INTEGRATED WEED MANAGEMENT IN SOYBEAN

A THESIS
SUBMITTED TO THE FACULTY OF
UNIVERSITY OF MINNESOTA

BY

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IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR THE DEGREE OF MASTER OF SCIENCE

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OCTOBER 2013

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I would like to thank my advisors Drs. Gregg Johnson and Donald Wyse for your guidance, support, and all the time you spent with me with both of your busy schedules. You have helped me grow so much personally and also in my research skills. Also, thank you to the members of my committee, Dr. Jeffery Gunsolus and Dr. Deborah Allan for technical advice and support.

I would also like to thank Kevin Betts for all of the hours of weed biomass harvesting – especially the giant ragweed biomass that you somehow magically managed to fit into one bag per plot. Thank you also to Paul and Tom at Waseca. You helped plant my cover crops, applied herbicides, taught me to run the dryer, and gave me great advice on technical problems. Thanks to the field crew at Waseca, I would not have completed this project without you!

Thanks to my fellow graduate students especially Adria, Mikey, Miriam, Wade, and Katherine. Your advice, encouragement, and good company made the journey go by so much faster. And finally thanks to my parents for believing in me, even if they could not understand my project or excitement over statistical results in the three years I worked on my thesis.

Abstract

Studies were conducted in 2011 and 2012 at two sites at the Southern Research and Outreach Center in Waseca, MN to evaluate different combinations of row spacing, soybean varieties, and early season weed control treatments on giant ragweed, common lambsquarters, and tall waterhemp density, biomass, and seed production. The early season weed control treatments consisted of a pre-emergence herbicide, winter rye cover, and radish/pennycress cover mixture. Overall, a flumioxazin, acetochlor, or winter rye treatment were the most effective in reducing weed density, biomass, and seed production. These two treatments generally resulted in at least a 50% reduction in total weed density compared to the control. A flumioxazin or winter rye treatment resulted in no weed seed production of common lambsquarters at Site 1 in 2011, compared to 2018 seeds m^{-2} in the control. Results demonstrate the importance of early season weed control as part of a comprehensive weed management plan. Soybean row spacing and variety were not as effective in reducing weed density, biomass, and seed production. However, they were important as part of an integrated weed management strategy when used in combination with the winter rye cover crop and flumioxazin or acetochlor in controlling weeds in soybeans. A fully integrated approach is needed to control weeds, either to prevent herbicide resistant weeds or to manage herbicide resistant weeds.

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Introduction

Weed management is one of the most important factors impacting agricultural productivity. Worldwide, weeds are the number one pest of crops, causing approximately 32% of the potentially attainable yield to be lost (Oerke and Dehne, 2004). In the Midwest, however, the average yield loss is 5% with current weed management systems (Fickett et al., 2013). Weeds directly compete with crops for limited resources which reduce crop yield and increase the cost of production. Weeds also impede the efficiency of crop harvest and harbor insects and diseases that can be harmful to crops. There are three goals of any weed management system: reduce weed density, reduce the amount of damage that a given density of weeds inflicts on an associated crop, and alter the composition of weed communities towards less aggressive and easier-to-manage species (Liebman et al., 2007). Although the current weed management system in the upper Midwest has, for the most part, been meeting these goals, recent trends suggest that these management strategies are shifting weed species selection to highly competitive and herbicide resistant species. This is thought to be the result of less diversified weed management strategies (Powles, 2008). For example, in the southern U.S. Palmer amaranth (*Amaranthus palmeri S. Wats*) has developed resistance to glyphosate and is greatly reducing soybean yields due to the highly competitive nature of Palmer amaranth (Chandi et al., 2013).

Historically, weed management systems included a diversified combination of chemical, cultural, and mechanical practices to control weeds. Mechanical practices such as cultivation in conjunction with pre-emergence and/or post-emergence herbicides were the primary method of weed control in corn and soybeans from the late 1950’s until the early 1990's. Over time herbicides increasingly replaced labor-intensive mechanical weed control practices primarily because of low cost, high effectiveness, and ease of use associated with herbicides (Adcok and Banks, 1991; Gianessi and Reigner, 2007; Holt and LeBaron, 1990). Current weed management systems have shifted to more simplistic tactics with an almost exclusive use of a single class of post-emergence herbicide, i.e. glyphosate, to control weeds. The combination of reduced tillage and simultaneous use of a single site-of-action has resulted in the development of weeds that are resistant, tolerant, or can escape the current glyphosate-based weed management system (Holt and Powels, 1993; Powels and Quin Yu, 2010).

The combination of limited tillage in a glyphosate-based weed management system has selected for weeds that can escape control by delayed emergence, in-row protection by the crop canopy, and differences in growth stage of weeds at the time of spraying (Scursoni et al., 2007). While weed escapes result in crop yield losses, herbicide resistance is becoming an even greater concern. Presently there are 14 weed species resistant to glyphosate in the United States (Heap, 2013). Four glyphosate resistance mechanisms have been identified in weeds. These mechanisms include amplification of 5-enolpyruvylshikimate-3-phosphate (EPSP) synthase gene, restricted translocation, mutation of the Pro 101 gene, and rapid cell death of glyphosate treated tissue (Devine, 2000; Healy-Fried et al., 2007; Robertson, 2010). Weeds that have developed these mechanisms of glyphosate resistance produce seeds which can remain in the soil for extended periods of time. Prior to the release of Roundup Ready technology, the Group 2 herbicides (ALS) were used extensively in both corn and soybean cropping systems. This led to the rapid selection of ALS–resistant weeds. When glyphosate crops came on the market they allowed farmers to successfully control ALS-resistant weeds by switching to glyphosate and Roundup Ready crops. However, over time, producers have selected for some weed populations which are resistant to both ALS and glyphosate herbicides in Minnesota.

In areas where weed resistance has developed, the primary strategy that has been used to control and delay development of herbicide resistant weeds has been to rotate the use of herbicide sites-of-action, or to tank mix herbicides with another herbicide site-of-action (Shaner et al., 2012). The basis for using multiple herbicide sites-of-action in a weed management system is to reduce the selection pressure placed on weed populations by either of the herbicide sites-of-action individually. This strategy should increase the odds that weeds surviving one herbicide are controlled by the other. Population models have shown tank-mixing multiple sites-of-action may reduce or delay the evolution of herbicide resistant weeds (Shaner et al., 2012).

Currently there are an estimated 20-25 million hectares of crop land impacted by glyphosate resistant weeds in the United States (Benbrook, 2012). Herbicide resistant weeds cause an increase in the cost of weed management and a greater potential for yield loss when the resistant weeds are not controlled. Costs of chemical control of fields with glyphosate resistant weeds are projected to increase 50-100% (Benbrook, 2012). Moreover, there are glyphosate-resistant weed species that are resistant to multiple herbicide sites-of-action. The development of weeds with multiple resistance limits the use of herbicide-based weed management strategies.

In the upper Midwest, the number of weed species resistant to glyphosate is increasing; however a proactive approach to manage resistance is still practical, unlike the southern region of the United States where they have to use a reactive approach to control weeds due to the development of glyphosate resistant Palmer amaranth populations. In the southern United States glyphosate resistant Palmer amaranth is suspected of infesting an estimated 250,000 ha of agronomic land (Culpepper et al., 2009). With less widespread glyphosate resistant populations in the upper Midwest a proactive management approach can be implemented to extend the usefulness of glyphosate. Proactive management extends the usefulness of a herbicide by decreasing the selection pressure it places on its target. This is accomplished by combining several weed management tools such as: including another herbicide site-of-action; increasing crop competition via narrow row crops; or introducing competitive crops into a weed management system. While this method of integrated weed management might increase the cost of pest management initially, it is much cheaper in the long term if the effectiveness of glyphosate can be maintained (Mueller et al., 2005).

Integrated weed management (IWM) is a method of weed control that uses multiple approaches. IWM uses knowledge of weed biology, (emergence, growth rate, fecundity) integrated with multiple weed control tools to manage weeds throughout the growing season (Thill et al., 1991). IWM is designed to strategically target components of the life cycle of weeds to diminish their growth and development. The multiple control tactics reduce weed populations without selecting for weed resistance or escapes (Mortenson et al., 2012). Having multiple disturbances reduces the selection pressure from any of the control tactics alone, and weeds that are not controlled by one tactic are controlled by another. These multiple control tactics are introduced throughout the whole growing season, which also reduces the likelihood weeds will escape control.

Disturbances that are used in IWM systems include crop rotation, crop competitiveness, row spacing, cover crops, tillage, fertilizer placement, and weed thresholds (Buhler, 2002). For example, a farmer might use a cover crop, followed by narrow row planted soybeans, and then a post-emergent herbicide in the soybean crop one year, and then would rotate to another crop the next year which would utilize different tools than the previous year. A weed that has to adapt to overcome multiple control tactics puts more energy towards surviving and reduces the energy it has at the end of the season to produce seed.

IWM is becoming more prevalent as a method of weed control around the world as the incidence of herbicide resistant weeds increases. IWM is currently practiced in Australia to control *Lolium ridgidum* Gaudin.(rigid ryegrass) populations with multiple herbicide resistance (Pannell et al., 2004). Glyphosate-resistant *Conyza canadensis* (L.) Cronq. (horseweed) has been controlled in no-till soybean by integrating cover crops and soil-applied residual herbicides (Davis et al., 2008). In Georgia, tillage and cover crop strategies are being developed for their effectiveness in controlling glyphosate-resistant Palmer amaranth. A rye cover and deep tillage was found to reduce Palmer amaranth emergence by 75% (Culpepper et al., 2010).

In the United States as a whole, adoption of IWM has been slow due to uncertainty of the efficacy of practices used in IWM to control weeds, along with the additional cost, time, and management required. (Moss, 2008). Farmers continue to rely on herbicides because of predictable control of weeds, and more flexible timing of control than many of the IWM control tactics. Conversely, long-term cropping-system experiments in the United States have shown that using an IWM approach can be just as profitable as a system that relies primarily on herbicides (Pimentel et al. 2005, Liebman et al. 2008, Anderson 2009). While these long-term studies have shown IWM approaches to be profitable, more research needs to be conducted combining several of these disturbances together to find the combinations that have the greatest impact on weed emergence, growth, and weed seed production (Barberi, 2001; Liebman and Dyck, 1993).

