Integrating cover crops and herbicides for horseweed and Palmer amaranth management in no-till soybean

by

Chelsea Marie McCall

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Approved by:

Major Professor
Dr. Anita Dille

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Abstract

Palmer amaranth and horseweed are problematic weeds in no-till soybeans in Kansas. Integrating cover crops and herbicide programs could suppress weed populations. To determine the emergence pattern and survival of horseweed, a study was conducted across six locations in eastern KS in 2014-2015 and 2015-2016. Horseweed seedlings and leaf number per seedling were recorded at two-week intervals. Cumulative GDDs required to reach 50% horseweed emergence increased from north to south. Horseweed survival ranged from 4 to 90%, and majority of horseweed emerged in the fall. Field studies were conducted to determine effects of cover crops and herbicide programs on Palmer amaranth near Manhattan, KS in 2014-2015 and 2015-2016. Five cover crop treatments included no cover, fall-sown winter wheat, spring-sown oat, pea, and mixture of oat and pea. Cover crops were terminated in May with glyphosate and 2,4-D alone or with residual herbicides of flumioxazin and pyroxasulfone. By 10 weeks after termination in 2014-2015, Palmer amaranth biomass and density, averaged across cover crops. was 95 and 69% less with residual herbicides than without, respectively, and Palmer amaranth biomass was 98% less in winter wheat and 91% less in spring oat, averaged across termination methods, compared to no cover. Time to 50% Palmer amaranth emergence was delayed with winter wheat, spring oat, and spring oat/pea mix without residual herbicide. Soybean yields were greater with residual herbicide and greater with winter wheat or spring oat cover crop in 2014-2015. A field study was conducted to determine suppression effects of cover crop and herbicide programs on horseweed and Palmer amaranth near Manhattan, KS in 2015-2016. Three fall treatments included fall-sown rye, a residual herbicide tank mix of glyphosate, dicamba, chlorimuron-ethyl, tribenuron-methyl, and AMS, and no fall application. Four spring treatments included no spring application or three herbicide tank mixes: glyphosate, dicamba, and AMS alone or with flumioxazin and pyroxasulfone as early preplant, or as split applied with 2/3 preplant and 1/3 at soybean planting. Similar levels of horseweed suppression were observed when some control measure was used in fall or spring. Fall rye completely suppressed horseweed while the fall herbicide suppressed biomass by 93% and density by 86% compared to no fall application. Palmer amaranth suppression was observed when a spring herbicide application was used. In rye, total weed biomass was reduced by 97% or more across all spring treatments. Total weed biomass was reduced with a spring herbicide was used. Soybean yields were least when no herbicide treatment was used in the spring. An integrated program of fall cover crops or herbicide applications together with spring herbicide applications maintained soybean yields.

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Chapter 1 - Literature Review

Overview

Soybean [*Glycine max* (L.) Merr.] is an economically important crop for the United States. In 2015, 33.5 million hectares of soybean were planted in the United States, and 1.6 million of those hectares were planted in Kansas (USDA 2016b). As an economically important crop, protecting these acres from yield loss is essential. One of the main causes of yield loss in soybeans is competition with weeds. Two problem weeds for soybeans in Kansas include horseweed [*Conyza canadensis* (L.) Cronq.] and Palmer amaranth [*Amaranthus palmeri* S. Watson]. Understanding horseweed and Palmer amaranth biology including their establishment, survival, fecundity, and herbicide-resistance characteristics in Kansas and how different management strategies affect them will give better insight for controlling populations in the future.

Horseweed

Biology and Establishment

Horseweed is a winter annual C3 broadleaf weed found throughout the United States that is known to be an early successional species (Regehr and Bazzaz 1979; Weaver 2001). Seedlings typically emerge from August through October, overwinter as a rosette, bolt in April or May, flower in July, and disperse seed in August (Weaver 2001). One advantage horseweed possesses is the ability to photosynthesize over a wide range of temperatures and light environments even in the winter (Regehr and Bazzaz 1976). This ability allows horseweed to have a competitive advantage in the spring when other plants are coming out of dormancy. However, horseweed has also been shown to emerge in the spring. The emergence patterns of horseweed have not been documented in Kansas. Is there a possible geographical influence on the emergence of horseweed, or does its emergence adapt with changing field management strategies. Buhler and Owen (1997) have shown that 28 to 32% of total horseweed emergence occurred in May through early June in Minnesota and Iowa, and Davis et al. (2007) showed greater than 90% of horseweed emerging in the spring in Indiana. Spring-emerging seedlings do not form a rosette but bolt almost immediately and complete the life cycle by August (Davis and Johnson 2008).

Seedling germination tends to increase after rainy periods when soil moisture is high, and seedlings may come from seed that were dormant in the soil seed bank or from freshly dispersed seed (Regehr and Bazzaz 1979). A plant canopy does not interfere with seedling germination of horseweed (Regehr and Bazzaz 1979). Horseweed populations establish on no-till fields better than conventionally-tilled fields (Bhowmik and Bekech 1993). No-till fields create a perfect environment for horseweed since seed germinates best when shallow seeded. Seeds buried deeper than 0.5 cm did not emerge (Nandula et al. 2006). Seed germination was reduced by 80% in the fall by leaving crop residue on soil surface in a no-tillage system (Bhowmik and Bekech 1993). On the other hand, in Southern Ontario, Canada, Tozzi and Van Acker (2014) suggested that tillage creates favorable recruitment microsites for new horseweed seedlings if tillage is timed so that new seed is dispersed after tillage. In no-till sites, the emergence of new plants decreased due to competition of other already established horseweed. Tillage management strategies can have an effect on horseweed emergence, which may be useful when developing an integrated weed management program for horseweed.

Survival

The main cause of death of fall-emerging plants is frost heaving during winter. However, fall-emerging plants tended to have higher survival rates in the spring than spring-emerging plants. Larger fall rosettes tend to survive winter frost-heaving better than smaller rosettes due to a better developed taproot system with large lateral roots (Regehr and Bazzaz 1979). Tozzi et al. (2014) observed that warming spells in March reduced plant survival by 50% and also negatively affected growth and fecundity.

Fecundity and Seed Dispersal

Horseweed is a self-pollinating plant that disperses its very small seed by wind (Dauer et. al. 2007; Weaver 2001). Plants can range from 10 to 180 cm in height (Weaver 2001). Regehr and Bazzaz (1979) found that the reproductive effort (weight of seeds per g dry weight) of horseweed was inversely related to plant height even though plant height was proportional to seed production. This suggests that energy allocation to plant height was more important than to seed production because seed dispersal by wind is important for species survival. A study by Dauer et al. (2007) showed that horseweed seeds can travel over 500 meters from the parent plant when dispersed. One plant can produce over one million seeds plant^{-1} without competition (Davis et al. 2009b). At a density of 10 plants m^{-2}, a single plant can produce more than 200,000 seeds (Bhowmik and Bekech 1993). Tozzi and Van Acker (2014) observed that fecundity did not differ between spring- and fall-emerging horseweed, but early fall and early spring emerging seedlings flowered several days earlier in the following summer compared to late fall or spring emerging seedlings.

Herbicide Resistance and Competition with Soybeans

Due to the extensive use of herbicides with the same site of action, weed populations have evolved herbicide resistance and have become an important issue for management. According to Heap (2017), there are 62 documented cases of herbicide-resistant horseweed worldwide. Within the United States, horseweed has developed resistance to the following herbicide sites of action: EPSPS inhibitors, ALS inhibitors, photosystem II inhibitors (groups 5 and 7), and photosystem I electron diverters. Seven populations have been recorded to have multiple herbicide resistance. Kansas so far has reported EPSPS-inhibitor and ALS-inhibitor herbicide resistance in horseweed, and 20% of 266 sampled populations in Indiana showed ALS-inhibitor resistance and 2% showed resistance to both ALS-inhibitor and EPSPS-inhibitor herbicides (Kruger et al. 2009).

Horseweed has very plastic growth that allows it to adapt to many different environments and still produce seed (Regeher and Bazzaz 1979). Sometimes herbicide-resistant weed populations can show fitness costs for possessing resistance. Davis et al. (2009b) showed that no horseweed populations showed fitness costs among EPSPS, ALS inhibitor, or dual EPSPS and ALS inhibitor herbicide-resistances. This means that herbicide-resistant horseweed was just as competitive as susceptible horseweed. Bruce and Kells (1990) found that horseweed reduced no-till soybean yields by 83% when not controlled, which was similar to another study where glyphosate-resistant horseweed reduced soybean yield by 83 to 93% when no control measures were used (Byker et al. 2013b). Davis and Johnson (2008) found that in competition with no-till soybeans, horseweed above the canopy produced 30,720 to 72,000 seeds plant^{-1} and plants below the canopy produced 7,545 to 11,740 seeds plant^{-1}. Davis et al. (2009a) suggests that horseweed was more likely to become a problem in continuous soybeans compared to a corn-soybean rotation, thus an integrated weed management approach should be used to help reduce horseweed populations in the field.

