethodim, *S*-metolachlor), herbicides that became registered during the course of the work (imazamox, linuron, trifluralin), and herbicides that the vegetable industry would like to see registered

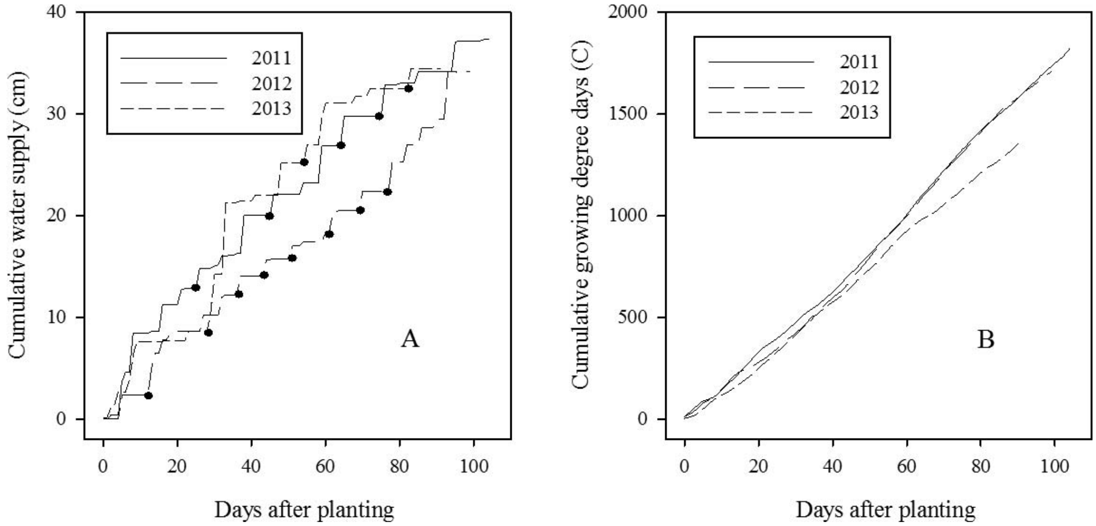

Figure 1. Cumulative water supply (A) and cumulative growing degree days (B) from planting to harvest in 2011, 2012, and 2013. Irrigation events are denoted with filled ovals.

for use on edamame in the future (imazethapyr, saflufenacil). Trifluralin was applied the day before planting and immediately incorporated to a depth of 5 cm with a field cultivator. Preemergence herbicides were applied immediately after planting. Postemergence herbicides were applied when edamame had three fully emerged trifoliate leaves. Emerged weeds were ≤ 10 cm in height at the time of POST application. All herbicides were applied with a compressed-air backpack sprayer with AI-11002 nozzles delivering 187 L ha^{-1} at 220 kPa (soil-applied treatments) or 275 kPa (POST treatments). With the exception of nontreated plots, all treatments were cultivated to a depth of 5 cm 3 d after POST application with a low-residue interrow cultivator. Additional details of the weed management treatments are listed in Table 1.

To reduce spatial heterogeneity of common weed populations, scarified seed of velvetleaf (*Abutilon theophrasti* Medik.) and wild-proso millet (*Panicum miliaceum* L.) were shallowly planted (~ 1 cm deep) directly in the center two crop rows immediately after edamame planting at a rate of 10 viable seed of each species per meter of row. Weed seed had been collected from local populations the previous year, stored air dry at room temperature, and tested for germination 4 wk prior to planting.

Data Collection. Two weeks after planting, percentage of crop injury from PRE herbicides was visually rated on a scale of 0 = no stunting or chlorosis, relative to the nontreated plot, to 100 = plant death. At that time, crop population density also was assessed in the center two rows across the length of each plot in order to quantify any crop stand loss. Ten days after POST treatment (corresponding to 7 d after interrow cultivation), percentage of crop injury from herbicides was visually rated as described earlier. Also 10 d after POST treatment, percentage of weed control was visually rated on a scale of 0 = no control, relative to the nontreated plot, to 100 = complete control for individual species and the overall weed community. Finally, total weed population density was assessed 10 d after POST treatment in two 0.25-m^{-2} quadrats centered over the crop row of each plot.

