PRODUCTION FACTORS TO IMPROVE EDAMAME EMERGENCE AND CROP
COMPETITIVENESS WITH WEEDS

BY

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THESIS

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ABSTRACT

There is a lack of information on edamame production in the United States, despite growing consumer demand. Edamame is typically managed similarly to grain soybean, but edamame differs in several key characteristics, including larger seed size in edamame. Seed size can affect emergence patterns and competitive ability. The available literature indicates edamame typically has low crop emergence and that there are relatively few weed management options for edamame. Little research has been done on the low crop emergence in edamame, but some have indicated that edamame is frequently planted too deep. There has been a successful push to get more herbicides labelled for use in edamame, but producers need complementing management tactics as herbicide resistance becomes more widespread. Integrated weed management plans can include several complementing weed management tactics, including cover crops and crop interference. Research was conducted near Urbana, Illinois to examine the roles of planting depth, cover crops, and crop interference in emergence and weed management in edamame production systems. Seed were separated into small and large size classes in the planting depth and interference trials to evaluate the relationships between seed size and planting depth and between seed size and crop interference.

Seed size did not affect total emergence, but smaller seed reached 50% emergence 0.7 days faster than large seed. Planting at 5 cm reduced total emergence by 19% and resulted in a 1.5 day delay in reaching 50% emergence relative to planting at 1 or 2 cm. These results indicate edamame should be planted shallower than is recommended for grain soybean. Results from the study on the use of cover crops in edamame indicate a fall-seeded rye cover crop terminated 6-8 weeks before edamame planting is the best cover crop residue system for suppressing weeds without suppressing the crop. The rye treatment terminated 6-8 weeks before edamame planting resulted in the same crop emergence but 19% lower weed emergence and 93% less weed biomass than the bare soil treatment. Results on the varying degrees of crop interference indicate that larger seeds within a cultivar can influence edamame's ability to tolerate weed interference and that edamame's weed suppressive ability can be affected by cultivar choice. Larger seed had 15 and 13% higher tolerance in terms of crop area and biomass, respectively, at 8 weeks after emergence. Compared to other cultivars, White Lion had 53% lower weed suppressive ability in terms of weed biomass at 8 weeks after emergence. These results improve understanding of crop emergence and integrated weed management plans in edamame production.

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CHAPTER 1: LITERATURE REVIEW

1.1 Introduction

American Midwest growers often incorporate grain soybean (*Glycine max (L.) Merr.*) in their crop rotations. Soybean is processed into a variety of useful products including industrial oils, biodiesel, and animal feed. In addition to their economic uses, soybean fixes atmospheric nitrogen that can be used by other grain crops, most often corn in the Midwest. Some estimates indicate that soybean can fix up to 72 kilograms of N per acre per year (Tisdale et al. 1993). This can be very beneficial for farmers trying to reduce their fertilizer input costs in corn, a heavy nitrogen feeder. In high fertility areas, such as the U.S. Midwest, legumes, such as soybean, have a large potential to increase the return on investment in corn cropping systems (Ojiem et al. 2014). Compared to a cereal grain monoculture, a cereal grain and legume rotation improves soil structure, disrupts certain pest populations, and alters soil nutrient balance as different crops remove and deposit different quantities of nutrients (Ball et al. 2005, Ojiem et al. 2014, Preissel et al. 2015). The same nutrient and rotation benefits U.S. growers currently get from the ubiquitous corn-soy rotation can be achieved with many possible leguminous crops, but growers currently prefer grain soybean because there is a well-established market. Vegetable soybean, or edamame, could be an alternative crop for producers. It is the same species as grain soybean, and edamame is increasing in popularity in the U.S. due its nutritional benefits (Kering and Zhang 2015). Domestic markets for this crop are expanding.

Edamame is not commonly grown in the United States, but it has been a very common crop and a popular food in Japan and China for centuries. Edamame is often touted as a health food because it is high in protein, as well as many diverse vitamins and minerals (Sanchez et al. 2005). Domestic edamame production is lower than domestic demand. Currently, edamame is not widely grown in the U.S., and most edamame consumed in the U.S. is imported from Taiwan or China (Dong et al. 2014). Edamame could be a viable alternative to grain soybean where producers are seeking to increase crop and income diversity. Late summer droughts in the U. S. southeast can make grain soybean difficult to grow without irrigation, but edamame growers can plant and harvest earlier in the season and thus avoid some risk of drought stress (Zhang and Kyei-Boahen 2007). Additionally, edamame is a high-value specialty crop due to developing markets and increasing consumer demand. Some estimates indicate that returns per acre could be

twice as much as the return per acre of grain soybean (Zhang and Kyei-Boahen 2007). This could allow producers greater income diversity.

The purpose of this review is to identify some of the common problems producers face in expanding current edamame production as well as to summarize the available literature on these problems. The most commonly-cited barriers to more widespread adoption of edamame are a lack of management knowledge, weed interference, and low crop emergence. Seed size emerges as a relevant crop characteristic affecting each of these problems. This review will focus on seed size in relation to each of these challenges.

1.2 Seed Biology

Soybean has epigeal emergence, which means the hypocotyl has to pull the cotyledons up through the soil (Casteel 2011). Soybean seed has large cotyledons relative to many other species, which can result in higher mechanical resistance in the soil. Hypocotyls may not have enough resources to completely pull cotyledons out of the soil, resulting in snapped hypocotyls, which increase seedling mortality. This mechanism can lower edamame stands. At the R7 stage, soybean seeds reach maximum dry matter and contain about 60% moisture (Vodkin et al. 2008). After this point, seeds begin desiccation and seed weight decreases as water is lost (Vodkin et al. 2008). Seeds and pods are brown and dry at the R8 stage, but optimal harvest time is when seeds are at 15% moisture (Vodkin et al. 2008).

1.2.1 Germination and Viability

To initiate germination, seeds need water and warm temperatures. All seeds have species specific conditions that optimize germination and emergence, and soybean seed are more sensitive to emergence environments than corn and sunflower (Helms et al. 1997). Seeds need to imbibe at least half their weight in water in order to germinate (Casteel 2011). Seedling development is positively correlated with initial soil moisture at planting (Helms et al. 1997). If there is not enough or inconsistent water after planting, emergence will be reduced if there is enough water for imbibition but not enough for emergence (Helms et al. 1997).

Larger crop seeds may need to be planted earlier or deeper to access deeper soil water reserves (Bewley and Black 1982). Soybean needs warmer soil temperatures in order to germinate. In soybean, planting one month earlier often results in reduced stands because cooler

temperatures slow emergence rates (Nafziger 2009). Casteel (2011) reports that 10 C is the lowest temperature at which soybean can germinate.

With optimal water and temperatures, soybean begin to emerge 5-21 days after planting (Casteel 2011); however, several environmental variables can reduce or inhibit germination. Harvest and planting timing and conditions can affect a seed's viability. For soybean, harvested seed must be above 10% moisture to prevent damage that would make seeds unviable (Casteel 2011). Light inhibits germination and can prevent radicle elongation; therefore shallow planting or exposed seeds may not have optimal germination or emergence rates (Bewley and Black 1982). Excessive CO_2 or low oxygen in the soil can also inhibit germination or increase seedling mortality (Bewley and Black 1982, Nafziger 2009). Morphological defects during seed formation can prevent proper seed formation and can alter the phenotype and function of resulting plants (Vodkin et al. 2008).

1.2.2 What determines seed size?

Seed size depends on genetic and environmental factors, but final seed size is not correlated to soybean seed quality (Nafziger 2009). Seed size is estimated to be between 26 and 50% heritable in soybean (Cober et al. 1997); however, paternal seed size has no effect on the final seed size of resulting progeny (Kilen 1980). The genes controlling seed size are not fully understood, but some seed coat and trichrome pigmentation genes can have an effect on final seed weight (Vodkin et al. 2008). The remaining 50-75% of seed size is determined by environmental conditions during seed fill. Final seed size is influenced by a significant genetic by environment interaction (LeRoy et al. 1991). Water stress during seed fill results in lower seed mass because the seed doesn't get enough water and the mother plant has reduced photosynthetic capacity due to insufficient water (Roach and Wulff 1987). Seed protein content is due primarily to the maternal environment (Roach and Wulff 1987).

Larger seeds are often found near the tops of the plants, and there is an inverse relationship between the mean seed weight at a given node and the number of pods on that node (Kilen 1980). Seeds in a given pod are usually fed with sugar from the leaves at the same node (Nafziger 2009). As light filters through the canopy, less light is getting to lower branches, which means the leaves on those branches have lower photosynthesis rates and lower sugar contents in those seeds. Cotyledon size affects nutrient availability for early seedlings. Cotyledons supply

nutrients for seedlings during the first 7-10 days and lose up to 70% of their dry matter during this nutrient reallocation (Casteel 2011). Larger cotyledons in larger seeds should be able to support more vigorous seedling growth. Mourtzinins et al. (2015) report no effect of differing seed mass on grain quality in terms of protein and oil content.

1.3 Edamame Management

Research to support the development of management practices for edamame is limited. Most planting decisions are based on grain soybean recommendations because there has not been sufficient research on how these factors affect edamame production and yields (Zhang and Kyei-Boahen 2007). Even basic factors, such as seeding rates and population targets, are based on grain soybean recommendations (Sanchez et al. 2005, Zhang and Kyei-Boahen 2007).

Optimal planting date is also uncertain in edamame. Planting date decisions are affected by germination temperatures because temperatures after planting need to be within the range for soybean germination, and the highest germination and emergence rates for grain soybean were between 25 and 35° C (Hopper et al. 1979). Edamame and grain soybean are the same species, but it is unknown if they have the same optimal germination temperatures.

Besides affecting weather conditions during emergence and germination, the literature suggests planting date has a season-long effect on the crop because it affects yields. Zhang and Kyei-Boahen (2007) found that in the U.S. southeast, planting one month earlier resulted in 8,400 lb/acre higher edamame fresh pod (R6) yields relative to planting one month later, and Li et al. (2014) reports that delaying planting by a month reduces edamame fresh pod yields by 4,000-6,000 kg/ha depending on cultivar. Even though earlier planting increased yields, planting too early can mean planting into cold soils that are unsuitable for germination. Temperatures must fall within the range (25-35° C) described by Hopper et al. (1979) to ensure germination.

Planting date can also affect the harvested seed. Edamame planting date affects the nutritional content of edamame seed because the weather during seed fill is affected by planting date (Li et al. 2014). Most studies on planting date include a range of dates and correlations between plant growth and yields. There is no optimal planting date for edamame, or for most vegetable crops, but several have attempted to use planting date to predict best management strategies. Planting one month earlier increased the palatability of edamame seed because the seed oil content increased by 15-45 mg/g and the seed sucrose content increased by 5-15 mg/g

relative to a one month planting delay (Li et al. 2014). Sucrose content is an especially important component of seed quality because most consumers prefer sweeter varieties of edamame, so planting date affects taste by affecting the sucrose content (Li et al. 2014). The literature suggests edamame yields would be highest if stands are planted as early as soil temperatures are warm enough to allow optimal germination.

The optimal planting depth for edamame is also unresolved. Madanzi et al. (2010) recommends planting grain soybean 2.5-5.0 cm deep, as emergence is reduced below 5 cm. The Illinois Agronomy Handbook recommends planting grain soybean 3.2-4.4 cm deep in the U.S. Midwest (Nafziger 2009). Shallow planting depths can lead to exposed roots, which increase mortality by approximately 50% when there is a 3 week drought following planting, resulting in low soil moisture (Madanzi et al. 2010). Madanzi et al. (2010), however, does not indicate exact planting depths but rather describes several planting methods; the shallowest depth, indicated by the observations of the researcher, was hand-opened furrows in a stale seedbed. Planting depth correlates to emergence timing and percentages. As planting depth increased from 1 to 5 cm, edamame emergence declined from about 95% to less than 40% (Zhang et al. 2013).

In addition, edamame has been found to be more sensitive to planting depth than grain soybean (Zhang et al. 2013). This may be due to the difference in seed sizes between edamame and grain soybean. Averaged across several grain soybean cultivars, small seeds, averaging 8.1 g per 100 seed, have 11% higher emergence than large seed, averaging 21.7 g per 100 seed, when planted at 3 cm (Burris et al. 1973). Averaged across cultivars and seed sizes, planting at 10 cm reduced emergence by 22% relative to planting at 3 cm (Burris et al. 1973). Burris et al. (1973) attributes the 22% increase in emergence from planting 7 cm shallower to faster drying at shallow depths as well as reduced mechanical resistance at shallow depths. Madanzi et al. (2010) reports an increase in mass of 7 g per 100 seed resulted in 40% higher stand counts at shallow planting depths and 5% higher stand counts at deep planting depth, based on the authors' observations of planting method and depth. There is, however, additional confounding factors in that study due to the variability in the planting methods; hand planting techniques often result in poorer seed to soil contact than mechanical planting tools, and although seed to soil contact was not addressed by Madanzi et al. (2010), it could have affected emergence from different depths because the depth was described solely by the planting method.

There has been very little research on edamame planting depth, but a few studies have attempted to find optimal depths. Sung (1992) reported that increasing planting depth from 2.5 to 5 cm resulted in 9% lower emergence and a 1 day delay to 50% emergence. Additionally, Zhang et al. (2013) reports that 10-20% higher edamame emergence was achieved at planting depths of 1-2 cm, which is shallower than the optimal planting depth for grain soybean of 2.5-5 cm.

Producers are slow to adopt edamame on a commercial scale because there are more constraints on harvest timing and handling relative to grain soybean. Grain soybean are harvested at physiological maturity, after they have dried down to 10-13% moisture in the field; this allows them to be stored for a long period of time without a significant decrease in quality. One barrier to edamame production is that edamame must be harvested fresh, during the R6 stage (around 80% moisture), and sold to consumers or frozen within a few days before it spoils. For maximum quality, edamame must be harvested during the appropriate harvest window, which only lasts a few days, and then immediately cooled (Kaiser and Ernst 2013). Additionally, the pods only remain fresh for about a week, even with optimal harvest timing and storage practices (Kaiser and Ernst 2013). This makes it a more difficult crop to harvest and market, but small-scale growers in Kentucky have found ways around this problem. University of Kentucky Extension sites report that farmers markets and small, local groceries are the most profitable way to market edamame as it does not need to be stored for as long (Kaiser and Ernst 2013). This type of marketing could appeal to many small farms as a way to increase crop and income diversity. Larger vegetable processors can harvest and process edamame on larger scales using expensive equipment and facilities that can be unattainable for small scale growers with fewer economic resources.

More research is needed on optimal management strategies for edamame. Some grain soybean management decisions may apply to edamame, but some factors will not transfer to edamame. Research is needed on optimal planting dates and planting depth in edamame.

1.4 Weed Control

An additional barrier to increasing edamame production is weed interference. Fewer herbicides are labeled for use on edamame relative to the number of products labeled for use in grain soybean. The most common weeds in soybean vary by year and region. In the U.S. Midwest, grain soybean producers cite giant ragweed, pigweed, chickweed, horseweed,

goosegrass, and giant crabgrass as most problematic on a management challenges survey (Gibson et al. 2005, Silvernail and Bomford 2006). Herbicides are the most common weed suppression technique for grain soybean. In 2003, in Indiana, herbicides were applied to 100% of grain soybean fields (Gibson et al. 2005). Widespread glyphosate use has led to glyphosate resistance in some weed species, including some of the most problematic weed species for soybean (Gibson et al. 2005).

Fewer herbicides are labeled for edamame than grain soybean because the criteria for registering herbicides for vegetable crops is different than the criteria for registering herbicides in grain crops (Williams 2015b). There are, as of March 2017, only eight herbicide active ingredients labeled for use in edamame coming from site of action groups 1, 2, 3, 6, 7, 14, and 15. Most edamame producers currently rely on crop rotation, mechanical cultivation, minimal herbicides, and hand weeding (Kaiser and Ernst 2013, Williams 2015b). These weed control methods can be very expensive on a large scale, especially if hand weeding is the primary tactic as labor is very expensive (Kaiser and Ernst 2013, Williams 2015b).

Weed interference can decrease yields and the nutritional contents of the soybean seed produced. Peer et al. (2013) found that grain soybean produced 37% higher yields in weed-free treatments. Additionally, weed interference reduced the number of seed per pod and the 100-seed-mass (Peer et al. 2013). Hunsberger (2006) found that soybean in weed-free environments had 49% more pods than the plants in weedy environments. There is also some evidence that seed are more nutritious with better weed control. Seed protein and oil content were highest under weed-free conditions (Peer et al. 2013).

Additionally, Nelson et al. (2007) found that the herbicide lactofen, a common grain soybean herbicide in the Protoporphyrinogen Oxidase (PPO) family, increased isoflavone concentrations in some grain soybean cultivars and in one edamame cultivar. Isoflavones have many human health benefits, including reduced cancer rates and improved cardiovascular health (Nelson et al. 2007). More cultivar screening is needed to determine if edamame cultivars are similarly affected. Tolerance and safety screening is also needed to label lactofen for use in edamame.

Another non-chemical weed control technique some producers use in soybean is cover crops, which can suppress weed populations in fields through biological, chemical, and physical mechanisms (Wortman et al. 2013). Cover crops can be either living (green mulches) or dead

plant matter covering the soil surface. Cover crops control weeds through enhanced weed seed predation, allelopathy, and light interception (Wortman et al. 2013). Many producers adopt cover crops because they have added benefits in addition to weed control. Cover crops improve soil structure and tilth, add organic matter, prevent erosion, and increase nutrient cycling (Moore et al. 1994).