Horseweed has also been shown to possess allelopathic properties. Shaukat et al. (2003) showed that extracts from horseweed inhibited the germination of tomato (*Solanum lycopersicum*), radish (*Raphanus raphanistrum* subsp. *sativus*), corn (*Zea mays*), mungbean (*Vigna radiata*), wheat (*Triticum aestivum*), and bulrush millet (*Pennisetum glaucum*).

Djurdjević et al. (2012) found that the free phenolics in the soil from horseweed accounted for 74% of the total free phenolics in the soil, and the free phenolic levels were highest while horseweed was in the rosette form and during early flowering. This may lend to horseweed's high competitive ability.

Palmer Amaranth

Biology and Establishment

Palmer amaranth is a C4 summer annual broadleaf plant (Ward et al. 2013) found anywhere from California to Massachusetts, and from Wisconsin to Texas (USDA 2016a). Palmer amaranth has the ability to adapt to many different environments, making it a successful weed. Even when a soil area is exposed to 87% shade, 12% of Palmer amaranth seed can still germinate (Jha et al. 2010b). The optimum temperature range for seed germination is 25 to 35 C, but seed can germinate anywhere from 10 to 40 C (Jha et al. 2010a). Palmer amaranth can emerge anytime from March through October as observed in a study in CA (Keeley et al. 1987). This ability to have growth plasticity enables Palmer amaranth to be an effective competitor. The presence of cover crops prior to Palmer amaranth emergence may suppress and delay its emergence early in the growing season in a crop like soybeans. The persistence of cover crop residue may reduce further emergence and growth of Palmer amaranth through the growing season.

Fecundity and Seed Dispersal

Palmer amaranth is a wind-pollinated dioecious plant with small, smooth seeds that are mainly dispersed by gravity, water and human activity (Ward et al. 2013). Plants grown without competition may produce 200,000 to 600,000 seeds plant^{-1} (Keeley et al. 1987). Even with soybean competition, plant biomass can range from 7.7 to 1143 g plant^{-1} and seed production can range from 1,011 to 796,135 seeds plant^{-1} (Schwartz et al. 2016).

Herbicide Resistance and Competition with Soybeans

Herbicide resistance has evolved quickly in Palmer amaranth. Heap (2017) documents 53 cases of herbicide-resistant Palmer amaranth throughout the world, 50 of which occurred in the United States. Resistance occurs with the following herbicide sites of action in the United States: microtubule inhibitors, photosystem II inhibitors (group 5), ALS inhibitors, EPSPS inhibitors, HPPD inhibitors, and PPO inhibitors. Kansas has documented Palmer amaranth resistance to ALS inhibitors, photosystem II inhibitors (group 5), HPPD inhibitors, and EPSPS inhibitors. Four different types of multiple resistance have been documented of which two populations are resistant to three different sites of action.

Palmer amaranth is a very competitive plant, causing 79% yield loss in soybeans at a density of 8 plants m^{-1} row (Bensch et al. 2003). Palmer amaranth can also lower its light compensation point 24%, increase leaf surface area 42%, and increase height in order to acclimate to 87% shade (Jha et al. 2008). This allows it to still produce seed even in a very competitive environment.

Palmer amaranth produces allelochemicals that may suppress plant growth. Connick et al. (1989) found that several volatile organic compounds from Palmer amaranth residue can suppress the germination of carrots (*Daucus carota* subsp. *sativus*), tomatoes (*Solanum lycopersicum*), and onions (*Allium cepa*). Palmer amaranth stem tissue incorporated into the soil also severely inhibited the growth of roots and shoots of grain sorghum (*Sorghum bicolor*) at concentrations of 50% of maximum seen in field conditions (Menges 1988).

Integrated Weed Management Options

There are many issues surrounding crop production that affect the ways weeds are managed. With the evolution of herbicide-resistant weed populations and environmental concerns, there is a push to manage weeds using a systems approach called integrated weed management (Davis et al. 2009a; Swanton and Weise 1991). A few tools used in this system include cover crops, conservation tillage, crop rotation, and herbicide use.

Cover Crops in Conservation Tillage

Weed Suppression

Tillage was a widely used method of controlling weeds, but it is quickly being replaced by conservation tillage due to its many soil benefits. Tillage is beneficial for controlling weeds by terminating living plants and burying seed. Conservation tillage tends to keep seed on the soil surface which provides many available microsites for small-seeded weeds to germinate (Chauhan et al. 2012). A benefit of keeping seeds on the soil surface may increase weed seed loss by predation. Bagavathiannan and Norsworthy (2013) found that predation caused 60% loss of Palmer amaranth seeds in conservation tillage. Total loss of seed is much lower for seeds that are buried in the soil by tillage. Crop residues did not affect predation rates but more residue cover may aid in keeping small seeds from becoming buried and less available to predation (Bagavathiannan and Norsworthy 2013).

One method that has been considered that may aid in weed suppression in no-till situations is the use of cover crops (Swanton and Weise 1991). Cover crops are plants grown between main crops but not harvested for profit. Some of the potential benefits of cover crops include pest suppression, improved soil and water quality, nutrient cycling efficiency, and cash crop productivity (Snapp et al. 2005). Cover crops can suppress weeds by competing for resources (sunlight, nutrients and water), interrupting life-cycles, producing allelopathic chemicals, changing the soil environment, contributing physical effects, reducing dispersal of propagules, enhancing weed seed decay, and maintaining surface residues (Chauhan et al. 2012; Halde et al. 2014; Nord et al. 2011; Rueda-Ayala et al. 2015; Snapp et al. 2005; Tribouillois et al. 2015; Westgate et al. 2005; Williams et al. 1998).

Some cover crops are better able to compete with weeds than others. Grass cover crops tend to be better competitors with weeds than legumes due to their ability to capture resources more efficiently and produce biomass more quickly (Brainard et al. 2011). Sorghum-sudangrass (*Sorghum x drummondii*) was able to reduce Powell amaranth (*Amaranthus powellii* S. Watson) biomass by 91% whereas soybean and cowpea (*Vigna unguiculata*) monocultures were only able to reduce weed biomass between 22 and 44% (Brainard et al. 2011). Beres et al. (2010) found that winter cereals were more effective than spring cereals at reducing both summer and winter annual dicot weed biomass. Small grain cereal crops such as winter barley (*Hordeum vulgare*), winter triticale (*Triticale hexaploide* Lart.), and winter rye (*Secale cereale*) reduced weed biomass more than hairy vetch (*Vicia villosa*) and Austrian winter pea (*Pisum sativum* subsp. *arvense*) (Silva 2014). However, another study showed that hairy vetch was better able to suppress weeds than winter barley because of the greater biomass hairy vetch produced in western Canada (Halde et al. 2014). Cover crops may also improve crop yield by retaining more moisture compared to bare ground (Liebl et al. 1992; Moore et al. 1994; Westgate et al. 2005).

Cover crops pair well with herbicide programs. With high weed seedbank densities, a cover crop may not be able to suppress weeds well enough alone, but the addition of a postemergence herbicide can reduce weed biomass (Nord et. al. 2011). The addition of spring herbicide applications reduced broadleaf weed biomass to zero for winter cereals, and partial herbicide applications were just as effective, showing some promise of cover crops reducing herbicide use (Beres et. al. 2010). Malik et. al. (2008) showed that using a half rate of atrazine with a rye cover crop had similar weed control levels compared to using a full rate of atrazine with no cover crop. Liebl et. al. (1992) found that herbicides did not significantly improve weed control, while De Bruin et al. (2005) showed that treatments including herbicides had the highest soybean yields whether cover crops were present or not. Davis et al. (2009a) found that winter wheat as a cover crop did not provide a crop yield advantage over residual herbicides.

Even with all the benefits of cover crops, Reddy (2001) found that net returns for all cover crops were negative due to the added expenses of seed, planting, and desiccation. De Bruin et al. (2005) found similar results though some locations did not see a negative economic return from the use of rye.

Wheat

Many studies have been conducted using wheat as a cover crop to suppress weeds. Davis et al. (2007) showed that a fall-sown winter wheat cover crop increased soybean and corn yields by suppressing horseweed through the majority of the growing season. However, depending on only a wheat cover crop for weed control was less effective compared to residual herbicides applied in the fall or spring in one year of the study. The ability of wheat to suppress weeds depends on the weed species. Wheat was not able to reduce common purslane (*Portulaca oleracea*) in corn, but had some reducing power in sunflower (Sci name) under different incorporation schemes (Boz 2003). Extracts of wheat residue were able to inhibit the germination of pigweed species and common purslane (Boz 2003). Wheat cover crop only reduced weed biomass by 21% without herbicides in one study (Norsworthy 2004), but wheat cover crop residue reduced pigweed species canopy volume by 58 to 85% and delayed pigweed species emergence through 21 days after planting soybean (Williams et al. 1998). Soybean had a competitive advantage over weeds following a wheat cover crop, however, too much wheat residue resulted in a reduction of overall soybean density by 53 to 64% (Williams et al. 1998).

