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Weed Control and Management for Vegetable Soybeans in Arkansas

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Weed Control and Management for Vegetable Soybeans in Arkansas

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ABSTRACT

Vegetable soybean [*Glycine max* (L.) Merr.], known as edamame, needs weed management tools. Releasing locally adapted edamame soybean varieties and registering herbicides are necessary for successful production and expanding the edamame industry. This research aimed to 1) identify herbicides labeled for grain soybean for potential use on edamame; 2) evaluate differential tolerance of edamame soybean varieties to selected grain soybean herbicides; and 3) identify a feasible edamame-based crop rotation system. For objective 1, 26 herbicide treatments were tested on AVS-4002 edamame including preplant (PPL), preemergence (PRE) and postemergence (POST) herbicides labeled for grain soybean. Preplant herbicides caused 9 to 28% crop stand loss and ≤12% injury on remaining plants 21 d after planting (DAP). Plots treated with pyroxasulfone PRE had 8 to 30% crop stand loss with no effect on yield. Postemergence herbicide treatments (acifluorfen, acifluorfen+bentazon, fomesafen, imazethapyr, imazamox+bentazon, and *S*-metolachlor+fomesafen) caused some injury, but did not reduce yield. For objective 2, 11 edamame and grain soybean varieties were treated with flumioxazin, metribuzin, sulfentrazone, and pyroxasulfone PRE and fomesafen POST. Metribuzin caused the highest crop stand reduction and injury. Flumioxazin and sulfentrazone caused 54% and 60% stand reduction, respectively. Postemergence application of fomesafen caused 11% leaf necrosis at 7 days after treatment. Grain soybean UA 5612 had the highest tolerance to sulfentrazone but was sensitive to metribuzin. Edamame varieties AVS 4002 and R07-7645 had good tolerance to pyroxasulfone. In summary, fomesafen and pyroxasulfone are good herbicides for edamame. Sulfentrazone can only be used on tolerant edamame varieties. For objective 3, four crop rotation systems were evaluated at Kibler and Rohwer, Arkansas. Rotations were composed of greenbeans/edamame (Rotation A), short-season soybean/edamame (Rotation B), sweet

corn/edamame (rotation C), and edamame monoculture (Rotation D). Yield of fall-harvested edamame relative to the monoculture in rotation C was 128% and 77% in 2014 and 2015, respectively. Inclement weather in both years compromised crop performance at Rohwer. The monoculture rotation is not sustainable; thus, possible crop diversification schemes need to be investigated. Edamame-based crop rotation systems will have more chance for success in the southern US where the crop growing period is longer.

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CHAPTER I

INTRODUCTION

Introduction

Soybean [*Glycine max* L. (Merr.)] is the most dominant oilseed crop in the United States, contributing a total of 108 M tons of soybean produced in the US in 2014 (FAO, 2015). The United States has the largest soybean production globally, followed by Brazil and Argentina (FAO, 2015). Soybean, contributes 34.5 billion dollars to the US economy (USDA-FAS, 2016; NASS, 2016). It is used for oil, feed production (grain type), and for human consumption (vegetable type) (Wang et al., 2005). Vegetable soybean is primarily grown in Asia. In China, it is popularly known as *mao dou* and edamame in Japan (Konovsky et al., 1994). Edamame was introduced in the US in late 1890s to early 1900s (Shurtleff and Aoyagi, 2009). Edamame is a promising, high-value crop in many states in the US including Arkansas. It was widely produced in Minnesota and Washington in the early 2000s (Shurtleff and Aoyagi, 2009). The demand for edamame was predicted to increase 12-15% annually in Arkansas (UAEX, 2013). The release of locally adapted edamame varieties is expected to be the catalyst for future research to define the best crop management practices for edamame. Investigations to increase yield would include optimizing agronomic practices such as seeding rates, fertilizer use, planting dates, and performance in double-crop systems (Ross, 2013). Unfavorable environmental conditions and pests, particularly weeds, significantly reduce vegetable soybean yield like in grain soybean. Weeds in grain soybean are controlled by chemical (herbicides) and non-chemical (double cropping or crop rotation, drill seeding or narrow rows, high population) techniques. Vegetable soybean production requires similar practices as grain soybean for weed management.

One of the most problematic weed species in soybean is Palmer amaranth (*Amarathus palmeri* L.) In Arkansas, and the southern US, Palmer amaranth ranks as the most troublesome weed in a soybean-based production system followed by morningglory species (*Ipomoea* spp.) and horseweed (*Conyza canadensis* L.) (SWSS, 2013; Ward et al. 2013).

Herbicide options for vegetable soybean are limited (Williams and Nelson, 2014). Some of the herbicide modes of action used in vegetable soybean include acetolactate synthase (ALS) inhibitor (imazethapyr, imazamox), acetyl-CoA carboxylase (ACCase) inhibitor (sethoxydim), microtubule inhibitor (pendimethalin), photosystem II inhibitor (metribuzin), protoporphyrinogen oxidase (PPO) inhibitor (fomesafen) and very long-chain fatty acid (VLCFA) inhibitor (*S*-metolachlor) (Scott et al., 2016). Increasing the herbicide options is one key factor in successful vegetable soybean production (Williams, 2015).

Soybean, rice (*Oryza sativa* L.), and field corn (*Zea mays* var. *indentata*) are commonly planted in rotation in North America. Crop rotation involves a systematic and recurring sequence of planting in the same land area where soil is prepared by conventional, minimum, or no-tillage and crops are planted in succession (Liebman and Dyck, 1993; Dick and Van Doren Jr, 1985). Unlike monoculture, good crop rotation systems improve soil health and minimize the occurrence of weeds and other pests (Souza et al., 2013). It has been reported that the weed seedbank size is reduced whenever a crop (i.e. soybean) is followed by another type of crop compared to monocropping (Cardina et al., 2002). Increased awareness of the positive environmental impact of crop rotation is important for increasing the adoption of sustainable farming practices to achieve high yields and improve economic returns.

The goal of this study was to evaluate potential weed control programs for edamame soybean and potential edamame-based cropping systems in Arkansas. These involved conducting varietal tolerance experiments to various herbicides applied PRE or POST and establishing crop rotation systems suitable for edamame soybean. The objectives of these experiments were to identify herbicides labeled for grain soybean that can be labeled also for edamame soybean production; to evaluate differential tolerance of edamame soybean varieties to flumioxazin, fomesafen, linuron, metribuzin, pyroxasulfone and sulfentrazone; and to identify crop rotation systems for edamame.

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CHAPTER II

REVIEW OF LITERATURE

Review of Literature

Edamame soybean

Asia is the origin of vegetable soybean cultivation [*Glycine max* L. (Merr.)] particularly in China and Japan (Konovsky et al., 1994). Vegetable soybean, known in China as *mao dou* (hairy bean) or *qingdou* (green bean) and edamame (beans and branches) in Japan, was introduced into the US in the 1990s (Shurtleff and Aoyagi, 2009). Edamame is consumed as a snack or processed food where it is recognized for its nutritional value and health benefits such as reduced risk of osteoporosis (Montri et al., 2006; Messina, 2000). Edamame has a slightly sweet, mild flavor and nutty texture, with less objectionable beany taste (Brar and Carter, 1993). Edamame contains lower levels of trypsin inhibitors, an enzyme which disrupts trypsin during digestion, and higher sucrose content compared to grain soybean (Tiffin and Gaut, 2001; Rodriguez et al., 2008; Kumar et al., 2011). Edamame is harvested when plants are at the reproductive (R6) stage having pods containing full-size green seeds at one of the four uppermost nodes with a fully expanded leaf (Konovsky et al., 1996; Fehr et al., 1971). Seeds of edamame are larger in size with relatively higher protein content compared to grain soybean (Brar and Carter, 1993). The stem of edamame has several podless nodes (Shanmugasundram et al., 1989). The pods and seed coat can easily shatter at maturity. (Smith and Van Duyne, 1951).

Edamame has similar plant development stages as grain soybean. After emergence, the vegetative phase starts when the unifoliate leaves (VC stage) are fully expanded and the reproductive phase begins when the plant starts to flower (R1 stage) (Fehr et al., 1971). The rate of plant development depends on several factors such as temperature, daylength, adequate soil moisture, nutrition and the absence of pests (Purcell et al., 2014).

Despite the number of edamame producers in the US, demand for edamame is increasing worldwide, prompting technological development in crop production (Mehbrahtu et al., 2004). Several growers in the US incorporate edamame in their crop portfolio to diversify the farming system and to increase income (Mentreddy et al., 2002).

Edamame production in the mid-Southern United States

Edamame is considered as an emerging crop of importance in US agriculture. Arkansas could potentially become a major producer of edamame in the United States. This is fueled by two factors: 1) the presence of a highly productive and progressive soybean breeding program at the University of Arkansas System Division of Agriculture, and 2) the establishment of an edamame processing industry in the Arkansas River Valley. Since the launching of the edamame industry in Arkansas in 2012, more than 800 acres are planted with edamame in the Arkansas River Valley and North Central Arkansas (Ross, 2013; UAEX, 2013). One goal of the edamame breeding program is to produce varieties with higher pod load and lesser pod shattering.

Zhang and Kyei-boahen (2007) studied several edamame varieties in the Mississippi Delta seeded during mid-April and early May. They reported that late-maturing varieties were generally taller, had more nodes per plant, pods per plant, and fresh green pod yield at full seed stage (R6) than the early-maturing varieties. Irrigation requirement of this crop is similar to that of field soybean. Studies in North Dakota and Japan showed that as long as water is adequate, edamame will grow well (Duppong and Valentini, 2005; Matsuo et al., 2013). In Arkansas, yield trials of edamame varieties indicated that the choice of variety is critical in achieving sustainable production.

Herbicides for edamame

Increasing demand for edamame prompted research to increase yield at harvest. Establishing an efficient weed control program is needed to meet demand on specialty crops like edamame (Fennimore and Doohan, 2008). However, since edamame seeds are for direct human food consumption, residue tolerances for herbicides in the consumable product need to be investigated before appropriate herbicides can be labeled for use. Also, the tolerance of edamame to all herbicides labeled for grain soybean is not known. Herbicides labeled for edamame includes Dual Magnum (*S*-metolachlor) applied preplant incorporated (PPI) or preemergence (PRE) and Pursuit (imazethapyr) applied postemergence (POST). The wide spectrum of herbicides used in grain soybean provides several potential herbicide modes of action for edamame including acetolactate synthase (ALS) inhibitor (imazethapyr, imazamox), acetyl-CoA carboxylase (ACCase) inhibitor (fluazifop), microtubule inhibitor (pendimethalin), photosystem II inhibitor (metribuzin), protoporphyrinogen oxidase (PPO) inhibitor (fomesafen) and very long-chain fatty acid (VLCFA) inhibitor (*S*-metolachlor) (Scott et al., 2016). Increasing the herbicide options is a key factor in successful vegetable soybean production.

Acetyl-CoA carboxylase-inhibitor herbicides control weeds by inhibiting the production of malonate, which is the key ingredient in fatty acid synthesis. Malonate is produced through the condensation of acetyl-CoA carboxylase with bicarbonate (Devine, 1997). Acetolactate synthase herbicides inhibit branched-chain amino acids and are considered to be among the most active group of herbicidal compounds (Ren et al., 2000); hence, their low-dose rates. Microtubule inhibitor herbicides disrupt microtubule polymerization during mitosis resulting in abnormal plant cells (Vaughn and Lehnen Jr, 1991). Photosystem II herbicides inhibit photosynthesis by binding to the D1 protein of the photosystem II reaction center in the chloroplast (Devine et.al., 1993; Rutherford and Krieger-Lizkay, 2001). Protoporphyrinogen oxidase inhibitors block the porphyrin pathway by inhibiting protoporhyrinogen IX oxidase (Protox), an enzyme that converts protoporphyrinogen IX to protoporphyrin IX (Proto) needed for chlorophyll and heme synthesis (Duke et al., 1991). Very long-chain fatty acid (VLCFA) inhibitors block VLCFA synthase necessary in the reaction of Coenzyme A activated fatty acids and malonyl-CoA (Böger et al., 2000).

Potential crops for edamame rotation

Although it is common for US growers to practice some kind of crop rotation, this is normally done in different years, with only one crop planted each year in Arkansas. Soybean-wheat is the only double-crop system feasible, besides planting multiple vegetable crops in one year. The growing season in the mid-southern US, Arkansas in particular, is not long enough to accommodate two full-season crops in one year. The probability of double-cropping agronomic crops (rice, corn, and soybean) to succeed hinges upon the availability of short-season varieties. Even then, there is always the risk of the second crop not making it to maturity before the first frost. Because edamame is a short-season crop, it lends the potential for planting a second crop to increase the growers' cash flow.

In terms of land production, soybean (*Glycine max* L.) is one of the primary crops grown in Arkansas. The top five soybean-producing counties in the state are Mississippi, Phillips, Crittenden, Poinsett, and Arkansas counties (USDA-NASS, 2017). Soybean is a short-day plant where the onset of flowering is regulated by exposure to a critical long period of darkness (Ashlock and Purcell, 2000). Compared to edamame, soybean is harvested at full maturity (R8) where 95% of the pods are mature or brown (Fehr et al., 1971). As in any other crop, soybean development is influenced by environmental factors such as temperature, day length and water availability (Ashlock and Purcell, 2000). When the disease cycle is interrupted, weed and insect infestations are minimized, soil productivity potential is increased (Ashlock et al., 2000) and full yield potential is more easily attained. A study by Dillon et al. (1999) shows that planting grain sorghum (*Sorghum bicolor* L.) in rotation with soybean may reduce soybean cyst nematode population. Planting early-maturing varieties, at optimum plant population, is also a key factor in achieving high soybean yield in a crop rotation system. A broad range of soybean maturity groups can produce similar yields in the mid-southern US although seeding densities vary by maturity (Edwards and Purcell 2005). The yield potential of soybean also depends on the maturity group and plant population (Edwards et al., 2005). A major challenge in implementing a soybean crop rotation system is reducing crop production cost, which can be addressed with the use of site-specific and precision agriculture technology (Ashlock et al., 2000).

Corn (*Zea mays* L.) is another crop of importance in Arkansas. In 2017, the estimated acres harvested was 595,000 (240,788 ha) with average state yield of 183 bushels acre^{-1} (11.42 metric tons ha^{-1}) (USDA-NASS, 2017). Corn was the most important agronomic crop of the early settlers in Arkansas (Espinoza and Ross, 2008). Successful corn production in Arkansas depends greatly on locally adapted, high-yielding hybrids and the efficiency of the farming operation (Espinoza, 2008). Corn is either used for human consumption (sweet corn) or livestock feed (field corn). Increased preference for sweet corn consumption in the US is observed especially if appealing characteristics such as dark green flag leaf color, ear length and kernel arrangement are present (Butzler et al. 2015). Good cultural management (crop cultivar and planting date) and timely chemical application (herbicide and insecticide) is necessary for sweet corn production (Kahn and Brandenberger, 2015).

Sweet corn (*Zea mays* var. *saccharata*) in Arkansas is planted as early as March, which makes it a good candidate for multiple cropping with other short-season crops in one year. Sweet corn planted no-till into desiccated cover crop or soybean stubble allows moisture conservation and reduces weed pressure (Burgos and Talbert, 1996; Carrera et al., 2004). However, planting sweet corn and edamame in rotation has not been studied.

Cowpea (*Vigna unguiculata*) is a primary source of protein in many of the world's regions (Ehlers and Hall, 1997). As early as the 1980s, cowpea has been a significant legume crop in the US (Fery, 1981). Cowpea is one of the major vegetable crops in the processed food industry besides being popular in the fresh food market. Cowpea is an important cash crop for many growers in the southern US. Cowpea is an excellent candidate for double-cropping systems because it is a short-season crop, highly productive, drought-tolerant and a nitrogen-fixing crop (Ehlers and Hall, 1997). Expanded herbicide labels for fomesafen and halosulfuron-methyl into cowpea (Burgos et al., 2007; Brandenberger et al., 2012) allows more flexibility in choosing crops to include in the rotation.

Greenbeans (*Phaseolus vulgaris*) is another vegetable legume crop of significance in US agriculture. This is a very popular vegetable in the US, processed or fresh, which is supported by breeding programs aiming to improve its nutritional quality, harvesting and processing efficiency, and taste (VandenLangenberg et al., 2012). In US vegetable cropping systems, legume crops like cowpea and greenbeans can be grown under various tillage techniques (strip tillage, no-tillage, conventional tillage) in rotation with different crops (Brainard et al., 2013).

Developing weed control programs for Arkansas edamame production

Weed management is a vital aspect of edamame production. Experiments on edamame variety response to herbicides were conducted in Illinois, Mississippi and Alabama (Williams et al., 2012; Zhang and Kyei-Boahen, 2007; Ogles et al., 2016). Soybean and vegetable crops (sweet corn, cowpea and greenbeans) grown in Arkansas are potential crop rotation partners for edamame. Conducting herbicide tolerance tests, varietal performance, and crop rotation studies will generate the information necessary for edamame growers to choose the appropriate varieties, weed control programs, and crop rotation schemes. This will facilitate sustainable growth in edamame production.