In addition to overall weed control, cover crops can be used as a non-chemical control option when fields become infested with herbicide-resistant weeds. Herbicide resistant weeds are becoming more common and many biotypes are becoming resistant to multiple herbicide sites of action, leaving producers with increasingly fewer chemical options for weed management. DeVore et al. (2013) found that cover crops could be a management tool for herbicide-resistant weeds, such as Palmer Amaranth, in grain soybean fields. Rye cover crops reduced Palmer Amaranth emergence by up to 71% in no-till soybean production (DeVore et al. 2013). Anderson (2014) found that cover crops in grain soybean could reduce or prevent establishment of horseweed, another problematic weed resistant to multiple herbicides. Moore et al. (1994) found that cover crops in grain soybean reduced emergence of redroot pigweed, another problematic resistant species.

Cover crops have a large potential for suppressing weed emergence and reproductive capacity. Proper cover crop management, specifically termination method, can reduce grass weed species biomass by up to 45% (Wortman et al. 2013). Four to eleven metric tons per hectare of winter rye residue have been shown to reduce pre-plant weed emergence by 56-98% and reduced end of season weed biomass by 93% in grain soybean fields (Forcella 2013). In Minnesota, Forcella (2013) found that 4-11 metric tons per hectare of rye residue could reduce hand weeding time, in terms of hours per hectare, by 70-80% or even entirely eliminate the need for hand-weeding in grain soybean. Even lighter residue covers, such as an oat/pea mixture at 0.3 metric tons per hectare, can reduce weed interference by up to 63% and can reduce grain soybean yield losses from weed competition by 14% (Anderson 2014).

Cover crops also have some drawbacks, namely a shift in the weed community and reduced crop emergence. Cover crops can cause the weed spectrum to shift between years to predominantly perennial weeds, which can be harder for producers to control (Anderson 2014, Forcella 2013). Perennial weed seed can get caught in the residue cover and become established in cover crop stands (Forcella 2013). These weed species can be more difficult for producers to

control because perennials have larger root systems and can regenerate aboveground biomass fairly quickly as well as survive many environmental stresses, like drought, better than annual weeds and crops. Cover crops may also reduce crop emergence. Cover crops can reduce crop emergence the same ways they reduce weed emergence: seed predation, allelopathy, and light interception (Wortman et al. 2013), but crop seeds face an additional barrier to emergence from cover crop residues: cover crops can reduce crop emergence by reducing seed to soil contact because they interfere with planting equipment, such as blocking packing or coulter wheels (Forcella 2013).

Further weed control can come from the soybean crop itself. This can be referred to as crop interference, the ability of the crop to interfere with and suppress weed growth. Jordan (1993) reported that crop interference is a key, possibly the most important, non-chemical tactic in integrated weed management. Crop interference can suppress weeds throughout the season and reduce yield losses as well as weed seed set, which could reduce the weed population as a long-term control strategy (Jordan 1993).

One of soybeans' competition strategies is to reduce the available light for weed seedling growth, which slows the development or reproduction of weed species. Soybean produces a full canopy because the branches grow to fill out available space, interfering with weed establishment. Weed suppression is highest after canopy closure, when crop plants in neighboring rows are large enough that their canopies meet, which allows them to severely reduce available light for weed seedlings. Producers and breeders want to achieve the earliest canopy closure possible, allowing the crop itself to control weeds from that point until the end of the season. Soybean grow vigorously at the beginning of the season, producing a lot of foliage in the early vegetative stages (Peer et al. 2013). This is beneficial because earlier crop canopy cover is important for weed seedling suppression (Place et al. 2011a).

Seed size can affect early season growth patterns. Seed size has been known to affect plant growth and development for decades (Fontes and Ohlrogge 1972, Sung 1992, TeKrony et al. 1987). One of the characteristic differences between grain soybean and edamame is that edamame has larger seed, often over 30 g per 100 seed (Dong et al. 2014). In a five-year University of Illinois study, Bernard (2005) compared grain soybean to edamame, focusing on the Gardensoy edamame lines. The study examined several characteristics of the soybean varieties used, including seed mass. Seed mass for two grain soybean cultivars was 15 and 20

grams per 100 seed, and the edamame varieties ranged from 20 to 35 grams per 100 seed, with an average of 25.3 grams per 100 seed (Bernard 2005). The smallest edamame seed was the same as the largest grain soybean seed used. These larger seed are characteristic of most edamame cultivars. Edamame are selected for large seed due to consumer preferences.

Seed size is correlated to seedling vigor and competitiveness. Longer et al. (1986) found that seeds 1.5 g per 100 seed larger could produce plants with more leaf and root biomass at early growth stages than small seed (Longer et al. 1986). Burris et al. (1973) and Place et al. (2011a) report that increasing seed size is positively correlated with seedling vigor and overall plant performance. When conditions at early growth stages are optimal, plants from large seed can become established before the small seeded plants, which would give the large seeded plants a competitive advantage over other plants in the crop row. The competitive advantage continues into maturity. Increasing seed mass by 13.6 g per 100 seed results in plants that are 5 cm taller at maturity than smaller seeded plants (Burris et al. 1973). The 5 cm taller plants are able to block light from the smaller seeded plants in the row, which can reduce yields from smaller seeded plants.

Place et al. (2011b) reports that a larger seed size is the most important indicator of weed suppressive ability. This may, however, be due to the pleiotropic effect reported by Place et al. (2011b) connecting small soybean seed size with the Natto leaf allele. The Natto leaf allele makes leaves longer and narrower, rather than producing full, rounded leaves (Place et al. 2011b). Full, rounded leaves intercept more light and are better at shading out competitors, but the long and narrow leaves with the Natto leaf allele cannot intercept as much light as fuller, rounded leaves. Place et al. (2011a and 2011b) may have seen the strong results connecting seed size to weed suppressive ability because of the reduced canopy coverage associated with the Natto leaf trait.

Rezapour et al. (2013) report that in some grain soybean cultivars, 6 g per 100 seed larger seeds produced more above-ground biomass at four and twelve days after germination: larger seed resulted in 2 mm longer shoots at 4 days after germination and 15 mm longer shoots at 12 days after germination. In two studies by Place et al. (2011a and 2011b), increasing seed mass by 9 g per 100 seed resulted in 22-37% less weed biomass at midseason (7 WAE). Place et al. (2011a) attribute this to the increased plant area and increased canopy coverage seen in large seeded treatments. However, smaller seed may have an advantage from higher photosynthetic

rates at early stages: Burris et al. (1973) found that decreasing seed mass by 14 g per 100 seed results in 6.4 mg $CO_2/dm^2/hr$ higher photosynthesis rates, which they attribute to fewer resources stored in the smaller seed.

Soybean's relatively large seed can affect the crop's competitive ability in other ways besides producing more seedling mass. Large seeds can have slower emergence rates. Sung (1992) found that, for edamame, increasing seed mass by 18 g per 100 seed resulted in a 1.3 day delay to 50% emergence. Hopper et al. (1979) found that in grain soybean, reducing seed mass by 11 g per 100 seed resulted in 0.5 fewer days to 50% emergence. Hoy and Gamble (1987) report increasing seed diameter by 0.12 mm results in 9% slower emergence. Delayed emergence is detrimental for soybean growers because it reduces the early season weed suppression, but it can also affect harvested grain.

A 10 day delay in emergence can reduce grain yields by 7 kg/ha and can reduce protein content by 2.3 g/1 g of seed mass (Mourtzinis et al. 2015). Madanzi et al. (2010) reports that in some cases, the 7 g per 100 seed smaller seed mass resulted in 84 kg/ha higher yields compared to large seed, and Madanzi et al. (2010) cites earlier emergence with smaller seeds as a predominant factor leading to the higher yield. Fontes and Ohlrogge (1972) found that stands planted with 8 g per 100 seed larger seeds had 5 g/plant higher yields and 27% fewer barren plants. Fontes and Ohlrogge (1972) report that yield differences are largely due to the higher rate of barren plants in small seed treatments and the higher light interception rates in large seed treatments, but they do not report light interception values. However, TeKrony et al. (1987) reports no significant effect of seed size on grain yield.

Seed yield is an important measurement for grain farmers because it represents potential profits. Seed yield measures both seed number and seed size. If growers started preferentially screening for larger seed sizes at planting, they might be able increase grain yields under some conditions (Adebisi et al. 2013). Adebisi et al. 2013 reports that seed size is correlated to several yield characteristics, including seeds per plant (correlation coefficient: 0.27) and pods per plant (correlation coefficient: 0.39). Burris et al. (1973) found that increasing seed mass by 14 g per 100 seed increased yields by 100-300 g in optimal environments but sub-par environments resulted in a yield increase of 20-100 g as seed size increased. In a study of three grain soybean cultivars, Morrison and Xue (2007) found that decreasing seed diameter by 0.79 mm resulted in 300 kg/ha lower yields.

However, the higher yield associated with larger seeds is not due to increased seed mass from inherited large seed sizes. Seed sizes are mostly determined by environmental conditions during the seed-filling stage and are not highly heritable. Large seed sizes have lasting influences on soybean growth and development. More research is needed to clarify the connection between soybean seed size and emergence timing as well as the relationship between these factors and seed yield.

The evidence is clear that larger seed produce more early-season biomass, which is related to early-season weed suppression; however there appears to be a trade-off for the early competitive advantage. More research is needed on weed control methods in edamame, on ways to increase crop competitiveness in edamame, and on the effect of crop interference on weed populations.

1.5 Crop Emergence

In order to take advantage of crop interference, producers need high emergence to achieve canopy closure, but current edamame producers struggle with low crop emergence. Many studies have documented low emergence in edamame (Sanchez et al. 2005, Williams 2015a). Williams (2015a) documented an average emergence below 35% among 136 diverse edamame cultivars. The low emergence may be due to several factors, but poor germination, improper planting depth, soil crusting, and seed size variability are the most commonly blamed management and quality issues (Sanchez et al. 2005).

One factor affecting emergence is mechanical resistance in the soil (Arndt 1964). Hopper et al. (1979) found that as temperatures decreased by 20 °C, grain soybean germination rates were 78.7% slower but emergence rates were 90.5% slower than when temperatures were warmer. Hopper et al. (1979) concludes that the discrepancy between the germination and emergence at the same temperatures indicate that mechanical resistance from soil is more limiting at lower temperatures. Edamame is likely to follow the same general pattern, but given that it has much larger seed, the mechanical resistance may be even greater than for grain soybean seed. Little research has been done on optimal planting depths for edamame, but it is likely the optimal depth for edamame differs from that of grain soybean.

Several studies report increased mechanical resistance from particular soils or with larger seed. Soybean have epigeal emergence, so the hypocotyl must pull the cotyledons through the

soil surface before the plant can become established (Zhang et al. 2013). If the cotyledons face more mechanical resistance from the soil than the force exerted by the hypocotyl, then the hypocotyl can snap, causing seedling mortality. Arndt (1965) studied the mechanical resistance of emergence and found that it is easier for seed to emerge in wetter soils. In wet soils, seed must exert at least 150 g of pressure to crack the soil surface, but if the soil is dry, seed must exert 200 g of pressure (Arndt 1965). The Illinois Agronomy Handbook recommends planting smaller grain soybean seed because of reduced mechanical resistance (Nafziger 2009).

Other factors that influence the amount of pressure seed must exert in order to emerge include the mechanical composition of soil, the seed size, the planting depth, and the proximity to natural soil cracks (Arndt 1965). Morrison and Xue (2006) studied the effect of soil texture and seed size on emergence rates and found that it is easier for large seeded plants to emerge from heavier soils, such as a clay soil, than for small seeds, which emerge better from lighter textured soils, such as sandy or sandy loam soils. Heavier textured soils had enhanced water holding capacity, which allowed larger seed to imbibe enough water to germinate, and it was easier for small seeded plants to emerge from light textured soils, likely due to the lower force needed to emerge (Arndt 1964, Morrison and Xue 2006). If there is a soil crust during the emergence period, then there will be very few natural soil cracks for the seed to exploit for easier emergence. This means the seed will need more force in order to emerge.

Because edamame is a larger seed than grain soybean, it comes as no surprise that it would have lower emergence rates. Zhang et al. (2013) reports that edamame hypocotyl and radicle weight is 0.44 g/plant higher than grain soybean and cotyledons weighed 0.83 g/plant more compared to grain soybean seed. This means they'll likely encounter more resistance as they attempt to emerge. The hypothesis of the Zhang et al. (2013) study was that seed characteristics, specifically larger sizes, hypertrophic cotyledons, and weaker hypocotyls, of edamame inhibited emergence at certain depths. They thought the larger seed size would encounter too much resistance at deeper depths. The low emergence in edamame is likely because of the seed characteristics described.

There is conflicting evidence over whether or not seed size affects field emergence in grain soybean. Larger grain soybean seed frequently have poor emergence and therefore show reduced stand densities, which are a disadvantage for crop interference (Place et al. 2011b). Edamame often reflects the same pattern as grain soybean: 18 g per 100 seed higher seed mass

resulted in 15% lower emergence, causing lower stand densities (Sung 1992). Small edamame seed are the same size as large grain soybean seed, which appear to already have emergence problems due to their size. However, there is some conflicting evidence on the extent and consistency of the reduced emergence in large seed or from large seeded cultivars.

The emergence environment and the seed's genetics play an important role in whether or not seed size affects emergence. Hoy and Gamble (1987) found that seed in the smallest 10% of a grain soybean cultivar of a given seedlot had 8.8% lower field emergence than the largest 10% of seed in the same seedlot, but this effect of seed size dissipated when seedlot vigor increased above a certain threshold. Hoy and Gamble (1987) report that the effects of seed size on emergence were more pronounced at lower seedbed temperatures, but they do not provide actual temperatures. Adebisi et al. (2013), Edwards and Hartwig (1971), and Hopper et al. (1979) similarly found that small grain soybean seed had an advantage over large seed from the same genetic background in terms of radicle and hypocotyl development. Sung (1992) reports on seed size in edamame; this study found that reducing seed mass by 18 g per 100 seed increased emergence by 15%.

In contrast, some studies find the highest emergence in medium and large seed. Burris et al. (1973) found decreasing seed mass by 14 g per 100 seed resulted in 11% lower emergence in grain soybean. Rezapour et al. (2013) found the highest emergence of medium seed, averaging 14.4 g per 100 seed, but smaller seed (11.6 g per 100 seed) performed better than larger seed (16.7 g per 100 seed) under drought conditions because the larger seed could not imbibe enough water for germination. Longer et al. (1986) found that, under stressful conditions, such as crusting conditions, larger grain soybean seed (14.3 g per 100 seed) had higher total emergence rates than smaller seed (12.7 g per 100 seed) of the same cultivar. Under stress conditions, seed needs extra resources in order to survive until they become autotrophic; however, if there is insufficient soil moisture, larger seed cannot imbibe enough water for germination. Kering and Zhang (2015) also found that larger seeded grain soybean cultivars, with seed mass over 20 g per 100 seed, had 8.7% higher emergence than smaller seeded cultivars with seed masses below 10 g per 100 seed.

There is additionally doubt as to whether seed size affects emergence at all. Fontes and Ohlrogge (1972) and TeKrony et al. (1987) found that seed mass differences of 8-14 g per 100 seed did not affect grain soybean emergence under normal weather conditions. Morrison and

Xue (2006), Mourtzinis et al. (2015), and Johnson and Luedder (1974) also found that grain soybean seed diameter differences of 0.6-1.6 mm did not affect total emergence. Current edamame producers typically have low emergence rates, so they do not benefit from the potential crop interference from early canopy closure. More research is needed to understand the extent and consistency of the relationship between seed size and emergence.

1.6 Knowledge Gaps

Most of the literature presented here describes grain soybean, but, not all grain soybean management decisions can be applied to edamame. Some of the grain soybean literature may apply to edamame, but there is limited knowledge on how best to manage edamame. Factors such as planting depth likely differ for edamame. In general, little is known about growing edamame in the U.S. Most studies on soybean are done with grain soybean, and even for that crop, Hopper et al. (1979) notes a lack of information on how seed size and emergence are interacting.

Although there are few edamame studies, some researchers have attempted to address the unique problems with this crop. Sanchez et al. (2005) found edamame production in Pennsylvania was limited by low emergence and tried to determine what factors were lowering emergence, and Zhang et al. (2013) attempted to provide some best management strategies by examining seed size and planting depth. Even fewer studies on seed size in edamame have been conducted. Sung (1992) examined 2 edamame cultivars, separated by size class, and found that 18 g per 100 seed smaller edamame seed had 15% higher field emergence and reached 50% emergence 1.3 days faster than larger seeds.

Sung (1992) also suggests decreasing seed size should be a goal of producers wishing to increase emergence. This differs from the prevailing idea in grain soybean research. Hopper et al. (1979) writes that, for grain soybean, seed grading based on size doesn't appear to be economically efficient; however, they do acknowledge that removing the smallest seed size class from planting stock could result in faster emergence and more uniform stands. The Illinois Agronomy Handbook describes the benefits of smaller grain soybean seed, namely faster germination and lower water requirements and mechanical resistance, potentially leading producers to favor small grain soybean seed or smaller-seeded cultivars (Nafziger 2009).

The extent to which seed size can affect edamame production is unknown. In edamame, choosing some seed sizes over others may be more economically efficient because the seed sizes are shifted to the larger end of the grain soybean range, the part of the spectrum with the most variable emergence. If seed size has a large impact on either emergence or weed competition, than it may be worthwhile for seed producers and individual growers to grade the seed stock on size. Depending on producer needs, seed sizing could be a valuable tool for meeting production goals. It may be more beneficial for areas with heavier weed interference to use larger seed because of their competitive advantage, but if weed populations are low, then it may be more important to achieve higher emergence rates with smaller seed.