Termination method affects how wheat can suppress weeds. Wheat terminated by herbicides and left standing reduced weed biomass 64% compared to wheat that was rolled with a roller-crimper, because of the shading effects of the standing residue on emerging weed populations (Moyer et al. 2000). Winter wheat provided excellent long-term suppression of dandelion (*Taraxacum officinale*) and Canada thistle (*Cirsium arvense*) (Moyer et al. 2000). Winter wheat also reduced redroot pigweed (*Amaranthus retroflexus* L.) biomass 68% by mid-July (Moore et al. 1994) and did not reduce soybean yield (Reddy 2001). Sometimes the addition of tillage prior to planting a cover crop aids in suppressing weeds. DeVore et al. (2013) found that deep tillage prior to wheat in a wheat double-cropped with soybean reduced Palmer amaranth density by 85 to 95% compared to no deep tillage and no prior wheat crop. Even though wheat has been found to be a competitive cover crop, Beres et al. (2010) showed that spring and winter wheat typically were the least competitive compared to other cereal grass species such as spring barley, triticale, and winter rye.

Oat

The vigorous growth of spring oat makes it a good candidate as a cover crop. Spring oat produced the greatest amount of biomass and showed long-term biomass suppression of browntop millet [*Urochloa ramosa* (L.) Nguyen] in soybean in Mississippi compared to other cover crops such as Italian ryegrass (*Lolium multiflorum*), rye, and wheat (Reddy 2001). Fall-sown oat reduced fall weed populations and reduced spring weed biomass, but did not affect weed density in the spring compared to an untreated area in one site-year, and no affect in second site-year in Ontario, Canada (O'Reilly et al. 2011). This may be due to the lower weed densities at the first site-year. Fall-sown oat compared to spring-sown oat tended to produce more biomass, reduce weed biomass, and increase dry bean yield more unless herbicides were used in-crop in Alberta, Canada (Blackshaw 2008).

Spring oat cover crop was shown to be least suppressive of weeds compared to Italian ryegrass and sorghum-sudangrass when all were planted in early March and desiccated in May or June, but all cover crops caused some yield loss in no-till Southern pea due to regrowth (Burgos and Talbert 1996). However, spring oat cover crop residue reduced Palmer amaranth density by the second year of study.

An oat cover crop prior to a cowpea crop with imazethapyr applied preemergence followed by sethoxydim applied postemergence resulted in greater than 89% control of all weeds (Burgos and Talbert 1996). Norsworthy (2004) showed that oat reduced weed biomass 84% without herbicides 3 weeks after corn emergence even though oat biomass was lower than rye which reduced weed biomass by 68%. Oats, rye, and wheat reduced weed biomass greater than 35% by 5 weeks after corn emergence (Norsworthy 2004).

Field Pea

Legumes such as field pea are often used as a cover crop to add nutrients to the soil and there may be potential for weed suppression. Pea was one of the top fixers and accumulators of nitrogen and reduced weed biomass the most compared to common vetch (*Vicia sativa*), faba bean (*Vicia faba*), grass pea (*Lathyrus sativus*), and narrow-leafed lupin (*Lupinus angustifolius*) in a study done in Germany (Rühlemann and Schmidtke 2015). A few studies have shown that pea was able to suppress weeds during cover crop growth since it is able to produce large amounts of biomass quickly, but cover crop residues degrade quickly (Silva 2015). Legume cover crops produce less biomass than cereal cover crops (Silva 2015). No yield benefit was observed for corn, sunflower (Dorn et al. 2015) or cotton (*Gossypium hirsutum*) (Norsworthy et al. 2010), and field pea can be hard to terminate with herbicides (Norsworthy et al. 2010). The addition of herbicides to field pea cover crop system may improve weed suppression.

Cereal and Legume Mixtures

To take advantage of the benefits legumes can offer while still providing better weed suppression, mixtures with grass species has been considered. Establishment of field pea can be challenging and can be slow to develop a canopy which may cause oat and pea mixes to be a poor cover crop for weed suppression (Brennan and Smith 2005). Increasing the seeding rate of these crops in a mixture may aid in cover crop development. Campiglia et al. (2010) showed that the use of a vetch/oat mix cover crop produced the highest cover crop biomass and increased tomato yields, but weed biomass production was also highest in vetch/oat mix cover crop and residue. Stand inconsistencies in peas caused oat/legume mix to have less biomass than oats, and did not reduce weed biomass and weed seed production as much as oats (Brennan and Smith 2005). However, when incorporated into the soil, oats and an oat/legume mix resulted in similar weed seed emergence rates early in the season (Brennan and Smith 2005). Another study has shown that a mix of hairy vetch and oat produced the highest cover crop biomass while oats produced the lowest (Campiglia et al. 2010). Cover crop mixtures of grasses and legumes may have some success suppressing weeds if establishment is successful.

Rye

Rye has been a common choice as a cover crop to suppress weeds due to allelopathic compounds, its vigorous growth and competitive ability (Boz 2003; Dhima et al. 2006; Didon et al. 2014; Nord et al. 2011). Allelopathic potential is seen in studies where plant competition for sunlight, nutrient, and water resources was not the main cause in weed seed germination or biomass reduction. Experiments using rye straw, residues, or extracts in lab and greenhouse conditions have shown reductions in germination and growth in shepherdspurse (*Capsella bursa-pastoris*), silky windgrass (*Apera spica-venti*), scentless false mayweed (*Tripleurospermum inodorum*), jungle rice (*Echinochloa colonum)*, redroot pigweed, barnyardgrass (*Echinochloa crus-galli*), and bristly foxtail (*Setaria verticillata*) (Boz 2003; Dhima et al. 2006; Didon et al. 2014). In field conditions, rye was able to reduce the germination by 14 to 50% and biomass growth by 40 to 97% of barnyardgrass, foxtail species, pigweeds, dandelion, Canada thistle, yellow nutsedge (*Cyperus esculentus*), Florida pusley (*Richardia scabra* L.), large crabgrass (*Digitaria sanguinalis*), wild radish (*Raphanus raphanistrum*), spreading dayflower (*Commelina diffusa*), ivyleaf morningglory (*Ipomoea hederacea*), velvetleaf (*Abutilon theophrasti*), common lambsquarters (*Chenopodium album*), and common cocklebur (*Xanthium strumarium*) (De Bruin et al. 2005; Liebl et al. 1992; Malik et al. 2008; Moore et al. 1994; Moyer et al. 2000; Reddy 2001; Williams et al. 1998). Rye cover that is chemically-terminated tends to reduce weed biomass more than mechanically-terminated rye due to greater light interception from upright residue arrangement (Moyer et al. 2000; Westgate et al. 2005). The use of a rye cover crop may not always reduce weed biomass and density and can be dependent on the year (O'Reilly et al. 2011). Rye may also delay weed emergence. DeVore et al. (2013) found that Palmer amaranth emergence was delayed after termination of a rye cover crop compared to treatments with no cover crop. Fall-seeded rye has been shown to reduce weed biomass further with the application of herbicides (Blackshaw 2008). Rye has been shown to produce higher amounts of biomass compared to oats and wheat and reduced weed biomass 68% without herbicides 3 weeks after corn emergence (Norsworthy 2004).

The effects of a rye cover crop on the following crop varies. The use of a rye cover crop without herbicides increased corn silage yield 15 to 20% compared to the no cover and no herbicide check, but corn yield was 10 to 31% less compared to corresponding herbicide-treated plots (Dhima et al. 2006). rye did not affect cotton yield (Korres and Norsworthy 2015) Soybeans were given a competitive advantage over weeds when a rye cover crop was used, but too high of residue could reduce soybean stand 53 to 64% (Williams et al. 1998), or not at all (De Bruin et al. 2005).Rye caused slower development, taller height, reduced dry matter accumulation, and delayed maturity in soybeans compared to rye-free soybeans (Westgate et al. 2005) and soybean had 69 % increased yield in rye cover crop compared to bare ground (Moore et al. 1994).

Herbicides

Even with the development of herbicide-resistant weeds, herbicides are still one of the main weed management tools used (Beckie 2006). The use of glyphosate has encouraged the adoption of no-till practices, but it has also resulted in the development of glyphosate-resistant weeds (Johnson et al. 2009). To combat herbicide-resistant weeds, the use of preemergence and postemergence herbicides and multiple effective modes of action are encouraged (Davis et al. 2009a).