Harvest date of each cultivar was determined by a majority of pods on upper plant nodes in the weed-free treatment being at the R6 stage. At the time of harvest, edamame plants were clipped at the soil surface from the center two rows for a length of 3 m. Crop population density and fresh biomass were measured. All weeds within a 1.5 (centered over middle two crop rows) by 3–m area were clipped at the surface and fresh biomass was measured. In addition, 50 individual plants of each cultivar per trial were clipped at the soil surface and measured individually for total plant mass and marketable pod mass. Relationships between total plant mass and marketable pod mass were quantified with linear regression. Coefficient of determination ranged from 0.802 to 0.981. Across years, slope coefficients were 0.410, 0.414, and 0.359 for Butterbean, IA1010, and Gardensoy 43, respectively. Crop plant biomass and slope coefficients of each cultivar in each year were used to estimate marketable pod yield of each plot.

The center two rows of weed-free plots were used to characterize crop development and growth. In addition to recording the R6 date, date of R1 (i.e., beginning flower) also was noted. At the time of R6,

Table 1. Weed management treatment for edamame tested in 2011, 2012, and 2013 near Urbana, IL.

Treatment	Herbicides	Timing	Rate	Interrow cultivation
			g ai ha^{-1}	
LIN	Linuron fb clethodim	PRE + POST	1,120 + 102	+
SAF	Saflufenacil fb clethodim	PRE + POST	25 + 102	+
TRI	Trifluralin fb clethodim	PPI + POST	840 + 102	+
MET	*S*-metolachlor fb clethodim	PRE + POST	1,790 + 102	+
MET + LIN	*S*-metolachlor + linuron fb clethodim	PRE + POST	1,790 + 1,120 + 102	+
MET + SAF	*S*-metolachlor + saflufenacil fb clethodim	PRE + POST	1,790 + 25 + 102	+
MET fb IMX	*S*-metolachlor fb imazamox[b] fb clethodim	PRE + POST + POST	1,790 + 35 + 102	+
MET fb IMZ	*S*-metolachlor fb imazethapyr[a] fb clethodim	PRE + POST + POST	1,790 + 35 + 102	+
Nontreated	–	–	–	–
Weed free	*S*-metolachlor fb clethodim + hand weeding	PRE + POST	1,790 + 102	+

[a] Nonionic surfactant (NIS; 0.25% v/v) was included in the imazethapyr POST treatment and clethodim was applied the same day.
[b] NIS (0.25% v/v) was included in the imazamox POST treatment and clethodim was applied the same day.

plant height, leaf area index (LAI), and intercepted photosynthetically active radiation (IPAR) were measured. Height was measured from the soil surface to the uppermost leaf. Canopy LAI was measured under full-sun conditions within 2 hr of solar noon at three locations in each plot with the use of a linear ceptometer (AccuPAR Linear Ceptometer; Decagon Devices, Pullman, WA). Ceptometer measurements of incident light above and below the crop canopy were used to estimate IPAR. Specifically, IPAR was estimated as unity minus the fraction of below-canopy to above-canopy measurements. All ceptometer measurements were taken perpendicular to, and centered across, the crop row. Growing degree days were determined with the use of a base temperature of 7 C and daily temperature data from a weather station located within 1 km of the experiments (Illinois State Water Survey, Champaign, IL).

Statistical Analysis. All response variables met assumptions of homoscedasticity and normality except weed density, weed biomass, and weed control ratings. Log transformation of weed density and biomass data met ANOVA assumptions. No transformations were found to improve weed control ratings; hence, analysis was conducted on observed values. Data were analyzed with the use of the PROC MIXED in SAS (Version 9.3, SAS Institute Inc., Cary, NC). Fixed effects included cultivar, weed management treatment, and their interaction. Random effects included year and replicate nested within year. Means were compared with the use of the protected, Bonferroni-corrected multiple comparison procedure (Neter et al. 1996).