The purpose of this work was to outline the barriers producers face when attempting to grow edamame: a lack of management knowledge, weed interference, and poor crop emergence, as well as how seed size can impact these. Very little research has been done on edamame. Little is known about the best management strategies for this crop. There have been a few studies on the importance of seed size in grain soybean, but only one study was done on seed size in edamame. The one study on seed size in edamame, Sung (1992), only examined two edamame cultivars and did not include a grain soybean variety for comparison. Future work should focus on finding best management practices in edamame and the relationship between soybean seed size and plant characteristics, such as emergence and weed suppressive ability. More knowledge of these factors will allow for expanded commercial production.

1.7 Literature Cited

Adebisi, M. A., T. O. Kehinde, A. W. Salau, L. A. Okesola, J. B. O. Porbeni, A. O. Esuruoso, and K. O. Oyekale. 2013. *Influence of different seed size fractions on seed germination, seedling emergence, and seed yield characters in tropical soybean (Glycine max L. Merrill)*. International Journal of Agricultural Research 8 (1): 26-33.

Anderson, R.L. 2014. *A cultural system to reduce weed interference in organic soybean*. Renewable Agriculture and Food Systems 30 (4): 392-398.

Arndt, W. 1965. *The nature of mechanical impedance to seedlings by soil surface seals*. Australian Journal of Soil Resources 3: 45-54.

Ball, B. C., I. Bingham, R. M. Rees, C. A. Watson, and A. Litterick. 2005. *The role of crop rotations in determining soil structure and crop growth conditions*. Canadian Journal of Soil Science 85 (5): 557-577.

Bernard, R. 2005. *Garden-type vegetable soybean varieties*. Illinois Agricultural Experiment Station.

Bernthal, D., E. Sanchez, and K. Kelley. 17 July 2004. *Investigating the use of living mulches in Edamame (Glycine max) field production for weed management*. Poster presented at 101st annual international conference of the American Society for Horticultural Science, Austin, TX. Published: HortScience 39 (4): 746.

Bewley, J. D and M. Black. 1982. "Environmental Control of Germination." *Physiology and biochemistry of seeds*. Berlin: Springer-Verlag. 276-333.

Burris, J. S., O. T. Edje, and A. H. Wahab. 1973. *Effects of seed size on seedling performance in soybeans: II. Seedling growth and photosynthesis and field performance*. Crop Science 13:207-210.

Casteel, S. 2011. *Soybean physiology: How well do you know soybeans?* Soybean Station, Purdue University.

Cober, E. R., H. D. Voldeng, and J. A. Frégau-Reid. 1997. *Heritability of seed shape and seed size in soybean*. Crop Science 37: 1767-1769.

DeVore, J. D., J. K. Norsworthy, and K. R. Brye. 2013. *Influence of deep tillage, a rye cover crop, and various soybean production systems on palmer amaranth emergence in soybean*. Weed Technology 27 (2): 263-270.

Dong, D., X. Fu, F. Yuan, P. Chen, S. Zhu, B. Li, Q. Yang, X. Yu, and D. Zhu. 2014. *Genetic*

*diversity and population structure of vegetable soybean (*Glycine max *(L.) Merr.) in China as revealed by SSR markers*. Genetic Resources and Crop Evolution 61: 173-183.

Edwards, C. J. and E. E. Hartwig. 1971. *Effect of seed size upon rate of germination in soybeans*. Agronomy Journal 63: 429-430.

Fontes, L. A. N. and A. J. Ohlrogge. 1972. *Influence of seed size and population on yield and other charcteristics of soybean (Glycine max* (L.) Merr.*)*. Agronomy Journal 64: 833-836.

Forcella, F. 2013. *Short- and full-season soybean in stale seedbeds versus rolled-crimped winter rye mulch*. Renewable agriculture and Food Systems 29 (1): 92-99.

Gibson, K. D., W. G. Johnson, and D. E, Hillger. 2005. *Farmer perceptions of problematic corn and soybean weeds in Indiana*. Weed Technology 19 (4): 1065-1070.

Helms, T. C., E. L. Deckard, and P. A. Gregoire. 1997. *Corn, sunflower, and soybean emergence influenced by soil temperature and soil water content*. Agronomy Journal 89: 59-63.

Hopper, N. W., J. R. Overholt, and J. R. Martin. 1979. *Effect of cultivar, temperature and seed size on the germination and emergence of soya beans (Glycine max* (L.) Merr.). Annals of Botany 44: 301-308.

Hoy, D. J. and E. E. Gamble. 1987. *Field performance in soybean with seeds of differing size and density*. Crop Science 27: 121-126.

Hunsberger, L. K. January 2006. *Comparison of non-chemical weed management systems in edible soybean*. Poster presented at ASHS Northeast Region Annual Meeting, Ithaca, NY. Published: HortScience 40 (3): 496.

Johnson, D. R. and V. D. Luedders. 1974. *Effect of planted seed size on emergence and yield of soybeans (Glycine max (*L.*) Merr.)*. Agronomy Journal 66: 117-118.

Jordan, N. 1993. *Prospects for weed control through crop interference*. Ecological Applications 3 (1): 84-91.

Kaiser, C. and M. Ernst. 2013. *Edamame*. Center for Crop Diversification Crop Profile: 1-4.

Kering, M. K. and B. Zhang. 2015. *Effect of priming and seed size on germination and emergence of six food-type soybean varieties*. International Journal of Agronomy 2015: 1-6.

Kilen, T. C. 1980. *Paternal influence on F_1 seed size in soybean*. Crop Science 20: 261-262.

LeRoy, A. R., S. R. Cianzio, and W. R. Fehr. 1991. *Direct and indirect selection for small seed of soybean in temperate and tropical environments*. Crop Sciences 31: 697-699.

Li, Y., M Du, Q. Zhang, G. Wang, J. Jin, S. Herbert, and X. Liu. 2014. *Planting date influences fresh pod yield and seed chemical compositions of vegetable soybean*. HortScience 49 (11): 1376-1380.

Longer, D. E., E. J. Lorenz, and J. T. Cothren. 1986. *The influence of seed size on soybean (Glycine max (L.) Merrill) emergence under simulated soil crust conditions*. Field Crops Research 14: 371-375.

Madanzi, T., C. Chiduza, S. J. Richardson-Kageler. 2010. *Effects of planting method and seed size on stand establishment of soybean (Glycine max (L.) Merrill cv. Soltaire)*. Soil and Tillage Research 106: 171-176.

Moore, M. J., T. J. Gillespie, and C. J. Swanton. 1994. *Effect of cover crop mulches on weed emergence, weed biomass, and soybean (Glycine max) development*. Weed Technology 8 (3): 512-518.

Morrison, M. J. and A. G. Xue. 2006. *The influence of seed size on soybean yield in short-season regions*. Canadian Journal of Plant Science 87 (1): 89-91.

Mourtzinis, S., J. M. Gaska, P. Pedersen, and S. P. Conley. 2015. *Effect of seed mass and emergence delay on soybean yield and quality*. Agronomy Journal 107 (1): 181-186.

Nafzier, E. 2009. *Soybean*. In *Illinois Agronomy Handbook*. 24th edn. University of Illinois Extension, Champaign, IL.

Nelson, K. A., G. E. Rottinghaus, and T. E. Nelson. 2007. *Effect of lactofen application timing on yield and isoflavone concentration in soybean seed*. Agronomy Journal 99: 645-649.

Ojiem, J. O., A. C. Franke, B. Vanlauwe, N. de Ridder, K. E. Giller. 2014. *Benefits of legume-maize rotations: Assessing the impact of diversity on the productivity of smallholders in Western Kenya*. Field Crops Research 168: 75-85.

Peer, F. A., B. Hassan, B. A. Lone, S. Qayoom, L. Ahmad, B. A. Khanday, P. Ssingh, and G. Singh. 2013. *Effect of weed control methods on yield and yield attributes of soybean*. African Journal of Agricultural Research 8 (48): 6135-6141.

Place, G. T., S. C. Reberg-Horton, T. E. Carter, Jr., and A. N. Smith. 2011a. *Effects of soybean seed size on weed competition*. Agronomy Journal 103 (1): 175-181.

Place, G. T., S. C. Reberg-Horton, D. A. Dickey, and T. E. Carter, Jr. 2011b. *Identifying soybean traits of interest for weed competition*. Crop Science 51: 2642-2654.

Preissel, S., M. Reckling, N. Schlafke, and P. Zander. 2015. *Magnitude and farm-economic*

value of grain legume pre-crop benefits in Europe: A review. Field Crops Research 175: 64-79.

Rezapour, R., H. Kazemi-arbat, M. Yarnia, and P. Zafarani-Moattar. 2013. *Effect of seed size on germination and seed vigor of two soybean (glycine max* L.*) cultivars.* International Research Journal of Applied and Basic Sciences 4 (11): 3396-3401.

Roach, D. A., and R. D. Wulff. 1987. *Maternal effects in plants*. Annual Review of Ecology and Systematics 18: 209-235.

Sánchez, E., K. Kelley, and L. Butler. 2005. *Edamame Production as influenced by seedling emergence and plant population*. Horttechnology 15 (3): 672-676.

Silvernail, A. and M. K. Bomford. 28 July 2006. *Weed control in organic edamame soybean production*. Poster presented at 103rd annual international conference of the American Society for Horticultural Science, New Orleans, LA. Published: HortScience 41 (4): 1031.

Sung, F. J. M. 1992. *Field emergence of edible soybean seeds differing in seed size and emergence strength*. Seed Science and Technology 20: 527-532.

TeKrony, D. M., T. Bustamam, D. B. Egli, and T. W. Pfeiffer. 1987. *Effects of soybean seed size, vigor, and maturity on crop performance in row and hill plots*. Crop Science 27: 1040-1045.

Tisdale, S. L., W. L. Nelson, J. D. Beaton, and J. L. Havlin. 1993. *Soil fertility and fertilizers*. 5th edn. Macillan, New York, NY.

Vodkin, L., S. Jones, D. O. Gonzalez, F. Thibaud-Nissen, G. Zabala, and J. Tuteja. 2008. "Genomics of Soybean Seed Development." *Genetics and Genomics of Soybean*. New York: Springer. 163-184.

Williams, M. M. 2015a. *Phenomorphological characterization of vegetable soybean germplasm lines for commercial production*. Crop Science 55: 1274-1279.

Williams, M. M. 2015b. *Managing weeds in commercial edamame production: Current options and implications*. Weed Science 63 (4): 954-961.

Williams, M. M. and R. L. Nelson. 2014. *Vegetable soybean tolerance to bentazon, fomesafen, imazamox, linuron, and sulfentrazone*. Weed Technology 28: 601-607.

Wortman, S. E., C. A. Francis, M. A. Bernards, E. E. Blankenship, and J. L. Lindquist. 2013.

Mechanical termination of diverse cover crop mixtures for improved weed suppression in organic cropping systems. Weed Science 61 (1): 162-170.

Zhang, Q. Y., M. Hashemi, S. J. Hebert, and Y. S. Li. 2013. *Different responses of preemergence and early seedling growth to planting depth between vegetable soybean and grain soybeans*. Legume Research 36 (6): 515-521.

Zhang, L. and S. Kyei-Boahen. 2007. *Growth and yield of vegetable soybean (edamame) in Mississippi*. HortTechnology 17 (1): 26-31.

CHAPTER 2: EFFECT OF PLANTING DEPTH AND SEED SIZE ON EDAMAME EMERGENCE

2.1 Abstract

Some have indicated that large seed size and planting too deep may be the cause of the low emergence in edamame. Edamame is typically planted at the same depth as grain soybean, despite the seed size differences, but the limited literature on edamame indicates that edamame should be planted shallower than is recommended for grain soybean (3.2-4.5 cm). The objective of the study was to determine the effects of planting depth and seed size on edamame emergence. The main plot effect was planting depth; target depths were 1, 2, 3, and 5 cm. The sub-plot was seed size. Seed from a popular edamame cultivar was separated into small and large aggregate size classes with a seed cleaner. The experiment was repeated four times. Emergence was counted daily, and days to 50% emergence was determined. Seed size did not affect total emergence, but reducing average seed diameter from 0.91 to 0.77 cm resulted in 0.7 fewer days to 50% emergence compared to larger seeds. Planting at 5 cm reduced total emergence by 19% compared to the other depths and resulted in an increase of 1.5 days to 50% emergence compared to planting at 1 or 2 cm. Results indicate edamame should be planted shallower than grain soybean in order to achieve the highest and fastest emergence.

2.2 Introduction

Edamame (*Glycine max (L.) Merr.*) is becoming a popular health food in the United States. However, edamame is rarely produced in the United States (Dong et al. 2014). There has been very little research on edamame management for commercial production. Current producers rely on established grain soybean management techniques for edamame production, despite the differences between grain soybean and edamame cultivars (Williams 2015a, Zhang et al. 2013). Several of the management techniques might translate well, given that edamame and grain soybean are the same species, but not all of the management decisions will apply to both crops. One of the most challenging reasons producers are reluctant to adopt edamame on a commercial scale is the low crop emergence (Sanchez et al. 2005).

Edamame cultivars routinely have poor emergence; less than 35% emergence is common in the literature, but germination is typically over 75% (Sanchez et al. 2005, Williams 2015). Crop emergence in soybean is often less than expected from germination tests alone, but the soil

conditions affecting emergence are largely unquantified (Hamman et al. 2002). Seedling emergence is affected by many factors, including seed quality and vigor, soil temperature and water content, soil particle composition and texture, seedling size, soil pathogens, and planting depth (Arndt 1964, Hamman et al. 2002). Most of the factors affecting emergence are dependent on the soil environment and on local weather, and are therefore, un-controllable.

Recommended planting depth of grain soybean is 3.2 to 4.5 cm in Illinois (Nafziger 2009), and Hummel et al. (1981) recommends planting grain soybean at 4 cm in central Illinois soils. However, Zhang et al. (2013) reports that edamame are more sensitive to deeper planting depths than grain soybean. Few studies have been done on how planting depth affects edamame emergence, but Zhang et al. (2013) found that edamame should be planted shallower than grain soybean to achieve optimal edamame emergence. However, the study by Zhang et al. (2013) was conducted in a growth chamber environment, and it is unclear whether the results could be applied to field production systems. Optimal planting depth for edamame is unknown.

One of the biggest differences between grain soybean and edamame cultivars is seed size. Edamame seed mass is more than 30 g per 100 seed compared to 15-20 g per 100 seed for grain soybean (Bernard 2005, Dong et al. 2014); edamame is often 55-76% larger than grain soybean seed (Williams 2015a). The literature is not conclusive on how seed size affects soybean emergence, but most studies find that smaller grain soybean seed have higher emergence than larger seeds. Adebisi et al. (2013), Burris et al. (1973), Hoy and Gamble (1987), and Kering and Zhang (2015) report that smaller seeds have 2-11% higher emergence. Burris et al. (1973) concluded that smaller seed within a given cultivar had higher emergence because there was less mechanical resistance. In a contradicting study by Longer et al. (1986), smaller seed had 13% higher emergence than larger seed of the same cultivar. Edamame, with seeds even larger than the large end of the range for grain soybean seeds, may have low emergence due to the observed detrimental effects of the large seed sizes.

Another factor lowering edamame emergence, relative to grain soybean, could be an interaction between large seed size and soil composition; mechanical resistance in the soil can prevent full seedling emergence (Arndt 1964). Larger seed may result in fewer plants emerging with fully intact leaves because hypocotyls can snap as they try to bring heavy cotyledons above the soil surface (Arndt 1964). This problem would be exacerbated in edamame because the large seeds have very large cotyledons compared to grain soybean. Soil resistance is, obviously,

greater from deeper depths (Arndt 1964, Morrison and Xue 2006). Soil resistance is likely one of the most limiting factors on edamame emergence.

This study aims to find ways to increase edamame emergence through two factors producers can control, specifically planting depth and seed size. The objective of this study was to determine the effects of planting depth and seed size on edamame emergence.

2.3 Materials and Methods

2.3.1 Germplasm and Seed Sizing

The study included Midori Giant, a popular commercially-available cultivar, used in commercial production. Seed were separated into discrete size classes with a seed cleaner (Clipper Cleaner, A. T. Ferrell Company, Bluffton, IN). The seed cleaner uses round holed screens ranging from 0.71-1.07 cm diameters in 0.04 cm increments. Individual seed size classes were then grouped into small and large aggregate size classes in such a way that size classes had approximately equal quantities of seed. The aggregate small size class included seed less than 0.79 cm in diameter, and the average diameter of seed in the small size class was 0.77 cm. The aggregate large size class included seed greater than 0.87 cm in diameter, and the average diameter of the large size class was 0.91 cm. Seed with diameter larger than 0.79 but smaller than 0.87 was omitted so the aggregate size classes, hereafter called size classes, would be discrete and there would be no overlap between small and large groups. Both size classes had germination over 80%. All seeds were treated with mefenoxam (3.37 g per 100 kg of seed) and fludioxonil (2.27 g per 100 kg seed; Apron Maxx, Syngenta Crop Protection, Greensboro, NC) before planting.

2.3.2 Site Characterization

Field experiments were conducted in 2016 at the University of Illinois Vegetable Crop Farm in Urbana, Illinois. There were four planting dates in one field. The previous crop was grain soybean. The soil was a Flanagan silt loam. The seedbed was prepared with a disc harrow and a field cultivator before each planting date to ensure a fine seedbed texture and to get better seed-to-soil contact. Planting was done with a cone planter (ALMACO, Nevada, IA). Before the first planting date, each planting unit on the planter was field-calibrated to determine unique settings to achieve each study depth.