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CHAPTER III

RESPONSE OF EDAMAME SOYBEAN 'AVS 4002' TO HERBICIDES

Abstract

Edamame is a vegetable soybean and its consumption is expected to rise in the United States. Weeds are a major constraint of this crop, though only a few herbicides are currently registered for use in edamame. Field experiments were conducted in 2013 and 2014 in Kibler, Arkansas, USA to evaluate the safety of 24 herbicide treatments on edamame 'AVS 4002' and their efficacy on prominent crop weeds. Three of the treatments were applied 7 days preplant (PPL), 15 were applied preemergence (PRE), and 6 treatments were applied postemergence (POST). In 2013, fomesafen (0.42 kg ha^{-1}), *S*-metolachlor+fomesafen premix (1.39 kg ha^{-1}), linuron (0.84 and 1.68 kg ha^{-1}), pyroxasulfone (0.14 kg ha^{-1}), sulfentrazone (0.21 kg ha^{-1}), and sulfentrazone+carfentrazone premix (0.31 kg ha^{-1}) did not affect the stand of edamame. The other treatments reduced crop stand from 16 to 40%. In 2014, all but two soil-applied treatments, fomesafen and sulfentrazone+carfentrazone, reduced the stand by 24 to 50%. Edamame compensated for stand loss in the majority of treatments; however, yield loss occurred with flumioxazin+chlorimuron (0.105+0.04 kg ha^{-1}; PRE), metribuzin (0.56 kg ha^{-1}; PRE), and sulfentrazone (0.21 and 0.42 kg ha^{-1}; PRE) applied alone or in tank mixture in 2013, and the high rate of sulfentrazone in 2014. The flumioxazin+chlorimuron premix (0.35 kg ha^{-1}) was safe when applied PPL rather than PRE. Pyroxasulfone and linuron are excellent PRE herbicide options for edamame and provided complete control of Palmer amaranth and other grasses. The premixes of flumioxazin+chlorimuron or saflufenacil+dimethenamid-P applied PPL provided excellent weed control (>89% at 35 DAP) without impacting crop yield. Among the POST treatments, acifluorfen and fomesafen were the best options for Palmer amaranth control, which provided at least 95 and 93% control, respectively, at 35 DAP. None of the foliar-applied (POST) herbicides caused yield loss.

Introduction

Vegetable soybean (*Glycine max* L. Merr.), hereafter referred to as edamame, is gaining popularity in the United States due to its potential health benefits and palatability. For instance, soy-protein consumption has been associated with reduced osteoporosis and cancer (Messina and Messina, 2000). Compared to grain soybean, edamame contains more vitamins and fewer anti-nutritional factors such as trypsin inhibitors (Rackis, 1978), which are typically high in grain soybean. Trypsin is responsible for protein digestion and its inhibition can lead to nutritional deficiency in humans and animals (Mello et al., 2003; Rodriguez et al., 2008; Tiffin and Gaut, 2001).

Given these potential benefits, edamame consumption is expected to rise in the United States, emphasizing the need for production and technological support for this commodity (Mehbrahtu et al., 2004). While the demand for edamame is increasing in the United States (Soyfoods Association of North America, 2018), edamame is commercially produced in only a few states, including Arkansas, Illinois, and Mississippi (Ross, 2013; Williams and Nelson, 2014; Zhang and Kyei-Boahen, 2007). The lack of effective weed control options limits the expansion of edamame production. Current cultural practices in controlling weeds in edamame include handweeding, rotary hoeing, inter-row cultivation and crop rotation. Development of new edamame cultivars for herbicide tolerance tests provide another avenue of managing weeds (Williams, 2015; Ogles et al., 2016). Apart from cultural weed control, herbicides offer effective and efficient weed control alternatives in edamame (Williams et al., 2017).

It is not known whether edamame is tolerant to all herbicides used in grain soybean. Fewer herbicides are registered for edamame compared to grain soybean; thus, herbicide options are available for weed management in edamame are limited. Some registered herbicides for edamame include bentazon, clethodim, fomesafen, imazamox, imazethapyr, linuron, *S*-metolachlor, sulfentrazone+carfentrazone, and trifluralin (IR4, 2015; Scott et al., 2016). These herbicides were approved under special state labels [FIFRA Section 24(c)] following initial efforts to diversify chemical weed control options for edamame growers. Herbicide manufacturers are generally reluctant to expand their product labels to high-value specialty crops such as edamame, fearing potential liability for crop injury (Williams and Nelson, 2014). Recently, pyroxasulfone was tested in Illinois for use in edamame (Williams et al. 2017). It has been observed that this herbicide causes minimal injury on edamame when applied PRE or early postemergence (EPOST). Confirmation of edamame tolerance to pyroxasulfone is another breakthrough in edamame weed management (Williams et al. 2017).

This research was conducted, in collaboration with IR-4 (http://ir4app.rutgers.edu/ir4FoodPub/simpleSch.aspx) to identify safe herbicide options for edamame production, particularly for the US mid-south.

Materials and Methods

Site description and field establishment

Field experiments were conducted at the Vegetable Research Station, Kibler, AR (35.37°N, 94.23°W) in 2013 and 2014 on Roxana loam (coarse silty, mixed, superactive, nonacid, thermic Typic Udifluvents) soil. The field used had no history of residual herbicide usage in the previous year. Edamame cultivar 'AVS 4002' was used in the test because it is commercially available in the state of Arkansas. The field was prepared using conventional tillage methods. Edamame seeds were planted with a mechanical planter on 24 June, 2013 and 24 May, 2014 in four-row plots, 6 m long, spaced 0.9 m apart at a target seeding rate of 217,360 seeds ha^{-1}. The experiment was conducted in a randomized complete block design (RCBD) with three replications. The crop was irrigated as needed with a lateral-move sprinkler system. Palmer amaranth (*Amaranthus palmeri* S. Watson) seed was broadcast-seeded, comprising approximately 90% of the total weed density in the plots. This location was naturally infested with grasses including red sprangletop (*Leptochloa panicea* Retz.) and goosegrass (*Eleusine indica* L.), which comprised approximately 10% of the total weed density.

Herbicide treatments

Twenty-four herbicide treatments were evaluated over two years (Table 1). Three treatments were applied preplant incorporated (PPL) at 7 days before planting, 15 were applied preemergence (PRE) at 1 day after planting (DAP), and 6 were applied postemergence (POST) at the 2- to 3-trifoliate leaf stage. A weed-free check (hand-weeded) was included as reference for the evaluation of phytotoxicity of herbicides on edamame and a weedy check was included as a reference for herbicide efficacy .

Herbicide treatments were applied using a CO_2-pressurized backpack sprayer fitted with four flat-fan nozzles (Teejet XR11002VS) spaced 46 cm apart, delivering 187 L ha^{-1} of spray volume at a pressure of 276 kPa. The weed-free check plots were hand-weeded as needed. In 2013, the whole area was treated with glyphosate (Roundup PowerMax®, Monsanto Corp., St. Louis, MO, USA 63167) at 1.12 kg ai ha^{-1} 3 DAP due to the high infestation of Palmer amaranth. Glyphosate was applied using a tractor-mounted sprayer fitted with four Teejet (110015VS) nozzles spaced 46 cm apart delivering 187 L ha^{-1} of spray volume.

Data collection

Crop stand was counted from the two middle rows (1 m length per row) of each plot 2 weeks after planting (WAP). Weed control and edamame crop injury were recorded 21 and 35 DAP for PPL and PRE treatments, respectively. For POST herbicide treatments, crop injury and weed control were evaluated 7 days after treatment (DAT) and 35 DAP. The POST evaluations at 7 DAT occurred 28 DAP. Weed control and edamame injury ratings were based on a scale of 0 (no weed control or crop injury) to 100% (plant death) relative to the weedy check and to the nontreated weed-free plots, respectively. At crop maturity (R8 growth stage), dry-seed yield was harvested from 2 m of the two middle rows on 4 October, 2013 and 30 October, 2014. Grain yield was adjusted based on the soybean standard moisture content of 13%. In addition, the number of pods per plant were counted from four random plants from the two middle rows. Partial return analysis was conducted using the formula proposed by Edwards et al. (2015), where: partial return (\$) = income (\$ ha^{-1}) – herbicide application cost (\$ ha^{-1}). Partial budgeting tracks only relevant costs and revenue changes across treatments. Costs for common activities such as planting, tillage, fertilizer application, irrigation, and land equipment ownership charges were the same across treatments. Partial returns allows for comparison of profitability across treatments but not an estimate of soybean profitability production using a particular treatment.

Statistical analysis

Data were subjected to analysis of variance (ANOVA) using SAS v. 9.4 (SAS Institute Inc., Cary, NC). Year and treatments were considered as fixed effect and replications were considered as random effects. Year by treatment interaction effects were significant; thus, data were analyzed separately by year. Crop stand loss (%) was calculated relative to the respective nontreated weed-free check in the same block. Data for crop stand loss (%) of each PPL or PRE herbicide, visible POST injury (%), weed control (%), edamame yield (mt ha^{-1}), and partial returns were subjected to ANOVA using the PROC GLM procedure in SAS. Means were separated using Fisher's Protected LSD ($\alpha = 0.05$) for stand loss, yield, weed control, and partial returns.

Results and Discussion

Overview of herbicide effect on 'AVS 4002' edamame

Several herbicide treatments caused significant stand reduction relative to the nontreated plots (Table 2). Preemergence application of metribuzin+chlorimuron premix (0.16+0.03 kg ha^{-1}) reduced edamame stand (no seedling emergence) by 50% in 2014. Crop stand loss can reduce yield depending on the severity of the stand reduction (Taylor-Lovell et al., 2001). In this study, stand loss with some treatments resulted in yield loss (Table 2). In 2013, dry bean yield from the nontreated weed-free plots averaged 3.30 mt ha^{-1}. The dry bean yield potential of AVS-4002 from 2009 to 2011 averaged 3.15 mt ha^{-1} (Chen et al., 2014) indicating that crop performance in 2013 (in Arkansas) was slightly above average. Edamame yield based on the weed-free check in 2014 was inferior (36% less) to that of 2013 due to occasional excessive rainfall (Fig. 1). Yields from herbicide-treated plots ranged from 1.08 to 3.47 mt ha^{-1}. Plants in the weedy check plots yielded 0.70 mt ha^{-1} and 2.28 mt ha^{-1} in 2013 and 2014, respectively. The majority of herbicide treatments tested were viable options for edamame, and the impact of specific herbicides on crop performance and weed control are presented in the following sections.

Soil-Applied Herbicides

Flumioxazin+chlorimuron proprietary mixtures

The mixture of flumioxazin [protoporhyrinogen oxidase (PPO) inhibitor] with chlorimuron [acetolactate synthase (ALS)-inhibitor] provides residual control of broadleaf weeds and certain annual grasses in grain soybean (Anonymous, 2013a; Taylor-Lovell et al., 2002). Preplant application of flumioxazin+chlorimuron (0.105 + 0.04 kg ai ha^{-1}) caused a 22 to 25% crop stand loss compared to the weed-free check (Table 2). Significant necrosis was observed on soybean cotyledons. Preemergence application also caused a similar reduction in plant population (20 to 26%), as the PPL treatment. The emerged seedlings showed minimal injury (0 to 12%) 21 DAP across years (Table 3). These plants compensated for stand loss to some extent by producing more branches (visual observation).

Edamame yielded 1.97 (2014) and 3.21 mt ha^{-1} (2013) with the PPL application of flumioxazin+chlorimuron, but yielded less [1.56 (2014) and 2.08 mt ha^{-1} (2013)] when the premix was applied PRE (Table 2). Yield loss caused by the PPL application was less (3 to 7%) compared to that of the PRE application (26 to 36%). In 2013, the PPL application timing resulted in 34% greater yield than the PRE application timing. In 2014, the yield difference between PPL and PRE was not significant, but yield was still numerically lower when flumioxazin+chlorimuron was applied PRE. Thus, flumioxazin+chlorimuron applied PPL is safer on edamame than when applied PRE. Overall weed control was 90 to 98% with this treatment regardless of timing in both years (Tables 4 and 5). Grass weed control was not adequate, although grass weeds comprised only 10% of the total weed population in the plots. Flumioxazin, as a component of an herbicide program, is an effective tool for controlling broadleaf weed species in soybean, especially *Amaranthus* species that have evolved resistance to glyphosate, ALS-inhibitor herbicides, or other herbicide sites of action (Taylor-Lovell et al., 2002). This treatment will need a supplemental herbicide to improve grass weed control.

Metribuzin and its proprietary mixture with chlorimuron

Metribuzin, a photosystem II inhibitor, controls annual broadleaf and grass weed species in soybean (Shaner, 2014). The application of metribuzin (0.56 kg ai ha^{-1}) PRE reduced edamame stand up to 38% and caused 5 to 57% injury to the remaining plants (Tables 2 and 3). Emerged seedlings had chlorotic cotyledons, which eventually turned necrotic. Overall crop injury (stand loss and health of seedlings) was severe in 2013 due to excessive rainfall from June to July (Fig. 1) and yield loss was significant with the metribuzin treatment (35%). Similar injury has been observed previously by other researchers due to excessive soil moisture (Miller et al., 2012). The proprietary mixture of metribuzin+chlorimuron (0.16 + 0.03 kg ai ha^{-1}) reduced crop stand 20 to 50% with negligible impact on the remaining plants (Tables 2). Both treatments provided 100% control of Palmer amaranth at 35 DAP (Table 4), and yields were 2.64 and 1.81 mt ha^{-1} in 2013 and 2014, respectively (Table 2 and 3).

Saflufenacil and saflufenacil+dimethenamid-P

Saflufenacil (0.07 kg ai ha^{-1}) is a PPO inhibitor with both soil and foliar activity. Its residual activity is affected by soil organic matter (Gannon et al., 2014). Saflufenacil reduced edamame stand 23 to 34% across years (Table 2), but the remaining plants incurred minimal injury (3 to 8%) (Table 3). Edamame yield was comparable to that of the weed-free check (Table 2). Saflufenacil has been reported to cause minor yield losses (10%) in grain soybean even at 0.045 kg ai ha^{-1} under cool, wet conditions (Miller et al., 2012). Thus, the margin of safety with saflufenacil is influenced greatly by environmental conditions. The PRE application of saflufenacil had very good control of Palmer amaranth at 21 DAP, but did not control grasses

(Table 4). Palmer amaranth control was only 77 to 88% 35 DAP in both years (Table 5). If combined with a sequential POST herbicide, this herbicide would be an effective PRE option, but it is a risky choice for edamame due to its potential to cause crop injury.

Dimethenamid-P is an inhibitor of long-chain fatty acid synthesis primarily used for controlling broadleaf weeds and small-seeded annual grasses (Böger, 2003; Anonymous, 2016). Saflufenacil+dimethenamid-P can be applied PPL or PRE to provide season-long control of broadleaves and annual grasses. This premix is valuable for resistance management, as it is comprised of two strong sites of action. Preplant application of saflufenacil+dimethenamid-P (0.03 + 0.29 kg ai ha^{-1}) reduced crop stand 9 to 28% in both years with negligible injury on emerged seedlings (5%) 21 DAP (Tables 2 and 3), resulting in yields of 3.35 mt ha^{-1} and 1.97 mt ha^{-1} in 2013 and 2014, respectively. This treatment, similar to flumioxazin+chlorimuron PPL, resulted in higher yields than sulfentrazone PPL, with yields equivalent to that of the weed-free check (Table 2). Regardless of time of application, saflufenacil+dimethenamid-P reduced crop stand up to 30%. In 2014, saflufenacil+dimethenamid-P PPL caused minimal injury (5 to 8%), similar to saflufenacil+dimethenamid-P PRE. The injury disappeared with time, as also shown by Mahoney et al. (2014b), but there is risk of significant yield loss if saflufenacil+dimethenamid-P is applied PPL. Saflufenacil+dimethenamid-P applied PRE controlled more than 94% of weeds at 21 DAP (Table 4), but by 35 DAP grasses recovered resulting in low overall weed control (87%).

Sulfentrazone and herbicides with proprietary mixture of sulfentrazone

Sulfentrazone and carfentrazone inhibit PPO, an enzyme involved in pigment synthesis (Shaner, 2014). The premix of sulfentrazone+carfentrazone applied 7 d PPL reduced crop stand up to 18% (Table 2), with the edamame seedlings showing barely noticeable (up to 3%)

symptomology at 21 DAP (Table 3). Despite causing minimal visible injury to edamame seedlings, this treatment resulted in significant yield loss (35 to 38%) across the two years. This indicates that the 7 days PPL interval might be too short for planting edamame after sulfentrazone application. The application of sulfentrazone+carfentrazone at planting (PRE) caused similar stand loss (7%) to sulentrazone+carfentrazone PPL in 2013, but caused 32% stand loss in 2014 (Table 2) when heavy rains occurred soon after planting (Fig. 1). However, in spite of a significant loss of plants in 2014, edamame produced similar yield to the nontreated weed-free check. The plants that survived the PRE application of sulfentrazone+carfentrazone were healthy and did not show reduced pod production. Like grain soybean, edamame can compensate for some stand loss if the plants are healthy. This was demonstrated in a study by Norsworthy et al. (2002), comparing two soybean seeding rates, wherein soybean planted at a lower seeding rate (370,000 seeds ha^{-1}) produced similar yield to that planted at the recommended seeding rate of 620,000 seeds ha^{-1}. The yield compensation was due to increased branching at lower plant populations. At high densities, pods were borne only on the main stem (Norsworthy et al., 2002). In like manner, edamame with low stand count produced additional pods, resulting in increased branch-fraction seed production. This ability to compensate for reduced plant population is reflected in the wide range of recommended plant populations for grain soybean (Ashlock et al., 2000; Ross et al., 2016).