Potential relationships between the crop and weed were investigated with the use of path analysis (Mitchell 2001). Standardized regression coefficients and latent variables were estimated for several candidate path analysis models with the use of the RAMONA subroutine of SYSTAT (Version 13.00.05. SYSTAT Software Inc., Richmond, CA). Terms in the models included crop and weed population density after emergence, weed control ratings, crop height and LAI at harvest, crop and weed biomass at harvest, and edamame pod yield. The most parsimonious model was selected using Akaike's Information Criterion. To determine the significance of edamame cultivar on crop–weed interactions, path analysis was conducted by cultivar.

Results and Discussion

Edamame Responses. Although both cultivar and weed management treatment had a significant effect on edamame responses ($P < 0.001$), their interaction was not significant ($P \geq 0.499$; Table 2). Hence, discussion of crop responses will focus on main effects only.

Use of saflufenacil applied PRE decreased edamame population density. For instance, the saflufenacil followed by clethodim (SAF) and *S*-metolachlor + saflufenacil followed by clethodim (MET + SAF) treatments reduced early crop population density 22% relative to the nontreated control (Table 2). Saflufenacil-mediated stand reductions also were detected at crop harvest. Interestingly, emerged seedlings exhibited very little (<5%) crop injury from any of the treatments (data not shown). Stunting and necrosis of grain-type soybean from saflufenacil applied PRE is cultivar specific, with injury increasing under cool, wet conditions following planting (Miller et al. 2012). Water supply 2 wk after planting was moderate to excessive, ranging from 6.5 to 8.6 cm, and soil crusting was observed each year (Figure 1A). Perhaps

Table 2. Crop and weed statistics (P from ANOVA) and mean characteristics. Response variables include edamame plant population density after emergence (early crop density), at harvest (late crop density), marketable pod yield, midseason weed density, velvetleaf (ABUTH), and ivyleaf morningglory (IPOHE) control 10 d after POST, and weed biomass at harvest. Within columns, for each factor, means not followed by common letters differ significantly based on Bonferroni-corrected multiple comparisons at $P < 0.05$.[a]

Effect	Early crop density	Late crop density	Marketable pod yield	Weed density	ABUTH control	IPOHE control	Weed biomass
	P						
Cultivar	<0.001	<0.001	<0.001	0.169	0.041	0.881	0.003
Treatment	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Cultivar * Treatment	0.999	0.999	0.499	0.547	0.991	0.940	0.637
	No. m^{-2}	No. m^{-2}	Mt ha^{-1}	No. m^{-2}	%	%	g m^{-2}
Butterbean	14.5 b	15.5 b	7.34 c	32.1 a	58 ab	52 a	408 a
IA1010	13.4 c	14.7 b	7.97 b	32.2 a	55 b	52 a	425 a
Gardensoy 43	17.2 a	18.1 a	9.63 a	27.9 a	62 a	51 a	296 b
LIN	15.5 ab	16.5 ab	7.79 b	28.0 b	61 b	47 b	530 b
SAF	13.2 b	14.0 b	8.29 ab	17.8 c	76 b	63 a	349 c
TRI	15.3 ab	16.6 ab	8.06 b	33.7 b	38 c	62 ab	460 b
MET	15.8 a	17.0 ab	7.88 b	25.8 bc	32 c	51 ab	458 b
MET + LIN	14.9 ab	15.9 ab	8.84 ab	8.8 c	78 ab	58 ab	214 c
MET + SAF	13.2 b	14.5 b	9.13 ab	4.6 d	92 a	65 ab	85 d
MET fb IMX	15.1 ab	16.8 ab	8.99 ab	12.9 c	79 ab	62 ab	65 e
MET fb IMZ	14.9 ab	16.3 ab	8.48 ab	20.8 bc	69 b	58 ab	274 c
Nontreated	16.8 a	17.1 a	6.33 c	124.2 a	0 d	0 c	952 a
Weed-free	15.3 ab	16.3 ab	9.36 a	–	–	–	–

[a] Refer to Table 1 for complete description of treatments.

the combined stresses of exposure to saflufenacil in the edamame germination zone and soil crusting prevented some seedlings from emerging.