Pre-emergent herbicides provide early season weed suppression by reducing weed density, biomass, and seed production (Hager et al., 2002; Schmenk and Kells, 1998). Pre-emergent herbicides add an additional herbicide site-of-action, and reduce the selection pressure from glyphosate. They also increase the uniformity of the weed cohort, which helps the glyphosate become more effective, and reduces weed escapes due to differences in growth stage when the post-emergent herbicide is applied (Gonzini et al., 1999). Pre-emergent herbicides can also delay the time of post-emergent herbicide application, which allows the post-emergent herbicide to better impact populations of weeds that have delayed emergence and multiple flushes during the growing season. Studies show incorporation of a residual herbicide with glyphosate can manage glyphosate-resistant weed populations by reducing the seed bank (Benbrook, 2012).

Cover crops are also used to suppress early weed growth through three primary mechanisms: competition for resources, buffering soil temperature fluctuations, and allelopathic effects. Cover crops are planted between cash crop rotations and generally are not harvested. Most cover crops are either chemically terminated, plowed under or winter killed before the cash crop is planted, reducing the chance of any negative effect on the cash crop. Because most cover crops are terminated before the cash crop is planted, competition for resources should not affect the crop, unless soil moisture is limited.

Cover crops can affect weed emergence by competing with weeds for water, nutrients, and light (Kruidhof et al., 2008; Kruidhof et al., 2009; Clark, 2007). Cover crops intercept red light and can reduce emergence in species that require red light to stimulate growth. Also, if weeds germinate, the light interception by the cover crop causes a change in the morphology of the weeds. Weeds that emerge into a cover crop have increased stem elongation and apical dominance compared to a weed that emerges without having to compete with a cover crop (Gramig and Stolenberg, 2009). This results in plants that have less energy to put towards seed production and in stalks that cannot support many seeds.

Cover crops can buffer the temperature fluctuations that some weeds use as a signal for germination in the spring (Teasdale and Mohler, 1993). This is because the mulch created by the cover crop blocks light transmittance to the soil surface and keeps soil moisture from evaporating. This extra soil moisture and reduced light keeps soils cooler. In weeds species that germinate over a large temperature range, reduction in temperature fluctuations may not be enough to stop the seed from germinating (Teasdale and Mohler, 1993).

Cover crops like *Secale cereal* L. (winter rye), produce allelopathic compounds which affect the germination and growth of weeds (Hartwig and Ammon, 2002). However these allelopathic compounds mainly affect small-seeded weeds, because large seeded weeds are able to overcome these effects (Kruidhof et al, 2011). Winter rye has previously been used as a living residue, green manure, or a crop. In a study looking evaluating the use of cover crops with herbicides, a winter rye cover crop provided 90% control of the weed species, and adding any herbicide to this system did not produce an increase in crop yield (Liebl et al., 1992). Winter rye residues have been shown to release two benzoxazinoid chemicals: 2,4-dihydroxy-1,4, (2H) – benzoxazin-3-one (DIBOA), and benzoxazolin-2(3H)-one (BOA) (Barnes and Putnam, 1987). These chemicals are thought to affect photophosphorylation and electron transport, similar to photosynthetic-inhibitor herbicides (Barnes and Putnam, 1987).

The effectiveness of allelopathic chemicals is environmentally dependent and differences between growing seasons can result in different levels of their effectiveness. Soil fertility, plant age at termination, environmental conditions, and cultivar all influence the production and subsequent effectiveness of allelopathic chemicals (Schulz et al., 2013). Liebl et al. (1992) were very successful at reducing weeds with a winter rye cover, but not all cover crops perform as well as rye in this study. Other cover crops such as tillage radish are able to suppress winter annual weed, but the suppression of spring annual weeds is not effective; thus some cover crops need to be combined with other tools to provide season long control of weeds.

Row spacing has been shown to reduce weed pressure. In the upper Midwest, crops are typically planted on a 76 cm row spacing. However, many growers plant soybeans in 38 cm row spacing. Narrow row soybeans can canopy as much as seven days earlier than wide row planted crops, and shade the soil between the rows. Narrow crop rows provide greater early season space capture within and between rows as well as increased leaf area index by equalizing plant distance within and among rows (Harder et al., 2007). Because of the greater early season space capture, narrow rows also intercept more light over the entire growing season, shading weeds and preventing them from emerging later in the season (Steckel and Spauge, 2004a; Norsworthy and Oliveria, 2004). This interception of light and quicker canopy cover results in greater weed suppression than wide rows.

Along with greater light interception, narrow rows also reduce the red: far red light that reaches the soil through the canopy of narrow rows. *Chenopodium album* L. (common lambsquarters) was found to respond to a reduction in light quality by elongation of the main stem, less leaf area, and a reduction of its seed production potential (Gramig and Stoltenberg, 2009). Yelverton and Coble (1991) found that as row spacing increased, there was a linear correlation with an increase in weed resurgence. Narrow rows can increase the control of late emerging species such as *Amaranthus rudis* Sauer (common waterhemp), which currently can escape the glyphosate weed management system. Narrow rows increase seedling mortality of emerged weeds and reduce seed production (Norsworthy and Oliveria, 2004; Steckel and Sprague, 2004; Steckel et al., 2003). However, some weed species such as *Setaria faberi* Herrm. (giant foxtail) are able to successfully complete their life cycle in narrow row cropping systems (Johnson et al., 1998).

The selection of competitive crops has been explored to a limited extent as a late season opportunity for weed control. Competitive soybeans were studied in the late 1990's and there were a few soybean varieties that were found to be more competitive with weeds. Traits that generally convey crop competiveness are increased leaf area, height, leaf area expansion rate, and plant canopy (Pester et al., 1999; Bussan et al., 1997). These traits mainly affected light interception during the growing season. Besides the above traits, soybean maturity has also been studied as a method of giving soybeans a more competitive edge over weeds. It is still unclear whether early or late maturing soybeans are more competitive with weeds (Yelvertion and Coble, 1991; Volloman et al., 2010; Nordby et al., 2007). However, these competitive varieties have never been combined with other weed control tactics into an integrated weed management system

In the upper Midwest, *Chenopodium album* L. (common lambsquarters), *Amaranthus tuberculatus* (Moq.) Sauer (tall waterhemp), and *Ambriosia trifida* L. (giant ragweed) have become problematic weeds in cropping systems currently using glyphosate as the primary mode of weed control (Johnson et al., 2012). These weeds species were also problematic in the 1990’s when Group 2 herbicides (ALS inhibitors) were used extensively in the corn and soybean rotation in the Upper Midwest.

These weed species have several characteristics that make them hard to control in the current Roundup Ready™ system. Common lambsquarters emerges very early during the growing season, and has an extended period of emergence from three to seven weeks. These plants can get very large before the first pass of glyphosate, making control difficult. Also, large weeds can canopy over other cohorts, reducing contact with glyphosate. Common lambsquarters is self-fertile, and can produce 70,000 seeds per plant (Harrison, 1990). Common lambsquarters seeds can survive in the seed bank and still germinate 12 years later (Burnside et al., 1996). Because of their prolific seed production and longevity in the weed seed bank, herbicide resistance traits could remain for an extended period of time.

Giant ragweed is one of the earliest emerging weed species in upper Midwest cropping systems and its phenomenal growth rate makes the optimal timing of post emergent herbicides difficult. While giant ragweed is not the most prolific seed producer, a single plant can still produce up to 5,000 seeds per plant (Baysinger and Sims, 1991). Giant ragweed is open pollinated, and the pollen can travel for many miles in the air. These mechanisms spread resistance genes to other giant ragweed populations quickly. There is also great genetic variability in the giant ragweed populations, because the origin of giant ragweed is the United States. However, giant ragweed has a very short half-life in the soil and this characteristic could be exploited to reduce the population of giant ragweed seeds in the weed seed bank.

Tall waterhemp is a late emerging weed species that can emerge over a period of eight weeks, sometimes past the last application of a post emergent herbicide (Hartzler et al., 1999). Tall waterhemp is an obligate outcrosser, and a prolific seed producer which can produce as many as one million seeds per plant (Sellers et al., 2003). The seeds can last 20 years in the soil and still be viable (Buhler and Hartzler, 2001).With such a potentially large seed bank to draw on for emergence, herbicide resistance would likely persist for a very long time.

Biotypes of giant ragweed have been found that are resistant to two sites-of-action, biotypes of common lambsquarters are resistant to four sites-of-action, and biotypes of tall waterhemp are resistant to six sites-of-action (Heap, 2013). Also, these species do have populations that have acquired multiple resistance to at least two different sites-of-action.

Giant ragweed, common lambsquarters, and tall waterhemp pose a special risk to the upper Midwest corn-soybean system. These weeds have been shown to develop herbicide resistance. Current strategies for controlling these weed species include heavy reliance on herbicide mixtures and/or herbicide resistant crops. However, these solutions remain herbicide-based and therefore may lead to development of resistance over time, suggesting that a new system of weed management should be considered. With the understanding of how various IWM tactics fit into an integrated weed management system, treatments were designed to evaluate the different combinations of early and late season disturbances that could lead to the development of IWM strategies for giant ragweed, common lambsquarters, and tall waterhemp in glyphosate-based soybean production systems.

Materials and Methods

Field Experiments. Field studies were conducted in 2011 and 2012 at two different sites at the Southern Research and Outreach Center near Waseca, MN. Site selection was based on historical information related to the occurrence of target weed species. Site 1 had a history of common lambsquarters infestation while Site 2 had a history of tall waterhemp infestations. The soil type at Site 1 was a Canisteo clay loam (fine-loamy, mixed, mesic Typic Endoaquoll) with pH 6.1, organic matter 5.6%, 22.3 ppm P, and 158.8 ppm K. The soil type at Site 2 was a Canisteo-Glencoe clay loam (fine-loamy, mixed mesic Typic Endoaquoll) with pH 7.5, organic matter 8.4%, 43 ppm P, and 168 ppm K. The experimental sites were planted to corn and harvested as silage on August 9, 2010. In 2011, both sites were chopped with a silage chopper on August 3 and tilled to incorporate residue. Then both sites were chisel plowed twice immediately following harvest to prepare the seed bed.