The application of sulfentrazone (0.21 kg ai ha^{-1}; PRE) alone caused 8% (2013) and 33% (2014) stand loss (Table 2). The level of stunting (up to 15%) observed on seedlings resulted in reduced edamame yield. The high rate of sulfentrazone (0.42 kg ai ha^{-1}) reduced the crop stand 40% in 2013. Stand reduction was similar in 2014 regardless of sulfentrazone rates. In 2014, the high rate of sulfentrazone (0.42 kg ai ha^{-1}) injured the emerged seedlings at 21 d after planting

68% and 30% in 2013 and 2014, respectively (Table 3). This resulted in 69 to 72% yield loss relative to the weed-free check across years. Therefore, sulfentrazone alone PRE is not a viable option for edamame. In grain soybean, sulfentrazone has been known to cause injury to some varieties even at the recommended rate. Taylor-Lovell et al. (2001) studied 15 varieties of grain soybean, four of which were found sensitive to the recommended rate of sulfentrazone. Stand loss across varieties ranged from 20 to 60% when treated with sulfentrazone at 0.22 kg ai ha^{-1}. The four sensitive varieties incurred 10 to 20% yield loss at this rate. Similarly, Taylor-Lovell et al. (2001) observed that a high rate (0.45 kg ai ha^{-1}) of sulfentrazone can cause stand loss up to 72%, leading to 20 to 30% yield loss in sensitive varieties.

The premix of *S*-metolachlor+sulfentrazone PRE (1.39+0.15 kg ai ha^{-1}) caused 20% stand reduction in 2013 and 34% in 2014 (Table 2). This treatment caused 8 to 15% stunting of seedlings at 21 DAP (Table 3). *S*-metolachlor+sulfentrazone PRE caused significant yield loss (33%) in 2013 when injury to emerged plants was 15% on average, but not in 2014 when injury was lower (8%). Thus, edamame can compensate for the loss of about 1/3 of plants if those remaining are healthy. Similarly, Mahoney et al. (2014b) reported 20% injury on grain soybean with *S*-metolachlor+sulfentrazone (3.2+0.84 kg ai ha^{-1}) at 14 DAP without incurring yield loss.

Excellent overall weed control, from 92 to 98% across years, was attained with a tank-mixed application of sulfentrazone+carfentrazone applied either PPL or PRE (Table 4). Sulfentrazone had excellent activity on Palmer amaranth but poor control of annual grasses. However, the safe planting interval for edamame with PPL applications of sulfentrazone+carfentrazone (0.28+0.03 kg ai ha^{-1}) needs to be investigated further.

Linuron

Edamame was tolerant to linuron PRE (0.84 and 1.68 kg ai ha^{-1}), a photosystem II inhibitor (Shaner, 2014). The high rate of linuron (1.68 kg ai ha^{-1}) reduced crop stand up to 34% (Table 2). Injury to the emerged seedlings was negligible ($\leq$ 5%) in both years (Table 3), similar to that reported by Williams and Nelson (2014). Yield was not affected even at the high rate. Linuron was one of the safest herbicides for edamame in this study. It was also reported to be safe on several dry bean (*Phaseolus vulgaris* L.) varieties (Soltani et al., 2006). The low rate of linuron (0.84 kg ai ha^{-1}) provided fair weed control (about 70%) in 2013 and 100% weed control in 2014 (Table 4). The higher rate of linuron (1.68 kg ai ha^{-1}) resulted in excellent (100%) overall weed control both years, but may reduce yield if the herbicide is leached to the seed zone by heavy rain (Salzman and Renner, 1992). Linuron at 0.42 kg ha^{-1} would provide a greater margin of safety, but would need to be mixed with a complementary herbicide to ensure acceptable weed control across different environmental conditions.

Fomesafen

Fomesafen, a PPO inhibitor, can be applied PRE to soybean and cucurbits without impacting yield with a reduced risk of carryover injury (Kleifeld et al., 1985; Peachey et al., 2012; Rauch et al., 2007). The persistence of fomesafen in the soil varies and is affected by factors such as soil texture, soil pH, organic matter content, and temperature at the time of application (Weber, 1993). Soil clay content plays a vital role in the sorption of herbicide in soil (Soltani et al., 2015). Fomesafen can be applied PRE to other leguminous crops besides soybean such as adzuki bean (*Vigna angularis*) and dry bean (*Phaseolus vulgaris*) (Anonymous, 2013b; Sikkema et al., 2009). Grain yield of edamame treated with fomesafen was similar to the weed-free check in both years (Table 2). In our study, fomesafen (0.42 kg ai ha^{-1}) applied PRE reduced crop stand up to 20% (Table 2), but the emerged plants were healthy (Table 3). This herbicide provided excellent control of Palmer amaranth irrespective of timings in both years, but due to poor control of grasses, the herbicide only provided 94-95% overall weed control (Tables 4 and 5).

Pyroxasulfone

Pyroxasulfone, like dimethenamid-P, is an inhibitor of very long chain fatty acid (VLCFA) synthesis, and is used in corn and soybean (Anonymous, 2013b). It controls annual grasses and broadleaf weeds and also suppresses yellow nutsedge (*Cyperus esculentus*). It can be tank-mixed with other herbicides and applied before or after crop emergence at various stages of crop growth. Pyroxasulfone (0.14 kg ai ha^{-1}) reduced crop stand up to 30%, but the remaining plants <5% injury (Tables 2 and 3) similar to that reported in grain soybean (McNaughton et al., 2014). Pyroxasulfone provided excellent weed control (100%) at 21 and 35 DAP (Tables 4 and 5). Likewise, high level of efficacy has been reported in a location infested with velvetleaf (*Abutilon theophrasti*) and *Amaranthus* species (Mahoney et al., 2014a) because pyroxasulfone has excellent activity on velvetleaf unlike other VLCFA inhibitors. Edamame yield in pyroxasulfone-treated plots was similar to that of the nontreated weed-free check, producing 3.11 and 2.14 mt ha^{-1} in 2013 and 2014, respectively (Table 2).

***S*-metolachlor and proprietary mixture with fomesafen**

S-metolachlor, like dimethenamid-P and pyroxasulfone, inhibits VLCFA (Shaner, 2014). *S*-metolachlor was among the first herbicides labeled for edamame (IR-4, 2015). In this study, *S*-metolachlor (1.12 kg ai ha^{-1}) reduced crop stand up to 44% (Table 2), but this did not result in a significant yield loss in either year. It appeared that the 'AVS 4002' cultivar tested here has lower tolerance than grain soybean to *S*-metolachlor. *S*-metolachlor is labeled for use in numerous agronomic and vegetable crops and is safe on black beans, applied PPL or PRE, causing less than 10% injury (Soltani et al., 2004).

The proprietary mixture of *S*-metolachlor+fomesafen (1.12+0.27 kg ai ha^{-1}) applied PRE caused similar stand loss (13 to 26%) as the *S*-metolachlor treatment alone. However, this treatment did not cause any visible injury on the emerged plants 21 DAP (Tables 2 and 3). Overall, PRE application of *S*-metolachlor+fomesafen provided excellent (96 to 99%) weed control (Table 4), and plants in this treatment yielded equivalent to the weed-free check.

Foliar-applied Herbicides (POST)

Fomesafen

Fomesafen (0.42 kg ai ha^{-1}) applied POST caused transient injury (23 to 40%, 7 d after treatment; 0 to 8%, 35 DAP). This was similar to the level of foliar necrosis on dry beans (*Phaseolus vulgaris* L.) recorded by Wilson (2005), and what is commonly observed on grain soybean. In grain soybean, the injury from foliar application of fomesafen was 11 to 24% at 1 week after treatment (WAT), which subsided to 1 to 5% at 4 WAT (Belfry et al., 2016). Several other legumes are more sensitive to fomesafen. When applied to cowpea (*Vigna unguiculata* L.), fomesafen caused higher foliar injury (55 to 90%), although the crop recovered completely 4 WAT and those with high injury matured late (Burgos et al., 2007). Fomesafen applied POST provided 93-100% control of Palmer amaranth and overall weed control ranged from 89 to 94% (Table 5). Fomesafen is very efficacious on difficult-to-control weeds such as common ragweed (*Ambrosia artemisiifolia* L.) and morningglory species (*Ipomoea spp.*) in snapbeans (*Phaseolus vulgaris* L.) (Bailey et al., 2003). Bailey et al. (2003) highlighted that fomesafen is highly beneficial in tolerant legume crops such as snapbeans for the control of several broadleaf weed species.

_S_-metolachlor and proprietary mixture with fomesafen

S-metolachlor+fomesafen POST caused 22 to 43% injury 7 DAT from the fomesafen component, though the crop recovered quickly (Table 3) and did not incur significant yield loss. Similar results were reported by Wilson (2005), where POST application of fomesafen caused transient leaf necrosis on dry beans without incurring any yield penalty. Generally, *S*-metolachlor does not injure emerged plants (Soltani et al., 2004) and combining *S*-metolachlor with a POST application of fomesafen provides season-long control of problematic weeds (Everman et al., 2009). Mixing herbicides with different modes of action also may slowdown the evolution of herbicide resistance (Mallory-Smith and Retzinger, 2003), as fomesafen applied POST increases control of broadleaf weeds such as Palmer amaranth without any adverse effect on soybean yield (Whitaker et al., 2010). However, this proprietary mixture is not a viable POST option for grass weed control.

Imazethapyr

Imazethapyr, an ALS inhibitor, has both soil and foliar activity and can be applied PRE or early-POST to edamame (Anonymous, 2013c). In this test, imazethapyr (0.07 kg ai ha^{-1}) was applied POST only, causing barely noticeable crop injury (<5%; 7 DAT) (Table 3), consistent with its high margin of safety on other leguminous crops (Hanson and Thill, 2001; Soltani et al., 2008). Overall weed control in plots treated with imazethapyr POST was 81 to 93% at 35 DAP (Table 5). Walsh et al. (2015) evaluated imazethapyr PRE in grain soybean and recorded 80% weed control. Edamame yield from plots treated with imazethapyr POST was 2.5 and 1.68 mt ha^{-}

^{1} in 2013 and 2014, respectively (Table 2). These yields were comparable to the weed-free check.

Acifluorfen

Acifluorfen (0.56 kg ai ha^{-1}), a PPO inhibitor, is applied POST in grain soybean to control annual broadleaf weeds including *Amaranthus* spp. (Shaner, 2014; Witkowski and Halling, 1989). Acifluorfen-treated plants showed 25 to 57% foliar injury 7 DAT (Table 2) as normally observed on grain soybean (Kapusta et al., 1986). The crop recovered completely 14 DAT and yielded 3.24 and 1.88 mt ha^{-1} in 2013 and 2014, respectively (Table 2). Acifluorfen provided excellent control of Palmer amaranth (95-100%) at 35 DAP (Table 5). Acifluorfen tank-mixed with bentazon (0.28+0.56 kg ai ha^{-1}) caused less crop injury (13% in 2013 and 27% in 2014) than acifluorfen applied alone (Table 2). However, this tank mixture also reduced the overall weed control at 35 DAP (84 to 92%), compared to acifluorfen applied alone (93 to 96%) (Table 5). This indicates possible antagonistic interaction between acifluorfen and bentazon for the control of a broad range of weeds as previously reported (Sorensen et al., 1987). In the study conducted by Sorensen et al. (1987), the uptake of ^{14}C acifluorfen in redroot pigweed (*Amaranthus retroflexus* L.) was reduced by 10% when bentazon was present. Acifluorfen applied alone or tank-mixed with bentazon did not impact edamame yield.

Tank mixture of imazamox and bentazon

Imazamox, an ALS inhibitor, and bentazon can be applied POST to grain soybean (Shaner, 2014). Postemergence application of imazamox+bentazon (0.05+0.56 kg ai ha^{-1}) did not injure the AVS-4002 edamame (Table 3). Previous research showed that imazamox and bentazon applied separately caused minimal or no injury to edamame (Williams and Nelson, 2014). A mixture of imazamox with other herbicide modes of action can provide season-long control of a broad spectrum of weeds (Anonymous, 2014; Anonymous, 2015). Overall weed control in plots treated with imazamox+bentazon ranged from 77 to 90% (Table 5) and crop yield was 2.81 and 1.84 mt ha^{-1} in 2013 and 2014, respectively (Table 1).

Partial return analyses

Herbicides help increase edamame yield, but add to production costs (Edwards et al., 2015). Partial returns, including revenue from soybean and herbicide costs, allow edamame growers to determine which herbicide is most profitable to use. In 2013, among the herbicide treatments tested, the PPL application of saflufenacil+dimethenamid-P (0.03+0.29 kg ai ha^{-1}) generated the highest partial return ($1,318) (Table 6). In 2014, the PPL application of flumioxazin+chlorimuron (0.105+0.04 kg ai ha^{-1}) and PRE application of pyroxasulfone (0.14 kg ai ha^{-1}) generated the highest partial returns $828 and $814, respectively), similar to the weed-free check. Preemergence application of sulfentrazone at 0.42 kg ai ha^{-1} had the least partial return among the herbicides used, generating $789 and $390 in 2013 and 2014, respectively.

Conclusion

Several herbicides labeled for grain soybean are safe on edamame 'AVS 4002'. These herbicides include premixes of flumioxazin+chlorimuron (PPL), saflufenacil+dimethenamid-P (PPL), pyroxasulfone (PRE), and linuron (PRE). Although many of the herbicides evaluated caused stand loss, the surviving plants generally compensated for reduced plant populations. Pyroxasulfone and linuron were excellent PRE herbicide options for edamame. Among the POST treatments (foliar applied), acifluorfen nd fomesafen were the best options in terms of weed control.

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Table 1. Herbicides tested on vegetable soybean ‘AVS 4002’ at the Vegetable Research Station, Kibler, Arkansas, USA from 2013 to 2014.

Common name[a]	Trade name[b]	Time[c]	Rate kg ha^{-1}	Cost[d] \$ ha^{-1}	Formulation kg L^{-1}/kg kg^{-1}	Manufacturer	Address	Source
flumioxazin+chlorimuron	Valor XLT*	PPL	0.105 + 0.04	22	40.3WDG	Valent USA	Walnut Creek, CA	www.valent.com
saflufenacil+dimethenamid-P	Verdict	PPL	0.03 +0.29	41	0.66EC	BASF Corporation	Research Triangle Park, NC	www.basf.com
sulfentrazone+carfentrazone	Spartan Charge*	PPL	0.28 +0.03	69	0.54L	FMC Corporation	Philadelphia, PA	www.fmc.com
fomesafen	Reflex	PRE	0.42	32	0.24LC	Syngenta Crop Protection, LLC	Greensboro, NC	www.syngenta.com
flumioxazin+chlorimuron	Valor XLT*	PRE	0.105 +0.04	22	40.3WDG	Valent USA	Walnut Creek, CA	www.valent.com
linuron	Linex	PRE	0.84	29	0.48L	Tessenderlo Kerley, Inc.	Phoenix, AZ	www.noasource com
linuron	Linex	PRE	1.68	38	0.48L	Tessenderlo Kerley, Inc.	Phoenix, AZ	www.novasource.com
metribuzin	Tricor	PRE	0.56	26	75DF	United Phosphorus, Inc.	King of Prussia, PA	www.upi-usa.com
metribuzin+chlorimuron	Canopy	PRE	0.16 +0.03	111	75DF	DuPont, Inc.	Wilmington, DE	www.cropprotection.dupont.com
pyroxasulfone	Zidua	PRE	0.14	43	85WDG	BASF Corporation	Research Triangle Park, NC	www.basf.com
saflufenacil	Sharpen	PRE	0.07	24	0.34SC	BASF Corporation	Research Triangle Park, NC	www.basf.com
saflufenacil+dimethenamid-P	Verdict	PRE	0.03 +0.29	20	0.66EC	BASF Corporation	Research Triangle Park, NC	www.basf.com

Table 1 (cont.). Herbicides tested on vegetable soybean 'AVS 4002' at the Vegetable Research Station, Kibler, Arkansas, USA from 2013 to 2014

Common name[a]	Trade name	Time[b]	Rate kg ha^{-1}	Cost[c] $ ha^{-1}	Formulation	Manufacturer	Address	Source
S-metolachlor	Dual Magnum	PRE	1.12	45	0.91EC	Syngenta Crop Protection, LLC	Greensboro, NC	www.syngenta.com
S-metolachlor +fomesafen	Prefix*	PRE	1.12 +0.27	47	0.64EC	Syngenta Crop Protection, LLC	Greensboro, NC	www.syngenta.com
S-metolachlor +sulfentrazone	Broadaxe	PRE	1.39 +0.15	76	0.84EC	FMC Corporation	Philadelphia, PA	www.fmc.com
sulfentrazone	Spartan	PRE	0.21	29	0.48F	FMC Corporation	Philadelphia, PA	www.fmc.com
sulfentrazone	Spartan	PRE	0.42	58	0.48F	FMC Corporation	Philadelphia, PA	www.fmc.com
sulfentrazone+ carfentrazone	Spartan Charge	PRE	0.28 +0.03	69	0.54L	FMC Corporation	Philadelphia, PA	www.fmc.com
acifluorfen	Ultra Blazer	POST	0.56	40	0.2SL	United Phosphorus, Inc.	King of Prussia, PA	www.upi-usa.com
(acifluorfen+bentazon)	Ultra Blazer + Basagran	POST	0.28 +0.56	104	0.25SL; 0.5SL	United Phosphorus, Inc.; BASF Corporation	King of Prussia, PA; Research Triangle Park, NC	www.upi-usa.com; www.basf.com
fomesafen	Flexstar	POST	0.42	37	0.23SL	Syngenta Crop Protection, LLC	Greensboro, NC	www.syngenta.com
(imazamox+bentazon)	Raptor + Basagran	POST	0.05 +0.56	126	0.12AS; 0.48SL	BASF Corporation	Research Triangle Park, NC	www.basf.com
imazethapyr	Pursuit	POST	0.07	32	0.24SL	BASF Corporation	Research Triangle Park, NC	www.basf.com
S-metolachlor +fomesafen	Prefix*	POST	1.12 +0.27	47	0.64EC	Syngenta Crop Protection, LLC	Greensboro, NC	www.syngenta.com

[ab]Abbreviations: Plus (+), = proprietary mixture; Parenthesis ( ) = tank-mixed, PPL, preplant; PRE, preemergence; POST, postemergence. Herbicide trade names with asterisks are premixes.