Planter calibration was conducted in the experimental area. Each planting unit was manually adjusted to plant at each target depth, and the edamame seeds were planted for 8 feet without the use of closing wheels. After each 8 foot trial, planting depth was measured from the top of the seed to the soil surface. Once a target depth was achieved, specific planter unit settings were noted, and this method continued until each planter unit had specific settings for each target depth. After each unit had target settings, all depths were planted with closing wheels, and depths were confirmed by uncovering several seeds and measuring from the top of the seed to the soil surface about one cm away from the furrow.

2.3.3 Field Experiment

The experiment was a split-plot randomized complete block design with four replications and was repeated four times throughout the season. Repetitions in time will hereafter be referred to as runs, and individual runs will hereafter be designated as A, B, C, and D. The main plot factor was planting depth with four levels: 1, 2, 3, and 5 cm. 1 and 2 cm were chosen as shallow depths, shallower than the optimal range for grain soybean planting. 3 cm was chosen to represent the shallow end of the grain soybean planting depth, and 5 cm was chosen as the deep depth, below the optimal range for grain soybean. The subplot factor was seed size, using the small and large size classes described earlier.

2.3.4 Data Collection and Analysis

Emergence was counted starting when hypocotyls were visible above the soil surface, and counts continued daily until all plants reached the V1 stage, with at least one fully-unfurled trifoliate leaf. The study was planted four times throughout the season to capture a range of environments in order to evaluate trends independent of planting environment. Cumulative precipitation (cm) and average daily soil temperature at 5 cm under bare soil conditions (C) were obtained from a weather station less than 1 km away from the experimental site (Water and Atmospheric Resources Monitoring Program, 2017).

Based on residual analysis, emergence data met ANOVA assumptions of normality, equality of variances, and independence (Hox 2002). Total emergence and days to 50% emergence were analyzed with an ANOVA model using the mixed procedure in SAS (version 9.4, SAS Institute Inc., Cary, NC). Seed size and depth were fixed effects, and the run was

treated as a random effect. Values followed by different letters are significantly different at α ≤ 0.05 based on the Tukey means separation test.

2.4 Results

2.4.1 Environments

Soybean needs a minimum soil temperature of 10 degrees Celsius for emergence (Casteel 2011), and 2 inch soil temperatures under bare soil in each trial were well above this minimum (Figure 2.1). Cumulative precipitation was 7.16 cm or higher during crop emergence in each trial, indicating that all trials had sufficient water for emergence (Figure 2.2).

2.4.2 Total Emergence

Seed size did not affect final emergence (P = 0.484, Table 2.1). Both small and large seed size classes had emergence < 60%. Planting depth affected final emergence (P < 0.001, Table 2.1). The three shallower depths had higher emergence than the deepest depth. The shallow depths had an average emergence of 63.5%, and the deepest depth had only 44.1% emergence (Table 2.1). There was no interaction between seed size class and planting depth (P = 0.825, Table 2.1).

2.4.3 Emergence Timing

Seed size class and planting depth both affected time to 50% emergence (P = 0.002 and P < 0.001, respectively, Table 2.1). Larger seeds took longer to emerge than smaller seeds of the same cultivar. Smaller seeds reached 50% emergence 0.7 days faster than larger seeds. As depth increased, days to 50% emergence increased. The two shallowest depths (1 and 2 cm) had 19% faster emergence than the deepest depth (5 cm) (P < 0.001, Table 2.1). There was no interaction between seed size class and planting depth (P = 0.435, Table 2.1).

2.5 Discussion

2.5.1 Total Emergence

Many other studies report low edamame emergence. Some of the factors lowering edamame emergence across diverse environments could be low germination, soil crusting, or water or temperature stress. Williams (2015) found low crop emergence in spite of the high

germination among seed lots planted in field trials. The author reported that in a study of 136 edamame cultivars, mean germination was over 78% but mean emergence was below 35%. Sanchez et al. (2005) reported that mean emergence for eight edamame cultivars over a three-year period was below 30%. Sanchez et al. (2005) does not report seed lot germination; however, they note soil crusting conditions limited crop emergence.

The germination for the seed lot in the present study was over 80%, and the mean crop emergence was ~60%. Based on studies by Sanchez et al. (2005) and Williams (2015), which found edamame emergence below 35%, mean crop emergence around 60% is not abnormally low for edamame in field experiments. The higher emergence reported in this study could be a result of a genetic predisposition for high emergence in the Midori Giant cultivar or a result of favorable environmental or soil conditions relative to the previous studies.

In previous research, seed size has been a significant factor in soybean emergence. Adebisi et al. (2013) report that decreasing seed mass by 4 g per 100 seed resulted in a 2% increase in total emergence and a 2% increase in germination. Burris et al. (1973) found that decreasing seed mass by 14 g per 100 seed resulted in 11% higher emergence. Kering and Zhang (2015) report that decreasing seed mass by 10 or more grams per 100 seed increased emergence by 5% but increased germination by 51%. Hoy and Gamble (1987) found that decreasing seed diameter by 0.12 mm resulted in 9% higher emergence. However, Longer et al. (1986) reported that decreasing seed mass by 1.5 g per 100 seed decreased emergence by 13%.

TeKrony et al. (1987) notes that under ideal conditions, there was no effect of seed size on soybean emergence. TeKrony et al. (1987) reports "near ideal" environmental conditions, which they believe masked the effects of measured traits: seed size and seed vigor. Burris et al. (1973) and Hoy and Gamble (1987) report "good" and "generally favorable" growing conditions but fails to include specific environmental detail. Weather conditions in the present study may have been ideal for soybean emergence: there was no water shortage and temperatures were well within the range for optimal soybean germination. As in TeKrony et al. (1987), the effect of seed size on total emergence in the present study could be obscured by ideal weather conditions during the emergence period. Another possible reason the present study showed no effect of seed size on total emergence could be the soil environment. The soil texture and composition in the present study may have been more favorable for crop emergence than the soil environments in the previously cited studies. Few of the previously listed studies include detailed soil

descriptions, but soil composition does affect emergence. The soil texture and composition in the present study may have created less mechanical resistance than the soil environments of previous studies.

The lowest crop emergence in this study resulted from the 5 cm planting depth (Table 2.1). Several studies report a negative correlation between crop emergence and planting depth (Hamman et al. 2002, Hummel et al. 1981). In addition to the soil resistance mentioned previously, deeper depths can result in lower emergence because of higher mortality due to the detrimental effects of delayed emergence. Delayed emergence extends the window of time in which seedlings are vulnerable (Hamman et al. 2002, Canakci et al. 2009). Delayed emergence can increase vulnerability to soil pathogens (Hamman et al 2002). As the emergence window is extended due to deeper planting depth, weather conditions can become increasingly variable, which can eventually result in soil crusting (Canakci et al. 2009). This wasn't a factor in the present study due to the ample water supply, but it could be a factor in other studies reporting similar results to those observed here.

Declining emergence from deeper depths can be attributed in part to mechanical resistance from the soil or to a lack of oxygen in saturated soil (Hummel et al. 1981). The simplest explanation for why deeper planting would decrease crop emergence is the soil's inherent mechanical resistance, which would prevent some seeds from emerging (Arndt 1964, Hummel et al. 1981). Mechanical resistance certainly affected the present study and could be the main factor lowering crop emergence at the 5 cm depth. Another factor could be anaerobic conditions in saturated soils. Such conditions can foster microorganisms fatal to seedlings (Hummel et al. 1981). The trials in the present study had ample water, which could have created anaerobic conditions at the deepest planting depth. The mechanical resistance from soil and anaerobic conditions resulting from too much water are the most likely factors decreasing crop emergence from deeper depths in the present study.

The present study is the first to show that the optimal range for field planting depth for edamame may be different than that for grain soybean. The recommended planting depth for grain soybean in the U.S. Midwest is 3.2-4.5 cm (Nafziger 2009). In the present study, depths shallower than the recommended range for grain soybean had higher emergence than the depth deeper than the recommended range. These results indicate that planting below the recommended depth for grain soybean may result in lower crop emergence for edamame and that

planting at the shallow end or shallower than the recommended depth for grain soybean will result in higher edamame emergence than planting at deeper depths.

However, planting too shallow can be just as detrimental to soybean emergence in some cases. When water is limiting, shallow depths may not have sufficient soil moisture for soybean germination (Hummel et al. 1981). Insufficient soil moisture can also cause mortality in newly emerged plants. Madanzi et al. (2010) notes that shallower plantings can lead to exposed roots, which exacerbates mortality in water-limited environments. Seeds need to imbibe half their weight in water in order to initiate germination, and shallower depths may dry out faster due to increased air flow across the soil surface. In the present study, there was sufficient water during the emergence period, so water was not limiting. If there had been a dry period during the trials, the results of this study might have shown the risks of planting too shallow, which could affect the overall conclusion, but as every trial period had ample water, there was no risk associated with shallow planting depth in this study.

2.5.2 Emergence Timing

There are several possible reasons why smaller seeds reached 50% emergence faster than larger seeds of the same cultivar. One potential reason could be the amount of water needed for germination. Soybean seeds must imbibe around 50% of the seed dry weight to start germination. Mourtzinis et al. (2015) reported that when water was limiting, emergence was delayed, which means water availability can affect emergence timing. Adebisi et al. (2013) found that smaller seeds started germination earlier compared to larger seeds of the same cultivars, and they cite water availability as a driving force. Smaller seeds will need to imbibe less water to initiate germination, which could result in faster emergence for smaller seeds (Kering and Zhang 2015). Edwards and Hartwig (1971) reported that smaller seeds germinated faster, and although they did not give a reason for this observation, it may have been due to the lower water requirement for smaller seed imbibition. The difference in emergence timing between seed sizes reported in the present study could be due to water availability.

As depth increased, the time to 50% emergence increased. Canakci et al. (2009) reports that emergence can be delayed by planting soybean at deeper depths. Results from the present study indicate that planting edamame shallower than the grain soybean recommendation (3.2-4.5

cm) reduces time to 50% emergence. Variable emergence timing in soybean is important because crop emergence timing affects final yields and weed management.

Variable crop emergence can affect soybean yields. Later emergence is correlated to lower yields due to reduced reproductive node numbers (Bastidas et al. 2008). This may be due to the shorter growing season resulting from delayed emergence. Additionally, Zhang and Kyei-Boahen (2007) reports that uniform emergence timing is essential for edamame seed harvest because physiologically mature (R8) edamame pods have a high degree of shattering. If some plants reach physiological maturity sooner than others in the field, producers risk seed loss either due to shattering in earlier maturating individuals or due to immature seeds in later maturing individuals.

Variable crop emergence timing can also affect weed control strategies in soybean because it can affect the window of time when herbicides can be applied (Coulter and Nafziger 2007). Foliar applied herbicides typically have stringent requirements on minimum pre-harvest windows. Additionally, delayed crop emergence results in reduced weed suppression because later crop emergence results in later canopy closure, reducing the competitive ability of the crop (Edwards and Hartwig 1971, Place et al. 2011).

2.6 Conclusions

Results from the present study indicate that Midori Giant seed should be planted shallower than the recommended planting depth for grain soybean. Planting shallower than the recommended range for grain soybean could increase edamame emergence in optimal environments, but there is also a risk of planting too shallow in water-limited environments. In the present study, the highest and fastest emergence resulted from a planting depth of 3 cm or shallower. Planting deeper than 3 cm resulted in lower final emergence and more days to 50% emergence. Reducing average seed diameter from 0.91 cm to 0.77 cm resulted in 10% faster emergence, but seed size did not affect final emergence.

2.7 Figures and Table

Figure 2.1 Average Soil Temperatures. Average daily soil temperatures (degrees C) were sampled to a depth of 5 cm under bare soil conditions. Temperatures were monitored from planting until twenty-one days after planting, the end of the longest emergence period. A, B, C, and D refer to the four trial repetitions. Soil temperature data was obtained from a site less than 1 km from field trials: Water and Atmospheric Resources Monitoring Program. Illinois Climate Network. (2017). Illinois State Water Survey, 2204 Griffith Drive, Champaign, IL 61820-7495.
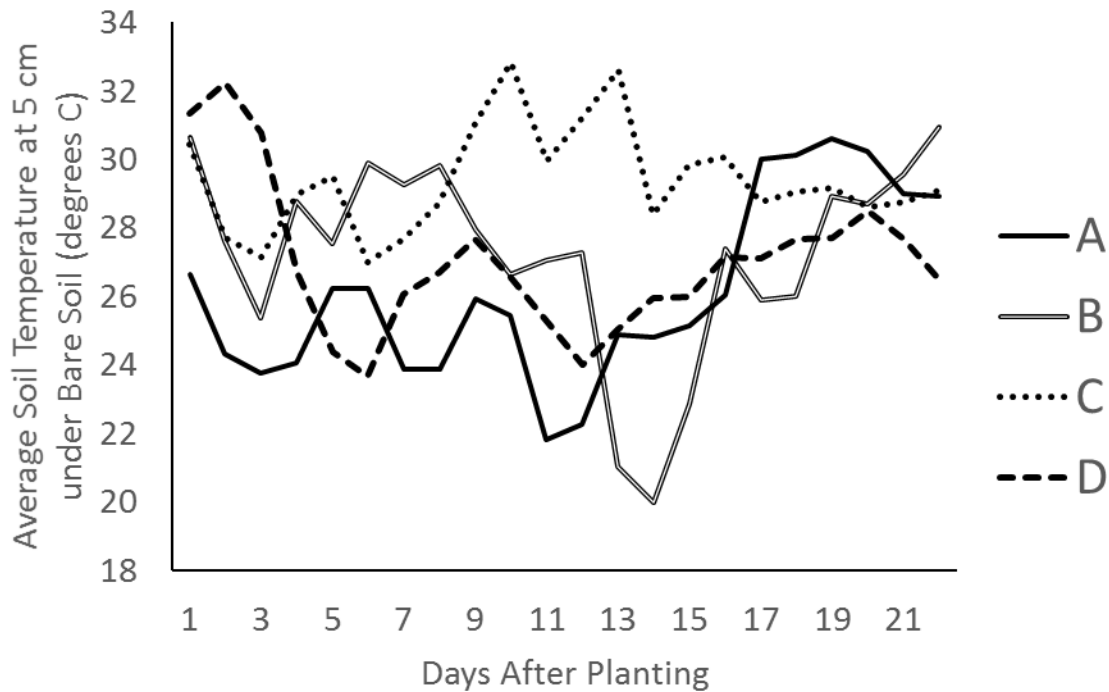
Figure 2.2 Cumulative Precipitation. Precipitation (cm) was monitored throughout each trial until twenty-one days after planting, which marked the end of the longest emergence period. A, B, C, and D refer to the four trial repetitions. Precipitation data was obtained from a site less than 1 km from field trials: Water and Atmospheric Resources Monitoring Program. Illinois Climate Network. (2017). Illinois State Water Survey, 2204 Griffith Drive, Champaign, IL 61820-7495.
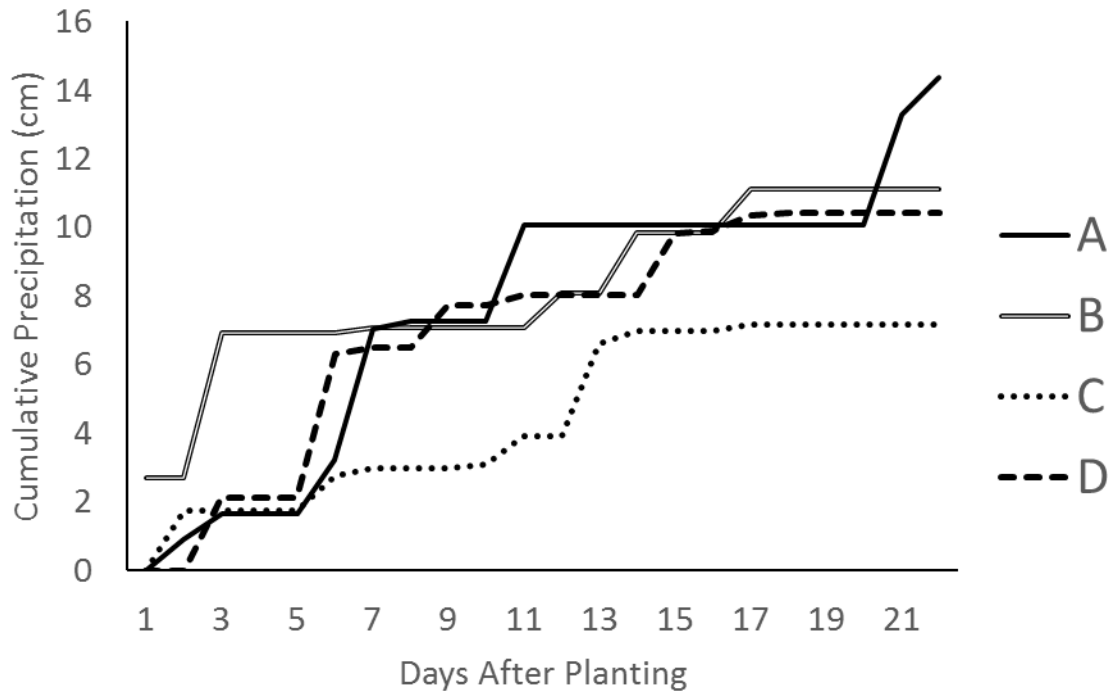
Table 2.1 Crop Emergence. Mean edamame emergence at three weeks after planting in field experiment near Urbana, IL in 2016 trials. Within each fixed effect, emergence percent or days to 50% emergence followed by different letters are significantly different at $\alpha < 0.05$ based on Tukey's means separation test.