The experimental design was a randomized complete block in a split-split plot arrangement with four replications. Whole plot size was 80 m by 120 m, sub-plots were

40 m by 30 m, and sub-sub plots were 10 m by 30 m. The whole plots were comprised of soybeans planted in 76 cm or 17.5 cm row spacing, sub-plots were comprised of a radish/pennycress cover crop mix, a winter rye cover crop, a pre-emergence herbicide treatment, and a control. The sub-sub plots were comprised of four soybean varieties. Winter rye (*Secale cerale* L. 'Wheeler') was planted on September 7 and August 16 in 2011 and 2012, respectively, at a rate of 20.6 kg ha^{-1} using a 4.5 m no-till drill with rows spaced 17.5 cm apart. The tillage radish (*Raphanus sativus* L. 'Groundhog') and field pennycress (*Thlaspi arvense* L.) were both planted on September 7, 2010 and August 16, 2011 at a rate of 2.2 kg ha^{-1} also using a 4.5m no-till drill with rows spaced 17.5 cm. The radish seed was planted 5 cm deep, and the pennycress was planted at 0.6 cm. Instead of allowing the pennycress seed to drop into the coulters as normal, the seed tubes were detached from the coulters and allowed to hang free. This allowed the pennycress seed to fall on the soil surface and then be lightly incorporated by the coulters as they passed over the seed. A Brillion seeder (Brillion, WI) was used over the study area to increase seed to soil contact. Flumioxazin (2-[7-fluoro-3,4-dihydro-3-oxo-4-(2-propynyl)-2H-1,4-benzoxazin-6-yl]-4,5,6,7-tetrahydro-1H-isoindole-1,3(2H)-dione) was applied to the soil at soybean planting at a rate of 72 g ai ha^{-1} in 2011. In 2012, acetochlor (2-chloro-N-(ethoxymethyl)-N-(2-ethyl-6-methylphenyl) acetamide) was applied at a rate of 275 g ai ha^{-1} one week after planting due to a weather induced delay that resulted in some soybean emergence by the time the pre-emergent herbicide could be applied.

On May 12, 2011 and May 8, 2012 glyphosate (N-(phosphonomethyl) glycine) was applied to the entire site at a rate of 1.26 kg a.e. ha^{-1} (De Bruin 2005). Soybean varieties MO4, MN1410, Parker, and Archer were planted May 16, 2011 and May 19, 2012 using a 4.5m no-till drill spaced at 76 cm (wide row treatments) or 17.5 cm (narrow row treatments) at a rate of 296,500 seeds ha^{-1}. Four weeks after planting, clethodim ((E,E)-(±)-2-[1-[[(3-chloro-2-propenyl)oxy]imino]propyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one) was applied to the entire study area at a rate of 0.25g ai ha^{-1} to control annual grass weeds.

Cover Crop Biomass and Stand Counts. Above-ground plant biomass was determined in four randomly placed $0.25m^2$ quadrats on October 15, 2010, May 5, 2011, October 21, 2011, and May 7, 2012. Within each quadrat, plants were cut at the soil surface, placed into brown paper bags and dried in a forced-air oven at 60° C for three days. Dried biomass was then weighed to the nearest hundredth of a gram to determine biomass on a dry-weight basis (Kruidhof et al 2008). Cover crop stands were measured in the fall and spring at the time of biomass sampling by counting the number of plants in each quadrat.

Weed Density, Biomass, and Seed Production. Weed density was evaluated over time by counting the number of emerged weeds in three permanent $0.33m^2$ quadrants in each sub-sub plot of the experiment. Within each quadrat, weeds were counted by species, recorded, and removed from the quadrat by cutting at the soil surface (Anderson 2008, Forcella et al 1992). Weed counts were taken at soybean planting, soybean emergence, V3-V4, and R1 (Anderson 2008). Weed biomass, except giant ragweed, was measured on August 20 in both years in a 1 m^2 area by randomly selecting from within each sub-plot in an area not used to measure weed density. Within the 1 m^2 area, individual plants were cut at the soil surface, identified by species, and placed into paper bags. The biomass was separated by species: common lambsquarters, giant ragweed, tall waterhemp, and all other weed species (non-target weeds). All biomass samples were dried at 60° C in a forced-air oven for three days and weighed to determine plant biomass on a dry-weight basis. (Davis et al 2005). Giant ragweed biomass was harvested on September 23rd both years, which was after the giant ragweed seeds had matured. Seed was threshed from the dried biomass of the common lambsquarters, giant ragweed, and tall waterhemp by processing the material through a belt thresher and then sieving out the seed through a seed sieve. The threshed seed was weighed, and the seed in a 0.5 g sub-sample of common lambsquarters and tall waterhemp seed was counted and used to calculate the total number of seeds present in the sample area. Due to the larger seed size of giant ragweed, sub-samples of 8g were used to estimate the seeds present in the giant ragweed samples. Seed counts were expressed as seeds m^{-2}.

Light Quality and Quantity. Light quantity measurements were taken at soybean R1 by positioning a digital camera mounted 1.5 meters above the ground level downwards to the ground. Trash bags were placed over weeds right before each picture was taken, so that an accurate measurement of the soybean canopy could be determined without weed canopy interference. The images were analyzed by SigmaScan Pro (v. 5.0 SPSS, Inc., Chicago, IL) and an output of the amount of light absorbed by the canopy was calculated. At the R1 stage of soybean development, light quality was measured at 10 cm above the soil surface at an upward, downward, and 45^0 angle to the ground. A flag was placed in each sub-sub plot in two replications of each site at the time of the first measurement and subsequent measurements were taken at each flag bi-weekly until the soybeans canopied.

Yield of Soybeans. Soybean seed yield was determined by harvesting the middle two rows in the 76.5 cm spacing treatments and from the middle six rows in the 17.5cm spacing treatments with a plot combine. Grain yields were adjusted to 13% moisture on a dry weight basis.

Statistical Analysis. All data were subjected to ANOVA. Main effects and interactions were tested for statistical significance. The SAS program PROC GLM (SAS Institute Inc. Cary, NC) was used to determine treatment effects on weed density, seed rain, plant biomass, light quality, light quantity, and soybean yield. Weed density data was log transformed prior to analysis to improve the normality and homogeneity of variances when necessary. After transformation of the weed density data (if necessary) treatment means were separated by Fishers Protected Least Significant Difference (LSD) test at $P < 0.10$ using the appropriate error term for all significant effects. The LSD means obtained from analyses were applied to the raw means (if data transformation was necessary) for presentation in all tables. However error terms cannot be back-transformed, thus differences among transformed LS means were indicated in tables with different letters.

Results and Discussion

Precipitation and average air temperatures during the growing season (April-September) of 2011 and 2012 for Waseca, MN are presented in Table 1. Precipitation in 2011 was above the 30-year average from May-July. However, August-September precipitation was 16.9 cm below the 30-year average for that time period. Precipitation in May of 2012 was above the 30-year average, but was 21.2 cm below the average from July-September. Average air temperatures were near normal in 2011 and 2012 with the exception of below normal air temperatures in April and May of 2011 and above normal temperatures in July of both years. Because of differences in biotic and abiotic variables between sites and years, data will be presented by individual environments (location by year) for weed density, weed biomass, and weed seed production.

Site 1 2011

Weed Density. Site 1 has a history of common lambsquarters infestation. In the fall of 2010 the average biomass of the radish and the winter rye was very similar (Table 2). However, there was very little pennycress biomass in the radish/pennycress plots. Spring cover crop biomass yields tended to be lower than those reported in other studies in the Midwest (Table 2) (DeBruin et al., 2005; Leavitt et al., 2011). This was likely due to low soil temperatures in April and May resulting from below normal air temperatures and above normal precipitation. Weed species present at this site (Table 3) throughout the growing season were common lambsquarters (average 0-2.8 seedlings m^{-2}), giant ragweed (average 0-0.13 seedlings m^{-2}), tall waterhemp (average 0-0.33 seedlings m-2), and some *Amaranthus spp* (pigweed) (average 0-2.33 seedlings m^{-2}) and *Setaria spp* (foxtail) (average 0-2.58 seedlings m^{-2}).

Winter rye cover crop and pre-emergence herbicide treatments reduced total weed density and common lambsquarters density across all sampling periods as compared to the control (Table 3). The radish/pennycress cover crop mixture did not reduce weed density as compared to the control for total weeds and common lambsquarters across all sampling periods. There was no difference in tall waterhemp density among the winter rye, pre-emergent treatment, and the radish/pennycress cover mixture as compared to the control at the soybean emergence sampling. However, the winter rye and pre-emergence treatment reduced tall waterhemp density as compared to the radish/pennycress cover mixture at soybean emergence. Similarly, giant ragweed density was reduced in the winter rye and the pre-emergent herbicide treatments at soybean emergence as compared to the radish/pennycress cover crop mixture treatments, but was not different from the control. There were no differences in tall waterhemp density among the control, radish/pennycress cover mixture, winter rye cover crop, or the pre-emergence herbicide treatments at soybean V3-V4. At soybean R1, tall waterhemp density was not reduced by the pre-emergence herbicide, winter rye cover, or the radish/pennycress cover mixture as compared to the control. However, as with the soybean emergence density counts, the winter rye cover and the pre-emergence herbicide were more effective in reducing tall waterhemp density as compared to the radish/pennycress cover mixture. At R1 there were no differences among these treatments in suppression of giant ragweed emergence. This is due to giant ragweed being an early emerging weed, and by sampling period V3-V4, 83% of giant ragweed had emerged (mid- June in 2011).

Row spacing and soybean varieties had little effect on weed density in 2011(data not shown). However, soybean variety M1410 reduced tall waterhemp density as compared to MO4 at the V3-V4 sampling period (Table 4). Surprisingly, MN1410 is considered a non-competitive variety due to small leaves and shorter height. Giant ragweed density was greater in narrow row soybeans (when averaged over soybean variety) where radish/pennycress was the cover crop treatment compared to all other combinations (Table 5).

Weed Biomass. The winter rye, pre-emergence herbicide, radish/pennycress cover mixture and soybean varieties had no effect on weed biomass at this site in 2011 (data not shown). Narrow soybean rows had greater giant ragweed biomass (194.9 g m^{-2}) compared to the wide rows (60.3 g m^{-2}) when averaged over all factors. Conversely, the only time when giant ragweed density was different between the narrow and wide soybean row treatments was at the V3-V4 sampling when giant ragweed density was higher in the narrow rows compared to the wide rows (when averaged over soybean variety). This result of higher biomass is contradictory to many other experiments that show a reduction in weed biomass as rows narrow (Hock et al., 2006; Harder et al., 2007). However, the soybean in narrow rows at Site 1 in 2011 were initially slower to emerge, and this would have enabled giant ragweed emergence.

Weed Seed Production. In 2011, common lambsquarters seed production was found to be affected by the cover crop and pre-emergence herbicide treatments (Table 6). Winter rye, the pre-emergent herbicide, and the radish/pennycress cover mixture all reduced seed production of common lambsquarters as compared to the control. The reduction of seed production by the winter rye and pre-emergent herbicide was expected due to the reduction in density of common lambsquarters at this site in 2011 (Table 3). However, even though the radish/pennycress mixture did not significantly affect the biomass of common lambsquarters there was some negative impact of the radish/pennycress cover crop mixture on seed production of common lambsquarters that was only quantified via seed production. Soybean variety and row spacing had no effect on weed seed production at site 1 in 2011(data not shown).