Crop injury following POST herbicide application was rare. In 2011 some leaf chlorosis was observed after POST applications, and only in *S*-metolachlor followed by imazamox followed by clethodim (MET fb IMX) and *S*-metolachlor followed by imazethapyr followed by clethodim (MET fb IMZ) treatments (data not shown). The level of crop injury was < 25%. Williams and Nelson (2014) reported edamame injury from 70 g imazamox ha^{-1} applied POST, although the level of injury among edamame entries was less than injury among grain-type soybean entries.

All weed management treatments increased marketable pod yield relative to the nontreated control, but only treatments with saflufenacil or *S*-metolachlor plus another herbicide were comparable to the weed-free treatment. For instance, weed-free pod yield averaged 9.36 Mt ha^{-1}; comparable to MET fb IMX and MET fb IMZ, which averaged 8.99 and 8.48 Mt ha^{-1}, respectively (Table 2). With one exception, treatments without a POST broadleaf herbicide produced lower pod yields than the weed-free treatment. Despite edamame population density reductions from saflufenacil, the SAF treatment had pod yields (8.29 Mt ha^{-1}) comparable to weed-free yields.

Edamame cultivars differed in important agronomic traits. Cultivar IA1010 was shorter, had a less dense canopy, and was earlier maturing than Gardensoy 43. For instance in weed-free plots, IA1010 matured in 83 d, compared to Gardensoy 43 maturing in 101 d (Table 3). At-harvest canopy LAI averaged 4.3 and 6.7 for IA1010 and Gardensoy 43, respectively. Moreover, pod yield differed among cultivars. Gardensoy 43 had the greatest pod yield, averaging 9.63 Mt ha^{-1}, followed by IA1010 and Butterbean at 7.97 and 7.34 Mt ha^{-1}, respectively (Table 2). Do such differences in crop development and growth among commercially available edamame cultivars influence weed growth?

Weed Responses. Predominant weed species included ivyleaf morningglory (*Ipomoea hederacea* Jacq.), velvetleaf, and wild-proso millet. In the nontreated plots, population densities averaged 1, 14, and 20 plants m^{-2} for ivyleaf morningglory, velvetleaf, and wild-proso millet, respectively. Following the POST application of clethodim in all but the nontreated plots, wild-proso millet was largely absent from the trials. In contrast, ivyleaf morningglory and velvetleaf persisted in all treatments.

Cultivars differed in their weed-suppressive ability. Weed biomass at crop harvest averaged 29% lower in Gardensoy 43 compared to the other two cultivars

Table 3. Weed-free cultivar characteristics. Response variables include days from planting to R1, days from planting to R6, and plant height, leaf area index (LAI), and intercepted light (IPAR) at the time of harvest. Within columns, means not followed by common letters differ significantly based on Bonferroni-corrected multiple comparisons at $P < 0.05$.

Effect	R1 date	R6 date	Plant height	LAI	IPAR
	P				
Cultivar	<0.001	<0.001	<0.001	<0.001	<0.001
	d	d	cm	$m^2\ m^{-2}$	%
Butterbean	51 b	88 b	92 b	4.9 b	90 b
IA1010	45 c	83 c	92 b	4.3 c	87 b
Gardensoy 43	61 a	101 a	107 a	6.7 a	96 a

(Table 2). Velvetleaf control ratings were marginally higher (7%) in Gardensoy 43 compared to IA1010. Much like grain-type soybean, edamame cultivars differ in susceptibility to certain insect pests (McPherson et al. 2008) and diseases (Williams et al. 2012). Crop health was unlikely contributing to cultivar differences in weed-suppressive ability in the present study, because minimal insect feeding or disease incidence was observed. Jordan (1992) hypothesized timing of weed suppressiveness might be dependent on the extent to which grain-type soybean exhibits indeterminate growth, with determinant soybean lines being most weed suppressive early in the season (<9 wk) versus indeterminant soybean lines of the same maturity group being most weed suppressive later. Both indeterminant (Butterbean and IA1010) and determinant (Gardensoy 43) cultivars were used in the present work; however, maturity differed among the lines. Despite the long period of crop–weed competition, compared to the other cultivars, greater weed suppressiveness of Gardensoy 43 makes sense, given the cultivar's more favorable canopy characteristics for light competition (i.e., height, LAI, and IPAR). This observation is similar to Akey et al. (1991), who reported grain-type soybean's effect on velvetleaf diminished once the weed overtopped the crop canopy and more effectively competed for light.