[c] A single herbicide application was made across all treatments; therefore, the cost includes only the cost of herbicides as obtained from commercial distributors and from the 2018 University of Arkansas Weed and Brush Control extension publication.

Table 2. Effect of herbicide treatments on crop stand, 21 DAP, and grain yield of edamame soybean ‘AVS 4002’ at the Vegetable Research Station, Kibler, Arkansas, USA[a]

Treatments			**Crop stand**		**Crop stand loss[c]**		**Grain yield**	
Herbicide common name	**Rate**	**Time[b]**	2013	2014	2013	2014	2013	2014
	kg ai ha^{-1}		plants ha^{-1} x 10,000		------%------		------mt ha^{-1}------	
Weedy check			16.49	20.48	-	-	2.28	0.70
Weed-free check			16.84	20.65	-	-	3.30	2.11
flumioxazin+chlorimuron	0.105+0.04	PPL	12.50	16.31	25	22	3.21	1.97
saflufenacil+dimethenamid-P	0.03+0.29	PPL	15.10	15.10	9	28	3.35	1.74
sulfentrazone+carfentrazone	0.28+0.03	PPL	13.71	18.05	18	14	2.14	1.30
fomesafen	0.42	PRE	15.97	16.66	4	20	3.25	1.95
flumioxazin+chlorimuron	0.105+0.04	PRE	13.19	15.45	20	26	2.08	1.56
linuron	0.84	PRE	14.58	15.97	15	24	3.03	1.74
linuron	1.68	PRE	14.23	13.71	13	34	2.88	1.38
metribuzin	0.56	PRE	10.41	10.42	38	36	2.15	1.81
metribuzin+chlorimuron	0.16+0.03	PRE	13.36	13.40	20	50	2.64	1.81
pyroxasulfone	0.14	PRE	15.27	14.93	8	30	3.11	2.14
saflufenacil	0.07	PRE	12.84	13.71	23	34	2.62	1.23
saflufenacil+dimethenamid-P	0.03+0.29	PRE	13.71	14.58	18	30	2.54	1.53
S-metolachlor	1.12	PRE	14.06	11.08	16	44	3.11	1.58
S-metolachlor+fomesafen	1.12+0.27	PRE	14.40	15.10	13	26	3.17	1.75
S-metolachlor+sulfentrazone	1.39+0.15	PRE	13.36	13.71	20	34	2.19	1.72
sulfentrazone	0.21	PRE	15.27	14.06	8	33	1.74	1.08
sulfentrazone	0.42	PRE	10.06	10.76	40	49	1.01	0.62
sulfentrazone+carfentrazone	0.28+0.03	PRE	15.45	14.23	7	32	2.62	1.58
acifluorfen	0.56	POST	16.67	15.27	-	-	3.24	1.88
acifluorfen+bentazon	0.28+0.56	POST	15.97	15.79	-	-	2.57	1.57
fomesafen	0.42	POST	16.49	18.22	-	-	3.47	1.70
imazamox+bentazon	0.05+0.56	POST	15.97	18.75	-	-	2.81	1.84
imazethapyr	0.07	POST	15.45	18.70	-	-	2.50	1.68
S-metolachlor+fomesafen	1.12+0.27	POST	15.45	16.31	-	-	3.21	1.62
LSD (0.05)[d]			**4.52**	**7.4**	**18**	**20**	**0.92**	**0.69**

[ab]Abbreviations: DAP, days after planting, PPL, preplant; PRE, preemergence; POST, postemergence.
[c]Crop stand loss was calculated relative to the weed-free check.
[d]Means separated using Fisher’s protected LSD (α = 0.05).

Table 3. Effect of herbicide treatments on edamame ‘AVS 4002’ seedlings at the Vegetable Research Station, Kibler, Arkansas, USA[a]

Treatments			Injury on remaining plants					
			2013			2014		
Herbicide common name	Rate	Time	21 DAP	28 DAP[b]	35 DAP	21 DAP	28 DAP[b]	35 DAP
	kg ai ha^{-1}		----------------%----------------			----------------%---------------		
flumioxazin+chlorimuron	0.105+0.04	PPL	12	--	2	0	--	7
saflufenacil+dimethenamid-P	0.03+0.29	PPL	5	--	0	5	--	0
sulfentrazone+carfentrazone	0.28+0.03	PPL	3	--	0	0	--	0
fomesafen	0.42	PRE	0	--	0	0	--	0
flumioxazin+chlorimuron	0.105+0.04	PRE	10	--	0	5	--	5
linuron	0.84	PRE	2	--	0	0	--	0
linuron	1.68	PRE	2	--	0	5	--	5
metribuzin	0.56	PRE	57	--	20	5	--	5
metribuzin+chlorimuron	0.16+0.03	PRE	3	--	7	5	--	5
pyroxasulfone	0.14	PRE	2	--	0	5	--	5
saflufenacil	0.07	PRE	3	--	2	8	--	5
saflufenacil+dimethenamid-P	0.03+0.29	PRE	18	--	5	7	--	5
S-metolachlor	1.12	PRE	0	--	0	0	--	0
S-metolachlor+fomesafen	1.12+0.27	PRE	0	--	0	0	--	0
S-metolachlor+sulfentrazone	1.39+0.15	PRE	15	--	13	8	--	5
sulfentrazone	0.21	PRE	10	--	3	8	--	5
sulfentrazone	0.42	PRE	68	--	70	30	--	10
sulfentrazone+carfentrazone	0.28+0.03	PRE	0	--	0	5	--	0
acifluorfen	0.56	POST	--	57	2	--	25	10
acifluorfen+bentazon	0.28+0.56	POST	--	27	3	--	13	2
fomesafen	0.42	POST	--	40	0	--	23	8
imazamox+bentazon	0.05+0.56	POST	--	0	0	--	0	0
imazethapyr	0.07	POST	--	5	3	--	0	0
S-metolachlor+fomesafen	1.12+0.27	POST	--	43	0	--	22	13
LSD (0.05)[c]			**8**	**8**	**6**	**5**	**6**	**5**

[a]Abbreviations: DAP; days after planting, DAT; days after POST treatment. POST herbicide was applied at (2-3 trifoliate) 21 DAP; 7

[b]DAT = also 7 days after POST, postemergence treatment.

[c]Means separated using Fisher’s protected LSD (α = 0.05).

Table 4. Herbicide efficacy, 21 DAP, Vegetable Research Station, Kibler, Arkansas, USA[a]

Treatments			**Weed control**			
Herbicide common name	Rate	Time	**2013**		**2014**	
			AMAPA[b]	Overall[c]	AMAPA[b]	Overall[c]
	kg ai ha^{-1}		----------%----------		----------%----------	
flumioxazin+chlorimuron	0.105+0.04	PPL	100	92	100	96
saflufenacil+dimethenamid-P	0.03+0.29	PPL	90	96	87	95
sulfentrazone+carfentrazone	0.28+0.03	PPL	95	92	93	95
fomesafen	0.42	PRE	98	94	100	100
flumioxazin+chlorimuron	0.105+0.04	PRE	100	90	100	90
linuron	0.84	PRE	100	99	100	100
linuron	1.68	PRE	100	100	100	100
metribuzin	0.56	PRE	97	99	100	100
metribuzin+chlorimuron	0.16+0.03	PRE	98	99	100	100
pyroxasulfone	0.14	PRE	100	100	100	100
saflufenacil	0.07	PRE	88	91	95	95
saflufenacil+dimethenamid-P	0.03+0.29	PRE	98	94	100	99
S-metolachlor	1.12	PRE	98	97	100	96
S-metolachlor+fomesafen	1.12+0.27	PRE	95	97	100	100
S-metolachlor+sulfentrazone	1.39+0.15	PRE	100	100	100	100
sulfentrazone	0.21	PRE	98	94	100	95
sulfentrazone	0.42	PRE	100	98	100	94
sulfentrazone+carfentrazone	0.28+0.03	PRE	97	94	100	98
LSD (0.05)[d]			**NS**	**4**	**1**	**2**

[a]Abbreviations: DAP, days after planting, PPL, preplant; PRE, preemergence; POST, postemergence.
[b]AMAPA = Palmer amaranth
[c]Overall weed control rating includes control of 90% Palmer amaranth and 10% red sprangletop goosegrass, eclipta
[d]Means separated using Fisher's protected LSD ($\alpha = 0.05$); NS = not significant.

Table 5. Herbicide efficacy, 35 DAP, at the Vegetable Research Station, Kibler, Arkansas, USA[a]

Treatments			**Weed control**			
Herbicide common name	Rate	Time	**2013**		**2014**	
			AMAPA[b]	Overall[c]	AMAPA[b]	Overall[c]
	kg ai ha^{-1}		----------%----------		----------%----------	
flumioxazin+chlorimuron	0.105+0.04	PPL	100	90	98	93
saflufenacil+dimethenamid-P	0.03+0.29	PPL	85	91	82	89
sulfentrazone+carfentrazone	0.28+0.03	PPL	92	87	92	89
fomesafen	0.42	PRE	100	95	97	94
flumioxazin+chlorimuron	0.105+0.04	PRE	100	89	100	90
linuron	0.84	PRE	98	96	90	90
linuron	1.68	PRE	100	99	95	93
metribuzin	0.56	PRE	97	96	93	93
metribuzin+chlorimuron	0.16+0.03	PRE	97	97	100	100
pyroxasulfone	0.14	PRE	100	100	100	100
saflufenacil	0.07	PRE	77	68	92	83
saflufenacil+dimethenamid-P	0.03+0.29	PRE	95	87	88	87
S-metolachlor	1.12	PRE	95	96	97	98
S-metolachlor+fomesafen	1.12+0.27	PRE	95	96	98	99
S-metolachlor+sulfentrazone	1.39+0.15	PRE	100	99	100	100
sulfentrazone	0.21	PRE	98	87	95	90
sulfentrazone	0.42	PRE	100	93	98	94
sulfentrazone+carfentrazone	0.28+0.03	PRE	95	88	95	92
acifluorfen	0.56	POST	100	96	95	93
acifluorfen+bentazon	0.28+0.56	POST	98	84	95	92
fomesafen	0.42	POST	100	94	93	89
imazethapyr	0.05+0.56	POST	70	81	93	93
imazamox+bentazon	0.07	POST	67	77	88	90
S-metolachlor+fomesafen	1.12+0.27	POST	97	90	97	90
LSD (0.05)[d]			**12**	**9**	**5**	**4**

[a]Abbreviations: DAP, days after planting, PPL, preplant; PRE, preemergence; POST, postemergence.
[b]AMAPA-Palmer amaranth
[c]Overall weed control rating includes control of 90% Palmer amaranth, and 10% red sprangletop goosegrass, eclipta
[d]Means separated using Fisher's protected LSD ($\alpha = 0.05$).

Table 6. Partial return from each herbicide treatment based on dry yield of AVS-4002 edamame, Vegetable Research Station, Kibler, Arkansas, USA.

Treatments			**Partial returns**[b]	
Herbicide common name	Rate	Time[a]	2013	2014
	kg ai ha^{-1}		$	$
Weed-free			1175	869
flumioxazin+chlorimuron	0.105+0.04	PPL	1212	828
saflufenacil+dimethenamid-P	0.03+0.29	PPL	1318	676
sulfentrazone+carfentrazone	0.28+0.03	PPL	1191	609
fomesafen	0.42	PRE	1134	761
flumioxazin+chlorimuron	0.105+0.04	PRE	1087	746
linuron	0.84	PRE	1036	470
linuron	1.68	PRE	1014	568
metribuzin	0.56	PRE	1060	591
metribuzin+chlorimuron	0.16+0.03	PRE	1071	701
pyroxasulfone	0.14	PRE	1284	814
saflufenacil	0.07	PRE	1168	650
saflufenacil+dimethenamid-P	0.0.03+0.29	PRE	922	662
S-metolachlor	1.12	PRE	1230	456
S-metolachlor+fomesafen	1.12+0.27	PRE	1248	522
S-metolachlor+sulfentrazone	1.39+0.15	PRE	748	625
sulfentrazone	0.21	PRE	860	612
sulfentrazone	0.42	PRE	789	390
sulfentrazone+carfentrazone	0.28+0.03	PRE	1092	731
acifluorfen	0.56	POST	908	596
acifluorfen+bentazon	0.28+0.56	POST	1058	442
fomesafen	0.42	POST	1114	676
imazamox+bentazon	0.05+0.56	POST	1058	812
imazethapyr	0.07	POST	1114	728
S-metolachlor+fomesafen	1.12+0.27	POST	1089	768
LSD (0.05)[c]			**403**	**210**

[a]Abbreviations: PPL, preplant; PRE, preemergence; POST, postemergence.
[b]Partial return ($) = Income ($ ha^{-1}) – herbicide application cost ($ ha^{-1}). Cost of weed control in weed-free treatment included $50 ha^{-1} for handweeding performed twice during the season. Dry edamame bean price used for calculation was $350 metric ton^{-1}.
[c]Means separated using Fisher's protected LSD ($\alpha = 0.05$).