Fixed Effects	Levels	Total Emergence (%)	Days to 50% Emergence
Size	Small	57.7	6.4^b
	Large	59.5	7.1^a
	P-Value	0.48	<0.01
Depth (cm)	1	62.9^a	5.9^b
	2	67.4^a	6.4^b
	3	60.1^a	7.1^{ab}
	5	44.1^b	7.6^a
	P-Value	<0.01	<0.01
Size*Depth	P-Value	0.83	0.44

2.8 Literature Cited

Adebisi, M. A., T. O. Kehinde, A. W. Salau, L. A. Okesola, J. B. O. Porbeni, A. O. Esuruoso, and K. O. Oyekale. 2013. *Influence of different seed size fractions on seed germination, seedling emergence, and seed yield characters in tropical soybean (*Glycine max *L. Merrill).* International Journal of Agricultural Research 8 (1): 26-33.

Arndt, W. 1964. *The nature of the mechanical impedance to seedlings by soil surface seals.* Australian Journal of Soil Research 3: 45-54.

Bastidas, A. M., T. D. Setiyono, A Dobermann, K. G. Cassman, R. W. Elmore, G. L. Graef, and J. E. Specht. 2008. *Soybean sowing date: The vegetative, reproductive, and agronomic impacts.* Crop Science 48: 727-740.

Burris, J. S., O. T. Edje, and A. H. Wahab. 1973. *Effects of seed size on seedling performance in soybeans: II. Seedling growth and photosynthesis and field performance.* Crop Science 13: 207-210.

Canakci, M., D. Karayel, M. Topakci, and A. Koc. 2009. *Performance of a no-till seeder under dry and wet soil conditions.* Applied Engineering in Agriculture 25 (4): 459-465.

Casteel, S. 2011. *Soybean physiology: How well do you know soybeans?* Soybean Station, Purdue University.

Coulter, J. A. and E. D. Nafziger. 2007. *Planting date and glyphosate timing on soybean.* Weed Technology 21 (2): 359-366.

Edwards, C. J. and E. E. Hartwig. 1971. *Effect of seed size upon rate of germination in soybeans.* Agronomy Journal 63: 429-430.

Hamman, B., D. B. Egli, and G. Koning. 2002. *Seed vigor, soilbourne pathogens, preemergent growth, and soybean seedling emergence.* Crop Science 42: 451-457.

Hox, J. J. 2002. *Multilevel analysis: Techniques and application.* Mahwah, NJ: Lawrence Erlbaum.

Hoy, D. J and E. E. Gamble 1987. *Field performance in soybean with seeds of differing size and density.* Crop Science 27: 121-126.

Hummel, J. W., L. E. Gray, and W. R. Nave. 1981. *Soybean emergence from field seedbed environments.* Transactions of the ASAE 24 (4): 872-878.

Kering, M. K and B. Zhang. 2015. *Effect of priming and seed size on germination and emergence of six food-type soybean varieties.* International Journal of Agronomy: 1-6.

Longer, D. E., E. J. Lorenz, and J. T. Cothren. 1986. *The influence of seed size on soybean (*Glycine max *(L.) Merrill) emergence under simulated soil crust conditions*. Field Crops Research 14: 371-375.

Madanzi, T., C. Chiduza, and S. J. Richardson-Kageler. 2010. *Effects of planting method and seed size on stand establishment of soybean [*Glycine max *(L.) Merrill cv. Solitaire]*. Soil and Tillage Research 106: 171-176.

Mourtzinis, S., J. M. Gaska, P. Pedersen, and S. P. Conley. 2015. *Effect of seed mass and emergence delay on soybean yield and quality*. Agronomy Journal 107 (1): 181-186.

Morrison, M. J. and A. G. Xue. 2006. *The influence of seed size on soybean yield in short-season regions*. Canadian Journal of Plant Science 87 (1): 89-91.

Place, G.T., S. C. Reberg-Horton, T. E. Carter, Jr., and A. N. Smith. 2011. *Effects of soybean seed size on weed competition*. Agronomy Journal 103 (1): 175-181.

Sanchez, E., K. Kelley, and L. Butler. 2005. *Edamame production as influenced by seedling emergence and plant population*. HortTechnology 15 (3): 672-676.

TeKrony, D. M., T. Bustamam, D. B. Egli, and T. W. Pfeiffer. 1987. *Effects of soybean seed size, vigor, and maturity on crop performance in row and hill plots*. Crop Science 27: 1040-1045.

Water and Atmospheric Resources Monitoring Program. Illinois Climate Network. (2017). Illinois State Water Survey, 2204 Griffith Drive, Champaign, IL 61820-7495.

Williams, M. M. 2015. *Phenomorphological characterization of vegetable soybean germplasm lines for commercial production*. Crop Science 55: 1274-1279.

Zhang, L. and S. Kyei-Boahen. 2007. *Growth and yield of vegetable soybean (Edamame) in Mississippi*. HortTechnology 17 (1): 26-31.

Zhang, Q. Y., M. Hashemi, S. J. Hebert, and Y. S. Li. 2013. *Different responses of preemergence and early seedling growth to planting depth between vegetable soybean and grain soybeans*. Legume Research 36 (6): 515-521.

CHAPTER 3: EVALUATING COVER CROP RESIDUE MANAGEMENT SYSTEMS IN EDAMAME PRODUCTION

3.1 Abstract

Vegetable processors need weed management options in order to expand edamame production in the United States. Fall-seeded cover crops have been shown to reduce weed populations, which is especially relevant in fields with herbicide resistant weed populations. It is unknown what role cover crops can play in edamame production. The objective of the study was to identify cover crop residue management systems that selectively suppress weeds without inhibiting edamame emergence. The three cover crop species were radish, canola, and rye. There were early and late termination dates for canola and rye treatments. The control was a bare soil treatment. There were eleven edamame cultivars and one grain soybean cultivar. Edamame emergence was counted for each row. Weed population data, emergence and biomass, represent the natural weed seed bank present in the study area. The late rye treatment reduced crop emergence by 32.6% from the bare soil treatment and was the only cover crop that reduced crop emergence compared to bare soil. The early and late rye treatments reduced weed emergence by 19% and 92%, respectively, compared to bare soil, but all cover crop treatments reduced midseason weed biomass by at least 31% compared to bare soil. Early rye was the best cover crop treatment because it had the same crop emergence as bare soil but also reduced weed emergence by 19% and weed biomass by 93%.

3.2 Introduction

Domestic demand for edamame (*Glycine max (L.) Merr.*) is increasing, but few producers are able to produce edamame at a commercial scale given the challenge of weed management in the crop (Williams 2015b). Despite the fact that edamame and grain soybean are the same species, relatively few chemical herbicides can be used in edamame production due to the fact that edamame is harvested and eaten fresh rather than harvesting at physiological maturity like grain soybean (Williams 2015b). Producers need more weed control options for edamame production, but getting more herbicides labeled for use in edamame is not the only solution.

As herbicide use becomes more widespread and more herbicides are applied in field production systems, more and more weeds are gaining resistance to multiple herbicide sites of

action. Producers need more types of weed control to complement chemical control methods. Producers need Integrated Weed Management (IWM) systems for edamame weed control that take advantage of multiple control tactics and different kinds of weed control techniques. These other weed control techniques include biological, physical, and cultural techniques that can complement the chemical options (Harker and O'Donovan 2013).

Fall-seeded cover crops are an example of cultural weed control technique that suppress weeds through biological (predation), chemical (allelopathy), and physical (light interception) mechanisms (Wortman et al. 2013). Cover crops can be used to manage many types of problematic weed species, but they can be especially useful when dealing with herbicide-resistant weeds. Producers facing dense herbicide-resistant weed populations often have to turn to biological and cultural weed management tools as chemical mechanisms continue to fail them.

One of the most frequently used weed control mechanisms producers turn to after chemical mechanisms fail is tillage (Price et al. 2016). Tillage can be useful in combating herbicide resistant weeds because it either buries weed seeds so deep they cannot emerge or brings them to the surface, causing seed desiccation. Producers have adopted low- or no-till practices in recent years to preserve soil structure and reduce costs, but no-till production increases reliance on herbicides for weed control. As herbicide resistance has spread, producers have begun incorporating tillage again (Price et al. 2016). However, tillage has several drawbacks, including release of stored soil carbon (Olson 2010), lowering long-term soil health, and increasing erosion potential (Price et al. 2016).

Cover crops can also control herbicide-resistant weeds, but instead of decreasing long-term soil health, like tillage does, cover crops actually increase soil health (Moore et al. 1994). Fall-seeded cover crops can be a very beneficial component of IWM systems due to the additional soil health benefits from incorporating residue.

In soybean, cover crops have been shown to suppress herbicide resistant weed populations. Palmer Amaranth (*Amaranthus palmeri S. Wats.*), horseweed (*Conyza canadensis (L.) Cronq.*), and redroot pigweed (*Amaranthus retroflexus L.*) have documented cases of herbicide resistance throughout the Midwest Corn Belt. DeVore et al. (2013) found that rye cover crops reduced Palmer Amaranth emergence by up to 71% in no-till soybean production. Anderson (2014) found that cover crops in grain soybean can reduce or prevent horseweed establishment. Moore et al. (1994) reports that cover crops reduced redroot pigweed emergence

by 63% in grain soybean. Overall, cover crops can be a valuable tool for managing herbicide resistant weed populations.

Dense cover crop residues, such as winter rye, can reduce pre-plant weed emergence by 56-98% and can substantially suppress weed biomass (Forcella 2013). Even less dense residue covers, such as an oat/pea mixture with less biomass, can reduce weed interference by up to 63% (Anderson 2014). However, the same mechanisms by which cover crops reduce weed interference and suppress weed biomass can lower crop emergence and suppress crop biomass because cover crops affect crop seeds the same ways they affect weed seeds (Wortman et al. 2013). Cover crops also have an additional physical mechanism reducing crop emergence. Heavier residue cover crops can reduce crop emergence by inhibiting seed to soil contact by interfering with coulter and packing wheels on planting equipment (Forcella 2013).

Reducing crop emergence would decrease the potential for edamame production on a commercial scale. Edamame often has low crop emergence; an average emergence rate of 35% or lower is common in the literature (Sanchez et al. 2005, Williams 2015a). Edamame has economic potential for domestic markets, but low crop emergence is a barrier for producers needing to supply large-scale markets. Cover crops would not be a viable management tactic if they compromise edamame emergence.

The extent to which fall-seeded cover crops can fit into commercial edamame production is unknown. The objective of this study was to identify cover crop residue management systems that selectively suppress weeds without inhibiting edamame emergence.

3.3 Materials and Methods

3.3.1 Experimental Design

Field experiments were conducted at the University of Illinois Vegetable Crop Farm in Urbana, Illinois. The experiments were conducted in different fields at the Vegetable Crop Farm each year. The soil in each field was a Flanagan silt loam. The previous crop in each field was grain soybean. The experiment was a split plot randomized complete block design with three replications and was conducted over three growing seasons. Main plots were cover crop residue management systems (hereafter simply called 'cover crop treatments'), and sub-plots were edamame cultivar. There were six cover crop treatments in this study, and there were eleven

edamame cultivars and one grain soybean cultivar included. Each sub-plot consisted of one 2.5-m row of 64 soybean seeds.

Cover crop plots were approximately 36 m^2. Cover crops were planted in the fall before each study year. Cover crops were radish (*Raphanus sativus L.*), canola (*Brassica napus L.*), and rye (*Secale cereal L.*). The radish and canola were planted by hand with a hand seeder on August 27th, 2013, September 23rd, 2014, and September 8th, 2015. Rye treatments were planted with a drill seeder on September 11th, 2013, September 25th, 2014, and September 25th, 2015.

Radish plots were terminated by sub-freezing winter temperatures. The canola and rye plots each had two termination dates, early and late, separated by approximately two weeks. The early-killed canola and early-killed rye were terminated with glyphosate in early- or mid-April, as weather allowed. The early termination dates were April 17th, 2014, April 17th, 2015, and April 5th, 2016. The late-killed canola and late-killed rye were terminated with glyphosate in late-April or early-May, again as weather allowed. The late termination dates were May 5th, 2014, May 6th, 2015, and April 15th, 2016. The spring of 2016 was much warmer than the spring seasons in 2014 and 2015, which resulted in much higher cover crop biomass and therefore earlier termination dates in 2016. In the 2014 season, the termination dates were April 17th and May 5th, but the canola treatments were terminated by the sub-zero temperatures over winter, like the radish. Therefore, in the first study year, there was no difference between the early and late termination canola treatments. These species and termination dates were chosen was to create a gradient of cover crop residues.

All main cover crop plots, including the bare soil control, were sprayed with glyphosate approximately one week before edamame planting to terminate any emerged weeds. Edamame seeds were planted into cover crop residues with a cone planter on May 27th, 2014, May 28th, 2015, and May 23rd, 2016. All soybean seed were treated with mefenoxam (3.37 g per 100 kg of seed) and fludioxonil (2.27 g per 100 kg seed; Apron Maxx, Syngenta Crop Protection, Greensboro, NC) prior to planting.

Weed populations in this study represent the natural weed seed bank present in the different fields used in this study. After the glyphosate burndown application before edamame planting in May, weeds were allowed to grow naturally without further herbicide application or any mechanical weeding until weed biomass samples were collected.

3.3.2 Data Collection

Oven-dried above-ground biomass was recorded in two 0.5 m^2 quadrats from each main cover crop plot prior to edamame planting in late May. Weeds that overwintered or emerged early in the season were collected with the above-ground biomass samples in the cover crop treatments; therefore, the weeds present in the control plot, bare soil, were also collected. Soil moisture, to 20 cm depth, and soil temperature, to 10 cm depth, were recorded just prior to planting.

The 100-seed mass and germination of each edamame seedlot was recorded for each cultivar prior to planting. Edamame emergence was counted daily for the entire length of the row from planting until all plants were at the V1 stage, with at least one fully-unfurled trifoliate leaf.

Weed emergence from the soil seed bank was counted once a week in four randomly-placed, permanent 0.25 m^2 quadrats within the main cover crop plots for four weeks, beginning between 2 and 4 weeks after planting. Emergence counts consisted of identifying weed seedlings, counting them, and removing them from the quadrat. Total aboveground weed biomass was taken once, approximately mid-season, between five and six weeks after emergence, from a random 1 m^2 (split into two 0.5 m^2 quadrats in years 1 and 2 and four 0.25 m^2 quadrats in year 3) per main cover crop plot. Weed biomass sampling consisted of sorting weeds into grasses and broadleaves and taking oven-dried weights. The study was terminated at six or seven weeks after emergence because the critical weed-free period for soybean ends at eight weeks after emergence.

3.3.3 Data Analysis

Data was analyzed in an ANOVA with the mixed procedure in SAS (version 9.4, SAS Institute Inc., Cary, NC). Data met ANOVA assumptions of normality, equality of variance, and independence based on residual analysis (Hox 2002). There were two ANOVA models in this study. Cover crop descriptions and weed population data were taken only in the main plot, cover crop, so it was the only fixed effect in the analysis of these variables. Edamame emergence data was counted in the sub-plot, edamame cultivar, so cover crop and edamame cultivar were the fixed effects in the analysis of this variable. Year and rep were treated as random effects in both models. Significant differences among treatment means were determined using the Tukey means separation test with $\alpha = 0.05$.

3.4 Results and Discussion

3.4.1 Cover Crops

Differences in residue biomass were observed among cover crop treatments at soybean planting (P < 0.001, Table 3.1). The lightest residue treatment was the bare soil control (4.3 g/m^2). Cover crop residues included radish (43.8 g/m^2), early-killed canola (120.5 g/m^2), early-killed rye (237.5 g/m^2), late-killed canola (236.0 g/m^2), and late-killed rye (900.3 g/m^2). Based on these results, the goal to create a gradient of cover crop residues was achieved. Davis (2010) found slightly less rye biomass (710-600 g/m^2) in central Illinois but did not include the other species in the present study. Hill et al. (2016) reports much higher radish biomass (400 g/m^2) and slightly higher rye biomass (1080 g/m^2) in Michigan studies. Differences in soil water content among cover crop treatments were also observed. At-planting soil moisture of early rye (18.16%) and late rye (19.64%) was higher than in all other cover crop treatments, which averaged 16.03% (P < 0.001, Table 3.1). Higher soil moisture in rye cover crop treatments is common but varies by region due to inherent soil characteristics; Davis (2010) reports significantly higher soil moisture in rye treatments than in bare soil treatments in central Illinois.

3.4.2 Edamame Emergence

The objective of the study was to identify cover crop residue management systems that selectively suppress weeds without inhibiting edamame emergence. Both cover crop treatment and edamame cultivar affected crop emergence (P < 0.001); however, there was no interaction effect of cover crop and edamame cultivar on crop emergence (P = 0.993, Table 3.2).

With one exception, cover crop treatments had similar crop emergence as the bare soil control, which was 71.1%. The late rye treatment reduced crop emergence by 32.6% compared to the bare soil control (P < 0.001, Table 3.2). The late rye treatment could have lowered soybean emergence by several mechanisms. Increased seed predation, reduced available light for seedling growth, increased allelopathic chemical concentrations in the seed zone, and physical interference are mechanisms by which cover crops reduce plant emergence (Forcella 2013, Wortman et al. 2013). Furthermore, poor seed to soil contact is a common problem when planting into high levels (e.g. 600 g/m2) of cover crop residues (Forcella 2013). Despite efforts to optimize planter performance in the present study, ~30% of edamame seed in the late rye

treatment were observed within rye residue on the soil surface. The high level of residue (900 g/m2) in the late rye treatment resulted in poor seed to soil contact and was likely the primary mechanism reducing crop emergence in the late rye treatment.