At Site 1 in 2011, the winter rye cover crop and the pre-emergent herbicide treatment were effective at reducing weed density and weed seed production. In general, cover crops can be effective tools in reducing weed density due to the physical barrier of mulch. The cover crops used in this study were chosen because of their high biomass potential as well as the potential to release allelopathic chemicals that interfere with germination and growth. In this study winter rye produced a larger amount of biomass compared to the pennycress by the spring of 2012. However, cover crop biomass production was considered low compared to other studies.

Site 1 2012.

Weed density. Fall cover crop biomass production was lower in 2011 compared to fall 2010 for the radish and winter rye (Table 2). This was likely due to below normal rainfall beginning in August and continuing into October of 2011 (Table 1). An increase in pennycress biomass in fall 2011 compared to fall 2010 may have been due to reduced competition from the radish cover crop.

In spring 2012, biomass of the winter rye and pennycress was greater than in 2011 (Table 2). The higher biomass production of the pennycress in 2012 is likely due to a corresponding reduction in radish biomass production in the fall. Moreover, soil growing degree days (SGDD) (base 10^{o} C) accumulated at a much faster pace in 2012 as compared to 2011 (88 and 310 SGDD in 2011 and 2012, respectively) by the time the plants were chemically terminated. The warm spring resulted in the emergence of later emerging weeds species at Site 1 in 2012. Weed species present throughout the growing season at this site (Table 3) were common lambsquarters (average 0-0.8 seedlings m^{-2}), tall waterhemp (average 0-0.5 seedlings m^{-2}), and some pigweed species (average 0-1.3 seedlings m^{-2}), *Solanum nigrum* L. (black nightshade) (average 0-2 seedlings m^{-2}), and foxtail species (average 0-3.0 seedlings m^{-2}).

There were no differences in common lambsquarters, tall waterhemp, and giant ragweed density among the pre-emergence herbicide treatment, the winter rye cover or the radish/pennycress cover mixture at soybean emergence as compared to the control (Table 3). At the V3-V4 soybean growth stage, the winter rye cover was the only treatment that reduced common lambsquarters density as compared to the control. For tall waterhemp there was no difference in density among the treatments as compared to the control at soybean emergence and V3-V4 sampling times. The winter rye cover, pre-emergence herbicide, and the radish/pennycress cover mixture reduced the density of giant ragweed as compared to the control at the V3-V4 sampling.

In a response similar to 2011, common lambsquarters density was reduced in the winter rye cover and pre-emergence herbicide treatments as compared to the control at soybean R1. However, the radish/pennycress cover did not reduce common lambsquarters density as compared to the control at soybean R1. Winter rye and the pre-emergent herbicide treatments reduced tall waterhemp density as compared to the control at the R1 sampling. However, the winter rye and the pre-emergent herbicide were not better at reducing tall waterhemp density than the radish/pennycress cover crop mixture. There was no giant ragweed present in the plots at the R1 sampling. For total weed densities, the winter rye, pre-emergence herbicide or radish/pennycress cover mixture reduced weed densities as compared to the control.

Common lambsquarters was not present at the soybean emergence sample timing due to optimal timing of the burn down application of glyphosate followed by high temperatures, which likely induced secondary dormancy in common lambsquarters (Forcella et al 1997). Greater accumulation of soil growing degrees in 2012 (310 SGDD) compared to 2011 (80 SGDD) likely resulted in a shift from early to late emerging weed species in our study. Below normal rainfall during fall 2011 and June-July 2012 may have also contributed to the overall low weed emergence.

Compared to 2011, an increase in cover crop biomass at site 1 in 2012 resulted in a greater suppression of total weed density when sampled at soybean emergence. This is not unexpected, as Teasdale and Mohler (2000) found an exponential relationship between mulch biomass and weed emergence, where higher levels of mulch result in a lower density of weeds. Grass species (C4 plants) typically have a higher C:N ratio than broadleaf plants (C3 plants) (Long, 1999), thus the mulch of broadleaf plants breaks down more quickly. This earlier addition of the nutrients from the decomposed mulch could increase the emergence of later emerging weed species. In the case of rye, a biomass of 5000 kg ha^{-1} of dry matter creates a mat on the soil surface that will tie up nitrogen due to the high carbon to nitrogen ratio of the surface material (approximately 60-80:1) (Malpassi et al., 2000; Rosecrance et al., 2000; Wells et. al, 2013). Studies have shown that nitrogen suppression can last 8 weeks and does not impact soybean yields (Wells et al., 2013). However, this period of nitrogen suppression can greatly affect weed species that are sensitive to high nitrogen rates such as *Amaranthus retroflexus* L. (redroot pigweed) and common lambsquarters (Blackshaw, 2004). For nitrogen sensitive species, comparable N deprivation can reduce shoot biomass, seed number, and total seed mass and as a result, the offspring can be less competitive in low-N environments (Tungate et al., 2006).

Row spacing and soybean variety treatments had little effect on weed emergence at Site 1 in 2012 (data not shown). There was no difference among the winter rye, pre-emergence herbicide treatment, the radish/pennycress cover mixture, and the control in the reduction of total weed density in narrow row soybean spacing at the V3-V4 sample timing (Table 7). In the wide row soybean spacing, the pre-emergence herbicide and the winter rye reduced total weed density compared to the control and the radish/pennycress cover (Table 7).

In 2011, weed density tended to be lower in the rye cover and pre-emergence herbicide treatments compared to the radish/pennycress cover (Table 3). In 2012, there was not a clear difference between the winter rye, radish/pennycress cover mixture, pre-emergence herbicide treatment, and the control on weed density. Lower overall weed density in 2012 may have been due to greater cover crop biomass accumulation, greater spring accumulation of SGDD, and a timely pre-plant herbicide application. These factors likely affected the success of early season weed disturbance on weed emergence.

Weed Biomass. In contrast to 2011, there was a significant difference among winter rye, pre-emergence, and the radish/pennycress cover treatments and their effect on the biomass of tall waterhemp and non-target weeds in 2012 (Table 8). Tall waterhemp and non-target weed biomass was higher in the winter rye and radish/pennycress cover mixture as compared to the control. The pre-emergent herbicide treatment was similar to the control for both tall waterhemp and non-target weed biomass. Non-target weed biomass includes all the weed biomass in the plots that was not common lambsquarters, giant ragweed, or tall waterhemp. Both the tall waterhemp and the weed species grouped in the non-target weed category are late emerging species. Therefore, greater weed biomass in the cover crop treatments compared to the pre-emergence herbicide treatment may have been due to above average temperatures in the spring that resulted in a higher rate of residue degradation as well a reduced amount of allelopathic chemicals that may have been present from the cover crops (Kobayashi, 2004). Also, the above average rainfall in May might have diluted allelopathic chemicals in the soil, and also increase biomass degradation. Thus, these late season weeds were unlikely to be affected by either the chemical or physical barriers of the cover crops when they emerged. Also, any nitrogen inhibition due to the cover crop mulch was likely reduced by the time these late emerging species germinated.

For the non-target weeds, row spacing was also found to be significant, with wide row soybeans resulting in greater weed biomass production (50.3g m^{-2} wide row and 29.7 g m^{-2} narrow row respectively). Narrow row soybeans capture more light over the season and result in quicker space capture in the soybean canopy, thus reducing weed biomass (Steckel and Spauge, 2004a; Norsworthy and Oliveria, 2004). Furthermore, late emerging weeds would likely experience a reduced light environment in narrow soybean rows thereby slowing growth. There was no effect of soybean variety on weed biomass in 2012.

In 2012 at Site 1, a warmer spring resulted in an increase in cover crop biomass of both the winter rye and pennycress. There was a lower overall weed pressure throughout the growing season, but the winter rye and pre-emergent herbicide treatments still reduced weed density compared to the control. Late emerging weed species had higher biomass production in the winter rye and radish/pennycress cover treatments compared to the control (Table 8). Due to low weed population density there were no differences in weed seed production. Soybean row spacing and soybean varieties did not affect weed density, biomass, or seed production.

Site 2 2011

Weed Density. Site 2 had a history of tall waterhemp infestation. Fall cover crop biomass production was slightly higher at Site 2 than at Site 1 in 2010 (Table 2). Ponding water in the spring of 2011 resulted in the elimination of one replicate due to lack of cover crop presence at the site. The spring cover crop biomass was also slightly higher in the spring of 2011 compared to Site 1. Weed species present throughout the growing season at this site (Table 9) were common lambsquarters (average 0.4 -24 seedlings m^{-2}), giant ragweed (average 0.3-6.1 seedlings m^{-2}), and tall waterhemp (average 0.2-15.9 seedlings m^{-2}), and some pigweed species (average 0-12 seedlings m^{-2}), *Abutilon theophrasti* Medik. (velvetleaf) (average 0-12 seedlings m^{-2}), and foxtail species (average 0-10 seedlings m^{-2}). However, this site was dominated by giant ragweed in 2011.

At soybean emergence, the pre-emergence herbicide and the winter rye reduced common lambsquarters density as compared to the control (Table 9). However, the radish/pennycress cover crop mixture was not different from the control. Tall waterhemp density at soybean emergence was reduced by the pre-emergent herbicide treatment as compared to the control, but there were no differences between the winter rye or radish/pennycress cover as compared to the control. However, the winter rye treatment reduced tall waterhemp density better than the radish/pennycress mixture. There was no difference in giant ragweed densities at soybean emergence among the winter rye, pre-emergence herbicide, radish/pennycress cover, and the control. For total weed densities, the winter rye cover crop and pre-emergence herbicide treatments reduced total weed density as compared to the control treatment (Table 9).

For the common lambsquarters and total weed density counts at soybean V3-V4 the winter rye and pre-emergent herbicide treatments reduced weed density as compared to the control. The pre-emergent herbicide reduced tall waterhemp density as compared to the control at V3-V4. The winter rye and radish/pennycress cover mix were no different from the control at reducing tall waterhemp densities at V3-V4. There was no difference in giant ragweed densities at soybean emergence among the winter rye, pre-emergence herbicide, radish/pennycress cover, and the control at V3-V4.

At the R1 sampling, common lambsquarters and total weed density were reduced by the winter rye and the pre-emergent herbicide treatments as compared to the control. Tall waterhemp densities were reduced by the winter rye and pre-emergent herbicide treatment as compared to the control, but there was no difference between winter rye and the radish/pennycress cover mixture. As in previous sampling timings, there were no differences among early season disturbances for giant ragweed densities.