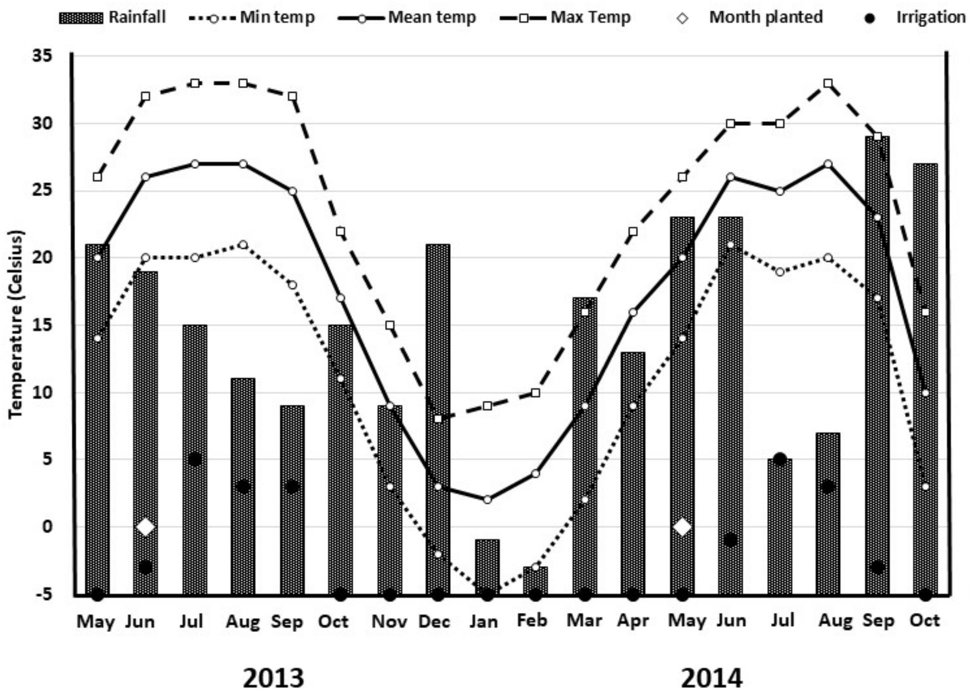

Figure 1. Rainfall and air temperature data during the course of the experiments in 2013 and 2014 at the Vegetable Research Station. (Source: Vegetable Research Station weather data, Kibler, Arkansas, USA)

CHAPTER IV

RESPONSE OF SELECTED EDAMAME SOYBEAN VARIETIES TO SULFENTRAZONE, FLUMIOXAZIN, PYROXASULFONE, METRIBUZIN AND FOMESAFEN

Abstract

Vegetable soybean, or edamame, [*Glycine max* (L.) Merr.] is a relatively young industry in the USA. Weed management in this burgeoning food crop is an important area of research. Field experiments were conducted in Arkansas to evaluate the tolerance of six vegetable soybean and five grain soybean lines to flumioxazin, metribuzin, pyroxasulfone, and sulfentrazone applied preemergence (PRE) and to fomesafen applied postemergence (POST). The experimental units were arranged in a randomized block split plot design (herbicide treatment as whole plot and soybean entries as subplot) with four replications in 2014 and 2015 at two locations (Fayetteville and Kibler, Arkansas). The experiment was arranged in a randomized block split-plot design (herbicide treatment as whole plot and soybean entries as subplot) with four replications. The PRE herbicides, except metribuzin, were safe on edamame soybean. Metribuzin PRE reduced the stand of edamame 'AVS-8080' and grain soybean Osage. The grain soybean 'Osage' was moderately sensitive to metribuzin (25 to 81% injury). Pyroxasulfone in general caused the lowest injury on emerged seedlings across soybean entries except edamame AVS-4002 (30%), R08-4004 (25%), and grain soybean Osage (29%). Fomesafen applied POST caused minimal (up to 11%) leaf necrosis 7 d after treatment. Soybean treated with fomesafen, pyroxasulfone, and sulfentrazone had similar relative yields across all entries. Grain soybean 5002T and UA-5612 had the highest relative yields (78 to 80%) among the grain soybeans tested while R07-7722 and R10-2890 had 91 to 101% relative yield among the edamame varieties tested. In conclusion, the edamame soybeans tested are tolerant to pyroxasulfone, but these entries were not all tolerant to flumioxazin or sulfentrazone, and none were tolerant to metribuzin. The tolerance of edamame soybean to fomesafen is the same as that of grain soybean.

Keywords: edamame, flumioxazin,fomesafen, metribuzin, pyroxasulfone, sulfentrazone

Introduction

Soybean is classified as either grain type (used for oil and feed) or vegetable type (used for human consumption) based on seed quality, time of harvest, and utility (Wang et al. 2005). Vegetable soybean (*Glycine max* (L.) Merr.), popularly known as edamame, is a specialty soybean. It is generally harvested at reproductive (R6) stage when plants have pods with full-size green seeds at one of the four uppermost nodes with a fully expanded leaf (Konovsky et al. 1996; Fehr et al. 1971). Consumption of edamame soybean originally started in East Asia particularly Japan and China, wherein the latter is still the largest producer of vegetable soybean to date (Dong et al. 2014). Demand for edamame soybean worldwide is projected to increase steadily due to its high protein content, palatability, health and nutritional benefits, as well as ease in preparation for culinary consumption (Brar and Carter 1993; Rao et al. 2002; Mebrahtu et al. 2004).

Edamame soybean was introduced into the US in the early 1990s (Shurtleff and Aoyagi 2009). The global trend of increasing demand for and marketing of edamame soybean is also observed in the US (Mimura et al. 2007). Some US growers are incorporating edamame in their crop portfolio to increase income, diversify the farming system and meet the demand for vegetable soybean (Mentreddy et al. 2002). In Arkansas, edamame soybean is an important specialty crop, signified by the establishment of a processing plant to propel its production and marketing (Chen et al. 2016).

The improvement of edamame soybean germplasm and testing of new varieties in several states including Illinois, Mississippi, and Washington is expected to boost edamame production (Williams 2015; Zhang and Kyei-Boahen 2007). However, weed management is the primary obstacle in growing edamame soybean as fewer herbicides are registered for this crop than in grain soybean (Williams 2015). Among the soybean herbicides and tank-mixes, carfentrazone+sulfentrazone, clethodim, fomesafen, imazamox, imazethapyr, linuron, *S*-metolachlor, and trifluralin are the only few options registered for edamame soybean production (Scott et al. 2016). Fomesafen, which is the most commonly used POST herbicide for the control of annual broadleaf weeds in grain soybean, was recently registered for edamame. The limited number of herbicides and locally adapted edamame varieties hamper the growth of commercial edamame production in the country. Interest in edamame production is promoted by progressive development of locally adapted varieties. Testing of more PRE and POST herbicides along with the development of new edamame varieties would provide the primary tools for managing weeds. Therefore, this study was conducted to evaluate the effect of four PRE herbicides used in grain soybean (sulfentrazone, flumioxazin, pyroxasulfone, metribuzin) and the POST application of fomesafen on edamame soybean lines developed for the southern US.

Materials and Methods

Site Description. Field experiments were conducted in the summer season of 2014 and 2015 at the Vegetable Research Station, Kibler, AR on Dardanelle silt loam soil (silty, mixed, active, thermic Typic Udifluvents) and at the Arkansas Agricultural Research and Extension Station, Fayetteville, AR on Captina silt loam (Fine-silty, siliceous, active, mesic Typic Fragiudults). Soybean was planted on 5 June, 2014 and 6 May, 2015 in Fayetteville. Field trials in Kibler were planted on 18 June, 2014 and 5 June, 2015. The crop was furrow-irrigated in Fayetteville and sprinkler-irrigated in Kibler. Rainfall, irrigation, and temperature data were recorded for both years (Figures 1, 2, and 3).

Experimental set-up. Six edamame soybean and five grain soybean varieties/lines were planted at 179,322 and 296,400 seeds ha^{-1}, respectively, through drill-seeding into a single-row plots in both locations. Hereafter, these soybean varieites/lines will be referred to as entries. Seeds were planted at a depth of 5 cm in rows 6.1-m long with 0.91 m spacing, separated by a 3-m alley. The experiment was arranged in a randomized block split-plot design (herbicide treatment as whole plot and soybean entries as subplot) with four replications. Four preemergence (PRE) and one postemergence (POST) herbicides were tested. PRE herbicides (sulfentrazone, 0.21 kg ha^{-1}; flumioxazin, 0.07 kg ha^{-1}; pyroxasulfone, 0.12 kg ha^{-1}; and metribuzin, 0.56 kg ha^{-1}) were applied 1 day after planting (DAP) while fomesafen (0.26 kg ha^{-1}) was applied at 2- to 3-trifoliate stage of the crop (Table 1). All treatments were applied using a CO_2 backpack sprayer with 4 flat fan nozzles (Tee Jet XR11002) spaced 46 cm apart, delivering 187 L ha^{-1} of spray volume. To keep the plots weed-free, the standard commercial herbicide *S*-metolachlor (1.12 kg ha^{-1}) PRE was broadcast-applied to the plots designated to be treated with fomesafen POST. Conversely, the plots designated to be treated with one of the four PRE herbicides were sprayed POST with imazethapyr (0.07 kg ha^{-1}) at 2- to 3-trifoliate leaf stage. At both locations, broadcast herbicides were applied with a tractor-mounted sprayer fitted with 110015VS nozzles spaced 46 cm apart, delivering 187 L ha^{-1} of spray volume at 262 kPa boom pressure.

Data recorded. Emerged soybean were counted in the middle section (1 m length) of each single-row plot at 21 DAP. Crop stand loss was assessed relative to the respective check plots. Percent crop stand loss was calculated using the formula [1]:

$$\left[\frac{[Crop\ stand\ (check) - Cropstand\ (treated)]}{Cropstand(check)}\right] * 100\% \qquad [1]$$

Crop injury was rated visually for each single-row plot at 21 DAP for all PRE treatments and at 7 d after POST treatment (DAT) with fomesafen. Crop injury rating was based on a scale of 0 (no injury relative to the respective check plot) to 100% (all dead). Dry bean yield was harvested at maturity stage (R8) because of the absence of a mechanical harvester for green pods. Soybean grains were harvested using a single-row combine. Yield per hectare was adjusted based on soybean standard moisture content of 13%. Relative yield was calculated based on the respective check plots using the formula:

$$\left[\frac{[Yield(treated)]}{Yield(check)}\right] * 100\%$$

Treatment effects were compared using the yield of treated plots relative to the respective check plots because each entry has a different yield potential. Also, the edamame lines were planted at a lower population than the grain soybean lines.

Statistical analyses. Data was subjected to analysis of variance (ANOVA) using SAS v. 9.4 using PROC GLIMMIX (SAS Institute Inc., Cary, NC) to evaluate differences between PRE herbicide and soybean varieties. Year and treatments were considered as fixed effects and replications were considered as random effects. The location and year interaction effects were significant, thus data were analyzed by year and location. Crop stand reduction and crop injury caused by PRE herbicides on grain soybean and edamame were analyzed separately by year and location. Relative crop yield, based on the weed-free (check) plot, were analyzed separately by year and location. Significant means were separated using Tukey's Honest Significant Difference (HSD) test at $\alpha = 0.05$. Prior to ANOVA, Shapiro-Wilk test was conducted to test the normality of residuals. All response variables followed normal distribution. Nontreated edamame stand, nontreated yield, and crop response to fomesafen (POST) by location interaction were not significant; thus these three variables were pooled across locations. All data were analyzed using least square analysis and significant means were separated using Fisher's Protected LSD test at $\alpha = 0.05$.

Results

Crop response to preemergence herbicides

Crop stand reduction. Grain soybean stand in 2014 ranged from 16 to 21 plants m^{-1} in Fayetteville and 17 to 29 plants m^{-1} in Kibler (Table 2). Edamame stand ranged from 8 to 11 plants m^{-1} in both locations in 2014. In 2015, grain soybean stand was 16 to 20 plants m^{-1} in Fayetteville and 15 to 21 plants m^{-1} in Kibler. Edamame stand in 2015 ranged from 9 to 13 plants m^{-1} in Fayetteville and 10 to 12 plants m^{-1} in Kibler.

Variety by herbicide interaction was not significant in Fayetteville in both years (Appendix Tables 1 and 2). The variety main effect was also not significant, but the herbicide main effect was significant in 2014. In 2015, the herbicide main effect was not significant. Sulfentrazone caused 40% crop stand reduction similar to flumioxazin (36%) and pyroxasulfone (30%) in 2014 (Figure 3) averaged across all soybean entries. In 2015, grain soybean UA-4913C (30%) and UA-5213C (25%) had similar stand loss among all varieties, averaged across herbicides (Figure 4). Crop stand for all soybean entries were reduced 2 to 10% except for grain soybean Osage (18%) and edamame AVS-8080 (15%).

The variety by herbicide interaction effect on stand loss was significant at Kibler in 2014. Metribuzin applied PRE caused the highest crop stand reduction on AVS-8080 (86%) among edamame soybean and on Osage (79%) among grain soybean in 2014, but was not always the most damaging treatment across all soybean lines (Table 3). In a related test, metribuzin caused moderate injury to Osage (UAEX, 2018). Pyroxasulfone applied PRE reduced the stand of all soybean entries <10% except two grain soybeans (UA-5213C and UA-5612) and three edamame entries (AVS-4002, R07-7722 and R10-2890).

The herbicide X variety interaction and main effects were not significant in 2015 at Kibler. The stand of all varieties was reduced similarly by the herbicide treatments at Kibler in 2015. Numerically, metribuzin caused more stand loss to edamame lines (35%) than to the grain soybean lines (24%) tested in 2015.

Injury on remaining plants from preemergence herbicide treatments. Crop injury pertains to the health of the surviving plants at the time of evaluation. At Fayetteville, the variety by herbicide interaction effect on soybean injury was significant in 2014. Flumioxazin and sulfentrazone applied PRE caused the highest injuries to remaining plants ranging from 33 to 48% (Table 4). Edamame R07-7645 seedlings were least affected by flumioxazin with only 9% injury among edamame entries. Seedlings with the least injury from sulfentrazone were edamame R10-2890 and R07-7645. Pyroxasulfone in general caused the lowest injury across soybean entries, except edamame AVS-4002 (30%), R08-4004 (25%), and grain soybean Osage (29%). R10-2890, which had the healthiest seedlings with pyroxasulfone or sulfentrazone incurred high injury with flumioxazin (28%) and metribuzin (25%). In 2015, variety by herbicide interaction was not significant at Fayetteville. Metribuzin was most injurious (42%) to edamame and grain soybean among the herbicides tested (Figure 5).

At Kibler, the variety by herbicide interaction effect on injury of soybean seedlings was significant in both years (Table 5). In 2014, metribuzin caused the highest injury on edamame AVS-8080 (98%) and grain soybean Osage (81%). Pyroxasulfone caused <25% stunting on seedlings of edamame AVS-8080 29% stunting on grain soybean UA-4913C. In 2015, metribuzin caused the highest injury on edamame varieties R07-7645 (90%) and AVS-8080 (>80%). Pyroxasulfone PRE caused significant injuries across all soybean entries except edamame AVS-8080 and R07-7645. Seedlings of edamame AVS-4002 incurred the least injury with sulfentrazone, pyroxasulfone, and flumioxazin.

Injury caused by fomesafen, postemergence. Fomesafen applied POST caused transient injury to all soybean entries (Table 6), which was the characteristic response to this herbicide. Injury was in the form of tiny to large necrotic spots on the leaves where the spray droplets hit, as expected from a contact herbicide like fomesafen. In 2014, the highest injury caused by fomesafen was 11% in Fayetteville and Kibler, which was observed on edamame AVS-8080 and Osage grain soybean, but was not different from all other soybean entries. In 2015, fomesafen caused <10% injury across entries at both locations.

Grain yield. The variety by herbicide interaction effect and the herbicide main effect on relative yield was not significant at Fayetteville in both years (Appendix tables 17 and 18). The grain soybean yield at Fayetteville ranged from 2.23 to 2.79 mt ha^{-1} in 2014 was 1.12 to 1.48 mt ha^{-1} in 2015 (Table 7). In both years, edamame yields were either comparable to the non-treated check or were slightly enhanced by the herbicide treatments. Yields of grain soybean were all equivalent to the non-treated check.

The variety by herbicide interaction effect on relative yield was not significant at Kibler in both years (Appendix tables 20 and 21). The variety main effect were significant in both years. Herbicide main effect was significant in 2014. In 2014, plots treated with metribuzin had 30% relative yield with respect to the non-treated check (Figure 6). Plots treated with fomesafen, pyroxasulfone and sulfentrazone had similar relative yield across all entries. In 2014, grain soybean 5002T and UA-5612 had the highest relative yields (78 to 80%) among the grain soybeans tested while R07-7722 and R10-2890 had 91 to 101% relative yield among the edamame varieties tested (Table 8). AVS-8080 (59%) and Osage (64%) had the lowest relative yields among edamame and grain soybeans, respectively. Relative yields of all soybean entries were similar in 2015 except for edamame R07-7645 (60%) which was lower than the rest of the entries.

Discussion

Varieties tested in this study had different sensitivity to PRE herbicides. Among the PRE herbicides tested, metribuzin was the most injurious overall. Metribuzin, a photosystem II inhibitor, is commonly used for weed control in grain soybean. Soybean tolerates metribuzin through rapid metabolism of the herbicide molecule (Mangeot et al. 1979). However, environmental factors such as high soil moisture, low soil temperatures, and high pH can increase the soybean injury from metribuzin application (Moshier and Russ 1981). Crop injury is manifested in reduced crop stand, stunting, chlorosis, and reduced yield (Moshier and Russ 1981). Sandy soil and soil with low soil organic matter promote the mobility of metribuzin down to the seed zone, causing increased injury on germinating seedlings following high rainfall or irrigation (Peter and Weber 1985). In our tests, metribuzin caused higher stand reduction of edamame in Kibler compared to Fayetteville because the soil at Kibler has a lighter texture than Fayetteville. Testing varieties for tolerance to metribuzin in edamame is needed just as grain soybean varieties are routinely rated for sensitivity to metribuzin. Metribuzin offers an additional mode of action for weed management of broadleaf weed species, especially protoporphyrinogen oxidase (PPO)-resistant Palmer amaranth (*Amaranthus palmeri* L.) (Salas et al. 2016). Sulfentrazone is a PPO inhibitor, which causes the disruption of cell membranes (Dayan et al. 1996). Sulfentrazone applied at a higher rate can stunt the growth of soybean varieties sensitive to this herbicide (Dayan et al. 1997). The level of injury from sulfentrazone treatment differed across locations due to differences in soil characteristics (Ohmes and Mueller 2007). Soil pH In

Fayetteville was 6.3 while in Kibler the soil pH ranged from 5.4 to 5.8. The Kibler soil also had lower clay content than in Fayetteville. Lower pH and lighter soil in Kibler resulted in higher crop injury than in Fayetteville. The reduction in edamame soybean stand (20 to 60%) in the current study was similar to the level of soybean response reported by Taylor-Lovell et al (2001). The residual activity of sulfentrazone varies with soil type especially, affecting weed control (Szmigielski et al. 2009; Ohmes and Mueller) besides affecting crop safety.