Horseweed Control

Herbicides for horseweed control need to be applied timely because horseweed can emerge in both the fall and the spring and is harder to terminate with herbicides after bolting in April or May. Residual herbicides applied in the fall or spring with glyphosate applied postemergence in-crop reduced horseweed density and seedbank densities more than glyphosate alone (Davis et al. 2007). Also, spring-applied herbicides were more effective than fall-applied herbicides because 90% of horseweed emerged in the spring at this location (Davis et al. 2007). If glyphosate-resistant horseweed is present, a good postemergence residual program containing different sites of action is encouraged (Byker et al. 2013b; Byker et al. 2013c; Chahal and Johnson 2012; Davis et al. 2009a). Relying on pre-emergence herbicides only resulted in the highest horseweed biomass due to the emergence of horseweed after the effectiveness of the residual herbicide had diminished (Reddy 2001). In Canada at a location where the majority of the horseweed emerged in the spring, spring pre-plant applications of s-metolachlor, flumetsulam, and clopyralid followed by post-emergence applications of 2,4-D choline/glyphosate DMA in corn provided 97 to 100% horseweed control (Ford et al. 2014). Horseweed control with 2,4-D may not be effective unless plants are small, densities are low, and it is applied around the time horseweed emerges (Davis et al. 2010). Some populations of horseweed may be more affected by certain auxinic herbicides than others, but in general dicamba was more effective than 2,4-D for horseweed control (Kruger et al. 2010). Using a residual pre-emergent herbicide with an effective post-emergence herbicide should provide the best season-long control of horseweed populations.

Palmer Amaranth Control

Pre-emergence herbicides are key for control because Palmer amaranth can emerge anytime from March to October (Keeley et al. 1987). Palmer amaranth control was 95% or better when pre-emergence herbicides were used while relying on post-emergence fomesafen or glufosinate only provided 52 to 69% control (Bell et al. 2015b). Soybeans planted in 19, 45, or 90-cm rows did not provide greater than 90% groundcover until 40 to 50 days after planting. Increased seeding rates of soybeans drilled at 383,000 to 588,000 seeds ha^{-1} provided 64 to 84% control of Palmer amaranth even when no postemergence herbicide was used, and a preemergence application of pyroxasulfone plus flumioxazin gave greater than 90% control through 60 days after planting soybean (Bell et al. 2015a). Flumioxazin and pyroxasulfone applied preemergence provided 95% or greater control of Palmer amaranth through soybean harvest, regardless of rye or wheat cover crops, soybean cultivar, or tillage method (Bell et al. 2016). Poor control was observed when no preemergence residual herbicides were evaluated (Bell et al. 2016). Glyphosate-resistant Palmer amaranth were controlled in a no-crop study when a preemergence herbicide was followed by a postemergence herbicide applied 6 to 7 weeks after the pre-emergence herbicide, and utilizing three or more herbicide sites of action (Meyer et al. 2015). For example, flumioxazin and pyroxasulfone applied pre-emergence reduced Palmer amaranth density to 8% of the nontreated check (Meyer et al. 2015). The use of flumioxazin and pyroxazulfone preemergence followed by postemergence herbicides should provide control of Palmer amaranth in soybean fields.

Conclusion

Horseweed as a winter annual and Palmer amaranth as a summer annual are both competitive and problematic weeds that may cause yield losses in no-till soybeans in Kansas. The evolution of herbicide resistance in these weeds requires the study of other methods of weed suppression. Knowing how these two weeds grow in Kansas is important for prescribing effective control methods. Many cover crops have been studied with variable success for weed suppression. Some weed suppression benefits have been seen with the use of cover crops and herbicide programs combined. Preemergence herbicides were not inactivated by surface residues (Liebl et al. 1994), which makes the use of cover crops with herbicide programs less of a concern. Studying the interactions of cover crops and herbicide programs on horseweed and

Palmer amaranth populations may provide additional methods producers may use to control these problem weeds.

The overall research goal is to examine how cover crops and herbicide programs can be integrated and used to suppress horseweed and Palmer amaranth populations in no-till soybean in eastern KS. Specific goals and objectives are to:

1. improve our understanding of horseweed population dynamics by (1) determining the seedling emergence patterns for horseweed across locations in eastern KS and (2) determining if there is a geographical influence on horseweed emergence timing and survival that cause more horseweed seedlings to emerge in the spring at southern locations (Chapter 2).
2. evaluate Palmer amaranth suppression with cover crop and herbicide programs by (1) comparing biomass accumulation among cover crops at time of termination, (2) determining reduction in Palmer amaranth and other weed biomass and density in response to cover crops and herbicide programs, and (3) quantifying the impact of these programs on uncontrolled Palmer amaranth and other weeds on soybean yield (Chapter 3), and
3. evaluate combined horseweed and Palmer amaranth suppression by (1) determining the level of horseweed, Palmer amaranth, and total weed suppression, and impact on soybean growth in response to cover crop, herbicide programs, and an integrated weed management program, and (2) quantify soybean yield in response to cover crop, herbicide programs, and horseweed and Palmer amaranth competition (Chapter 4).

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Chapter 2 - Emergence Timing and Survival of Horseweed (*Conyza canadensis*) Populations in Eastern Kansas

Abstract

Horseweed can be a problematic weed in no-till soybeans in Kansas. A study was conducted in eastern Kansas to determine the emergence pattern and survival of horseweed. Populations were observed at four locations in 2014-2015 and at five locations in 2015-2016. Observation rings were established along a field edge at each location in October 2014 and September 2015. In four pairs of rings, horseweed seedling and leaf number per seedling were recorded at two-week intervals and seedlings pulled from four rings, while survival was tracked in the other four rings. Cumulative GDD among locations generally increased when moving from north to south locations. Cumulative GDD required to reach 50% horseweed emergence increased from north to south. In 2015-2016, calendar date for 50% emergence was later at the southern locations. A majority of horseweed in eastern KS emerged in the fall with some spring emergence observed in Ottawa, Iola, and Parsons in 2014-2015. Very little spring emergence occurred at any location in 2015-2016. With warmer winter maximum temperatures and cooler winter minimum temperatures, overwinter survival of horseweed seedlings was low because of frost-heaving in Iola and Parsons or self-thinning in Ottawa and Oswego in 2015-2016.

Introduction

Horseweed [*Conyza canadensis* (L.) Cronq.] can be a problematic weed in no-tillage soybean production (Bruce and Kells 1990; Byker et al. 2013). To determine what practices may work best to control this weed species, its life cycle must be understood. Horseweed usually has a winter annual lifecycle where the seeds germinate in the fall anytime from August through October. The emerged plant overwinters as a rosette, bolts in April or May, flowers in July, and disperses seed in August (Regehr and Bazzaz 1979; Weaver 2001). However, some studies have shown that a sizeable portion of some horseweed populations have a summer annual lifecycle where seedlings emerge in the spring, bolt, and produce seed within the same year (Buhler and Owen 1997; Davis et al. 2007; Davis and Johnson 2008). Some studies suggest that few seeds are left in the soil seedbank from previous years to produce new seedlings (Bhowmik and Bekech 1993), while others have shown a large proportion of emergence from seed that were dormant in the soil as well as from seed that were freshly dispersed (Regehr and Bazzaz 1979).

Two environmental factors that affect timing of horseweed germination are soil moisture and temperature. Seedling germination tends to increase after rainy periods when soil moisture is high (Regehr and Bazzaz 1979). For winter annual weeds, seed dormancy is alleviated by high temperatures experienced during summer, while low temperatures during winter induce seed dormancy. The opposite is true for summer annuals (Batlla and Benech-Arnold 2007). Germination base temperature can vary depending on the geographic location of a horseweed population. The base temperature for a horseweed population in California was 13 C (Steinmaus et al. 2000), but the germination base temperatures of populations from Ontario, Iran, the UK, and Spain ranged from 8 to 14 C (Tozzi et al. 2013). In eastern Kansas, average temperatures and rainfall tend to increase when moving from north to south (ACIS 2017). These environmental differences could affect the emergence patterns of horseweed, with a shift from fall to spring emergence as one moves from north to south. No studies have been conducted in Kansas to determine horseweed emergence patterns.

Survival overwinter is also important for understanding horseweed establishment. The main cause of death of fall-emerging horseweed plants in Illinois fields was frost heaving during winter, but if the rosettes were large with sufficient lateral roots to prevent frost heaving, their overwintering survival was greater than for spring-emerging plants (Regehr and Bazzaz 1979). In Ontario, warm weather in March followed by cold temperatures reduced fall-established horseweed survival by 50% and reduced subsequent growth and fecundity (Tozzi et al. 2014).

The overall goal of this project was to improve our understanding of horseweed population dynamics in Kansas. The specific objectives of this study were to 1) determine the seedling emergence patterns for horseweed across locations in eastern Kansas and 2) determine if there is a geographical influence on horseweed emergence timing and survival that cause more horseweed seedlings to emerge in the spring at southern locations.

Materials and Methods

Observations of horseweed emergence and survival

Observation locations were identified and established in the fall on October 15 and 16, 2014, and on September 10, 16, and 30, 2015, across eastern Kansas, approximately north to south along longitude 95.5°W. The four locations in 2014 included Hiawatha, Ottawa, Iola, and Parsons, while the five locations in 2015 included Hiawatha, Topeka, Ottawa, Iola, and Oswego. Details on each location, establishment date, and soil types are in Table 2.1 and a map of the locations is included in Figure 2.1.