Soybean variety and soybean row spacing had no effect on weed density at site 2 in 2011(data not shown). Site 2 results were very similar to the results reported for Site 1, where the winter rye and pre-emergence treatments tended to reduce weed density more than soybean variety and soybean row spacing. However, unlike Site 1, weed emergence at site 2 was higher, with giant ragweed densities up to 6 seedlings in a 1 m^2 area. Higher weed emergence at Site 2 may have been due to site location (toe slope, depressional area) resulting in plentiful moisture in the spring and higher organic matter.

At Site 2 in 2011 the winter rye cover and pre-emergence herbicide treatments effectively suppressed common lambsquarters and tall waterhemp. Neither the winter rye, the pre-emergence herbicide, nor the radish/pennycress cover mixture were effective at reducing giant ragweed densities.

The average rye biomass production at site 2 was 591 g dry matter ha^{-1} (Table 2), which was inadequate to suppress giant ragweed, given that the recommended biomass for rye mulch that will control weeds is 9000 kg ha^{-1} (Teasdale and Mohler, 2000). The ability to increase rye biomass production through fertilization, cultivar selection, plant age, and planting density is the key to providing weed suppression through allelopathy. Reberg-Horton (2005) found differences in the amount of allelopathic toxins produced among ten different cultivars of rye as well as the age of the plant suggesting that a combination of choosing the right cultivar and terminating it at the correct age could have increased the effect of allelopathic suppression by rye on giant ragweed. However, due to the short growing season in the upper Midwest, none of the aforementioned strategies to increase biomass may be applicable.

Weed Biomass. Tall waterhemp biomass was affected by row spacing, with wide rows having about twice as much tall waterhemp biomass compared to the narrow rows (115.8 g m^{-2} wide and 64.3 g m^{-2} narrow). A reduction in weed biomass was also found by Steckel and Sprauge (2009) comparing wide versus narrow rows. Waterhemp is a later emerging weed and the increase in the soybean canopy greatly reduces the survival of the late emerged waterhemp and reduces weed seed production (Steckel et al., 2003; Steckel and Sprague, 2004; Uscanga-Mortera, 2007).

Giant ragweed biomass resulted in a variety by cover interaction (Table 10) which indicated that Archer provided additional control of giant ragweed biomass in the control plot compared to all other varieties. There were no differences among varieties across the winter rye and radish/pennycress treatments. MO4 was not as effective as the other varieties at reducing giant ragweed biomass in the pre-emergence herbicide treatment. With Archer, here were no differences in giant ragweed biomass among the winter rye, pre-emergence herbicide, or radish/pennycress cover mixture treatments. The soybean variety MO4 by pre-emergent herbicide treatment reduced giant ragweed biomass as compared to the control. Variety MN1410 combined with the pre-emergence herbicide produces the least amount of giant ragweed biomass as compared to the control and radish/pennycress cover mixture. Parker with the winter rye or radish/pennycress cover mixture treatment reduced giant ragweed biomass as compared to the control.

Overall, the older soybean varieties, Archer and Parker, were more effective in reducing the biomass of giant ragweed. Older soybean varieties are taller with broader leaves than the more current soybean varieties which are shorter with smaller leaves. The newer varieties of soybeans used in this study did not reduce giant ragweed biomass, and this may be because they have been bred over time to put more energy into seed, and are less likely to divert energy towards more vegetative growth. Thus, newer soybean varieties may be more dependent on early season weed control to reduce giant ragweed growth. Even though data in Table 10 shows a reduction in giant ragweed biomass, there was still enough biomass in the best three treatments to reduce soybean yield. Less than two giant ragweed plants per nine meters of row are needed to reduce yield in soybean by 46-50% after full season interference (Baysinger and Sims, 1991).

The non-target weeds exhibited a variety by row interaction (Table 11). In the narrow rows there were no differences among varieties, but in the wide rows Archer and MN1410 did not suppress weed growth as well as M04 and Parker. Archer was better in narrow rows at suppressing weed growth, with about a 50% reduction as compared to Archer grown in wide rows. There were no differences of non-target weed biomass among row spacing with MO4 and MN1410 soybean varieties. However, Parker reduced biomass in wide rows compared to the narrow rows.

Archer only effectively suppressed non-target weeds when grown in narrow rows. This was an unexpected result, as Archer is considered a competitive variety with large leaves and greater height than the non-competitive varieties in the study. M04 and Parker may not exclusively need to be grown in narrow rows to give them a competitive advantage. The inconsistency on the effect of these treatments as compared to Site 1 shows how important multiple disturbances can be on a site with heavy weed pressure. This site and year was very mixed in the effectiveness of the treatments on weed biomass. Row spacing was good at reducing tall waterhemp biomass, probably by closing the canopy quicker by 7 days (data not shown). However variety, while not significant by itself, interacted with row or cover to affect weed growth.

Site 2 in 2011 had a very high weed density, which was dominated by giant ragweed. Winter rye and the pre-emergent herbicide were the only consistent treatments that reduced weed density compared to the control. However, none of the early season disturbances reduced giant ragweed density. Tall waterhemp biomass was reduced in narrow rows, and this was probably because it is a late emerging weed which is affected by the reduced light quantity under the soybean canopy. Archer provided additional reduction of giant ragweed biomass in the control sub-plots. However, the newer soybeans may need early season weed control because they could not compete against giant ragweed. For the later emerging non-target weed species, Archer needs to be planted in narrow rows to be competitive. There were no differences in weed seed production at Site 2 in 2011.

Site 2 2012.

Weed density. Winter rye and the radish cover crop produced less biomass in the fall of 2012 than in 2011 at this site (Table 2). However, there was a large increase in the biomass of the pennycress, similar to Site 1 in 2012. Also, the biomass production of the cover crops at this site in the fall of 2011 was greater than at Site 1. The greater production of biomass compared to Site 1 is likely due to the soil higher organic matter, which allowed this site to hold onto moisture so the cover crops could become better established in the fall. In spring 2012, biomass of the winter rye and pennycress was greater than in 2011 (Table 2). The higher biomass production of the pennycress in 2012 was likely due to a corresponding reduction in radish biomass production in the fall, and the increase in accumulated growing degree days.

The warm spring resulted in the emergence of later emerging weed species at Site 2 in 2012. Weed species present throughout the growing season at this site (Table 9) were common lambsquarters (average 0-3.1 seedlings m^{-2}), giant ragweed (average 0.2-6.3 seedlings m^{-2}), tall waterhemp (average 0-11.8 seedlings m^{-2}), and also some pigweed species (average 0-12 seedlings m^{-2}), velvet leaf (average 0-7.25 seedlings m^{-2}), and foxtail species (average 0-14.3 seedlings m^{-2}). However, this site was again dominated by the emergence of giant ragweed in 2012.

At the soybean emergence sampling time there were no common lambsquarters or tall waterhemp weeds present in the plots (Table 9). Giant ragweed weed densities were reduced with the winter rye treatment as compared to the control. Also, at soybean emergence the radish/pennycress mixture reduced giant ragweed density as compared to the pre-emergent herbicide. The radish/pennycress and winter rye treatments reduced total weed density at soybean emergence as compared to the control.

At V3-V4 the pre-emergent herbicide and the winter rye treatment reduced common lambsquarters density as compared to the control. The radish/pennycress mixture was not better at reducing common lambsquarters density than the control. Winter rye and pre-emergent herbicide treatments reduced tall waterhemp density as compared to the control. However, the radish/pennycress cover mixture increased the germination of tall waterhemp compared to the control. For giant ragweed the pre-emergent herbicide and winter rye treatment reduced the density as compared to the control. The radish/pennycress cover mixture was no different than the control at reducing giant ragweed density. Total weed density at V3-V4 was effectively reduced by the pre-emergence herbicide and the winter rye treatment compared to the control. The radish/pennycress mixture had a higher density of total weeds compared to the control.

At R1 the winter rye cover crop and pre-emergent herbicide treatment reduced common lambsquarters density as compared to the control. The pre-emergent herbicide reduced the density of tall waterhemp as compared to the control at R1. The winter rye and radish/pennycress cover mixture were undifferentiated from the control at reducing tall waterhemp density. There were no differences among treatments compared to the control for giant ragweed density at the R1 sampling. Winter rye and the pre-emergent herbicide treatments reduced total weed density as compared to the control. The radish/pennycress treatment had a higher density of weeds compared to the control.

Soybean variety and soybean row spacing had no effect on weed density at Site 2 in 2012 (data not shown). These results are similar to 2011 at this site. Similar to Site 1, the timing of the pre-plant glyphosate application resulted in no common lambsquarters seedlings emerging by the first sampling count of weeds at soybean emergence. Also, as the pre-emergent herbicide was applied seven days after planting in 2012 it was not as effective at reducing weed density at soybean emergence as compared to 2011. Giant ragweed density was higher in 2012 due to warm temperatures and moist soil early in the spring. Giant ragweed density both years at this site was exceptionally high and was extremely hard to control. In 2012 the winter rye gave better suppression of giant ragweed initially, but the pre-emergent herbicide became more effective than the winter rye later in the season at soybean V3-V4. Because the pre-emergence herbicide had a different mode of action compared to 2011 there was little activity on giant ragweed in 2012.

There was an increase in the density of weeds that emerged at soybean V3-V4 in the radish/pennycress treatments as compared to the control. Other studies also show fall seeded radish can sometimes increase weed emergence the following summer (Charles et al., 2006; Lawley et al., 2011, 2012; Gieske, 2013). Radish can accumulate up to 180 kg/ha of nitrogen in their leaf tissue in Minnesota by mid-October, and deposits the accumulated nitrogen on the soil surface in the spring as the radish plants decompose (Gieske, 2013). The radish reduced pennycress development in the fall and with the placement of a large amount of nitrogen on the soil surface in the spring, pennycress was unable to control spring emerging weeds.