Flumioxazin, like sulfentrazone, is a PPO-inhibitor herbicide (Dayan and Duke 1996). Flumioxazin offers excellent residual control on susceptible weeds in cotton, field corn and soybean (Anonymous 2016). Flumioxazin is available as a proprietary mixture with other herbicides, such as chlorimuron, providing a broader spectrum of residual control of broadleaf weeds and annual grasses (Anonymous 2013a). When soil moisture content is high, the adsorption of flumioxazin to the soil is reduced (Ferrell et al. 2005) thus, flumioxazin molecules are mobile in wet soils, which increases the risk of injury to germinating seeds and seedlings. In 2015, plenty of rainfall (30 to 48 cm) occurred after planting within the month of May at both locations (Figure 1). Increased rainfall increases the risk of herbicide phytotoxicity on germinating seed (Taylor-Lovell et al. 2001). Preemergence application of flumioxazin in soybean under favorable environmental conditions provides additional broadleaf weed control resulting in increased soybean yield (McNaughton et al. 2014).

Pyroxasulfone inhibits the synthesis of very-long chain fatty acids in the plant (Shaner 2014). Pyroxasulfone applied PRE controls annual grasses, sedges and broadleaf weeds that infest field crops such as corn and soybean (Anonymous 2013b). It can be retained at the upper 7.5 cm of the soil profile and has a half-life (DT50) of 47 to 134 days (Westra et al. 2014). Pyroxasulfone can be applied either PRE or preplant incorporated (PPI) without causing injury to grain soybean (McNaughton et al. 2014). It is also safe to use on edamame (Williams et al. 2017).

Fomesafen, a PPO inhibitor, is usually applied POST and is a common herbicide for grain soybean. Grain soybean is tolerant to fomesafen because it can metabolize and deactivate the herbicide via homoglutathione conjugation facilitated by glutathione S-transferase enzyme (Skipsey et al. 2007). Different levels of enzyme activity or enzyme production confers differential tolerance to fomesafen across plants. Like grain soybean, edamame is tolerant to fomesafen (Williams and Nelson 2014; Altemose et al. 2011). Fomesafen contributes to effective postemergence weed control resulting in better yield. Our results were similar to a previous study showing different (but minimal) levels of injury from fomesafen across edamame and grain soybean entries, but without negative consequences on yield (Williams and Nelson 2014). Williams and Nelson (2014) reported 12% injury from fomesafen across all varieties of edamame and grain soybeans tested. Belfry et al. (2016) reported that POST application of fomesafen on eight soybean varieties caused 24, 17 and 5% injury at 1, 2 and 4 wk after treatment, respectively. Therefore, fomesafen can cause leaf necrosis and desiccation, but soybean can recover from these injuries (Harris et al. 1991).

Other leguminous crops were also tolerant to fomesafen. Dry bean (*Phaseolus vulgaris*) is highly tolerant, has with negligible (3.5%) injury from fomesafen application (Wilson 2005). A study of six dry bean varieties showed consistent high tolerance to fomesafen, with <10% injury from three times the field use rate (Wilson 2005). Cowpea (*Vigna unguiculata*) has lesser tolerance to fomesafen than dry bean and soybean, incurring more than 30% injury from foliar fomesafen application, followed by quick recovery (Burgos et al. 2007). Cowpea varieties also differ in sensitivity to fomesafen, in terms of the degree of foliar burn from foliar treatment, but with no effect on yield (Burgos et al. 2007).

Conclusion

Edamame soybean varieties differ in tolerance to metribuzin, flumioxazin, pyroxasulfone and sulfentrazone. The PRE herbicides tested in this study can injure both edamame and grain soybean. The risk of injury increases with excessive soil moisture. Metribuzin is the most injurious herbicide to grain soybean Osage and edamame AVS-8080. Pyroxasulfone is the safest PRE herbicide overall to grain soybean and edamame. Grain soybean 5002T and edamame R07-7722 were most tolerant soybean entries to the preemergence herbicides tested. Postemergence application of fomesafen is safe to grain soybean and edamame. Edamame varieties may differ in tolerance to the labeled residual herbicides; therefore, varietal testing with all labeled herbicides and potential herbicides is needed. The edamame and grain soybean varieties tested were equally tolerant to fomesafen postemergence.

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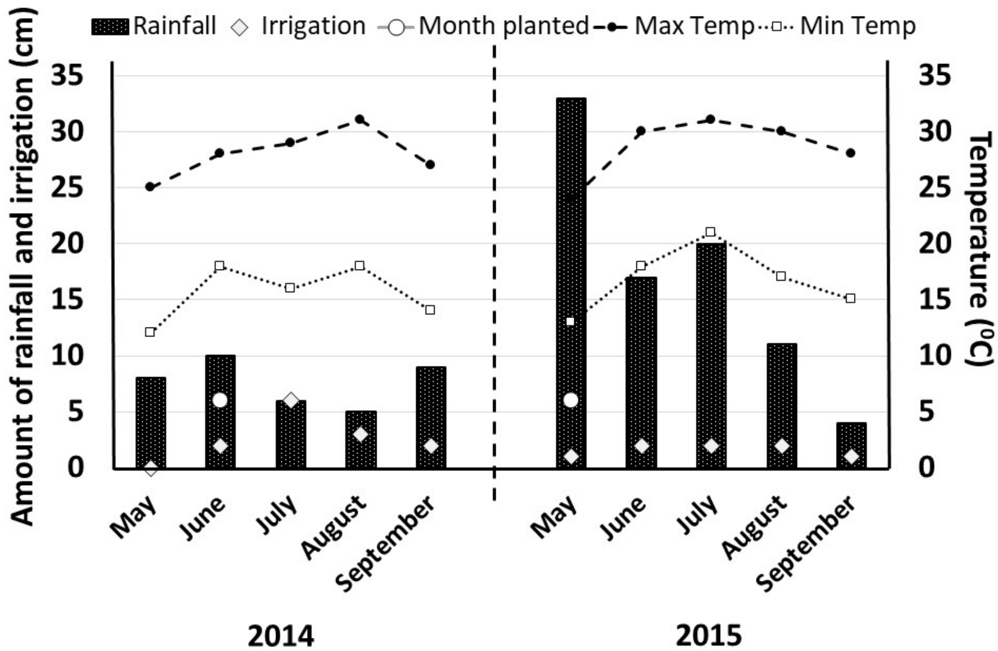

Fig. 1. Temperature , irrigation and rainfall data, Arkansas Agricultural Research and Extension Center, Fayetteville, AR

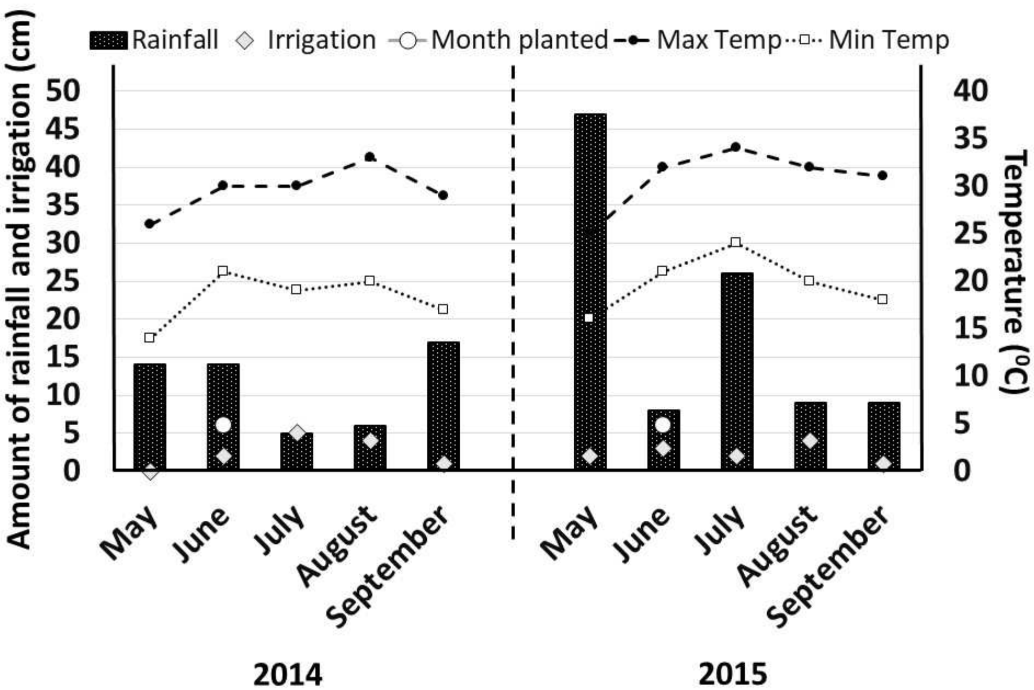

Fig. 2. Temperature, irrigation and rainfall data, Vegetable Research Station, Kibler, AR

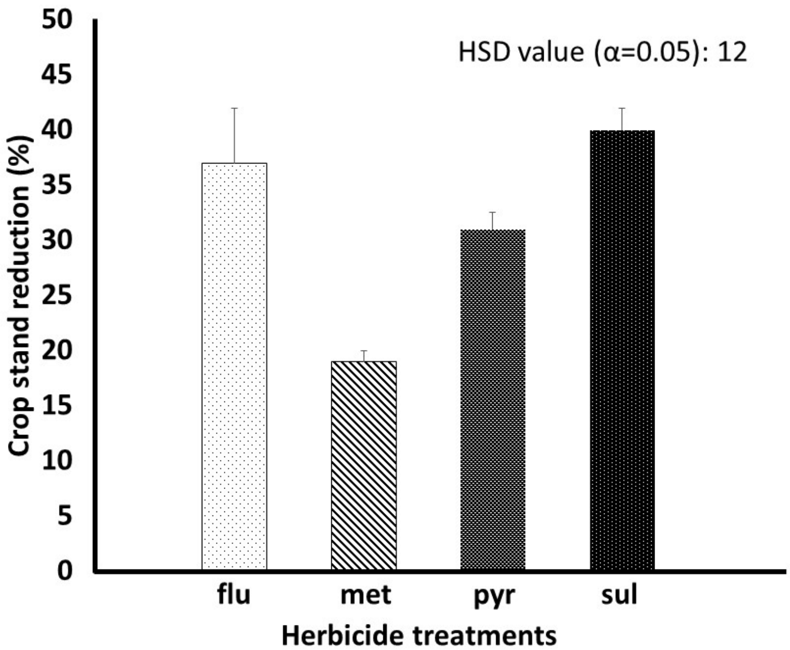

Fig. 3. Crop stand reduction averaged across preemergence herbicides relative to the respective nontreated checks of 5 grain soybean and 6 edamame entries (21 DAP) in 2014 at the Arkansas Agricultural Research and Extension Center, Fayetteville, AR. Abbreviations: flu=flumioxazin; fom=fomesafen; met=metribuzin; pyr=pyroxasulfone; sul=sulfentrazone

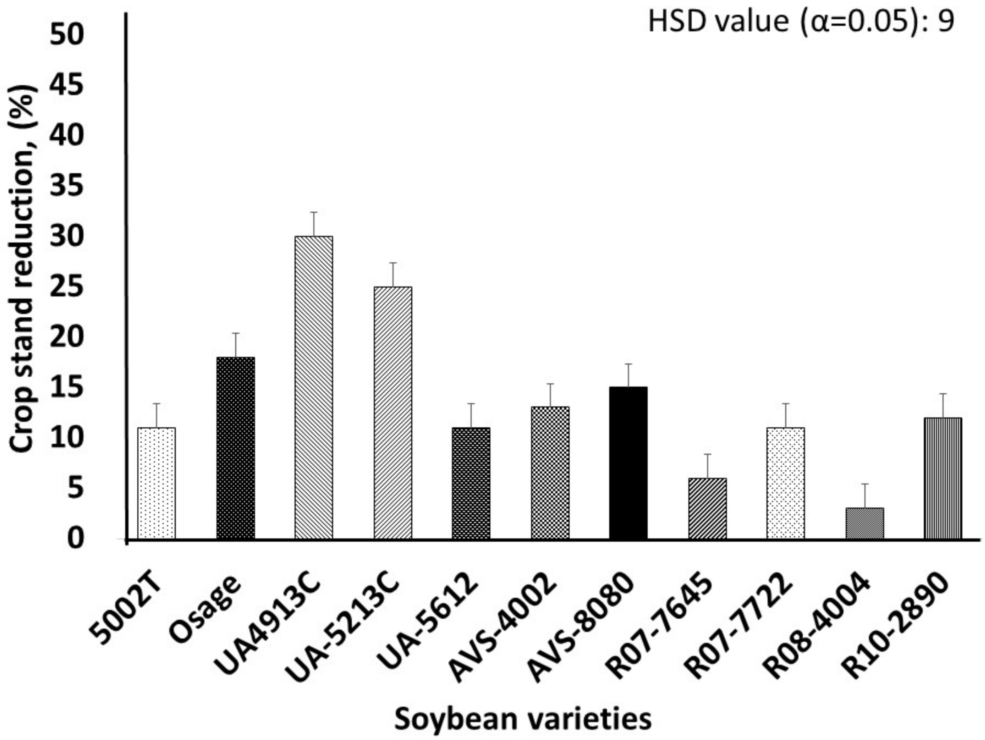

Fig. 4. Crop stand reduction averaged across preemergence herbicides relative to the respective nontreated checks of 5 grain soybean and 6 edamame entries (21 DAP) in 2015 at the Arkansas Agricultural Research and Extension Center, Fayetteville, AR.

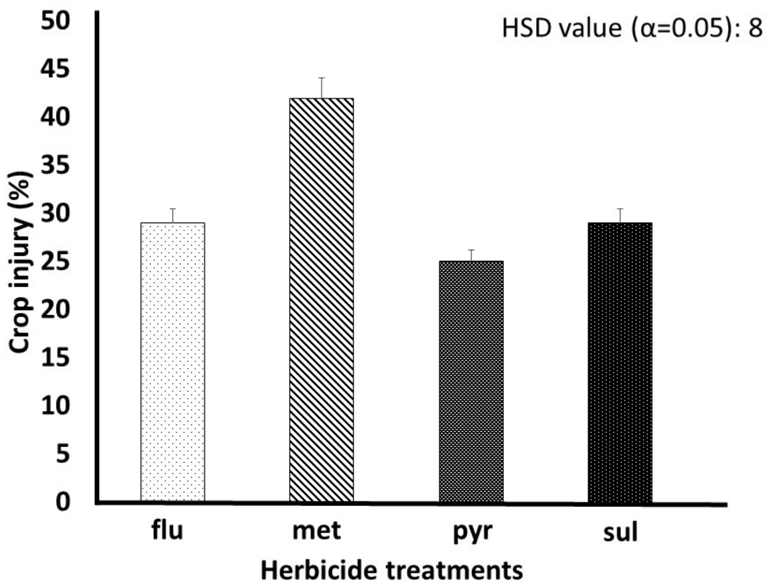

Fig. 5. Injury averaged across all soybean entries (5 grain soybean and 6 edamame) in response to preemergence herbicides relative to the respective nontreated checks (21 DAP) in 2015 at the Arkansas Agricultural Research and Extension Center, Fayetteville, AR. Abbreviations: flu=flumioxazin; fom=fomesafen; met=metribuzin; pyr=pyroxasulfone; sul=sulfentrazone

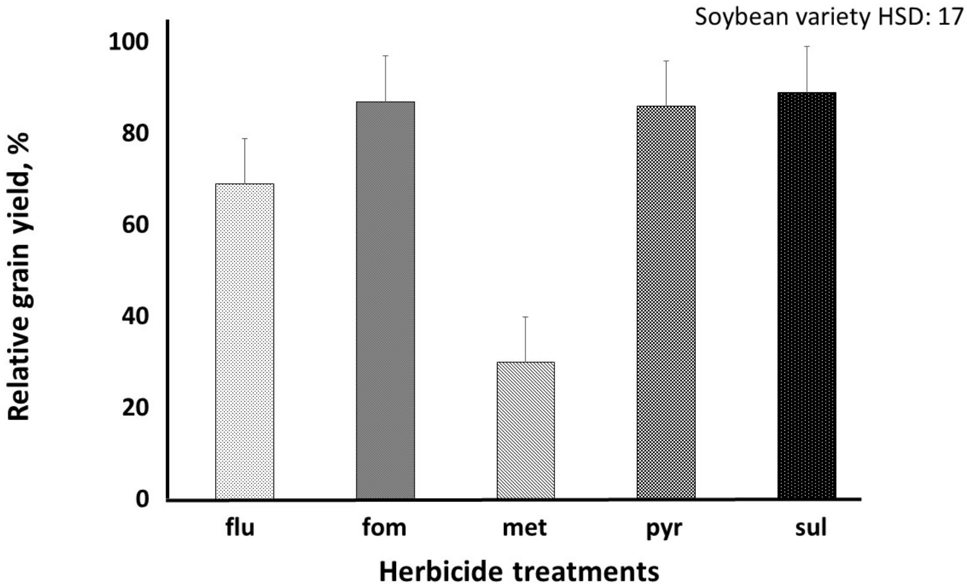

Fig. 6. Effect of herbicide treatments on relative grain yield across all soybean entries grown in 2014 at the Vegetable Research Station, Kibler, AR. Abbreviations: flu=flumioxazin; fom=fomesafen; met=metribuzin; pyr=pyroxasulfone; sul=sulfentrazone

Table 1. Herbicides tested on soybean entries grown at the Vegetable Research Station, Kibler and at the Arkansas Agricultural Research and Extension Center, Fayetteville, Arkansas in 2014 and 2015

Active ingredient	Trade name	Formulation	Rate (kg ai ha^{-1})	Timing[a]
fomesafen	Reflex	2 LC	0.26	POST
flumioxazin	Valor	51 WDG	0.07	PRE
metribuzin	Tricor	75 DF	0.56	PRE
pyroxasulfone	Zidua	85 WDG	0.12	PRE
sulfentrazone	Spartan	4 F	0.21	PRE

[a]Abbreviations: PRE = preemergence herbicide applied 1 d after planting; POST = postemergence herbicide applied at 2- to 3- trifoliate stage of soybean. S-metolachlor (1.12 kg ha^{-1}) was applied PRE to plots intended for fomesafen treatment. Imazethapyr (0.07 kg ha^{-1}) was applied POST at 2 to 3-trifoliate leaf stage to plots treated with flumioxazin, metribuzin, pyroxasulfone and sulfentrazone.