At each location four pairs of 20-cm diameter PVC rings were placed at field edges where horseweed populations were known to occur. The rings were kept in place using landscape staples. For one ring in each pair, the number of horseweed seedlings and leaf number per seedling were recorded and the plants were left to track growth and survival throughout the study. In the other ring of each pair, the number of horseweed seedlings and leaf number per seedling were recorded and seedlings were removed to track emergence timing in the absence of competition. All other weed seedlings were removed from both rings. Observations were recorded every two weeks from time of establishment until April 28, 2015 and April 8, 2016.

Statistical analysis

Count data (seedling number ring^{-1}) were converted to cumulative proportional emergence based on maximum final count, and related to cumulative growing degree days (GDD). The calculation for GDD is:

$$GDD = \frac{T_{max}+T_{min}}{2} - T_{base} \qquad \text{Equation 2.1}$$

where T_{max} was the maximum temperature (C) for each day, T_{min} was the minimum temperature (C) for each day, and T_{base} was the base temperature (13C) for horseweed emergence (Steinmaus et al. 2000). Maximum and minimum temperatures for each day and location were obtained from the Applied Climate Information System (ACIS). Daily GDDs were summed over time to determine cumulative GDD starting from August 1 both years. The relationship between cumulative proportional horseweed emergence and cumulative GDD for each year and location were modeled using a nonlinear, 3-parameter sigmoid regression in SigmaPlot v. 12.0 (Systat Software Inc., San Jose, CA):

$$y = \frac{a}{(1+\exp\left(\frac{-(x-x_0)}{b}\right))} \qquad \text{Equation 2.2}$$

where y is the proportion of total emerged horseweed plants, x is the cumulative GDD, x_o is the cumulative GDD for 50% horseweed emergence (inflection point), a is the maximum proportion of total emerged, and b is the slope of the line at the inflection point. To determine if locations had different emergence patterns, the regression lines were compared using a pairwise F-test:

$$F = \frac{(SSResid_R - SSResid_F)/(dfResid_R - dfResid_F)}{SSResid_F/dfResid_F} \qquad \text{Equation 2.3}$$

where F is the calculated value, $SSResid_R$ is the residual sum of squares for one line fit to data from two locations, $SSResid_F$ is the sum of the residual sums of squares for two separate lines fit to the data for each location, $dfResid_R$ is the residual degrees of freedom for one line fit to the data, and $dfResid_F$ is the sum of the degrees of freedom for two separate lines fit to the data. The calculated F-value was compared to the distribution of F (Table A 14, Snedecor and Cochran 1989) with df determined using:

$$\frac{df_N}{df_D} = \frac{(dfResid_R - dfResid_F)}{dfResid_F} \qquad \text{Equation 2.4}$$

where df_N is the degrees of freedom in the numerator, df_D is degrees of freedom in the denominator, $dfResid_R$ is the residual degrees of freedom for one line fit to the data, and $dfResid_F$ is the sum of the degrees of freedom for two separate lines fit to the data. If the calculated value of F was greater than the F-value in the Table, two separate lines were different than one line fit to all the data for both locations.

Results and Discussion

Temperature and precipitation patterns and amounts were different among locations and years across eastern Kansas. In both years, the maximum temperatures for each location throughout the study were warmer, while the minimum temperatures for each location were cooler than their corresponding 30-year averages (Tables 2.2 to 2.6). The warmer winter maximum temperatures may have allowed for continued horseweed growth during the winter, resulting in reduced winter hardiness that may have contributed to lower survival because of the cooler minimum temperatures. Total rainfall in Highland, Ottawa, and Iola in 2014-2015 was less than the 30-year average. Little rainfall occurred from the end of February through the beginning of April at all locations (Tables 2.2, 2.4 through 2.6). Total rainfall was less than the 30-year average at Ottawa and was greater than the 30-year average in Iola and Oswego in 2015-2016. October had no rain at Ottawa with smaller rain events occurring before and after that time period, which reduced horseweed germination during that time. Timely rainfall events promoted the emergence of new flushes of horseweed in the fall. For example, at Ottawa in 2015-2016, rain events after the dry spell in October resulted in a large increase in newly emerged seedlings (Figure 2.2).

Average temperatures and total precipitation for each year increased when moving from north to south. This would suggest locations farther south would be more conducive to the emergence of horseweed, however, increased temperatures in those areas may also increase evaporation rates. The weather station for Topeka was located near an airport, which may have affected the temperatures and rainfall at that site due to the presence of buildings and other structures. Because the field sites were located some distance away from many of the weather stations used, the weather experienced by the field sites may differ from the weather data that was collected.

More GDD were accumulated over time as one moved from north to south (Figure 2.3). However, Iola in 2014-2015 and Topeka in 2015-2016 had greater cumulative GDD than what was expected. This may have been due to differences in the environment for the weather stations used such as the locations of buildings, concrete, or asphalt compared to other locations. This may explain some of the earlier emergence that was seen in locations farther south. From mid-November on, GDD accumulation rates were similar among locations through the end of the April (Figure 2.3).

In 2014-2015, observation sites were established after horseweed seedlings had already begun emergence. On the day of establishment, emergence ranged from 2 to 24 plants ring^{-1} among locations. In 2015-2016, horseweed seedlings were already established at Hiawatha, Topeka, and Oswego by the day of establishment, and emergence ranged from 1 to 19 plants ring^{-1} among those three locations. No horseweed had emerged by the day of establishment at Ottawa or Iola in 2015-2016. Total cumulative emergence was much lower at Parsons in 2014-2015 with only an average of 8.5 seedlings emerged compared to the other three locations (average of 18 emerged seedlings) (Table 2.8). In 2015-2016, total cumulative emergence was greatest at Ottawa with 257 plants ring^{-1} followed by Oswego with 124 plants ring^{-1} and was lowest at Hiawatha with 5.8 plants ring^{-1}.

Cumulative emergence of horseweed by GDD in 2014-2015 differed among locations based on the F-test (Figure 2.4). The most northern location, Hiawatha, required the fewest cumulative GDD for 50% horseweed emergence (Table 2.8), followed by Ottawa, Parsons, and Iola. Cumulative horseweed emergence in 2015-2016 differed among locations (Figure 2.4) with Hiawatha and Topeka being similar and requiring the fewest cumulative GDD to reach 50% emergence (Table 2.7). The calendar dates for 50% horseweed emergence ranged from September 6 at Topeka to October 23 at Oswego, moving from north to south (Table 2.8). Across both years, more GDD were accumulated before horseweed began to germinate and emerge at more southern locations, likely waiting for cooling environmental conditions prior to winter that are optimum for winter annual weed species germination. For winter annual species, the warm temperatures of summer alleviate seed dormancy which promotes the germination and emergence of seed in the fall when temperatures and moisture are adequate (Batlla and Benech-

Arnold 2007). The cycling of cooling in the fall may be such that the base temperature for germination is reached later in the season in the south compared to earlier in the north.

In eastern Kansas, majority of horseweed seedlings emerged in the fall with spring-emerging horseweed only accounting for 5.5% of the population at Hiawatha, 14.7% at Iola, and 9.7% at Parsons in 2014-2015 (Figure 2.5). No spring emergence was observed at any of the locations in 2015-2016 (Figure 2.6). Maximum horseweed emergence in rings where plants were not removed occurred in late October at all locations in 2014-2015 (Figure 2.7). These horseweed populations were reduced after the first fall frost at all locations except Hiawatha (Figure 2.7). A complete picture of fall emergence patterns in 2014 may be limited because rings were established late and only two observations were taken. Maximum horseweed emergence in 2015-2016 occurred in September for Ottawa, Topeka, and Iola, in late October for Hiawatha, and in late November for Oswego (Figure 2.2). More seedlings emerged in 2015-2016 at Ottawa and Iola than 2014-2015 and Oswego also had high seedling emergence. Population densities at Hiawatha were much lower in 2014-2015 than 2015-2016. At Ottawa and Oswego, horseweed populations were reduced prior to the first frost in 2015-2016 because of very high seedling emergence and self-thinning (Figure 2.2) as well as low rainfall amounts in October 2015 at those locations (Tables 2.4 and 2.6). Horseweed survival rates ranged from 4 to 67% at Ottawa, Iola, Parsons, and Oswego, the four most southern locations, compared to 70 to 90% survival at Hiawatha and Topeka (Table 2.7). Overall, horseweed emergence was less at Hiawatha and Topeka in 2015-2016 compared to other locations. Horseweed populations were reduced due to frost-heaving over the winter or self-thinning because of high plant densities. In 2014-2015, Iola and Parsons experienced 51 and 56% survival, respectively, possibly due to frost heaving or winter kill. In 2015-2016, Ottawa and Oswego experienced only 6 and 15% survival, respectively, most likely due to self-thinning of high densities or a lack of rainfall in October, and Iola experienced 4% survival due to frost heaving because of the higher clay content of the soil (personal observation). Frost-heaving reduced horseweed survival rates to 14, 18, and 84% at three locations in Illinois by March in 1974 and in general smaller horseweed rosettes tended to experience greater mortality rates than larger rosettes (Regehr and Bazzaz 1979).