Weed Biomass. At Site 2 in 2012 there was a significant difference among the winter rye, the radish/pennycress cover mixture, the pre-emergence herbicide treatment, and the control on the biomass of tall waterhemp and giant ragweed (Table 12). There was no difference in tall waterhemp biomass among the winter rye, pre-emergence herbicide, and radish/pennycress treatments as compared to the control. However, the winter rye and the pre-emergent herbicide treatments were more effective at reducing tall waterhemp biomass than the radish/pennycress treatment. This pattern is similar to the tall waterhemp density counts where the radish/pennycress had the highest counts at soybean V3-V4 (Table 9), while the pre-emergent herbicide and winter rye had the lowest. These differences in control could be due to the allelopathic chemicals not being effective on tall waterhemp, but also there is the possibility that the allelopathic chemicals were already broken down by the time the tall waterhemp started emerging in 2012. Giant ragweed biomass was reduced in the winter rye and the radish/pennycress treatments compared to the control. The pre-emergent herbicide was grouped with the control because the pre-emergent herbicide in 2012 did not provide any activity on giant ragweed and was applied seven days after planting. There was no effect of soybean variety or soybean row spacing at site 2 in 2012.

Weed Seed Production. In 2012 differences in tall waterhemp seed production were found to be affected by the winter rye, the radish/pennycress mixture, and the pre-emergent herbicide treatments (Table 13). There were no differences of the treatments as compared to the control. However, the winter rye and pre-emergent herbicide did reduce seed production as compared to the radish/pennycress cover mixture. It is of interest to note that the mean separations for tall waterhemp seed production were similar to the biomass production of tall waterhemp in this environment (Table 12).

In this study none of the sites achieved the 9000 kg dry matter ha^{-1} of rye biomass (Table 2) recommended to prevent yield loss from weeds (Teasdale and Mohler, 2000; Smith et al., 2011). This low production of biomass affected the thickness of the mulch mat, which in turn affected the emergence of weeds. The thickness of the mat could be improved by fertilizing, cultivar selection, or by increasing the planting density. However, due to the short growing season, these strategies may not be enough to increase the biomass to 9000 kg ha^{-1} in the upper Midwest. However, even with the smaller amount of biomass produced in this study, the winter rye was able to reduce density of common lambsquarters and tall waterhemp.

This study found common lambsquarters and tall waterhemp were controlled fairly consistently with either a winter rye cover or a pre-emergence herbicide treatment, while giant ragweed control was more inconsistent. This result agrees with many studies which have reported that allelopathic chemicals affect small seeded species, but are less effective with large seeded species (Kruidhof, 2011; Liebman et al., 2007). This phenomenon is thought to be due to two processes. First, small seeds have a higher surface to soil ratio, therefore the exposure to the allelopathic chemicals would be at a much higher rate. Second, when cover crops are left as mulch, the allelopathic toxins may not diffuse very deeply into the soil profile, which means that large seeded species, like giant ragweed which can emerge from greater depths are not affected by the allelopathic toxins. Thus, another method of weed control combined with allelopathic producing cover crops will need to be used to control large seeded weeds that emerge over the growing season.

Over all the sites and years, weed density was most effectively reduced with a pre-emergent herbicide or a winter rye cover crop. This was not an unexpected result, as the treatments that impact later in the growing season, such as row spacing and soybean varieties, would not have had a chance to express themselves. Soybean row spacing and varieties were important in affecting the light quality and quantity later on in the season (data not shown), but because there was no emergence of weeds after R1in both years and sites of this study, they did not impact weed biomass and seed production. In this study the radish/pennycress cover mixture did not consistently control weeds because the pennycress was not able to suppress weeds in the spring that germinated in response to the nitrogen placed on the soil by the decomposed radish. The radish/pennycress system would have to be further adjusted to make it more effective controlling weeds. Planting pure stands of pennycress can reduce winter annual weed biomass in the spring compared to a radish/pennycress cover mixture. At Site 1 weeds were dominated by common lambsquarters in 2011 and by tall waterhemp in 2012. However, at Site 2, both years were dominated by giant ragweed biomass and none of the treatments were able to effectively control giant ragweed.

Overall, winter rye and the pre-emergence herbicide were the most effective in reducing weed density, biomass, and seed production. Winter rye cover crop and pre-emergent herbicide were generally the most consistent in reducing weed density. Results demonstrate the importance of incorporating an early season weed disturbance in a comprehensive weed management plan. While soybean row spacing and soybean variety are not as effective, they were important in combination or with a cover crop or a pre-emergence herbicide treatment in controlling weeds in the soybeans. While this study did not sample weeds past the R1 sampling period, it is important to recognize the importance of late season disturbance after this period of time. More research is needed to explore the integration of early and late season weed disturbance for the control of important weed species in soybean cropping systems. A fully integrated approach is needed to address weed suppression, especially in fields were herbicide-resistant weeds are present as well as a tool to prevent herbicide-resistant weed species from becoming established.

Tables

Table 1. Precipitation and average air temperatures in 2011 and 2012 at Waseca, MN.

Month	Precipitation (cm)			Avg. Air Temperature (^{0}C)		
	2011	2012	Average[a]	2011	2012	Average[a]
April	3.1	7.8	8.2	6.6	8.7	7.8
May	11.9	14.6	10.0	13.9	17.1	14.8
June	13.2	10.8	11.9	20.3	21.0	20.3
July	18.3	5.3	11.2	24.6	24.9	22.2
August	2.3	3.7	12.1	21.1	21.0	21.0
September	2.2	2.4	9.3	15.3	16.3	16.3
Departure from normal	-11.7	-18.1		-0.6	6.5	

[a] 30-year average from 1981-2010 at Waseca, MN

Table 2. Cover crop biomass at both Site 1 and Site 2 in 2011 and 2012 at Waseca, MN.[b]

Cover crop	October 15, 2010	May 5, 2011	October 21, 2011	May 7, 2012
		$g\ m^{-2}$		
Site 1				
Radish	73.9 a	0.0[a]	22.0 a	0.0
Pennycress	1.1 b	92.0 a	3.6 b	272.0 a
Winter rye	71.6 a	438.0 b	19.8 a	586.0 b
Site 2				
Radish	136.0 a	0.0	100.0 a	0.0
Pennycress	1.3 b	113.0 a	4.8 b	358.0 a
Winter rye	109.0 a	591.0 b	75.0 a	577.0 b

[a] The radish winter killed, and there was no biomass in the spring.

[b] Means within the same column and year followed by the same letter are not significantly different (α>0.10).

Table 3. Weed density at soybean emergence, V3-V4, and R1 stages by species at site 1 in Waseca, MN in 2011 and 2012.[a]

	Total weeds[c]			Common Lambsquarters			Tall Waterhemp			Giant Ragweed		
	Soybean Stage											
Treatment	EM[b]	V3-V4	R1	EM	V3-V4	R1	EM	V3-V4	R1	EM	V3-V4	R1
2011	average number of weeds m^{-2}											
Winter rye	0.38 b	0.29 b	0.25 b	0.17 b	0.00 b	0.00 b	0.00 b	0.04 a	0.04 b	0.04 b	~[d]	0.04 a
Pre-emergence herbicide[e]	0.79 b	0.46 b	0.25 b	0.00 b	0.08 b	0.17 b	0.00 b	0.08 a	0.00 b	0.04 b	~	0.04 a
Radish/Pennycress	7.38 a	3.58 a	4.04 a	2.25 a	2.33 a	2.63 a	0.21 a	0.33 a	0.25 a	0.13 a	~	0.04 a
Control	8.13 a	3.21 a	3.63 a	2.33 a	2.33 a	2.75 a	0.08 ab	0.29 a	0.17 ab	0.08 ab	~	0.00 a
2012												
Winter rye	0.00 b	~[d]	0.00 b	0.00 a	0.00 c	0.00 b	0.00 a	0.21 a	0.00 b	0.00 a	0.00 b	0.00 a
Pre-emergence herbicide[e]	0.04 b		0.00 b	0.00 a	0.17 bc	0.00 b	0.00 a	0.04 a	0.04 b	0.00 a	0.00 b	0.00 a
Radish/Pennycress	0.04 b		0.00 b	0.00 a	0.79 a	0.04 ab	0.00 a	0.5 a	0.13 ab	0.04 a	0.00 b	0.00 a
Control	0.33 a		0.17 a	0.00 a	0.54 ab	0.13 a	0.00 a	0.5 a	0.38 a	0.00 a	0.04 a	0.00 a

[a] Means within the same column and year followed by the same letter are not significantly different ($\alpha > 0.10$).
[b] EM = emergence.
[c] Total weeds consist of *Amaranthus* species, *Setaria* species, common lambsquarters, tall waterhemp, and giant ragweed
[d] Significant row by cover interaction therefore means not shown.
[e] Pre-emergence herbicide was flumioxazin in 2011 and acetochlor in 2012.

Table 4. Effect of soybean variety on tall waterhemp density at soybean V3-V4 in Waseca, MN in 2011 at Site 1.[a]

Soybean Variety	Tall waterhemp
	plants m^{-2}
M04	0.38 a
Parker	0.21 ab
Archer	0.17 ab
MN1410	0.00 b

[a] Means followed by the same letter are not significantly different (α>0.10).

Table 5. Giant ragweed density at soybean V3-V4 at Site 1 in Waseca, MN in 2011 as affected by the interaction of row spacing and winter rye, radish/pennycress or pre-emergence herbicide treatments.[a]

Row spacing	Pre-emergence herbicide[b]	Winter Rye	Radish/ Pennycress	Control
	plants m^{-2}			
Wide	0.05 ar	0.00 ar	0.00 ar	0.00 ar
Narrow	0.00 ar	0.02 ar	0.11 bs	0.00 ar

[a] Means within the same table followed by the same letter are not significantly different (α>0.10). The letters a-b are used to compare the winter rye, radish/pennycress cover mixture, and pre-emergence treatments across row spacing. The letters r-t are used to compare row spacing across the winter rye, radish/pennycress, and pre-emergence treatments.

[b] Pre-emergence herbicide was flumioxazin.

Table 6. Common lambsquarters seed production as affected by winter rye, radish/pennycress, and a pre-emergence herbicide treatment at Site 1 in 2011 at Waseca, MN.[a]

Treatment	Common lambsquarters
	average seed m^{-2}
Winter rye	0 a
Pre-emergence herbicide[b]	0 a
Radish/pennycress	365 a
Control	2018 b

[a] Means followed by the same letter are not significantly different (α=0.10).
[b] Pre-emergence herbicide is flumioxazin.

Table 7. Site 1 total weed density at soybean V3-V4 as affected by the interaction of row spacing and winter rye, radish/pennycress or pre-emergence herbicide treatments in 2012 at Waseca, MN.[a]

Row spacing	Pre-emergence herbicide[b]	Winter Rye	Radish/ Pennycress	Control
	average number of weeds m^{-2}			
Wide	0.25 br	0.17 br	6.42 ar	6.42 ar
Narrow	2.17 ar	0.58 ar	1.83 ar	0.33 as

[a] Means within the same table followed by the same letter are not significantly different (α>0.10). The letters a-b are used to compare the winter rye, radish/pennycress cover mixture, and pre-emergence treatments across row spacing. The letters r-t are used to compare row spacing across the winter rye, radish/pennycress, and pre-emergence treatments.