Table 2. Soybean stand in nontreated check plots (21 DAP), in 2014 and 2015 at the Arkansas Agricultural Research and Extension Station, Fayetteville and Vegetable Research Station, Kibler, Arkansas[a]

	Crop Stand			
Variety	**2014**		**2015**	
	Fayetteville	Kibler	Fayetteville	Kibler
	----plants m^{-1}----			
Grain Soybean				
5002T	21	19	20	15
Osage	20	18	16	16
UA-4913C	18	18	19	20
UA-5213C	20	18	20	21
UA-5612	16	17	19	20
Edamame				
AVS-4002	9	11	10	12
AVS-8080	10	11	11	11
R07-7645	11	11	9	10
R07-7722	10	11	9	10
R08-4004	9	10	11	10
R10-2890	8	8	13	12
LSD[b]	4	5	4	4

[a]Abbreviation: DAP, days after planting.
[b]Means are separated using Fisher's Protected LSD ($\alpha = 0.05$).

Table 3. Soybean stand reduction with preemergence herbicides (21 DAP) in 2014 and 2015 at the Vegetable Research Station, Kibler, Arkansas[a]

	Crop stand		**Crop stand reduction**							
Variety	Nontreated		flumioxazin		metribuzin		pyroxasulfone		sulfentrazone	
	2014	2015	2014	2015	2014	2015	2014	2015	2014	2015
	plants m^{-1}		------%------		------%------		------%------		------%------	
Grain Soybean										
5002T	15	14	30	12	25	0	10	7	13	16
Osage	11	15	9	0	79	25	9	10	25	0
UA-4913C	18	14	39	1	4	39	8	0	9	2
UA-5213C	19	15	24	7	23	16	41	12	28	5
UA-5612	16	16	71	16	49	38	32	13	14	6
Edamame										
AVS-4002	24	14	20	7	29	60	30	5	18	9
AVS-8080	13	16	2	7	86	32	10	20	33	2
R07-7645	20	15	38	20	12	56	10	9	36	3
R07-7722	12	16	15	6	10	6	40	5	15	8
R08-4004	11	16	23	8	28	32	25	5	0	5
R10-2890	19	17	3	12	25	25	36	19	16	16
HSD[b]	2014	2015	2014	2015						
	CS: **12**	CS: **NS**	H: **14**	**NS**						
			V: **8**	**NS**						
			H*V:**15**	**NS**						

[a]Abbreviations: DAP, days after planting.

[b]Tukey's Honest Significant Difference (HSD) at α = 0.05 to compare nontreated crop stand means (CS), herbicide (H), variety (V), herbicide x variety interaction (H*V)

Table 4. Soybean injury (21 DAP) from preermergence herbicides in 2014 at the Arkansas Agricultural Research and Extension Center, Fayetteville, Arkansas[a]

Variety	Crop injury			
	flumioxazin	metribuzin	pyroxasulfone	sulfentrazone
	%	%	%	%
Grain Soybean				
5002T	15	21	9	30
Osage	34	31	29	26
UA-4913C	20	31	8	26
UA-5213C	16	26	8	14
UA-5612	26	20	6	18
Edamame				
AVS-4002	43	14	30	44
AVS-8080	39	15	16	26
R07-7645	9	28	9	13
R07-7722	33	13	14	48
R08-4004	24	15	25	36
R10-2890	28	25	6	6
HSD[b]				
Herbicide	**NS**			
Variety	**9**			
Variety x Herbicide	**16**			

[a]Abbreviation: DAP, days after planting.

[b]Means are separated using Tukey's Honest Significant Difference (α = 0.05).

Table 5. Soybean injury (21 DAP) from preemergence herbicides in 2014 and 2015 at the Vegetable Research Station, Kibler, Arkansas[a]

	Crop injury							
Variety	flumioxazin		metribuzin		pyroxasulfone		sulfentrazone	
	2014	2015	2014	2015	2014	2015	2014	2015
Grain Soybean	--------%--------		--------%--------		--------%--------		--------%--------	
5002T	54	50	74	69	34	38	51	50
Osage	53	45	81	65	45	40	58	41
UA-4913C	51	44	75	74	29	31	56	50
UA-5213C	51	41	79	70	48	29	38	36
UA-5612	49	47	79	65	35	29	34	41
Edamame								
AVS-4002	50	36	74	70	43	34	54	36
AVS-8080	26	41	98	83	21	23	24	35
R07-7645	45	40	71	90	33	26	38	36
R07-7722	53	38	70	70	38	37	59	45
R08-4004	49	49	74	75	35	33	58	34
R10-2890	49	34	66	60	30	32	26	35
HSD[b]	2014	2015						
Herbicide	**18**	**10**						
Variety	**11**	**NS**						
V X H	**35**	**12**						

[a]Abbreviation: DAP, days after planting.

[b]Means are separated using Tukey's Honest Significant Difference ($\alpha = 0.05$).

Table 6. Response of soybean entries to fomesafen applied postemergence, 7 days after treatment, in 2014 and 2015 at the Arkansas Agricultural Research and Extension Station, Fayetteville and Vegetable Research Station, Kibler, Arkansas.

Variety	**Crop injury**			
	2014		**2015**	
	Fayetteville	Kibler	Fayetteville	Kibler
	----------%----------		----------%---------	
Grain Soybean				
5002T	5	10	6	6
Osage	10	11	6	5
UA-4913C	8	6	6	5
UA-5213C	6	11	8	6
UA-5612	6	8	5	6
Edamame				
AVS-4002	6	11	5	6
AVS-8080	11	6	6	6
R07-7645	5	11	6	5
R07-7722	8	6	5	5
R08-4004	5	5	6	6
R10-2890	8	8	6	5
LSD[a]	**NS**		**NS**	

[a] NS = not significant based on Fisher's Protected LSD (α = 0.05).

Table 7. Relative grain yield of soybean entries averaged across all herbicide treatments in 2014 and 2015 at the Arkansas Agricultural Research and Extension Center, Fayetteville, Arkansas

Variety	Yield, nontreated[a]		Relative yield[b]	
	2014	2015	2014	2015
Grain Soybean	-------mt ha^{-1}-------		-------%-------	
5002T	2.75	1.14	91	111
Osage	2.79	1.21	97	91
UA-4913C	2.61	1.12	115	114
UA-5213C	2.31	1.48	102	94
UA-5612	2.23	1.22	131	125
Edamame				
AVS-4002	1.75	1.07	145	106
AVS-8080	0.74	0.14	100	136
R07-7645	2.61	1.28	106	100
R07-7722	1.84	0.87	132	146
R08-4004	1.89	0.89	133	108
R10-2890	2.08	0.67	114	146
HSD	**1.39**	**0.97**	**42**	**45**

[a,b]Means are separated using Tukey's Honest Significant Difference ($\alpha = 0.05$). Relative yield values of $\geq$100% are better than the check yield.

Table 8. Relative grain yield averaged across all herbicide treatments in 2014 and 2015 at the Vegetable Research Station, Kibler, Arkansas

Variety	**Nontreated yield[a]**		**Relative yield with herbicide treatment[b]**	
	2014	2015	2014	2015
	-------mt ha^{-1}-------		-------%-------	
Grain Soybean				
5002T	2.74	0.29	80	147
Osage	3.66	0.44	64	122
UA-4913C	3.48	0.60	66	106
UA-5213C	3.40	0.82	72	95
UA-5612	3.73	0.89	78	84
Edamame				
AVS-4002	3.05	0.59	73	94
AVS-8080	0.41	0.28	59	114
R07-7645	2.46	0.69	82	60
R07-7722	2.27	0.53	101	112
R08-4004	2.39	0.44	85	107
R10-2890	2.54	0.61	91	95
HSD	**1.00**	**0.42**	**30**	**65**

[a,b]Means are separated using Tukey's Honest Significant Difference ($\alpha = 0.05$). Relative yield values of ≥100% are better than the nontreated check yield.

CHAPTER V
CROP ROTATION SYSTEMS FOR AVS 8080 EDAMAME IN ARKANSAS

Abstract

Crop rotation, coupled with appropriate herbicide programs, is a tool for sustainable weed management in edamame (*Glycine max* L.), which can increase farm income and diversify local food sources. A study was conducted at Kibler and Rohwer, Arkansas in 2014 and 2015 to identify feasible crop rotations with AVS 8080 edamame, which is commercially grown in Arkansas. The study included edamame rotations with greenbean (*Phaseolus vulgaris*) followed by (fb) edamame (Rotation A), short-season soybean fb edamame (Rotation B), sweet corn (*Zea mays* var. *saccharata*) fb edamame (rotation C), and edamame fb edamame (Rotation D). *S*-metolachlor (1.12 kg ha^{-1}) was applied to edamame and greenbeans as preemergence herbicide. Wheat (*Triticum aestivum*) was planted as fall cover crop on rotations A, B, and D. Spinach (*Spinacea oleracea*) was planted as fall-spring cash crop for rotation C. Fomesafen (0.26 kg ha^{-1}) was applied to edamame at third trifoliate in all rotation systems. Crop injury, weed control and relative yield were recorded. Weed control and crop stand were good in both years. In 2014, relative edamame yield ranged from 109 – 128 %. In 2015, relative edamame yield ranged from 71 – 77%. No data was obtained at Rohwer due to inclement weather in both season. This study indicated that edamame can be grown as a rotation crop with sweet corn, greenbeans and soybean in Arkansas.

Introduction

Crop rotation is a proven sustainable concept in agriculture. Crop rotation is a method of growing different crops in succession in the same field, accompanied by compatible crop maintenance programs (Bullock 1992; Liebman and Dyck 1993). Different tillage practices (conventional tillage, minimum, or zero tillage) are utilized to facilitate the culture of different crops (Dick and Van Doren Jr, 1985). Compared to monocrop systems, crop rotation has several advantages, including enhanced soil physical and chemical properties. Crop rotation improves soil organic matter content and breaks the pathogenic cycle in the soil (Souza et al., 2013). Soil structure is improved (Johnston et al. 1942) and the control of insect pests, diseases, and weeds is enhanced in crop rotation systems (Tingle and Chandler, 2004). It is a sustainable weed management strategy that minimizes the overall impact of crop production on the environment (Gonzalez-Diaz et al. 2012). Researchers demonstrated previously that crop rotation is an integral part of weed management to prevent weed seed dispersal, weed shift, and weed infestation (Thill and Mallory-Smith, 1997; Mcworther and Shaw, 1982). Bullock (1992) highlighted the importance of crop rotation in weed control since weeds proliferate with crops that have similar growth requirements. Conditions above and below the soil surface influence seed survival, including weed seeds (Moody-Weis and Alexander, 2007). Cardina et al. (2002) reported reduction in soil seedbank size when different crops are grown in rotation. In addition, crop rotation prevents late-season weed seed deposition in the soil (Anderson et al. 2007), reducing the emergence of dry- and cool-season weeds (Anderson, 2009). Increased awareness of environmental impact of crop rotation on control of weeds in edamame (*Glycine max* L. Merr.) is important to achieve sustainable edamame production. Edamame is a promising, high-value crop in Arkansas and in many states in the USA. Edamame demand in Arkansas is projected to increase 12-15% annually (UAEX, 2013). Crop rotation is highly important in edamame production because it is a short-season crop that is harvestable in less than three months (Shanmugasundaram, 1981). Without a second crop, the farm would be unproductive the rest of the year. However, information concerning the performance of edamame soybean in rotation with other crops is limited. The goal of this study is to determine a feasible crop rotation program for edamame soybean in Arkansas.

Materials and Methods

Site description. Field experiments were conducted at the Vegetable Research Station, Kibler, AR (35.37°N, 94.23°W) and at the Southeast Research and Extension Center, Rohwer, AR (34.48°N, 91.17°W) in 2014 and 2015. Soil at the Vegetable Research Station, Kibler is coarse silty, mixed, superactive, nonacid, thermic Typic Udifluvents (Roxana loam). Soil at the Southeast Research and Extension Center is a Sharkey clay with <1% organic matter and a pH of 7.2. Four rotation treatments were established consisting of edamame 'AVS 8080', grain soybean Armor 28-R24, greenbean Roma II (*Phaseolus vulgaris*), and sweet corn Honey Select (*Zea mays* var. *saccharata*) (Table 1). Sweet corn, grain soybean and greenbean were drill-seeded in four-row plots, 6 m long, 0.9 m row spacing. Edamame was planted at an average seeding rate of 179,250 seeds ha^{-1}. Spinach (*Spinacea oleracea* L.) and wheat (*Triticum aestivum* L.) were drill-seeded as fall cover crops at rate of 72,600 seeds $acre^{-1}$ and 174,240 seeds $acre^{-1}$, respectively. The experiment was conducted in a randomized complete block design with three replications. Spring crops were planted in April and edamame was planted as a summer crop in mid-August for both years (Table 1 and 2). Fall cover crops were planted during the last week of October to first week of November in 2014 and in December 2015 (Table 3).

Herbicide treatments were applied using a CO_2-backpack sprayer with a handheld boom fitted with 4 flat fan nozzles (Teejet XR11002VS) spaced 46 cm apart, delivering 187 L ha^{-1} of spray volume at 228 kPa. S-metolachlor (1.12 kg ha^{-1}) was applied PRE to grain soybean, sweet corn, edamame and greenbeans. Mesotrione (0.22 kg ha^{-1}) was applied to sweet corn POST. Fomesafen (0.26 kg ha^{-1}) was applied to edamame and grain soybean at third trifoliate. Greenbeans were soil-incorporated at V8 stage and edamame was planted a week after greenbean incorporation. Greenbeans were soil incorporated due to severe beetle infestation. Wheat was planted as fall cover crop on rotations A, B, and D. Spinach was planted as fall-spring crop for rotation C.

Data collection. Crop stand count of edamame was taken at 21 d after planting (DAP) from two middle rows (1 meter long). No harvest data was gathered for greenbeans since the crop was incorporated after pod-formation. Sweet corn yield was collected from two, 1- m rows in the middle of the plot. Dry soybean seeds were collected at harvest. Green edamame pod yield was collected from four plants in the two middle rows at harvest. Beans were not shelled. Relative yield of edamame from rotations A, B and C were calculated based on the monoculture edamame fall crop using the formula:

$$\left[\frac{[Yield(in\ rotation)]}{Yield(edamame\ monoculture\ fall\ crop)}\right] * 100\%$$

Soil samples were collected using an 8-cm diameter soil core with 10 cm depth before crop establishment. Soil samples were analyzed for available nutrient, pH and cation exchange capacity at the Lonn Mann Research Station, Marianna, AR (Table 4 and 5).

Statistical analysis. Data were subjected to analysis of variance using JMP Pro v. 12 (JMP, Version 12; SAS Institute Inc., Cary, NC). Relative yield means were separated using Fisher's Protected LSD ($\alpha = 0.05$).

Results

Data presented here are only for the Kibler location. The experiments at Rohwer were flooded in both years. The Rohwer location had high clay content and with the strong rain events in those years, some or all crops were compromised, or could not be planted at the right time. Therefore, no data were collected for Rohwer. At Kibler, yield from edamame followed by edamame (monoculture) ranged from 7 mt ha^{-1} and 5.8 mt ha^{-1} in 2014 and 2015, respectively. Crop yields from each rotation are reported for this experiment. Preliminary data are presented to provide insight on the hurdles involved in planting different crops in rotation with edamame.

Soil tests. Soil pH in Kibler ranged from 6.7 to 7.1 after planting of crops during spring and summer (Table 4 and 5). In general, the potassium and magnesium contents in the soil were higher in the spring than in the summer. Cation exchange capacity (CEC) ranges were higher in the spring crops (9.99 to 10.89 cmol kg^{-1}) compared to the summer crops (9.13 to 9.36 cmol kg^{-1}).