Conclusions

The majority of horseweed seedlings emerge in the fall in eastern KS though there may be a few seedlings that emerge in the spring on the year, and not just in the southern portion of the state. Cumulative GDDs for each location tended to increase as one moves south. The calendar date for 50% horseweed emergence tended to be later the farther south the location in 2015-2016. Horseweed emergence patterns across locations suggested that more cumulative GDDs are needed by horseweed populations for emergence the farther south the population is located, however, this may be due to cooler temperatures occurring later in the year the farther south a location. Ottawa, Iola, Parsons, and Oswego tended to experience greater horseweed mortality compared to Hiawatha and Topeka which may be due to environment or over-population. Overall, the majority of horseweed emerge in the fall across eastern KS and overwinter survival was affected by dry fall conditions, self-thinning of high density stands, and frost-heaving.

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Tables and Figures

Table 2.1 Study locations, soil types, and establishment date at each location.

Location	Location Name	Latitude	Longitude	Soil Type	Establishment Date
Hiawatha	Klinefelter Farm	39.841746°N	95.477110°W	Kennebec silt loam	October 16, 2014 September 16, 2015
Topeka	Kansas River Valley Experiment Station	39.077021°N	95.769316°W	Eudora-Bismarckgrove silt loam	September 30, 2015
Ottawa	East Central Kansas Experiment Station	38.541808°N	95.241214°W	Woodson silt loam	October 15, 2014 September 10, 2015
Iola	farmer's field	37.908620°N	95.317883°W	Kenoma silt loam, Zaar silty clay	October 15, 2014 September 10, 2015
Parsons	KSU Southeast Agricultural Research Center	37.363472°N	95.290296°W	Parsons silt loam	October 15, 2014
Oswego	farmer's field	37.140615°N	95.230770°W	Parsons silt loam	September 10, 2015

Table 2.2 Monthly maximum, minimum, and 30-year average temperatures (C) and monthly and 30-year average precipitation for the 2014-2015 and 2015-2016 growing seasons for Hiawatha, KS.

Month	Temperature						Precipitation		
	2014-2015		2015-2016		30-yr Average		2014-2015	2015-2016	30-yr Average
	Max	Min	Max	Min	Max	Min			
	C						mm		
August	35.0	10.0	32.8	7.2	30.4	17.6	120	51	96
September	33.9	1.1	35.0	7.8	26.2	12.4	79	50	92
October	30.6	-0.6	30.6	-1.1	19.6	5.9	80	20	68
November	20.6	-12.8	26.1	-5.0	11.0	-1.1	4	97	48
December	15.6	-13.3	17.8	-11.1	3.4	-7.6	36	70	30
January	22.8	-19.4	17.8	-21.1	2.4	-9.3	10	15	20
February	16.7	-21.1	23.9	-9.4	5.2	-7.3	40	12	29
March	29.4	-14.4	25.6	-8.3	11.2	-1.3	32	40	55
April	27.8	-2.2	27.8	-4.4	18.0	5.4	53	177	86

Table 2.3 Monthly maximum, minimum, and 30-yr average temperatures (C) and monthly total and 30-yr average precipitation for the 2015-2016 growing season for Topeka, KS.

Month	Temperature				Precipitation	
	2015-2016		30-yr Average		2015-2016	30-yr Average
	Max	Min	Max	Min		
	C				mm	
August	33.9	10.0	31.4	19.0	79	108
September	35.6	9.4	26.9	13.5	189	93
October	30.6	-1.7	20.2	7.1	23	77
November	26.1	-3.3	12.6	0.6	130	47
December	21.1	-7.2	5.4	-5.4	69	34
January	20.0	-16.1	4.4	-6.9	23	22
February	25.6	-8.3	7.2	-4.6	9	34
March	26.7	-4.4	13.6	0.7	58	63
April	28.3	-1.7	19.3	6.4	176	90

Table 2.4 Monthly maximum, minimum, and 30-yr average temperatures (C) and monthly total and 30-yr average precipitation for the 2014-2015 and 2015-2016 growing seasons for Ottawa, KS.

Month	Temperature						Precipitation		
	2014-2015		2015-2016		30-yr Average		2014-2015	2015-2016	30-yr Average
	Max	Min	Max	Min	Max	Min			
	C						mm		
August	37.8	11.7	33.9	10.6	31.3	18.9	46	68	103
September	35.6	2.8	34.4	8.3	26.7	13.6	143	69	105
October	29.4	1.7	30.0	-2.2	20.3	7.3	154	9	84
November	22.2	-13.3	24.4	-4.4	12.5	0.6	11	118	69
December	16.1	-15.0	19.4	-7.2	5.3	-5.5	61	112	45
January	23.3	-18.3	20.0	-16.7	4.2	-7.1	8	18	31
February	20.0	-15.6	23.9	-8.9	7.4	-5.1	13	16	37
March	27.2	-11.7	25.6	-5.0	13.2	0.2	15	40	68
April	30.0	-3.3	27.2	-2.2	18.8	6.1	99	96	98

Table 2.5 Monthly maximum, minimum, and 30-yr average temperatures (C) and monthly total and 30-yr average precipitation for the 2014-2015 and 2015-2016 growing seasons for Iola, KS.

Month	Temperature						Precipitation		
	2014-2015		2015-2016		30-yr Average		2014-2015	2015-2016	30-yr Average
	Max	Min	Max	Min	Max	Min			
	C						mm		
August	35.0	13.3	37.8	11.7	31.3	19.3	40	209	93
September	33.3	3.9	35.6	9.4	26.8	14.0	178	41	109
October	29.4	2.2	31.7	-0.6	20.6	7.8	90	40	96
November	22.8	-15.6	24.4	-2.8	13.2	1.4	23	160	67
December	16.1	-15.0	21.1	-6.7	5.8	-4.8	73	92	45
January	22.8	-17.8	21.1	-16.1	4.8	-6.6	6	20	33
February	21.7	-15.6	25.0	-8.3	8.1	-4.3	29	13	41
March	26.7	-11.1	25.6	-3.9	13.7	0.7	23	28	77
April	34.4	-1.1	31.1	-2.2	19.3	6.5	117	153	104

Table 2.6 Monthly maximum, minimum, and 30-yr average temperatures (C) and monthly total and 30-yr average precipitation for the most southerly locations, Parsons 2014-2015 and Oswego 2015-2016.

Location	Month	Temperature				Precipitation	
		2014-2015		30-yr Average		2014-2015	30-yr Average
		Max	Min	Max	Min		
		C				mm	
Parsons	August	37.8	11.7	32.4	19.2	46	84
	September	35.6	6.7	27.4	14.2	221	119
	October	30.0	2.2	20.9	7.5	151	98
	November	22.8	-14.4	13.7	1.8	30	75
	December	17.8	-12.8	6.8	-4.1	40	52
	January	23.3	-17.2	5.6	-5.7	12	36
	February	21.7	-14.4	8.7	-3.3	16	45
	March	26.1	-8.9	13.9	1.7	43	81
	April	28.3	-1.7	19.5	6.9	177	111
		2015-2016		30-yr Average		2015-2016	30-yr Average
Oswego	August	36.1	10.6	32.6	19.1	157	90
	September	34.4	8.3	27.6	14.1	38	124
	October	29.4	-0.6	21.2	7.1	40	105
	November	24.4	-6.1	14.1	1.1	206	76
	December	21.1	-7.8	7.1	-4.9	143	58
	January	21.7	-14.4	5.8	-6.4	24	42
	February	25.6	-10.0	9.1	-4.2	13	50
	March	25.6	-5.0	14.3	1.0	123	88
	April	28.3	-2.2	19.8	6.3	129	110

Table 2.7 Average, minimum, and maximum cumulative emerged horseweed, and average, minimum and maximum final density among keep rings and average percent of cumulative total survived in keep rings in 2014-2015 and 2015-2016 by location.

Year	Location	Cumulative Total (SE)	Min Cumulative Total	Max Cumulative Total	Final Density (SE)	Min Final Density	Max Final Density	Percent of Cumulative Survived
		plants ring^{-1}						%
2014-2015	Hiawatha	20.0 (8.4)	9	45	18.0 (8.4)	8	43	90.0
	Ottawa	17.8 (2.6)	10	21	12.0 (2.2)	6	16	67.4
	Iola	16.3 (4.6)	8	29	8.3 (3.2)	2	17	50.9
	Parsons	8.5 (1.0)	6	11	4.8 (0.9)	2	6	56.5
2015-2016	Hiawatha	5.8 (1.0)	4	8	4.5 (1.3)	2	8	77.6
	Topeka	13.3 (1.4)	10	16	9.3 (2.3)	3	13	69.9
	Ottawa	257.0 (17.9)	231	308	15.8 (4.3)	8	27	6.1
	Iola	41.5 (23.3)	13	111	1.5 (0.9)	0	3	3.6
	Oswego	124.0 (24.3)	66	185	18.3 (8.3)	2	37	14.8

Table 2.8 Parameter estimates describing the relationship between cumulative horseweed emergence and cumulative GDD using Equation 2.2 and the predicted date of 50% emergence.