[b] Pre-emergence herbicide was flumioxazin.

Table 8. Winter rye, radish/pennycress, and pre-emergence treatment effects on end of season weed biomass at Site 1 at Waseca, MN in 2012.[a]

Treatment	Tall waterhemp	Non-target weeds[c]
	g biomass per m^2	
Winter rye	28.6 a	77.6 a
Pre-emergence herbicide[b]	1.7 b	15.9 b
Radish/Pennycress	30.7 a	61.4 a
Control	5.8 b	3.7 b

[a] Means within the same column followed by the same letter are not significantly different (α>0.10).

[b] Pre- emergence herbicide was acetochlor.

[c] Non-target weeds comprised *Amaranthus* species and *Solanum nigrum* (black nightshade).

Table 9. Weed density at soybean emergence, V3-V4, and R1 stages by species at site 2 in 2011 and 2012 at Waseca, MN.[a]

Treatment	Total weeds[c]			Common Lambsquarters			Tall Waterhemp			Giant Ragweed		
	Soybean Stage											
	EM[b]	V3-V4	R1	EM	V3-V4	R1	EM	V3-V4	R1	EM	V3-V4	R1
2011	average number of weeds m^{-2}											
Winter rye	19.0 b	14.5 b	11.8 b	12.9 bc	4.9 b	2.7 b	1.0 bc	3.4 ab	4.4 bc	2.5 a	1.9 a	0.3 a
Pre-emergence herbicide[d]	6.1 b	6.6 b	9.9 b	0.4 c	2.1 b	4.1 b	0.2 c	1.1 b	2.9 c	1.7 a	0.6 a	0.4 a
Radish/Pennycress	55.9 a	54.7 a	36.3 a	11.5 ab	18.8 a	15.5 a	7.4 a	14.8 a	7.0 ab	5.4 a	2.3 a	3.0 a
Control	46.6 a	61.9 a	51.2 a	20.9 a	23.7 a	24.0 a	4.7 ab	15.9 a	15.9a	6.1 a	3.8 a	0.8 a
2012												
Winter rye	0.3 c	14.4c	4.3 b	0.00 a	0.0 c	0.2 b	0.0 a	4.8 c	2.7 a	0.3 c	1.9 c	0.6 a
Pre-emergence herbicide[d]	8.5 a	4.0 d	1.3 c	0.00 a	0.9 b	0.2 b	0.0 a	0.2 d	0.1 b	6.3 a	0.2 d	0.2 a
Radish/Pennycress	4.0 b	57.3 a	12.8 a	0.00 a	2.3 a	0.6 a	0.0 a	22.3 a	3.9 a	2.7 b	4.9 a	1.1 a
Control	8.9 a	29.3 b	5.9 b	0.00 a	3.1 a	0.9 a	0.0 a	11.8 b	2.3 a	6.3 ab	3.8 a	0.4 a

[a] Means within the same column and year followed by the same letter are not significantly different (α>0.10).
[b] EM = emergence.
[c] Total weeds comprise *Abutilon theophrasti*, *Setraia* species, *Amaranthus* species, common lambsquarters, tall waterhemp, and giant ragweed.
[d] Pre-emergence herbicide was flumioxazin in 2011 and acetochlor in 2012.

Table 10. Giant ragweed biomass at Site 2 in 2011 at Waseca, MN as influenced by the interaction of soybean variety and winter rye, radish/pennycress, and pre-emergence herbicide treatment.[a]

Treatment	Archer	M04	MN1410	Parker
	$g\ m^{-2}$			
Control	247.8br	688.8ar	767.5ar	703.5ar
Radish/Pennycress	308.0ar	464.3ars	612.4ars	245.3as
Winter rye	315.5ar	51.3as	273.7ast	197.0as
Pre-emergence herbicide[b]	373.0br	834.8ar	38.2bt	289.3brs

[a] Means within the same table followed by the same letter are not significantly different (α>0.10). The letters a-b are used to compare winter rye, radish/pennycress, and pre-emergence herbicide treatments across varieties. The letters r-t are used to compare varieties across winter rye, radish/pennycress, and pre-emergence herbicide treatments.
[b] Pre-emergence herbicide is flumioxazin.

Table 11. Non-target weeds[b] biomass at Site 2 in 2011 at Waseca, MN as affected by the interaction of soybean row space and variety.[a]

Row Spacing	Archer	MO4	MN1410	Parker
		g m^{-2}		
Wide	59.9ar	11.5br	42.4ars	5.8bs
Narrow	23.2as	11.1ar	24.9ar	37.4ar

[a] Means within the same table followed by the same letter are not significantly different (α>0.10). The letters a-b are used to compare row space across varieties. The letters r-t are used to compare varieties across row space.

[b] Non-target weeds biomass comprise of *Amaranthus* species and *Abutilon theophrasti*.

Table 12. Winter rye, radish/pennycress, and pre-emergence herbicide treatment effects on tall waterhemp and giant ragweed biomass at Site 2 in 2012 at Waseca, MN.[a]

Treatment	Tall Waterhemp	Giant ragweed
	g m^{-2}	
Winter rye	88.7b	258.7b
Pre-emergence herbicide*	44.5b	560.5a
Radish/Pennycress	289.6a	354.8b
Control	176.3ab	561.4a

[a] Means within the same column followed by the same letter are not significantly different ($\alpha>0.10$).
[b] Pre-emergence herbicide was acetochlor.

Table 13. Winter rye, radish/pennycress, and pre-emergence herbicide treatment effects on seed production of tall waterhemp at Site 2 in 2012 at Waseca, MN.[a]

Treatment	Tall waterhemp
	average seed m^{-2}
Control	7942 ab
Radish/Pennycress	9165 a
Winter rye	2051 b
Pre-emergence herbicide[b]	2630 b

[a] Means within the same column followed by the same letter are not significantly different (α>0.10).
[b] Pre-emergence herbicide is acetochlor.

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Appendix

Appendix A. Effect of row spacing, cover, and soybean variety on weed density at Site 1 in 2011 at Waseca, MN[a,b]

	totalweeds 1[d,e]	AMARE 1	CHEAL 1	totalweeds 2	AMARE 2	CHEAL 2	AMBTR 2	totalweeds 3	CHEAL 3
Rep	ns	ns	*	**	ns	ns	ns	ns	ns
Row space	ns	ns	ns	ns	ns	ns	*	ns	ns
Cover[c]	***	ns	***	***	ns	***	*	***	***
Row * Cover	ns	ns	ns	ns	ns	ns	***	ns	ns
Variety	ns	ns	ns	ns	*	ns	ns	ns	ns
Variety * row	**	ns	ns	ns	ns	ns	ns	ns	ns
Variety *cover	ns	ns	ns	ns	ns	ns	ns	ns	ns

[a] Significance at α=.10: *= <0.10, **=<.05, ***=<.01, ns= not significant

[b] All data log transformed.

[c] Cover treatments include: winter rye, radish/pennycress cover mixture, and pre-emergence herbicide

[d] AMBTR = *Ambriosa trifida*; CHEAL= *Chenopodium album*; AMARE = *Amaranthus tuberculatus*

[e] Time of sample: 1 = soybean emergence, 2 = soybean stage V3-V4, 3= soybean stage R1

Appendix B. Effect of row spacing, cover, and soybean variety on light quality (R:FR light) at Site 1 in 2011 at Waseca, MN.[a]

Light quality	(up) 1[b]	(45^0)1	(down)1	(45^0) 2	(down) 2
Rep	ns	ns	ns	ns	ns
Row space	ns	ns	ns	ns	ns
Cover[c]	*	***	**	*	***
Row * Cover	ns	ns	*	ns	**
Variety	**	ns	ns	ns	ns
Variety * row	ns	ns	ns	ns	*
Variety *cover	ns	ns	ns	ns	ns

[a] Significance at α=.10: *= <0.10, **=<.05, ***=<.01, ns=not significant

[b] Direction of the probe relative to the ground is indicated in parentheses, while the sample timing follows. Measurements began at soybean stage R1.

[c] Cover treatments include: winter rye, radish/pennycress cover mixture, and pre-emergence herbicide

Appendix C. Effect of row spacing, cover, and soybean variety on light quantity (soybean canopy cover) at Site 1 in 2011 at Waseca, MN.[a]

	Week 1[b]	Week 2
Rep	ns	ns
Row space	ns	ns
Cover[c]	*	ns
Row * Cover	ns	ns
Variety	ns	ns
Variety * row	**	ns
Variety *cover	ns	ns

[a] Significance at α=.10: *= <0.10, **=<.05, ***=<.01, ns= not significant
[b] Measurements began at soybean stage R1
[c] Cover treatments include: winter rye, radish/pennycress cover mixture, and pre-emergence herbicide

Appendix D. Effect of row spacing, cover, and soybean variety on biomass and seed harvest at Site 1 in 2011 at Waseca, MN.[a,b]

	Soybean yield	CHEAL biomass	CHEAL seed	AMARE seed	AMBTR biomass	AMBTR seed
Rep	ns	*	**	ns	**	ns
Row space	ns	ns	ns	ns	***	**
Cover[c]	*	ns	**	ns	ns	ns
Row * Cover	ns	ns	ns	ns	ns	ns
Variety	***	ns	ns	ns	ns	ns
Variety * row	ns	ns	ns	ns	ns	ns
Variety *cover	ns	ns	ns	ns	ns	ns

[a] Significance at α=.10: *= <0.10, **=<.05, ***=<.01, ns=not significant.
[b] AMBTR = *Ambriosa trifida*; CHEAL= *Chenopodium album*; AMARE = *Amaranthus tuberculatus*
[c] Cover treatments include: winter rye, radish/pennycress cover mixture, and pre-emergence herbicide

Appendix E. Effect of row spacing, cover, and soybean variety on weed density at Site 1 in 2012 at Waseca, MN.[a,b]

	totalweeds 2[d,e]	AMARE 2	CHEAL 2	totalweeds 3
Rep	**	**	***	ns
Row space	ns	ns	ns	ns
Cover[c]	**	ns	**	***
Row * Cover	ns	ns	ns	ns
Variety	ns	ns	ns	ns
Variety * row	ns	ns	ns	ns
Variety *cover	ns	ns	ns	ns

[a] Significance at α=.10: *= <0.10, **=<.05, ***=<.01, ns=not significant.

[b] All data log transformed.