Four edamame cultivars (Gardensoy 42, Msiono Green, Mojo Green, and WSU910a) had lower emergence than the grain soybean (Asgrow AG-3253) cultivar ($P < 0.001$, Table 3.2). Edamame emergence as low as 35% is not uncommon (Sanchez et al. 2005, Williams 2014). In the present study, mean edamame emergence ranged from 56-71% (Table 3.2), which is higher than reported in previous studies. Weather conditions during the present study were ideal for soybean emergence (Table A.1) and could help explain the higher mean edamame emergence than in previous work. During the emergence window, average air temperatures were well above the minimum 12°C needed for soybean germination and precipitation was slightly above the 30-year average, indicating sufficient soil moisture for germination (Table A.1).

3.4.3 Weed Emergence

Predominant weed species included common purslane (*Portulaca oleracea L.*), several Amaranthus species, velvetleaf (*Abutilon theophrasti Medik.*), and common lambsquarter (*Chenopodium album L.*). In addition, a few other species were infrequently observed, including unidentified grass species and broadleaf weeds that included carpetweed (*Mollugo verticillata L.*), dandelion (*Taraxacum officinale G.H. Weber ex Wiggers*), horseweed (*Conyza Canadensis (l.) Cronq.*), kochia (*Kochia scoparia (l.) Schrad.*), and venice mallow (*Hibiscus trionum L.*) (Table 3.3). With one exception, purslane accounted for 79-89% of emerged weeds in cover crop treatments, but in the late rye treatment, purslane accounted for only 52% of emerged weeds (Table 3.3).

Weed population density varied across cover crop treatments. Weed density, ranked low to high, was late rye < early rye < bare soil < radish < early canola < late canola (Table 3.3). There are several possible explanations for the higher weed emergence in the radish and the two canola treatments compared to the bare soil treatment. Although there were no significant soil moisture differences between radish, canola, and bare soil cover crop treatments at edamame planting (Table 3.1), soil moisture is dynamic, and there may have been times (not sampled) when soil moisture was higher and more favorable for weed emergence in the radish and canola treatments compared to the bare soil. The higher surface residues in the radish and canola

treatments, relative to bare soil, would protect the soil and allow greater water retention in the soil in those treatments. The higher water content could stimulate weed seed germination. The radish and canola treatments also break up the soil and allow more natural cracks to form, which could help weed seeds emerge due to increased light and oxygen availability (Arndt 1965). Additionally, Hill et al. (2016) found that cover crops with high N content, such as red clover (*Trifolium pretense L.*), stimulated emergence of common lambsquarter, giant foxtail (*Setaria faberi Herrm.*), and velvetleaf. The relationship between N content of the cover crop biomass and weed emergence was especially strong when there was adequate soil moisture (Hill et al. 2016).

Lawley et al. (2012) believes radish can also stimulate weed emergence through a chemical mechanism. Lawley et al. (2012) evaluated the effect of decomposing tillage radish residue on several annual weeds and reported that both tillage radish surface residues and soil amended with radish residues can stimulate emergence in chickweed (*Stellaria media (l.) Vill.*), lambsquarter, common ragweed (*Ambrosia artemisiifolia L.*), and redroot pigweed. Lawley et al. (2012) observed that aqueous extracts from living tillage radish in November inhibited emergence in the aforementioned weed species in petri dishes but that extracts from winter-killed radish in March stimulated emergence. Perhaps leachates from radish residues in the present study could explain the higher weed emergence observed in the radish treatment relative to the bare soil in the present study.

The radish, early canola, and late canola had higher weed emergence, which can be a problem for producers. Higher weed density can affect weed management plans. As weed density increases, herbicides can become less effective under certain conditions (Myers et al. 2005). Myers et al. (2005) reports that crop and weed plants with more biomass can interfere with herbicide coverage and interception on smaller weeds, occasionally blocking all herbicide interception, which is problematic for both systemic and contact herbicides. This could also apply if there are high enough weed populations that even small individuals can interfere with herbicide interception on similarly sized plants. Higher weed density is also correlated to higher herbicide escape rates, which could require subsequent herbicide applications to control these escapes (Scursoni et al. 2007). These altered weed management plans might necessitate more and varied herbicide treatments, creating a positive feedback system with herbicide resistant weeds, a major impetus for incorporating cover crops into weed management systems (Harker and O'Donovan 2013).

Early and late rye treatments were the only cover crop treatments that suppressed weed emergence relative to bare soil. There are several possible reasons for lower weed emergence in the rye treatments. The late rye treatment had three times or more surface residue than all other cover crop residues. Several studies report a negative correlation between surface residue and weed emergence (Price et al. 2016, Ryan et al. 2011). However, the amount of residue at soybean planting doesn't fully account for differences in weed emergence among cover crop treatments in the present study.

Rye cover crops can suppress common annual weed emergence even with only moderate to light residue biomass (Forcella 2013). One benefit to cover crops is that they can be used to control herbicide resistant weeds. Rye cover crops have been shown to reduce Amaranthus species emergence by 63-71% (DeVore et al. 2013, Moore et al. 1994). Amaranthus species are especially problematic weeds because researchers have confirmed multiple herbicide resistance in several Amaranthus species.

Mehring et al. (2016) reports that rye cover crops suppressed emergence of several weed species, including lambsquarters, redroot pigweed, hairy nightshade (*Solanum sarrachoides auct. non Sendtner*), yellow foxtail (*Setaria glauca (L.) Beauv.*), Pennsylvania smartweed (*Polygonum pensylvanicum L.*), purslane, wild buckwheat (*Polygonum convolvulus L.*), and Eastern black nightshade (*Solanum ptychanthum Dunal*), and attributed the lower emergence to allelopathic chemicals in rye residues. The rye cover crop resulted in a minimum of 93% weed control regardless of biomass level and termination method (Mehring et al. 2016). Mehring et al. (2016) reports similar findings as the present study and attributes results to allelopathy; rye cover crops suppressed purslane, lambsquarters, pigweed, and foxtail emergence compared to mixed stand radish/turnip or canola/rye cover crops.

Allelochemicals in decomposing rye residues could have reduced weed emergence in the present study. Another potential factor limiting weed emergence in the rye treatments could be the low soil nitrogen resulting from rye biomass. Rye biomass has a high C:N ratio, which can reduce soil N and can increase weed seed persistence in the soil seedbank (Hill et al. 2016).

3.4.4 Mid-Season Weed Biomass

All cover crop treatments reduced weed biomass relative to the bare soil treatment, which averaged 155 g/m2. Weed biomass, ranked low to high, was late rye = early rye < late canola <

early canola = radish < bare soil (Table 3.4). Radish and canola treatments, despite having higher weed densities than bare soil treatments, exhibited a suppressive effect on weed growth. There were species differences between cover crop treatments, but common purslane was the most common weed species in each cover crop treatment (Table 3.3). Early and late rye treatments had the lowest weed density and resulted in the lowest mid-season weed biomass.

Several studies report that as rye residue increases, Amaranthus species control increases. Amaranthus species are especially problematic for producers because they have high fecundity and high herbicide resistance levels. Ryan et al. (2011) found a negative relationship between rye residue levels and pigweed biomass, but the relationship was not linear at low rye residue levels. Price et al. (2016) found that the use of cover crops reduces herbicide resistant Palmer Amaranth populations relative to winter fallow systems. Palmer Amaranth is an especially problematic weed species in the southeastern United States. Price et al. (2016) reports a negative relationship between cover crop residue biomass and Palmer Amaranth survival. Ryan et al. (2011) reports that foxtail and pigweed emergence was completely suppressed at rye residue levels above 1500 g/m^2. In the present study, the late terminated rye treatment only reached an average of 900 g/m^2.

3.5 Conclusions

The objective of this study was to identify cover crop residue management systems that selectively suppress weeds without inhibiting edamame emergence. The early rye treatment was the best candidate for edamame production because it did not reduce crop emergence but did reduce weed interference both in terms of emergence and biomass. The early rye treatment was planted at the same rate as the late rye treatment but was terminated earlier in the season, in early or mid-April. The early rye treatment had the same edamame emergence as the bare soil control. The early rye treatment reduced weed emergence by 18.5% and weed biomass by 85.4% relative to the bare soil treatment.

3.6 Tables

Table 3.1 Differences between cover crop treatments. Mean surface vegetation biomass (g/m^2) and soil water content (%) at edamame planting in field trials near Urbana, IL in 2014, 2015, and 2016. Biomass and water content values followed by different letters are significantly different at $\alpha \leq 0.05$.

		Vegetation Biomass (g/m2)	Soil Water Content (%)
Cover	Bare Soil	4.3[d]	15.99[c]
	Radish	43.8[d]	15.97[c]
	Early Canola	120.5[c]	16.04[c]
	Early Rye	237.5[b]	18.16[b]
	Late Canola	236.0[b]	16.13[c]
	Late Rye	900.3[a]	19.64[a]
	P-Value	<0.001	<0.001

Table 3.2 Crop Emergence. Mean edamame emergence at 14-20 days after planting in 2014, 2015, and 2016. Within each fixed effect, emergence followed by different letters are significantly different at $\alpha \leq 0.05$.

Fixed Effect	Levels	Emergence (%)
Cover	Bare Soil	71.1^{ab}
	Radish	74.5^{a}
	Early Canola	74.3^{a}
	Early Rye	66.5^{b}
	Late Canola	69.3^{b}
	Late Rye	38.5^{c}
	P-Value	<0.001
Cultivar	AGS292	64.8^{ab}
	Asgrow AG-3253	74.8^{a}
	BeSweet292	64.7^{ab}
	Gardensoy11	68.4^{ab}
	Gardensoy42	60.1^{b}
	IA1010	71.1^{ab}
	IA2076	66.1^{ab}
	Misono Green	61.0^{b}
	Mojo Green	63.5^{b}
	Sunrise	66.7^{ab}
	WSU729	71.1^{ab}
	WSU910a	56.1^{b}
	P-Value	<0.0001
Cover*Cultivar	P-Value	0.993

Table 3.3 Weed Populations by Cover Crop. Mean total weed emergence (no/m^2) in each cover crop treatment. Contribution to weed density indicates the mean species emergence (no/m^2) in a given cover crop treatment. Values followed by different letters are significantly different at $\alpha < 0.05$.

		Contribution to Weed Density					
		POROL	AMARA	ABUTH	CHEAL	GRASS	OTHER
Cover Crop Treatment	Average Total number of Weeds Emerged in sub-plot						
	No/m^2	Average No/m^2					
Bare Soil	96.0^d	85.8^c	2.0^d	0.8^b	0.2^c	1.8^b	5.4^c
Radish	113.4^c	92.3^c	11.2^a	1.0^b	0.6^b	1.8^b	6.4^{bc}
Early Canola	146.2^b	124.6^b	9.1^b	1.8^a	0.4^{bc}	2.2^b	8.1^b
Early Rye	77.7^e	61.2^d	5.0^c	1.2^b	0.2^c	2.2^b	7.8^{bc}
Late Canola	170.8^a	146.3^a	5.0^c	0.9^b	1.0^a	4.4^a	13.1^a
Late Rye	7.3^f	3.8^e	1.0^d	0.0^c	0.4^{bc}	0.4^c	1.7^d
P-Value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

POROL = Common Purslane (*Portulaca oleracea L.*)

AMARA = Aamaranthus spp.

ABUTH = Velvetleaf (*Abutilon theophrasti Medik.*)

CHEAL = Common Lambsquarter (*Chenopodium album L.*)

GRASS includes all grass species

OTHER includes carpetweed (*Mollugo verticillata L.*), dandelion (*Taraxacum officinale G.H. Weber ex Wiggers*), horseweed (*Conyza Canadensis (L.) Cronq.*), kochia (*Kochia scoparia (l.) Schrad*), and venice mallow (*Hibiscus trionum L.*).

Table 3.4 Weed Biomass. Mean weed biomass (g/m^2) observed in each cover crop treatment. Biomass samples were collected between five and six weeks after planting. Values followed by different letters are significantly different at $\alpha < 0.05$.

		Mid-Season Weed Biomass
		g/m^2
Cover	Bare Soil	155.38[a]
	Radish	116.39[b]
	Early Canola	98.26[b]
	Early Rye	22.62[d]
	Late Canola	54.78[c]
	Late Rye	10.44[d]
	P-Value	<0.001

3.7 Literature Cited

Anderson, R. L. 2014. *A cultural system to reduce weed interference in organic soybean*. Renewable Agriculture and Food Systems 30 (4): 392-398.

Arndt, W. 1965. *The nature of the mechanical impedance to seedlings by soil surface seals*. Australian Journal of Soil Research 3: 45-54.

Davis, A. 2010. *Cover-crop roller—crimper contributes to weed management in no-till soybean*. Weed Science 58 (3): 300-309.

DeVore, J. D., J. K. Norsworthy, and K. R. Brye. 2013. *Influence of deep tillage, a rye cover crop, and various soybean production systems on Palmer Amaranth emergence in soybean*. Weed Technology 27 (2): 263-270.

Forcella, F. 2013. *Short- and full-season soybean in stale seedbeds versus rolled-crimped winter rye mulch*. Renewable Agriculture and Food Systems 29 (1): 92-99.

Harker, K. N. and J. T. O'Donovan. 2013. *Recent weed control, weed management, and integrated weed management*. Weed Technology 27 (1): 1-11.

Hill, E. C., K. A. Renner, C. L. Sprague, and A. S. Davis. 2016. *Cover crop impact on weed dynamics in an organic dry bean system*. Weed Science 64 (2): 261-275.

Hox, J. J. 2002. *Multilevel analysis: Techniques and application*. Mahwah, NJ: Lawrence Erlbaum.

Lawley, Y. E., J. R. Teasdale, and R. R. Weil. 2012. *The mechanism for weed suppression by a forage radish cover crop*. Agronomy Journal 104 (2): 205-214.

Mehring, G. H., J. E. Stenger, and H. M. Hatterman-Valenti. 2016. *Weed control with cover crops in irrigated potatoes*. Agronomy 6 (1): Article 3.

Moore, M. J., T. J. Gillespie, and C. J. Swanton. 1994. *Effect of cover crop mulches on weed emergence, weed biomass, and soybean (*Glycine max*) development*. Weed Technology 8 (3): 512-518.

Myers, M. W., W. S. Curran, M. J. Vangessel, B. A. Majek, B. A. Scott, D. A. Mortensen, D. D. Calvin, H. D. Karsten, and G. W. Roth. 2005. *The effect of weed density and application timing on weed control and corn grain yield*. Weed Technology 19 (1): 102-107.

Olson, K. R. 2010. *Impacts of tillage, slope, and erosion on soil organic carbon retention*. Soil Science 175 (11): 562-567.

Price, A. J., C. D. Monks, A. S. Culpepper, L. M. Duzy, J. A. Kelton, M. W. Marshall, L. E.

Steckel, L. M. Sosnoskie, and R. L. Nichols. 2016. *High-residue cover crops alone or with strategic tillage to manage glyphosate-resistant Palmer Amaranth (*Amaranthus palmeri*) in southeastern cotton (*Gossypium hirsutum*).* Soil and Water Conservation 71 (1): 1-11.

Ryan, M. R., S. B. Mirsky, D. A. Mortensen, J. R. Teasdale, and W. S. Curran. 2011. *Potential synergistic effects of cereal rye biomass and soybean planting density on weed suppression.* Weed Science 59 (2): 238-246.

Sánchez, E., K. Kelley, and L. Butler. 2005. *Edamame Production as influenced by seedling emergence and plant population.* Horttechnology 15 (3): 672-676.

Scursoni, J. A., F. Forcella, and J. Gunsolus. 2007. *Weed escapes and delayed weed emergence in glyphosate-resistant soybean.* Crop Protection 26 (3): 212-218.

Williams, M. M. 2015a. *Phenomorphological characterization of vegetable soybean germplasm lines for commercial production.* Crop Science 55: 1274-1279.

Williams, M. M. 2015b. *Managing weeds in commercial edamame production: Current options and implications.* Weed Science 63 (4): 954-961.

Wortman, S. E., C. A. Francis, M. A. Bernards, E. E. Blankenship, and J. L. Lindquist. 2013. *Mechancial termination of diverse cover crop mixtures for improved weed suppression in organic cropping systems.* Weed Science 61 (1): 162-170.

CHAPTER 4: THE ROLE OF EDAMAME SEED SIZE IN CROP-WEED INTERACTIONS

4.1 Abstract

Vegetable processors need more weed management tools in order to expand edamame production in the United States. Crop competitive ability can be part of integrated weed management (IWM) plans, and soybean seed size can affect crop competitive ability. Edamame seed are larger than grain soybean seed, but the role of seed size in edamame and weed interactions is unknown. The objective was to quantify the effect of edamame seed size on crop tolerance (CT) to weed interference and weed suppressive ability (WSA). The first hypothesis was that larger seed would have higher CT and WSA than small seed of the same cultivar, and the second hypothesis was that cultivar would affect CT and WSA. Crop tolerance and WSA were estimated by comparing plants in weedy plots to plants in monoculture plots. The main plot was cultivar; there were five edamame and one grain soybean cultivar. The sub plot was seed size; seed were sorted with a seed cleaner, and two aggregate size classes were formed, small and large seed. The sub-sub plot was presence or absence of velvetleaf. Results indicate that CT was more affected by seed size and that WSA was more affected by crop cultivar. For instance, small seed had a $CT_{biomass}$ at 8 weeks after emergence of 0.81 and large seed had a $CT_{biomass}$ of 0.93. Similar results were observed for CT_{height} at 2 weeks after emergence and CT_{area} at 8 wekks after emergence. The White Lion cultivar had 52.8% lower $WSA_{biomass}$ than the average WSA of all other cultivars at 8 weeks after emergence. Increasing seed size could be used in IWM to improve CT, but increasing seed size has no potential for long-term weed management because it was unable to suppress weed biomass. Choosing a more competitive crop cultivar could be used for long-term weed management in IWM because cultivar had a bigger effect on WSA.