Year	Location	Parameter Estimates[a]			R^2	Date of 50% Emergence
		a (SE)	b (SE)	x_0 (SE)		
		Proportion		GDD		
2014-2015	Hiawatha	1.00 (0.02)	46.9 (7.1)	568 (5.1)	0.98	October 15, 2014
	Ottawa	1.00 (0.01)	14.1 (9.2)	661 (1.8)	0.99	October 15, 2014
	Iola	0.96 (0.04)	51.8 (13.2)	729 (11.6)	0.88	October 17, 2014
	Parsons	0.95 (0.02)	19.3 (12.1)	714 (4.0)	0.93	October 15, 2014
2015-2016	Hiawatha	1.02 (0.03)	74.0 (20.6)	452 (15.8)	0.87	September 16, 2015
	Topeka	1.00 (0.01)	95.0 (20.8)	423 (48.4)	0.98	September 6, 2015
	Ottawa	0.98 (0.01)	20.5 (6.5)	542 (12.9)	0.99	September 22, 2015
	Iola	0.96 (0.01)	20.6 (9.4)	560 (21.8)	0.97	September 22, 2015
	Oswego	1.22 (0.17)	132.5 (31.0)	755 (45.2)	0.83	October 23, 2015

[a] a is maximum proportion of total horseweed emergence, b is slope at the inflections point, and x_0 is cumulative GDD for 50% horseweed emergence.

Figure 2.1 Map of the locations used for the study. Stars indicate field site locations.

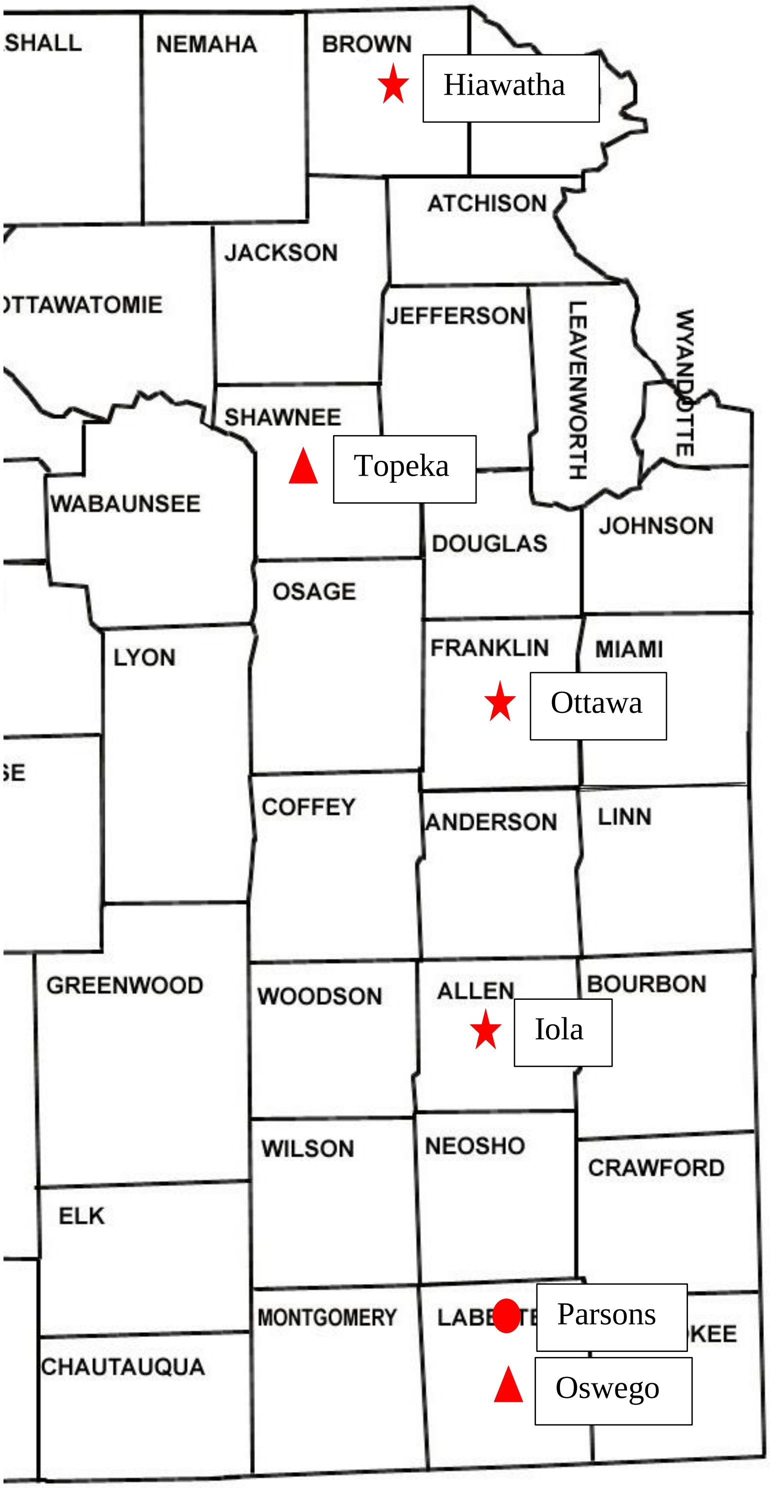


Figure 2.2 Proportion of maximum horseweed emergence in keep rings by calendar date in 2015-2016. Vertical lines represent the beginning of fall (solid), winter (dashed) and spring (dot and dash). Open circles represent the first frost for each location. Error bars represent the standard error of the mean.

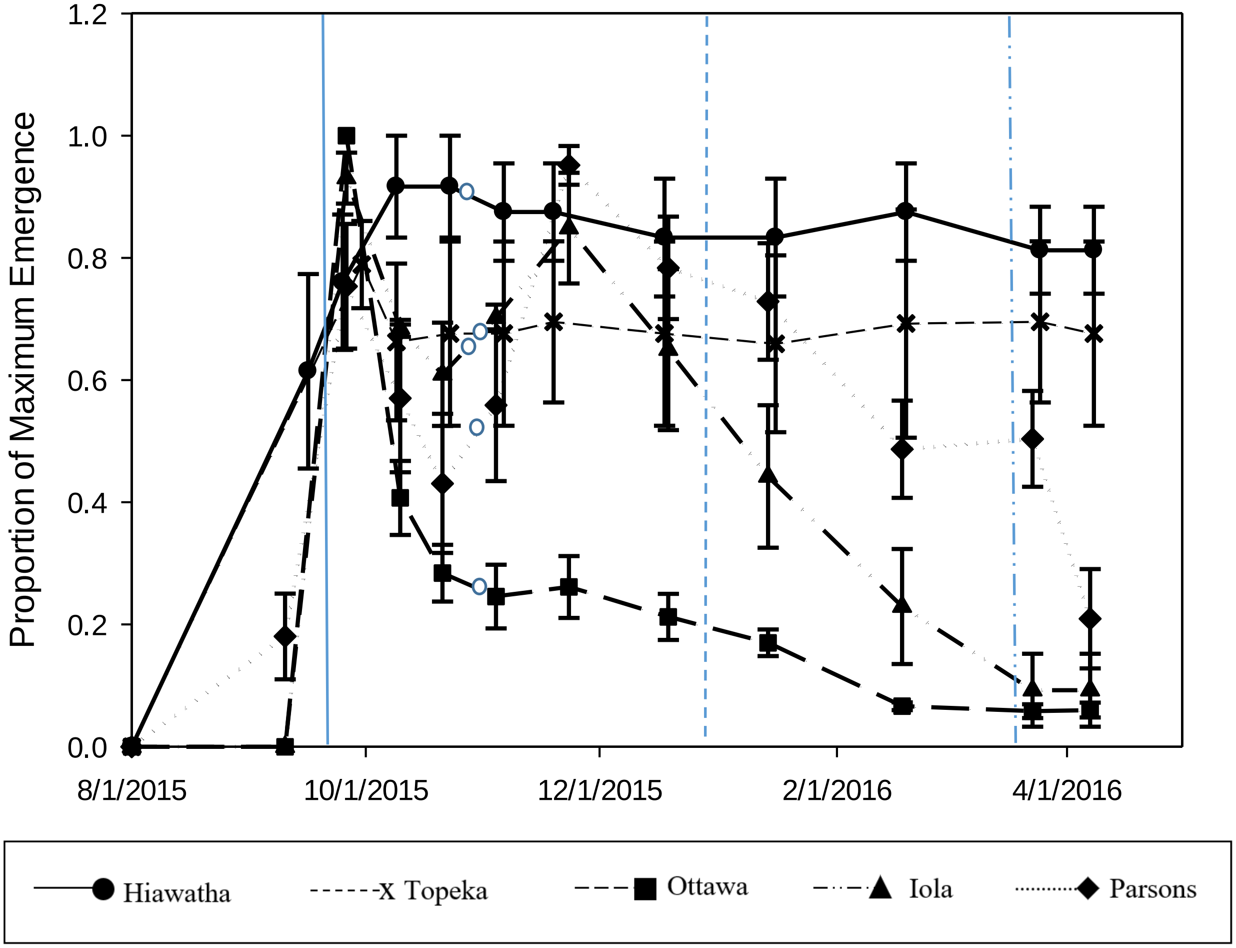


Figure 2.3 Cumulative GDD by calendar date in (A) 2014-2015 and (B) 2015-2016.