[c] Cover treatments include: winter rye, radish/pennycress cover mixture, and pre-emergence herbicide

[d] CHEAL= *Chenopodium album;* AMARE = *Amaranthus tuberculatus*

[e] Time of sample: 1 = soybean emergence, 2 = soybean stage V3-V4, 3= soybean stage R1

Appendix F. Effect of row spacing, cover, and soybean variety on light quality (R:FR light) at Site 1 in 2012 at Waseca, MN.[a]

	(up)1[b]	(45^0)1	(down)1	(up)2	(45^0)2	(down)2	(up)3	(45^0)3	(down)3	(up)4	(45^0)4	(down)4
Rep	ns	ns	ns	**	*	ns	**	ns	ns	ns	ns	ns
Row space	ns	**	ns	**	**	**	**	**	*	ns	ns	ns
Cover[c]	ns	ns	ns	ns	*	ns	ns	ns	*	*	**	*
Row * Cover	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	*	ns
Variety	ns	ns	ns	*	ns	ns	***	**	ns	***	***	***
Variety * row	ns	ns	ns	ns	ns	**	**	*	ns	**	**	*
Variety *cover	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

[a] Significance at α=.10: *= <0.10, **=<.05, ***=<.01, ns=not significant.

[b] Direction of the probe relative to the ground is indicated in parentheses, while the sample timing follows. Measurements commenced at soybean stage R1

[c] Cover treatments include: winter rye, radish/pennycress cover mixture, and pre-emergence herbicide

Appendix G. Effect of row spacing, cover, and soybean variety on light quantity (soybean canopy cover) at Site 1 in 2012 at Waseca, MN.[a]

	Week 1[b]	Week 2	Week 3
Rep	ns	ns	ns
Row space	**	ns	ns
Cover[c]	ns	ns	ns
Row * Cover	ns	ns	ns
Variety	ns	ns	ns
Variety * row	ns	ns	ns
Variety *cover	ns	ns	ns

[a] Significance at α=.10: *= <0.10, **=<.05, ***=<.01, ns= not significant

[b] Measurements began at soybean stage R1

[c] Cover treatments include: winter rye, radish/pennycress cover mixture, and pre-emergence herbicide

Appendix H. Effect of row spacing, cover, and soybean variety on biomass and seed production at Site 1 in 2012 at Waseca, MN.[a]

	soybean biomass	soybean yield	AMARE biomass[c]	Non-target[b] weed biomass
Rep	ns	**	**	**
Row space	**	ns	ns	*
Cover[d]	*	ns	***	**
Row * Cover	ns	ns	ns	ns
Variety	ns	***	ns	ns
Variety * row	ns	ns	ns	ns
Variety *cover	ns	ns	ns	ns

[a] Significance at α=.10: *= <0.10, **=<.05, ***=<.01, ns=not significant.

[b] Non-target weed biomass is comprised of pigweed and *Solanum nigrum* L. (black nightshade)

[c] AMARE = *Amaranthus tuberculatus*

[d] Cover treatments include: winter rye, radish/pennycress cover mixture, and pre-emergence herbicide

Appendix I. Effect of row spacing, cover, and soybean varieties on weed density at Site 2 in 2011 at Waseca, MN.[a,b]

	Total weeds	AMARE	CHEAL[c]	AMBTR	Total weeds2	AMARE2	CHEAL2	AMBTR2	Total weeds3	AMARE3	CHEAL3	AMBTR3
Rep	ns	*	**	ns	ns	**	ns	ns	ns	**	*	ns
Row space	ns	ns	**	ns	ns	ns	ns	ns	ns	ns	ns	ns
Cover[d]	**	**	*	ns	***	***	***	ns	***	**	***	ns
Row * Cover	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Variety	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Variety * row	ns	ns	ns	ns	*	ns	**	ns	ns	ns	ns	ns
Variety *cover	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

[a] Significance at α=.10: *= <0.10, **=<.05, ***=<.01, ns=not significant.
[b] All data log transformed.
[c] AMBTR = *Ambriosa trifida;* CHEAL= *Chenopodium album;* AMARE = *Amaranthus tuberculatus*
[d] Cover treatments include: winter rye, radish/pennycress cover mixture, and pre-emergence herbicide

Appendix J. Effect of row spacing, cover, and soybean variety on light quality (R:FR light) at Site 2 in 2011 at Waseca, MN.[a,b]

	(up) 1	(45^0)1	(down)1	(up) 2	(45^0) 2	(down) 2
Rep	ns	ns	ns	*	ns	ns
Row space	ns	ns	*	*	ns	ns
Cover[c]	**	*	**	ns	ns	*
Row * Cover	ns	ns	ns	ns	ns	ns
Variety	ns	ns	ns	ns	ns	ns
Variety * row	ns	**	ns	ns	*	**
Variety *cover	ns	ns	ns	ns	ns	ns

[a] Significance at α=.10: *= <0.10, **=<.05, ***=<.01, ns=not significant.
[b] Direction of the probe relative to the ground is indicated in parentheses, while the sample timing follows. Measurements were commenced at soybean stage R1.
[c] Cover treatments include: winter rye, radish/pennycress cover mixture, and pre-emergence herbicide.

Appendix K. Effect of row spacing, cover, and soybean variety on light quantity (soybean canopy cover) at Site 2 in 2011 at Waseca, MN.[a]

	Week 1[b]	Week 2
Rep	ns	ns
Row space	**	ns
Cover[c]	*	ns
Row * Cover	ns	**
Variety	*	ns
Variety * row	ns	ns
Variety *cover	ns	**

[a] Significance at α=.10: *= <0.10, **=<.05, ***=<.01, ns= not significant
[b] Measurements began at soybean stage R1
[c] Cover treatments include: winter rye, radish/pennycress cover mixture, and pre-emergence herbicide

Appendix L. Effect of row spacing, cover, and soybean variety on biomass and seed harvest at Site 2 in 2011 at Waseca, MN.[a,b]

	Soybean biomass	Soybean yield	CHEAL biomass	CHEAL seed	AMARE biomass	Non-target weed biomass	AMBTR biomass
Rep	ns	ns	ns	ns	*	ns	ns
Row space	ns	ns	ns	ns	*	ns	ns
Cover[c]	**	**	ns	ns	ns	ns	ns
Row * Cover	ns	ns	ns	ns	ns	ns	ns
Variety	ns	ns	ns	ns	ns	**	ns
Variety * row	ns	*	ns	ns	ns	**	*
Variety *cover	ns	ns	ns	ns	ns	ns	**

[a] Significance at α=.10: *= <0.10, **=<.05, ***=<.01, ns= not significant
[b] AMBTR = *Ambriosa trifida;* CHEAL= *Chenopodium album;* AMARE = *Amaranthus tuberculatus*
[c] Cover treatments include: winter rye, radish/pennycress cover mixture, and pre-emergence herbicide

Appendix M. Effect of row spacing, cover, and soybean variety on weed density at Site 2 in 2012 at Waseca, MN.[a,b]

	Total weeds	AMBTR[c]	Total weeds 2	AMARE2	CHEAL 2	AMBTR 2	Total weeds 3	AMARE 3	AMBTR 3
Rep	ns	ns	ns	ns	ns	ns	***	**	ns
Row space	ns	ns	ns	ns	*	ns	ns	ns	ns
Cover[d]	***	**	***	***	***	ns	***	***	ns
Row * Cover	ns	ns	ns	ns	ns	ns	ns	ns	ns
Variety	ns	ns	ns	ns	ns	ns	ns	*	**
Variety * row	ns	ns	ns	ns	ns	ns	ns	ns	**
Variety *cover	ns	ns	ns	ns	ns	ns	ns	ns	ns

[a] Significance at α=.10: *= <0.10, **=<.05, ***=<.01, ns= not significant

[b] All data log transformed.

[c] AMBTR = *Ambriosa trifida;* CHEAL= *Chenopodium album;* AMARE = *Amaranthus tuberculatus*

[d] Cover treatments include: winter rye, radish/pennycress cover mixture, and pre-emergence herbicide

Appendix N. Effect of row spacing, cover, and soybean variety on light quality (R:FR light) at Site 2 in 2012 at Waseca, MN.[a]

	(up)1[b]	(45º)1	(down)1	(up)2	(45º)2	(down) 2	(up)3	(45º)3	(down)3	(up)4	(45º)4	(down) 4
Rep	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Row space	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Cover[c]	***	***	***	***	***	***	***	***	***	**	***	**
Row * Cover	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Variety	ns	ns	ns	ns	ns	ns	ns	ns	ns	**	ns	ns
Variety * row	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Variety *cover	ns	ns	ns	ns	ns	ns	ns	ns	ns	***	ns	ns

[a] Significance at α=.10: *= <0.10, **=<.05, ***=<.01, ns= not significant

[b] Direction of the probe relative to the ground is indicated in parentheses, while the sample timing follows. Measurements were commenced at soybean stage R1.

[c] Cover treatments include: winter rye, radish/pennycress cover mixture, and pre-emergence herbicide

Appendix O. Effect of row spacing, cover, and soybean variety on light quantity (soybean canopy cover) at Site 2 in 2012 at Waseca, MN.[a]

	Week 1[b]	Week 2	Week 3
Rep	ns	**	ns
Row space	ns	**	ns
Cover[c]	**	**	**
Row * Cover	ns	ns	ns
Variety	ns	ns	ns
Variety * row	ns	ns	ns
Variety *cover	ns	ns	ns

[a] Significance at α=.10: *= <0.10, **=<.05, ***=<.01, ns= not significant
[b] Measurements were commenced at soybean stage R1.
[c] Cover treatments include: winter rye, radish/pennycress cover mixture, and pre-emergence herbicide

Appendix P. Effect of row spacing, cover, and soybean variety on biomass and seed production at Site 2 in 2012 at Waseca, MN.[a]

	soybean biomass	AMARE[b] biomass	AMARE seed	Non-target weed biomass	AMBTR biomass
Rep	ns	ns	ns	ns	ns
Row space	ns	ns	ns	ns	ns
Cover[c]	ns	**	*	ns	**
Row * Cover	ns	ns	ns	ns	ns
Variety	ns	ns	ns	ns	ns
Variety * row	ns	ns	*	ns	ns
Variety *cover	ns	ns	ns	ns	ns

[a] Significance at α=.10: *= <0.10, **=<.05, ***=<.01, ns= not significant

[b] AMBTR = *Ambriosa trifida;* AMARE = *Amaranthus tuberculatus*

[c] Cover treatments include: winter rye, radish/pennycress cover mixture, and pre-emergence herbicide