Herbicide treatments had a large effect on the weed community. Treatments with saflufenacil or *S*-metolachlor plus another herbicide had among the lowest midseason weed densities, with the MET + SAF treatment reducing weed density from a high of 124 plants m^{-2} in the nontreated control, to 4.6 weeds m^{-2} (Table 2). Although no treatment was particularly effective at controlling ivyleaf morningglory (≤ 63%), treatments including *S*-metolachlor with linuron, saflufenacil, or imazamox provided among the best control (≥ 78%) of velvetleaf. Perhaps the most revealing data is weed biomass at crop harvest. *S*-metolachlor treatments, especially with imazamox, resulted in the least weed biomass (Table 2).

Of the treatments studied, MET fb IMX resulted in among the greatest crop yield, and least weed density and biomass, and did not reduce crop population density. The treatments *S*-metolachlor + linuron followed by clethodim (MET + LIN) and MET fb IMZ also resulted in comparable outcomes; however, they did not suppress weed biomass as much as MET fb IMX. Moreover, although imazamox, linuron, and *S*-metolachlor are registered for use on edamame, currently imazethapyr is approved only in a limited number of states. A significant limitation to treatments using imazamox or imazethapyr is the occurrence of weed populations resistant to ALS-inhibiting herbicides. Globally there are more weed populations resistant to ALS-inhibiting herbicides than any other mode of action. In the United States alone, populations of 46 species have documented resistance to ALS-inhibiting herbicides, some of which exhibit resistance to multiple herbicides (Heap 2014). Managing herbicide resistance requires not only a multifaceted approach, but also landowners and growers having an accurate perception of the effectiveness of current practices and realistic expectation of future technology (Norsworthy et al. 2012).

Edamame–Weed Relationships. Aspects of the weed–crop community measured in this work are known to influence soybean yield. For instance, relationships between weed population density and grain-type soybean performance have been quantified extensively (see Zimdahl 2004). In addition, grain-type soybean population density not only affects crop growth and yield, but also has implications to weed management (Norsworthy and Oliver 2001). Path analysis was conducted in order to investigate potential relationships between the crop and weed that may not be apparent from univariate analyses.

A maximum-likelihood comparison of several candidate path analysis models indicated the most parsimonious model included crop and weed population density after emergence, crop and weed biomass at harvest, and edamame pod yield (Figure 2). Results of path analysis indicated certain relationships were consistent across cultivars. For instance, weed population density had a direct positive association with weed biomass (path coefficients 0.155 to 0.429) and direct negative association with crop biomass (−0.374 to −0.507). In addition, crop population density had