4.2 Introduction

Edamame (*Glycine max (L.) Merr.*) consumption is increasing in the United States, but most edamame consumed in the U.S. is produced in China or Taiwan (Dong et al. 2014). American vegetable growers and processors are interested in producing edamame; however, weed interference remains a major barrier to commercial production (Williams 2015b). Current commercial production depends on mechanical weed control (Kaiser and Ernst 2013, Williams

2015b). Recent reports show edamame yield losses due to weed interference around 33% (Williams 2015b). Weeds directly reduce crop yields, disrupt machine harvest, and can contaminate harvested product. Efforts to facilitate herbicide registration in recent years have led to federal labels for eight herbicide active ingredients in edamame. While the vegetable industry now has nascent weed management options in edamame, potential issues related to herbicide resistance and weed escapes necessitate development of more integrated weed management systems.

Integrated weed management (IWM) utilizes multiple tactics aimed at giving the crop an advantage over weeds, with the goal of reducing weed growth and fecundity (Harker and O'Donovan 2013, Jordan 1993). Integrated weed management systems are used to suppress weed population density, reduce the environmental impact of herbicides, increase sustainability, and reduce selection pressure on weeds (Harker and O'Donovan 2013). Integrated weed management includes biological, chemical, mechanical, and cultural weed management techniques. Cultural weed management refers to management actions that reduce weed species seedling establishment and weed fecundity. Specific tactics include crop interference, rotation, and maintaining high soil fertility (Jordan 1993). An important part of cultural weed management is competitive interactions between crops and weeds, such as choosing more competitive cultivars or more vigorous seedlots (Bussan et al. 1997, Harker and O'Donovan 2013, Jordan 1993). Crop competitive ability refers to how well the crop competes with neighboring plants, including weeds and other crop plants, for limited resources (Lindquist et al. 1998). Crop competitive ability is a useful tool in IWM in soybean (Bussan et al. 1997, Harker and O'Donovan 2013, Jordan 1993, Lindquist et al. 1998, Place et al. 2011a), and some have suggested seed size could be used to increase soybean's competitive ability (Burris et al. 1997, Place et al. 2011a, Place et al. 2011b).

A characteristic phenotypic difference between grain soybean and edamame is that edamame has larger seeds. Grain soybean seed mass is often 15 to 20 g per 100 seed, but edamame seed mass is often over 30 g per 100 seed (Bernard 2005); some edamame seed are 55-76% larger than grain soybean seed (Dong et al. 2014, Williams 2015a). When comparing across grain soybean cultivars, differences in mass between small and large seeded cultivars range from 2-17 g per 100 seed, and within a given grain soybean cultivar, differences in seed mass range from 1-14 g per 100 seed (Adebisi et al. 2013, Burris et al. 1973, Fontes and Ohlrogge 1972,

Longer et al. 1986, Madanzi et al. 2010, Mourtzinis et al. 2015, Place et al. 2011a, Rezapour et al. 2013). Although seed size varies within and among edamame cultivars, how seed size affects edamame growth and competitive ability is relatively unknown. Within a given edamame cultivar, edamame seed mass can vary by as much as 18 g per 100 seed (Sung 1992).

Soybean seed size is controlled by genetics and environmental conditions during the seed fill stage. Soybean seed size is a multigenic trait that is approximately 0.26-0.50 heritable (Cober et al. 1997, Mourtzinis et al. 2015). Optimal environmental conditions for maternal growth during seed fill also favor seed growth (Li et al. 2014, Nafziger 2009). Water stress during seed fill reduces seed mass because the maternal plant's photosynthetic capacity is compromised (Roach and Wulff 1987).

Previous research found seed size may be useful in IWM in grain soybean. Because large seed produces more above- and below-ground biomass at seedling stages than small seed, large seed have an early competitive advantage over the weed (Burris et al. 1973, Fontes and Ohlrogge 1972, Longer et al. 1986, Place et al. 2011a). Place et al. (2011a) reported increasing grain soybean seed mass by 9 g per 100-seed reduced midseason weed biomass by 22-37%. Place et al. (2011b) report that increasing seed mass by 14.6 g per 100-seed reduced weed biomass by 12.7 g/m^2 at 7 WAE. As grain soybean seed size increases, so does the crop seedling size. Seed that were 14 g per 100-seed larger resulted in 30 mm taller shoots at 1 WAE and a unifoliate area 3.6 cm^2 larger (Burris et al. 1973). Increasing seed mass by 2 g per 100-seed increased shoot biomass by 0.25 g and root biomass by 0.1 g at 10 days after germination (Longer et al. 1986). Seed size appears to have an effect on crop growth through 7 WAE, as evidenced by crop seed size and seedling height correlations (0.38-0.64; Place et al. 2011b).

Competitive ability can be measured in terms of crop tolerance and weed suppressive ability. Crop tolerance (CT) refers to the crop's ability to maintain normal emergence, growth, and yield despite competition with weeds (Bussan et al. 1997, Jordan 1993, So et al. 2009). Weed suppressive ability (WSA) refers to the crop's ability to reduce the emergence, growth, and fecundity of weed species (Bussan et al. 1997, Jordan 1993, So et al. 2009). Both CT and WSA are important components of IWM. Increasing crop competitive ability, thereby increasing WSA, is a valuable preventative weed management technique (Jordan 1993). Very little research has been done on edamame management, and the extent to which seed size can be part of IWM for edamame is unknown.

The overall goal of the study was to determine the role of edamame seed size on crop-weed interactions. The objective was to quantify the effect of edamame seed size on CT and WSA. The first hypothesis was that, within a cultivar, crop plants grown from large seed would have higher CT and WSA than crop plants grown from small seed. The second hypothesis was that crop cultivar would affect CT and WSA. Although numerous weed species are problematic in edamame, velvetleaf (*Abutilon theophrasti Medik.*) was chosen as a model weed species for this study because of crop loss potential (Hagood et al. 1980), seedbank longevity (Lueschen et al. 1993), and incidence of herbicide resistance (Gray et al. 1995).

4.3 Materials and Methods

4.3.1 Germplasm Selection and Seed Sizing

Five edamame cultivars and one grain soybean cultivar were used (Table 4.1). Seed availability dictated the edamame cultivars selected for this study. The grain soybean cultivar, Hutcheson, was chosen because previous research showed seed-size-mediated effects on weed suppressive ability with this cultivar (Place et al. 2011a). Prior to planting, seed of each cultivar was sorted on round-hole screens in a seed cleaner (Clipper Cleaner, A. T. Ferrell Company, Bluffton, IN) in 0.4 mm diameter increments beginning with the smallest size. Seed of each size class were counted. The median size class of each cultivar was omitted in order to create two distinct size classes. Seed of size classes smaller than the median class were grouped together for the 'small' size class, and seed larger than the median class were grouped together for the 'large' size class (Table 4.1). All crop seed was treated with mefenoxam (3.37 g per 100 kg of seed) and fludioxonil (2.27 g per 100 kg seed; Apron Maxx, Syngenta Crop Protection, Greensboro, NC) prior to planting.

4.3.2 Site Characterization

Field experiments were conducted in 2015 and 2016 at the University of Illinois Vegetable Crop Farm near Urbana, Illinois. Experiments were located in different fields each year. The experiment each year followed the soybean phase of a sweet corn-soybean rotation. The soil was a Flanagan silt loam. The seedbed was prepared using a disc harrow and field cultivator to ensure weed free planting conditions and a fine seedbed. Experiments were planted on June 4th, 2015 and May 20th, 2016 using a cone planter (ALMACO, Nevada, IA).

4.3.3 Experimental Design

The experimental design was a split-split plot randomized complete block with four replications. Main plots measuring 18.6 m^2 were assigned one of six crop cultivars. Seed size class was assigned to sub plots measuring 9.3 m^2. Presence or absence of velvetleaf was assigned to sub-sub plots measuring 2 rows on 76 cm spacing. There were also four velvetleaf monoculture treatments in each replicate. Velvetleaf was seeded at the time of crop planting. Both the crop and weed seed were planted at 30 seed per m to a depth of 2.5 cm. S-metolachlor was applied preemergence at a rate of 1870 g a.i. ha^{-1} to the entire experiment within 2 days of planting. The experiment was kept free of non-target weeds for the remainder of the season with one pass of an inter-row cultivator and by hand-weeding.

4.3.4 Data Collection

Before planting, 100-seed mass and germination were determined for each size class within each cultivar. Germination was characterized using a rolled towel test at 15.6 °C. After planting, seedlings were counted daily across each 2.4 m-long row for both the crop and velvetleaf. Seedlings were counted until all plants reached the V1 stage. The final emergence count was converted to plants per m^2 for the stand count. Plant height was measured on two edamame and two velvetleaf plants per row. Height was measured weekly until 7 weeks after emergence (WAE). Crop height was measured from the soil surface to the apical meristem, and velvetleaf height was measured from the soil surface to the apex of the youngest fully extended leaf. Leaf area index (LAI) was measured in full-sun within 2 hours of solar noon with a linear ceptometer (AccuPAR Linear Ceptometer; Decagon Devices, Pullman, WA) in crop and weed monoculture plots at 2 and 6 WAE. Avoiding alleys, the ceptometer was placed parallel to the base of a row in each monoculture plot.

Four plants each of the crop and weed were harvested from each sub-sub plot 4 and 8 WAE by cutting at the soil surface. Leaf area and stem area were measured on an area meter (LI-3100C, LI-COR, Lincoln, NE). Leaves and stems were pooled and oven dried to a constant mass and weighed.

The experiment was terminated 8 WAE, the end of the critical weed-free period for soybean. The critical period is the window of time in which competition can cause yield loss,

which for soybean is between 2 and 7 WAE (Place et al. 2011a). Moreover, if seed size were to affect CT and WSA, the effect would likely be detected within 8 WAE. Place et al. (2011a) found the effect of seed size on aboveground plant growth dissipated at 5 WAE.

4.3.5 Statistical Analysis

Crop tolerance and WSA were calculated for plant height, area, and biomass (Jacob et al. 2016, So et al. 2009). Crop tolerance estimates (CT_{height}, CT_{area}, $CT_{biomass}$) were calculated as the fraction of weedy crop response divided by the weed-free crop response within each replicate at each sampling time. Estimates of WSA (WSA_{height}, WSA_{area}, $WSA_{biomass}$) were calculated as:

$$WSA_Y = 1 - (Y_{mixed}/Y_{monoculture}) \tag{1}$$

where Y_{mixed} is velvetleaf response in the crop and $Y_{monoculture}$ is velvetleaf response in monoculture within each replicate at each sampling time. Crop tolerance and WSA were defined on a scale of zero to one, with values closer to one representing higher CT and higher WSA.

Data were analyzed with an ANOVA model in SAS (version 9.4, SAS Institute Inc., Cary, NC) using the mixed procedure. Based on residual analysis, data met ANOVA assumptions of independence, normality, and equality of variances (Hox 2002). ANOVAs were conducted on observed crop and weed emergence, monoculture LAI, and CT and WSA estimates. Seed size and cultivar were treated as fixed effects in the ANOVA models, and year and rep were considered random effects. The ANOVA model for observed emergence also included weed presence or absence as a fixed effect, but the ANOVA models for observed LAI and the CT and WSA estimates did not include weed presence or absence. In order to reduce the risk of making type I errors when examining the effects of competition between two species, the significance level was set at $\alpha = 0.1$ (Murtaugh 2014).

4.4 Results and Discussion

4.4.1 Conditions

Water supply and soil temperature were not limiting factors for plant emergence or seedling growth. In 2015, June had 12.2 cm more precipitation than the 30-year average (data not shown), setting a record as the second wettest month ever recorded for the state of Illinois (NOAA 2015). Champaign County received 200% of normal rainfall in June 2015 (NOAA 2015). The following month received an additional 10.7 cm precipitation. In 2016, May and July

had near-normal conditions, while June precipitation was 7 cm higher than the 30-year average. Across both years, mean daily air temperatures were often at or above the 30-year normal, ranging from 10.6 to 33.9 °C.

4.4.2 Emergence

Crop emergence was not affected by crop seed size or interactions among treatment factors (P ≥ 0.132, Table 4.2) but was affected by the presence of weeds (P < 0.001) and crop cultivar (P < 0.001). Crop emergence was 2.1% higher in weed free treatments than weedy treatments (Table 4.2). Among cultivars, emergence of Triple Play was highest (86.6%) and emergence of White Lion was lowest (48.3%). Velvetleaf emergence averaged 40.7% and was unaffected by crop seed size, cultivar, or their interaction (P ≥ 0.384, data not shown).

4.4.3 Crop Tolerance

Variability in crop emergence resulted in different crop population densities among cultivars. To determine if population density contributed to CT and WSA, an adhoc analysis of covariance (ANCOVA) was conducted. Using stand count (plants/m^2) as a covariate, an ANCOVA model yielded the same results as the ANOVA model, which indicates the effects of the treatments were independent of stand count. Therefore, only the ANOVA results will be presented.

The hypothesis that large seeds would have higher CT than small seeds of the same cultivar was supported by results. Crop seed size affected CT$_{height}$ two WAE (P = 0.019) and CT$_{area}$ (P = 0.020) and CT$_{biomass}$ eight WAE (P = 0.061, Table 4.3). There was a significant cultivar by size interaction on CT$_{area}$ at 4 WAE (P = 0.083), but none of the other CT terms had significant interactions. The lack of interaction allows an analysis of how cultivar affects CT estimates as well. The second hypothesis, that crop cultivar would affect CT, is not supported by results. Cultivar only affected CT$_{height}$ at 6 WAE (P = 0.038, Table 4.3) but didn't affect any other CT variables.

Plants from large seed had greater tolerance in crop height to velvetleaf interference (CT$_{height}$) two WAE than plants from small seed (Table 4.3). This is likely due to the fact that plants from large seed produce taller seedlings that can better tolerate weed interference. Burris et al. (1973) found a positive relationship between seed size and seedling height. A seed mass

increase of 14 g per 100-seed resulted in 30 mm taller seedlings one WAE (Burris et al. 1973). The CT_{height} results could be a response to shading from weeds. However, it is important to note that plants from large seeds had an early and significant response to shading, and that plants from small seed showed a lag in this shade response. Place et al. (2011a) report that the relationship between seed size and height continued through seven WAE, when they report a positive correlation between seed size and midseason soybean height. The present study found no effect of seed size class on CT_{height} after two WAE.

Plants from large seed were able to maintain shoot growth while experiencing velvetleaf interference better than plants from small seed. By eight WAE, plants from large seed had 15% and 13% higher CT_{area} and $CT_{biomass}$, respectively, than plants from small seed (Table 4.3). The higher CT estimates are likely due to the fact that plants from larger seed produce more biomass at both seedling and midseason growth stages. Longer et al. (1986) and Place et al. (2011a and 2011b) indicate the effects of seed size on crop biomass can be seen as early as 10 days after germination and continue through at least seven WAE. Longer et al. (1986) reported that increasing seed mass by 2 g per 100-seed increased seedling root and shoot biomass by 0.1 and 0.25 g, respectively. Place et al. (2011b) found that large seed produced 50.8 g/m^2 more soybean biomass at 7 WAE. Place et al. (2011a) reports that at 7 WAE, an increase in seed mass of 9 g per 100-seed resulted in 6-24% higher soybean dry biomass. The higher biomass of plants from large seed likely help the crop withstand weed interference.

The hypothesis that larger seeds of a given cultivar would have higher CT than small seeds was true for seedling (2 WAE) height and midseason (8 WAE) area and biomass. The hypothesis that cultivar would affect CT was only supported for CT_{height} at 6 WAE. In later height and earlier area and biomass measurements, seed size had no effect on CT. CT_{height} for seedlings (2 WAE) was positively affected by seed size, as in the study by Burris et al (1973). This early height advantage can create an early competitive advantage against weeds, as indicated by Place et al. (2011a and 2011b).

4.4.4 Weed Suppressive Ability

The hypothesis that plants from large seed would have higher WSA than plants from small seed of the same cultivar was not supported by results. Crop seed size affected WSA_{height} at 4 WAE (P = 0.067, Table 4.4) but didn't affect WSA_{height} before or after 4 WAE. Seed size had

no effect on other WSA variables. There were no significant interactions among treatment factors on WSA variables. Since there are no significant interactions, it is possible to analyze the effects of cultivar independent of seed size. The second hypothesis, that crop cultivar would affect WSA, is supported by results. Crop cultivar affected WSA_{height} at 6 WAE (P = 0.003, Table 4.4), WSA_{area} at both 4 and 8 WAE (P = 0.004, P < 0.001), and $WSA_{biomass}$ at both 4 and 8 WAE (P = 0.002, P < 0.001).

Plants from large seed were able to suppress velvetleaf better than plants from small seed, but only for velvetleaf height measured four WAE (Table 4.5). Place et al. (2011a) reported that larger seeds resulted in higher weed suppressive ability for at least one grain soybean cultivar, the Hutchison cultivar, but results in the present study do not show similar results. Results in the present study could be the result of higher LAI in the large seed treatments, compared to small seed, two WAE (P = 0.078, Table 4.5). The large seeds' higher crop LAI meant the large seed treatments were producing plants that reduced available light for neighboring plants. That could have suppressed velvetleaf growth in the crop canopy. Place et al. (2011a) also reported a positive relationship between seed size and light interception three WAE but not at five WAE. Such results align with the present study: seed size affected crop LAI at two WAE but had dissipated by six WAE (Table 4.5).