Sweet corn followed by edamame rotation. Green edamame yield from this rotation was the highest among the treatments with 128% and 77% in 2014 and 2015, respectively, relative to the monoculture edamame (Table 6). Sweet corn yield was low especially in 2015 (26.25 mt ha^{-1}) due to high infestation of corn earworm (*Helicoverpa zea* L.) (Table 7). The station crew were not able to manage the insect pest infestation in this study.

Greenbean followed by edamame rotation. The greenbean crop could not be grown to harvest due to severe infestation of rust (*Uromyces viciae*). Thus, the crop was soil-incorporated to serve as green manure. The relative green edamame yield from this rotation was better in 2014 (109 mt ha^{-1}) compared to 2015 (74 mt ha^{-1}) (Table 6).

Soybean followed by edamame rotation. Relative edamame yield from the soybean followed by edamame rotation was better in 2014 (122 mt ha^{-1}) compared to 2015 (71 mt ha^{-1}) (Table 6). The grain soybean variety we used can potentially fit as a good partner for edamame crop rotation due to the soybean's maturity group. Grain soybean yield was 2.5 mt ha^{-1} and 1.9 mt ha^{-1} in 2014 and 2015, respectively.

Summary

This study indicated that planting edamame in rotation to crops such as grain soybean, sweet corn and greenbean is feasible since usually there is sufficient planting window for two crops in a year. However, producing two crops successfully in a year requires a higher level of planning and management. In this study, insects and diseases compromised sweet corn and greenbeans. Much research is needed across locations and years to generate a sound crop rotation recommendation for edamame. Weather condition is the primary determinant for crop rotation feasibility. Several crop rotation schemes are feasible in regions with longer growing periods on the basis of preliminary yield data from this research. The second important factor is the availability of herbicides that can be used with a safe crop rotation interval for the rotational crop.

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Table 1. Planting dates and herbicides used for spring crops at the Vegetable Research Station, Kibler, AR in 2014 and 2015.

Crop rotation	Crop	Timing[a]	Herbicide	Date planted	
				2014	2015
A	Greenbeans	PRE	*S*-metolachlor	April 28	May 4
		POST	No herbicide		
B	Soybean	PRE	*S*-metolachlor	April 28	May 4
		POST	imazethapyr		
C	Sweet corn	PRE	*S*-metolachlor	April 28	May 4
		POST	mesotrione		
D	Edamame	PRE	*S*-metolachlor	April 28	May 4
		POST	imazethapyr		

[a]Abbreviations: PRE, preemergence; POST, postemergence.

Table 2. Planting dates and herbicides used for summer crops at the Vegetable Research Station, Kibler, AR in 2014 and 2015.

Crop rotation	Crop	Timing[a]	Herbicide	Date of seeding	
				2014	2015
A	Edamame	PRE	*S*-metolachlor	August 11	August 22
		POST	imazethapyr		
B	Edamame	PRE	*S*-metolachlor	August 20	August 22
		POST	imazethapyr		
C	Edamame	PRE	*S*-metolachlor	August 11	August 22
		POST	imazethapyr		
D	Edamame	PRE	*S*-metolachlor	August 11	August 22
		POST	imazethapyr		

[a]Abbreviations: PRE, preemergence; POST, postemergence.

Table 3. Planting dates and herbicides used for fall crops at the Vegetable Research Station, Kibler, AR in 2014 and 2015.

Crop rotation	Crop	Timing[a]	Herbicide	Date of seeding	
				2014	2015
A	Wheat	PRE	No herbicide	November 17	December 12
		POST	No herbicide		
B	Wheat	PRE	No herbicide	November 17	December 12
		POST	No herbicide		
C	Spinach	PRE	*s*-metolachlor	October 28	Not planted
		POST	No herbicide		
D	Wheat	PRE	No herbicide	November 17	December 12
		POST	No herbicide		

[a]Abbreviations: PRE, preemergence; POST, postemergence.

Table 4. Soil nutrient availability index, soil pH, and estimated cation exchange capacity after planting of spring crop.

Crop rotation	Spring crop	Soil nutrient availability index						pH	CEC[a]
		P	K	Ca	Mg	SO_4	Fe		
		ppm							cmol kg^{-1}
A	Greenbean	146	167	1114	181	14	196	6.8	10.10
B	Soybean	182	182	1221	196	12	222	6.9	10.78
C	Sweet corn	179	199	1066	183	16	223	6.4	9.99
D	Edamame	183	180	1321	208	15	222	7.1	10.89

[a]Abbreviations: CEC: cation exchange capacity

Table 5. Soil nutrient availability index, soil pH, and estimated cation exchange capacity after planting of summer crop.

Crop rotation	**Summer crop**	**Soil nutrient availability index**						**pH**	**CEC[a]**
		P	K	Ca	Mg	SO_4	Fe		
		------------------------ppm------------------------							cmol kg^{-1}
A	Edamame	169	163	1093	178	22	214	6.7	9.96
B	Edamame	170	150	1065	177	11	219	7.1	9.28
C	Edamame	152	151	1055	162	15	204	7.0	9.13
D	Edamame	169	181	1161	188	14	215	7.0	9.91

[a]Abbreviations: CEC: cation exchange capacity

Table 6. Relative yield of edamame fall-harvested crop following different summer-harvested crops compared to fall edamame monoculture Vegetable Research Station, Kibler, AR in 2014 and 2015.

Crop rotation	**Crop sequence**	**Actual edamame yield**		**Relative yield of edamame[a]**	
		2014	2015	2014	2015
		----------mt ha^{-1}----------		---------%---------	
A	greenbeans fb edamame fb wheat	3.79	3.41	109	74
B	grain soybean fb edamame fb wheat	4.00	3.28	122	71
C	sweet corn fb edamame fb spinach	4.45	3.56	128	77
D	edamame monoculture	3.48	4.62	-	-
LSD[b]		**NS**	**NS**	**NS**	**NS**

[a]Relative yield was calculated based on the yield of fall-harvested edamame, following a summer harvested edamame.
[b]Means were separated using Fisher's protected LSD (α = 0.05).

Table 7. Yield of spring-planted crops at the Vegetable Research Station, Kibler, AR in 2014 and 2015

Year	**Spring crop yield**			
	Greenbean[a]	Soybean[b]	Sweetcorn[c]	Edamame[d]
	--mt ha-1--			
2014	-	2.5	64.75	7.0
2015	-	1.9	26.25	5.8
LSD[e]	NA	NS	17.49	NS

[a]Greenbean was soil-incorporated as green manure because of severe disease infestion.
[b]Soybean dry yield at harvest.
[c]Fresh sweet corn ears.
[d]Fresh edamame pods.
[e]Means were separated using Fisher's protected LSD (α = 0.05); NA=not applicable; NS=not significant.

CONCLUSION

In Arkansas, several grain soybean herbicides have been labeled for edamame soybean weed control. These include sulfentrazone, *S*-metolachlor and fomesafen. Metribuzin, a grain soybean herbicide, can cause injury to edamame soybean as it does to some grain soybean varieties. Flumioxazin and pyroxasulfone provide effective weed control applied as preemergence. Some of the herbicides tested in this study (especially metribuzin, sulfentrazone, and flumioxazin) can reduce plant stand of edamame. However, the remaining plants can compensate for reduced plant population provided that the plants are healthy and the stand reduction is not severe, as in the general case with metribuzin. Edamame varieties developed in Arkansas are additional tools that can be combined with appropriate herbicides to achieve sustainable weed management. AVS-4002 edamame has lower tolerance than grain soybean to some herbicides . AVS-8080 edamame is highly sensitive to metribuzin. The best crop rotation system is sweet corn followed by AVS-8080 edamame. Environmental conditions are the greatest determinants for successful diversification of edamame-based cropping system. Varietal development and additional herbicides for edamame are essential aspects of integrated weed management strategies to maximize production efficiency, plant a compatible second crop, and to slow down the evolution of herbicide-resistant weeds.

APPENDIX

Appendix table 1. ANOVA table for crop stand reduction, Fayetteville, 2014

Source	df	SS	MS	F ratio	Prob>F
Herbicide	3	11654.20	3884.75	7.319	0.0001
Variety	10	9151.92	915.92	1.7243	0.0818
V x H	30	9741.94	324.731	0.6118	0.9407
Rep	3	8587.24	2862.41	5.3929	0.0016
Error	129	68470.01	530.78		
Total	175	107605.30			

Appendix table 2. ANOVA table for crop stand reduction, Fayetteville, 2015

Source	df	SS	MS	F ratio	Prob>F
Herbicide	3	836.841	278.947	0.8546	0.4666
Variety	10	9856.67	985.667	3.0197	0.0018
V x H	30	9582.28	319.409	0.9786	0.5062
Rep	3	997.477	332.492	1.0186	0.3867
Error	129	42106.52	326.407		
Total	175	63379.79			

Appendix table 3. ANOVA table for crop stand reduction, Kibler, 2014

Source	df	SS	MS	F ratio	Prob>F
Herbicide	3	21232.3	7077.45	31.7051	<0.0001
Variety	10	9026.3	902.63	4.0435	<0.0001
V x H	30	24234	807.80	3.6187	<0.0001
Rep	3	1462.88	487.627	2.1844	
Error	129	28796.37	223.23		
Total	175	84751.85			

Appendix table 4. ANOVA table for crop stand reduction, Kibler, 2015

Source	df	SS	MS	F ratio	Prob>F
Herbicide	3	2919.61	973.203	0.988	0.4007
Variety	10	10511.3	1051.13	1.0671	0.3923
V x H	30	31057.3	1035.24	1.0509	0.4078
Rep	3	362.244	120.748	0.1226	0.9466
Error	129	127072.5	985.058		
Total	175				

Appendix table 5. ANOVA table for crop injury at 21 DAP, Fayetteville, 2014

Source	df	SS	MS	F ratio	Prob>F
Herbicide	3	3964.11	1321.37	5.5058	0.0722
Variety	10	5961.03	596.103	2.4838	0.0093
V x H	30	10608.3	353.611	1.4734	0.0014
Rep	3	3147.97	1049.32	4.3723	0.0057
Error	129	30959.28	239.994		
Total	175	54640.69			

Appendix table 6. ANOVA table for crop injury at 21 DAP, Fayetteville, 2015

Source	df	SS	MS	F ratio	Prob>F
Herbicide	3	7741.48	2580.49	30.133	<0.0001
Variety	10	1393.18	139.318	1.6268	0.1059
V x H	30	2164.77	72.1591	0.8426	0.7001
Rep	3	902.841	300.947	3.5142	0.0172
Error	129	11047.16	85.637		
Total	175	12202.27			

Appendix table 7. ANOVA table for crop injury at 21 DAP, Kibler, 2014

Source	df	SS	MS	F ratio	Prob>F
Herbicide	3	41112.9	13704.3	104.0811	<0.0001
Variety	10	4565.91	456.591	3.4677	0.0005
V x H	30	9913.64	330.455	2.5097	0.0002
Rep	3	4808.38	1602.79	12.1729	<0.0001
Error	129	16985.37	131.67		
Total	175	77386.2			

Appendix table 8. ANOVA table for crop injury at 21 DAP, Kibler, 2015

Source	df	SS	MS	F ratio	Prob>F
Herbicide	3	32440.7	10813.6	116.3543	<0.0001
Variety	10	1428.7	142.87	1.5373	0.1352
V x H	30	3829.44	127.648	1.3735	0.0196
Rep	3	5327.35	1775.78	19.1075	<0.0001
Error	113	10501.82	92.936		
Total	159	53528.01			

Appendix table 9. ANOVA table for crop injury caused by fomesafen, Fayetteville, 2014

Source	df	SS	MS	F ratio	Prob>F
Variety	10	165.90	16.59	2.25	0.2799
Rep	3	29.54	9.84	1.34	<0.0415
Error	30	220.45	7.35		
Total	43	415.90			

Appendix table 10. ANOVA table for crop injury caused by fomesafen, Fayetteville, 2015

Source	df	SS	MS	F ratio	Prob>F
Variety	10	22.72	2.27	0.4688	0.897
Rep	3	10.79	3.59	0.7422	0.535
Error	30	145.45	4.84		
Total	43	178.98			

Appendix table 11. ANOVA table for crop injury caused by fomesafen, Kibler, 2014

Source	df	SS	MS	F ratio	Prob>F
Variety	10	247.73	24.77	3.37	0.061
Rep	3	110.79	36.93	5.03	0.0048
Error	30	220.45	7.34		
Total	43	578.98			

Appendix table 12. ANOVA table for crop injury caused by fomesafen, Kibler, 2015

Source	df	SS	MS	F ratio	Prob>F
Variety	10	17.04	1.74	0.4839	0.8872
Rep	3	6.82	2.27	0.6452	0.5921
Error	30	105.68	3.52		
Total	43	129.55			

Appendix table 13. ANOVA table for nontreated crop stand of soybean varieties, Fayetteville, 2014

Source	df	SS	MS	F ratio	Prob>F
Variety	10	1052.40	105.24	15.58	<0.0001
Rep	3	42.07	14.02	2.08	0.1245
Error	30	202.68	6.76		
Total	43	1297.16			

Appendix table 14. ANOVA table for nontreated crop stand of soybean varieties, Fayetteville, 2015

Source	df	SS	MS	F ratio	Prob>F
Variety	10	667.55	66.75	8.35	<0.0001
Rep	3	17.52	5.84	0.73	0.5417
Error	30	239.73	7.99		
Total	43	924.76			

Appendix table 15. ANOVA table for nontreated crop stand of soybean varieties, Kibler, 2014

Source	df	SS	MS	F ratio	Prob>F
Variety	10	775.41	77.54	7.03	<0.0001
Rep	3	14.98	4.99	0.45	0.7172
Error	30	330.78	11.03		
Total	43	1121.16			

Appendix table 16. ANOVA table for nontreated crop stand of soybean varieties, Kibler, 2015

Source	df	SS	MS	F ratio	Prob>F
Variety	10	1272.41	127.24	13.21	<0.0001
Rep	3	92.64	30.88	3.21	<0.0371
Error	30	288.86	9.63		
Total	43	1653.91			

Appendix table 17. ANOVA table for relative yield of soybean varieties, Fayetteville, 2014

Source	df	SS	MS	F ratio	Prob>F
Herbicide	4	5405.53	1351.38	0.8703	0.4833
Variety	10	58133.48	5813.35	3.7436	0.0002
V x H	40	34089.64	852.24	0.5488	0.9858
Rep	3	22748.12	7582.71	4.8831	0.0029
Error	152	236034.17	1552.85		
Total	209	356410.94			

Appendix table 18. ANOVA table for relative yield of soybean varieties, Fayetteville, 2015

Source	df	SS	MS	F ratio	Prob>F
Herbicide	4	23221.90	5805.48	1.3680	0.2473
Variety	10	91490.20	9149.02	2.1558	0.0230
V x H	40	161206.60	4030.17	0.9496	0.5615
Rep	3	16773.22	5591.07	1.3174	0.2706
Error	162	687508.37	4243.88		
Total	219	980200.29			

Appendix table 20. ANOVA table for relative yield of soybean varieties, Kibler, 2014

Source	df	SS	MS	F ratio	Prob>F
Herbicide	4	132897.81	33224.45	40.56	<0.0001
Variety	10	30106.79	3010.68	3.68	0.0002
V x H	40	19142.19	478.55	0.58	0.9761
Rep	3	14969.73	4989.91	6.09	0.0006
Error	162	132677.58	819.00		
Total	209	329794.1			

Appendix table 21. ANOVA table for relative yield of soybean varieties, Kibler, 2015

Source	df	SS	MS	F ratio	Prob>F
Herbicide	4	30156.96	7539.24	1.745	0.1426
Variety	10	287912.14	28791.21	6.663	<0.0001
V x H	40	173202.39	4330.06	1.002	0.4764
Rep	3	35610.99	11870.33	2.747	0.0447
Error	162	699921.2	4320.50		
Total	219				

Appendix table 22. ANOVA table for nontreated yield of soybean varieties, Fayetteville, 2014

Source	df	SS	MS	F ratio	Prob>F
Variety	10	14.2	0.142	4.38	0.0008
Rep	3	11.2	3.73	11.61	<0.0001
Error	30	9.72			
Total	43				

Appendix table 23. ANOVA table for nontreated yield of soybean varieties, Fayetteville, 2015

Source	df	SS	MS	F ratio	Prob>F
Variety	10	5.41	0.541	3.75	0.0025
Rep	3	2.34	0.78	5.43	0.0043
Error	29	4.17			
Total	42	11.79			

Appendix table 24. ANOVA table for nontreated yield of soybean varieties, Kibler, 2014

Source	df	SS	MS	F ratio	Prob>F
Variety	10	35.15	3.52	20.70	<0.0001
Rep	3	1.60	0.53	3.15	0.0393
Error	30	5.09			
Total	43	41.84			

Appendix table 25. ANOVA table for nontreated yield of soybean varieties, Kibler, 2015

Source	df	SS	MS	F ratio	Prob>F
Variety	10	1.50	0.15	4.93	0.0003
Rep	3	0.07	0.02	0.78	0.5124
Error	30	0.91	0.03		
Total	43				