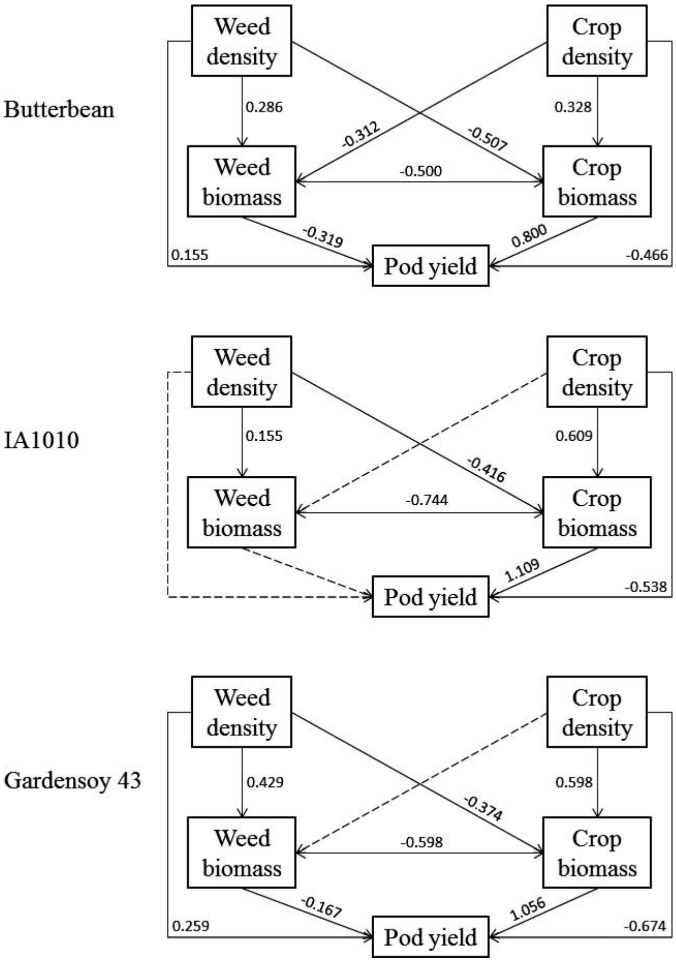

Figure 2. Path analysis model of hypothetical relationships among early crop/weed plant population density, late crop/weed biomass, and edamame yield for three cultivars: Butterbean, IA1010, and Gardensoy 43. Solid, bold arrows indicate significant associations ($P < 0.05$) between variables, whereas dashed arrows indicate nonsignificant associations. Standardized regression coefficients are reported for significant associations.

a direct positive association with crop biomass. Crop population density also had a strong indirect linkage to weed biomass that was mediated through crop biomass, as evidenced by negative path coefficients (-0.500 to -0.744) for all cultivars. Interestingly, a direct negative association was observed between crop population density and pod yield (-0.466 to -0.674), suggesting crop seeding rate may have been too high for optimal pod yield. The seeding rate used in this study was somewhat arbitrary, as optimal plant population density for edamame is poorly defined (Sánchez et al. 2005).

Other key relationships varied among cultivars. For instance, variability in weed population density was associated with pod yield for Butterbean and Gardensoy 43, although why the association was positive is unclear. This observation is not likely to result from crop injury from certain herbicides and subsequent loss of yield potential (e.g., saflufenacil reducing weed and crop population density), because cultivar responses were equally affected by weed management treatment ($P \geq 0.499$). Also common to Butterbean and Gardensoy 43 was that weed biomass had a direct negative relationship to pod yield; a response not observed in IA1010. These observations are not easily explained, because Butterbean and IA1010 were very comparable to each other, and different from Gardensoy 43 in terms of development, growth, and weed-suppressive ability. Collectively, the work shows edamame–weed interactions are not identical across cultivars. Traits linked to grain-type soybean competitiveness with weeds, such as early vigor (Rose et al. 1984), leaf area (Jordan 1993), maturity group (Place et al. 2011), and seed size (Place et al. 2011) also vary among edamame cultivars available in the United States. Further research is needed to develop a mechanistic understanding of edamame-weed interactions, including the extent to which edamame can be improved to compete with weeds.

Commercial production of edamame in the United States seems achievable given the increasing consumer demand for edamame, vegetable processor interest in domestic production, and a well-developed, research-supported soybean industry. Although weeds are a major hurdle to domestic edamame production, this work demonstrates that recent advances in weed management are both timely and of practical use. Although few herbicides are currently available for use in the crop, the MET fb IMX treatment maintained crop yield equivalent to the weed-free treatment, and greatly reduced biomass of species observed in this work. Certainly, further improvements in crop production are necessary. For instance, more effective weed management in edamame would result from research and development that (1) improves crop establishment, (2) makes greater use of mechanical and cultural tactics, (3) utilizes crop traits that improve competitive ability, (4) facilitates registration of additional herbicide modes of action, and (5) reduces seed production of weed plants escaping management. In the meantime, the vegetable industry now has nascent weed management options in edamame, which will likely decrease reliance on hand weeding and result in crop production costs that are more competitive in the global market.

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