Among cultivars, White Lion was the least suppressive of velvetleaf. For instance, $WSA_{biomass}$ of White Lion was 52.8% lower than the average WSA of all other cultivars eight WAE (Table 4.4). White Lion also had the poorest canopy among cultivars (Table 4.5). Compared to velvetleaf monocultures, White Lion only suppressed velvetleaf area and biomass at eight WAE by 18 and 13%, respectively (Table 4.5). A combination of poor emergence and slow canopy development likely accounted for some of the poor WSA of White Lion.

4.5 Conclusions

The objective was to quantify the effect of edamame seed size in crop-weed competitive interactions. Seed size has potential for improving CT to weed interference but has very little potential for suppressing velvetleaf growth and fecundity. Place et al (2011a) suggests that seed size sorting in soybean could be a valuable weed management tactic for producers utilizing IWM. However, Place et al. (2011a) also suggests that the beneficial effects of larger seed sizes may only be useful in fields with very dense weed populations and that producers with less dense

weed populations may not benefit as much. When considering IWM in edamame, increasing seed size, which increases CT, can be included in IWM as a short-term strategy for maintaining high yields in a given season or in a field with especially high weed populations, but it does not affect long term weed management because it does not have a consistent effect on WSA.

Cultivar has more potential for increasing WSA than for improving CT. Choosing a more competitive cultivar, one with a higher WSA, can have a greater effect on long-term weed management and should be considered in IWM in edamame as a way of reducing weed fecundity. Results indicate that seed sizing within an edamame cultivar improves crop tolerance to velvetleaf interference but may not provide much benefit to weed suppressive ability and that choosing certain cultivars over others is the best strategy to include in IWM because it has the most potential to increase velvetleaf suppression.

4.6 Tables

Table 4.1 Seed Characterization: Mean observed seed descriptions for each size class in the edamame and grain cultivars averaged over two study years (2015-2016) in Urbana, IL.

			Average Diameter (cm)		Average 100-Seed Mass (g)		Germination (%)	
Cultivar	**Source**	**Type**	**Small**	**Large**	**Small**	**Large**	**Small**	**Large**
Hutcheson	Oklahoma Seed	Grain	0.59	0.71	12.2	17.7	97.0	98.0
Midori Giant	Wannamaker Seeds	Edamame	0.82	1.00	29.4	37.8	93.0	93.5
VS1	Anonymous	Edamame	0.81	0.98	26.1	31.8	93.0	93.5
VS6	Anonymous	Edamame	0.82	0.99	27.6	35.0	91.5	94.0
Triple Play	Tainong Seeds	Edamame	0.81	0.98	26.5	31.2	95.0	95.5
White Lion	Kitizawa Seeds	Edamame	0.83	0.98	20.5	36.9	95.5	82.0

Table 4.2 Crop Emergence: Mean edamame emergence at 17 and 25 days after planting in field experiments near Urbana, IL in 2015 and 2016. Within each fixed effect, emergence followed by different letters are significantly different at $\alpha \leq 0.1$.
ANOVA results on observed emergence values.

Fixed Effects	Levels	Emergence (%)
Size	Small	76.2
	Large	76.8
	P-Value	0.554
Weeds	Weedy	75.5[b]
	Weed Free	77.6[a]
	P-Value	<0.001
Cultivar	Hutcheson	85.4[a]
	Midori Giant	77.0[c]
	VS1	84.0[ab]
	VS6	77.8[bc]
	Triple Play	86.6[a]
	White Lion	48.3[d]
	P-Value	<0.001
Size*Weeds	P-Value	0.154
Size*Cultivar	P-Value	0.132
Weeds*Cultivar	P-Value	0.283
Size*Weeds*Cultivar	P-Value	0.238

Table 4.3 CT Area and Biomass Results: Mean crop tolerance (CT) estimates for height at 2, 4, and 6 weeks after emergence; area at 4 and 8 weeks after emergence; and biomass at 4 and 8 weeks after emergence in field experiments near Urbana, IL in 2015 and 2016. Within each fixed effect, CT estimates followed by different letters are significantly different at $\alpha \leq 0.1$.

Fixed Effects	Levels	CT_{Height}			CT_{Area}		$CT_{Biomass}$	
		2 WAE	4 WAE	6 WAE	4 WAE	8 WAE	4 WAE	8 WAE
Size	Small	0.97^b	1.01	1.06	1.07	0.88^b	1.01	0.81^b
	Large	1.04^a	1.04	1.06	1.04	1.04^a	1.06	0.93^a
	P-Value	0.019	0.145	0.929	0.654	0.020	0.561	0.061
Cultivar	Hutcheson	1.04	1.04	1.07^{ab}	1.09	0.85	1.02	0.78
	Midori Giant	0.97	1.02	1.04^{ab}	1.13	0.98	1.10	0.90
	VS1	0.99	1.02	1.04^{ab}	1.01	0.92	1.05	0.87
	VS6	1.00	0.99	1.05^{ab}	0.99	0.95	0.97	0.84
	Triple Play	0.99	1.02	1.02^b	0.97	1.09	0.99	1.01
	White Lion	1.02	1.06	1.13^a	1.14	1.00	1.11	0.82
	P-Value	0.661	0.517	0.038	0.635	0.419	0.902	0.329
Size*Cultivar	P-Value	0.505	0.567	0.432	0.083	0.342	0.141	0.139

*Mean crop monoculture values for Area 4 WAE, Area 8 WAE, Biomass 4 WAE, and Biomass 8 WAE are 369.1 cm^2, 1393.4 cm^2, 2.3 g, and 12.1 g, respectively.

Table 4.4 WSA Area and Biomass Results: Mean weed suppressive ability (WSA) estimates for height at 2, 4, and 6 weeks after emergence; area at 4 and 8 weeks after emergence; and biomass at 4 and 8 weeks after emergence in field experiments near Urbana, IL in 2015 and 2016. Within each fixed effect, WSA estimates followed by different letters are significantly different at $\alpha \leq 0.1$.

Fixed Effects	Levels	WSA Height			WSA Area		WSA Biomass	
		2 WAE	4 WAE	6 WAE	4 WAE	8 WAE	4 WAE	8 WAE
Size	Small	0.98	1.03[b]	0.88	0.39	0.55	0.49	0.54
	Large	1.02	1.08[a]	0.89	0.44	0.59	0.56	0.60
	P-Value	0.250	0.067	0.740	0.131	0.299	0.188	0.135
Cultivar	Hutcheson	0.95	1.09	0.88[b]	0.42[a]	0.60[a]	0.53[a]	0.60[a]
	Midori Giant	0.96	0.97	0.87[b]	0.50[a]	0.62[a]	0.67[a]	0.62[a]
	VS1	1.06	1.05	0.89[b]	0.46[a]	0.70[a]	0.64[a]	0.73[a]
	VS6	1.02	1.05	0.88[b]	0.43[a]	0.67[a]	0.54[a]	0.70[a]
	Triple Play	0.98	1.05	0.85[b]	0.52[a]	0.65[a]	0.54[a]	0.64[a]
	White Lion	1.03	1.12	0.96[a]	0.15[b]	0.18[b]	0.22[b]	0.13[b]
	P-Value	0.604	0.388	0.003	0.004	<0.001	0.002	<0.001
Size*Cultivar	P-Value	0.679	0.181	0.522	0.204	0.700	0.146	0.482

*Mean velvetleaf monoculture values for Area 4 WAE, Area 8 WAE, Biomass 4 WAE, and Biomass 8 WAE are 335.1 cm^2, 2548.1 cm^2, 2.1 g, and 28.9 g, respectively.

Table 4.5 LAI Values: Mean observed LAI values for crop monoculture treatments in field experiments near Urbana, IL in 2015 and 2016. Within each fixed effect, LAI values followed by different letters are significantly different at $\alpha \leq 0.1$.

Fixed Effects	Levels	LAI 2 WAE	LAI 6 WAE
Size	Small	1.39^b	5.32
	Large	1.49^a	5.26
	P-Value	0.078	0.643
Cultivar	Hutcheson	1.13^{bc}	5.22^b
	Midori Giant	1.56^{ab}	5.21^b
	VS1	1.74^a	5.48^b
	VS6	1.51^{ab}	5.29^b
	Triple Play	1.94^a	6.32^a
	White Lion	0.76^c	4.19^c
	P-Value	<0.001	<0.001
Size*Cultivar	P-Value	0.211	0.748

4.7 Literature Cited

Adebisi, M. A., T. O. Kehinde, A. W. Salau, L. A. Okesola, J. B. O. Porbeni, A. O. Esuruoso, and K. O. Oyekale. 2013. *Influence of different seed size fractions on seed germination, seedling emergence, and seed yield characters in tropical soybean (Glycine max* L. Merrill*).* International Journal of Agricultural Research 8 (1): 26-33.

Bernard, R. 2005. *Garden-type vegetable soybean varieties*. Illinois Agricultural Experiment Station.

Burris, J. S., O. T. Edje, and A. H. Wahab. 1973. *Effects of seed size on seedling performance in soybeans: II. Seedling growth and photosynthesis and field performance*. Crop Science 13:207-210.

Bussan, A. J., O. C. Burnside, J. H. Orf, and K. J. Puettmann. 1997. *Field evaluation of soybean (Glycine max) genotypes for weed Competitiveness*. Weed Science 45 (1): 31-37.

Cober, E. R., H. D. Voldeng, and J. A. Frégau-Reid. 1997. *Heritability of seed shape and seed size in soybean*. Crop Science 37: 1767-1769.

Dong, D., X. Fu, F. Yuan, P. Chen, S. Zhu, B. Li, Q. Yang, X. Yu, and D. Zhu. 2014. *Genetic diversity and population structure of vegetable soybean (*Glycine max *(L.) Merr.) in China as revealed by SSR markers*. Genetic Resources and Crop Evolution 61: 173-183.

Fontes, L. A. N. and A. J. Ohlrogge. 1972. *Influence of seed size and population on yield and other charcteristics of soybean (Glycine max* (L.) Merr.*).* Agronomy Journal 64: 833-836.

Gray, J. A., D. E. Stoltenberg, and N. E. Balke. 1995. *Productivity and intraspecific competitive ability of a velvetleaf (Abutilon theophrasti) biotype resistant to atrazine*. Weed Science 43 (4): 619-626.

Hagood, E. S., T. T. Bauman, J. L Williams, and M. M. Schreiber. 1980. *Growth analysis of soybeans (Glycine max) in competition with velvetleaf (Abutilon theophrasti).* Weed Science 28 (6): 729-734.

Harker, K. N. and J. T. O'Donovan. 2013. *Recent weed control, weed management, and integrated weed management*. Weed Technology 27 (1): 1-11.

Hox, J. J. 2002. *Multilevel analysis: Techniques and application*. Mahwah, NJ: Lawrence Erlbaum.

Jacob, C. E., E. N. Johnson, M. F. Dyck, and C. J. Willenborg. 2016. *Evaluating the competitive ability of semileafless field pea cultivars*. Weed Science 64 (1): 137-145.

Jordan, N. 1993. *Prospects for weed control through crop interference*. Ecological Applications 3 (1): 84-91.

Kaiser, C. and M. Ernst. 2013. *Edamame*. Center for Crop Diversification Crop Profile: 1-4.

Li, Y., M Du, Q. Zhang, G. Wang, J. Jin, S. Herbert, and X. Liu. 2014. *Planting date influences fresh pod yield and seed chemical compositions of vegetable soybean*. HortScience 49 (11): 1376-1380.

Lindquist, J. L., D. A. Mortensen, and B. E. Johnson. 1998. *Mechanisms of corn tolerance and velvetleaf suppressive ability*. Agronomy Journal 90: 787-792.

Longer, D. E., E. J. Lorenz, and J. T. Cothren. 1986. *The influence of seed size on soybean (Glycine max (L.) Merrill) emergence under simulated soil crust conditions*. Field Crops Research 14: 371-375.

Lueschen, W. E., R. N. Andersen, T. R. Hoverstan, and B. K. Kanne. 1993. *Seventeen years of cropping systems and tillage affect velvetleaf (Abutilon theophrasti) seed longevity*. Weed Science 41 (1): 82-86.

Madanzi, T., C. Chiduza, S. J. Richardson-Kageler. 2010. *Effects of planting method and seed size on stand establishment of soybean (Glycine max (L.) Merrill cv. Soltaire)*. Soil and Tillage Research 106: 171-176.

Mourtzinis, S., J. M. Gaska, P. Pedersen, and S. P. Conley. 2015. *Effect of seed mass and emergence delay on soybean yield and quality*. Agronomy Journal 107 (1): 181-186.

Murtaugh, P.A. 2014. *In defense of P values*. Ecology 95 (3): 611-614.

Nafzier, E. 2009. *Soybean*. In *Illinois Agronomy Handbook*. 24th edn. University of Illinois Extension, Champaign, IL.

National Oceanic and Atmospheric Administration (NOAA). 2015. *Record wet June for parts of central /SE IL – Updated July 12*. http://www.weather.gov/ilx/June_2015_hvyrain

Place, G. T., S. C. Reberg-Horton, T. E. Carter, Jr., and A. N. Smith. 2011a. *Effects of soybean seed size on weed competition*. Agronomy Journal 103 (1): 175-181.

Place, G. T., S. C. Reberg-Horton, D. A. Dickey, and T. E. Carter, Jr. 2011b. *Identifying soybean traits of interest for weed competition*. Crop Science 51: 2642-2654.

Rezapour, R., H. Kazemi-arbat, M. Yarnia, and P. Zafarani-Moattar. 2013. *Effect of seed size on germination and seed vigor of two soybean (glycine max L.) cultivars.* International Research Journal of Applied and Basic Sciences 4 (11): 3396-3401.

Roach, D. A., and R. D. Wulff. 1987. *Maternal effects in plants*. Annual Review of Ecology and Systematics 18: 209-235.

So, Y. F., M. M. Williams, J. K. Pataky, and A. S. Davis. 2009. *Principle canopy factors of sweet corn and relationahips to competitive ability with wild proso millet (Panicum miliaceum).* Weed Science 57: 296-303.

Sung, F. J. M. 1992. *Field emergence of edible soybean seeds differing in seed size and emergence strength*. Seed Science and Technology 20: 527-532.

Williams, M. M. 2015a. *Phenomorphological characterization of vegetable soybean germplasm lines for commercial production*. Crop Science 55: 1274-1279.

Williams, M. M. 2015b. *Managing weeds in commercial edamame production: Current options and implications*. Weed Science 63 (4): 954-961.

APPENDIX: SUPPLEMENTAL TABLE

Table A.1 Monthly temperature and precipitation records throughout the experimental period.

Year	Month	Low Temp (°C)	High Temp (°C)	Mean Temp (°C)	Cumulative Precipitation (cm)	Cumulative snow (cm)	Event
2013	August	16.1	27.8	23.1	0.91	0.00	Radish and Canola planting
	September	15.6	28.9	21.1	1.73	0.00	Rye planting
	October	1.7	24.4	12.8	9.12	0.00	
	November	-7.2	14.4	3.6	3.91	0.00	
	December	-11.7	10.6	-3.0	5.66	25.40	
2014	January	-22.8	4.4	-7.1	4.06	36.58	
	February	-18.9	7.8	-7.2	7.67	37.08	
	March	-12.8	11.1	1.6	3.53	9.40	
	April	1.7	18.9	11.7	10.01	0.51	
	May	7.8	25.6	17.9	11.13	0.00	Soybean Planting
	June	17.8	27.2	23.0	20.85	0.00	
	July	16.7	26.1	21.1	22.10	0.00	
	August	16.7	27.2	23.1	3.86	0.00	
	September	10.6	26.1	18.3	8.74	0.00	Cover Crop Planting
	October	3.9	21.1	12.2	12.60	0.00	Soybean Seed Harvest
	November	-10.0	12.2	1.4	6.15	2.29	
	December	-9.4	7.2	0.6	4.60	0.00	
2015	January	-16.1	3.9	-4.1	3.63	11.18	
	February	-16.1	6.7	-7.3	3.12	31.50	
	March	-14.4	14.4	3.1	4.32	21.34	
	April	6.7	18.9	12.2	9.19	0.00	
	May	8.9	23.9	18.7	15.42	0.00	Soybean planting
	June	15.6	26.1	22.3	23.27	0.00	
	July	17.8	27.8	23.1	10.72	0.00	
	August	17.2	26.1	22.3	8.03	0.00	
	September	13.9	27.2	21.1	16.36	0.00	Cover Crop Planting
	October	4.4	19.4	13.6	3.15	0.00	Soybean Seed Harvest
	November	-6.1	17.2	7.7	11.20	4.57	

Table A.1 (Cont.)

Year	Month	Low Temp (°C)	High Temp (°C)	Mean Temp (°C)	Cumulative Precipitation (cm)	Cumulative snow (cm)	Event
	December	-2.8	15.6	4.7	18.97	0.00	
2016	January	-15.6	8.9	-2.7	2.31	10.16	
	February	-10.6	12.2	0.7	3.10	17.27	
	March	-1.7	16.7	8.8	8.92	0.00	
	April	1.1	20.0	11.7	8.28	0.00	
	May	8.3	23.9	16.7	9.63	0.00	Soybean Planting
	June	18.3	27.8	23.5	18.08	0.00	
	July	15.6	27.8	24.1	11.28	0.00	
	August	20.0	27.8	24.6	10.54	0.00	
	September	13.9	27.8	21.9	13.69	0.00	Soybean Seed Harvest