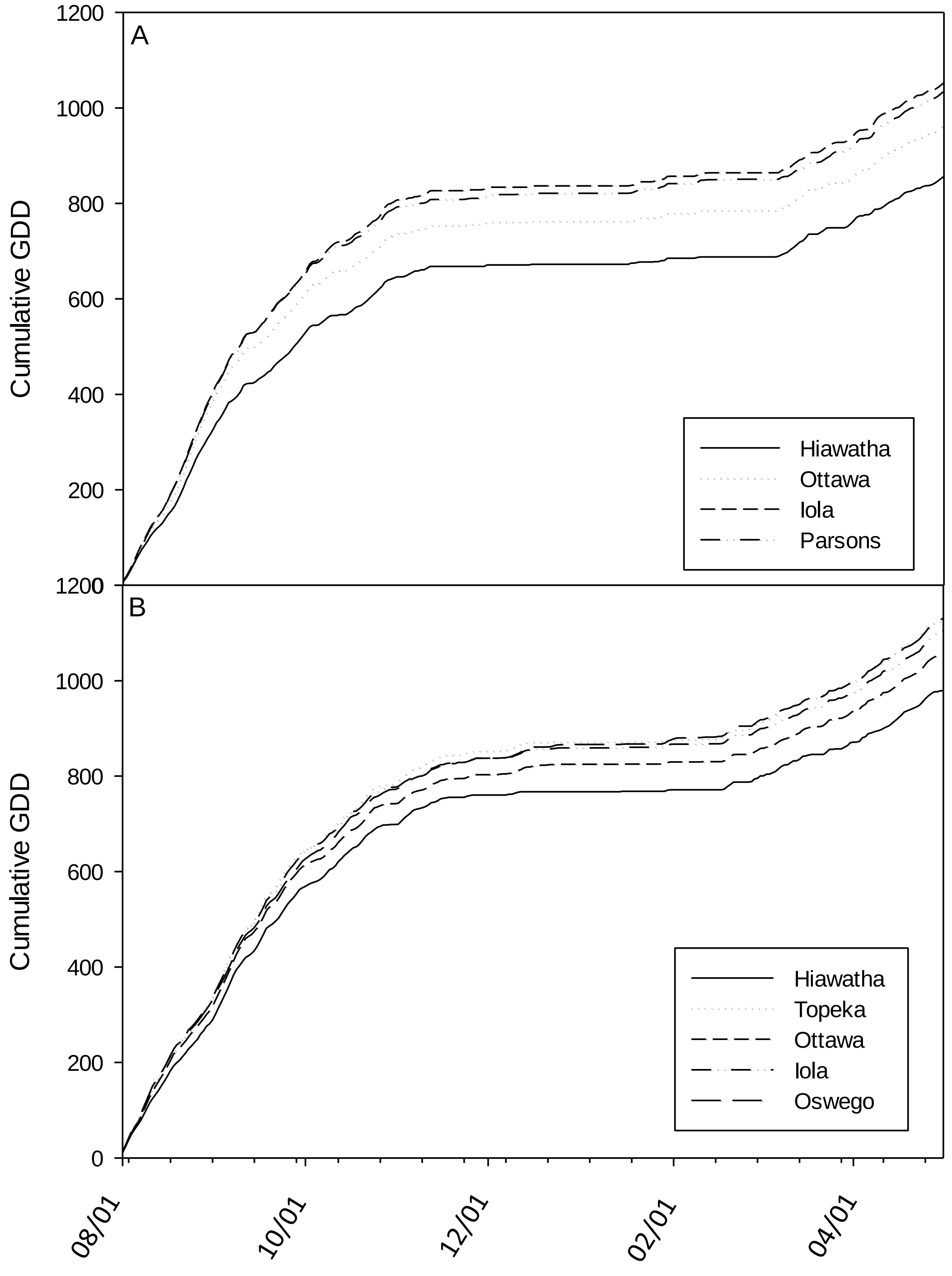


Figure 2.4 Cumulative proportion of total horseweed emergence in the absence of competition in (A) 2014-2015 and (B) 2015-2016. Points are the average of four rings on day of observation. See Table 2.7 for parameter estimates for the regression.

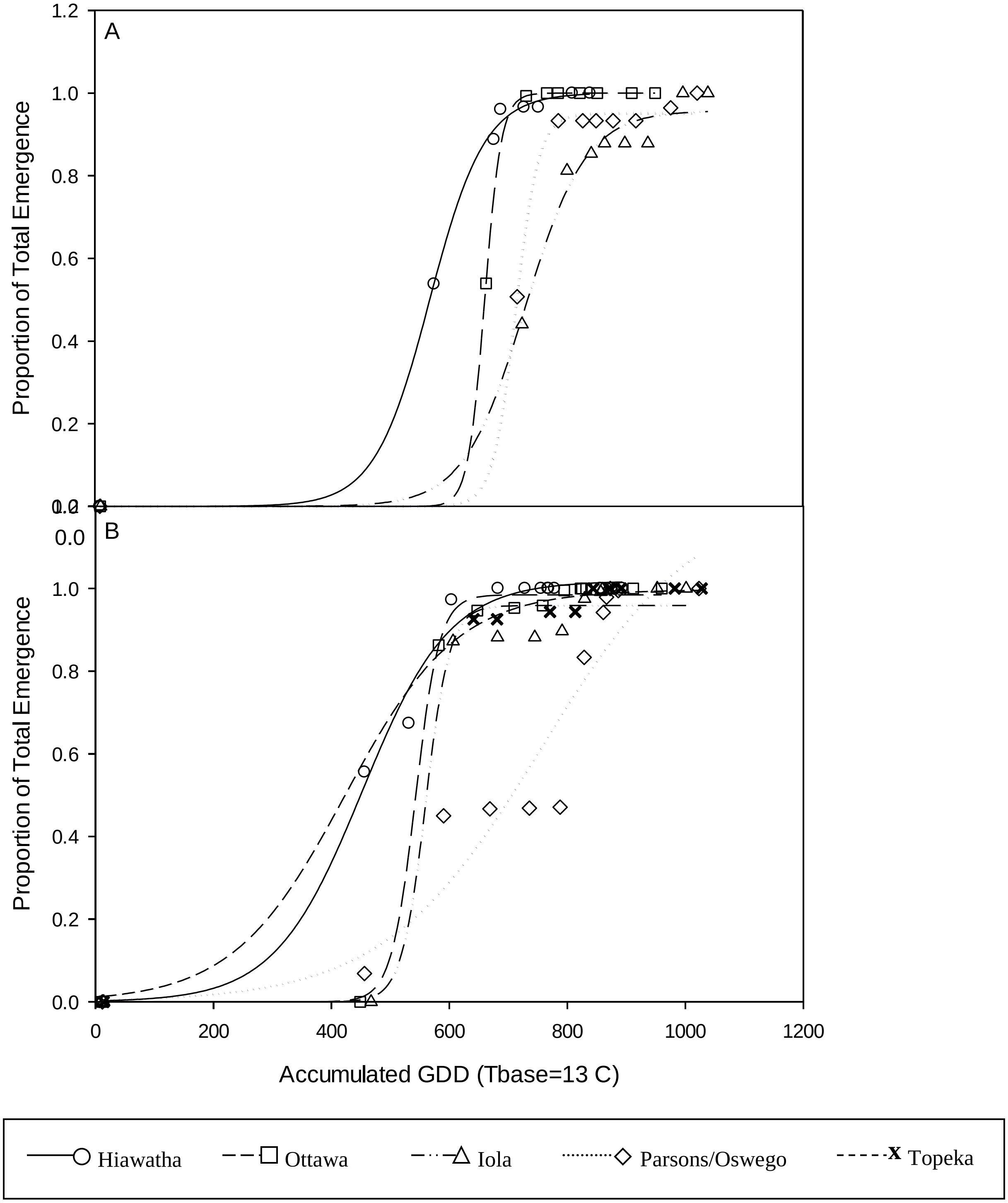


Figure 2.5 Cumulative proportion of total horseweed emergence by calendar date in the absence of competition 2014-2015. Data points are the average of each pull ring at day of observation. Regression lines are predicted fit of Equation 2.2. Vertical lines represent the beginning of fall (solid), winter (dashed), and spring (dot and dash).

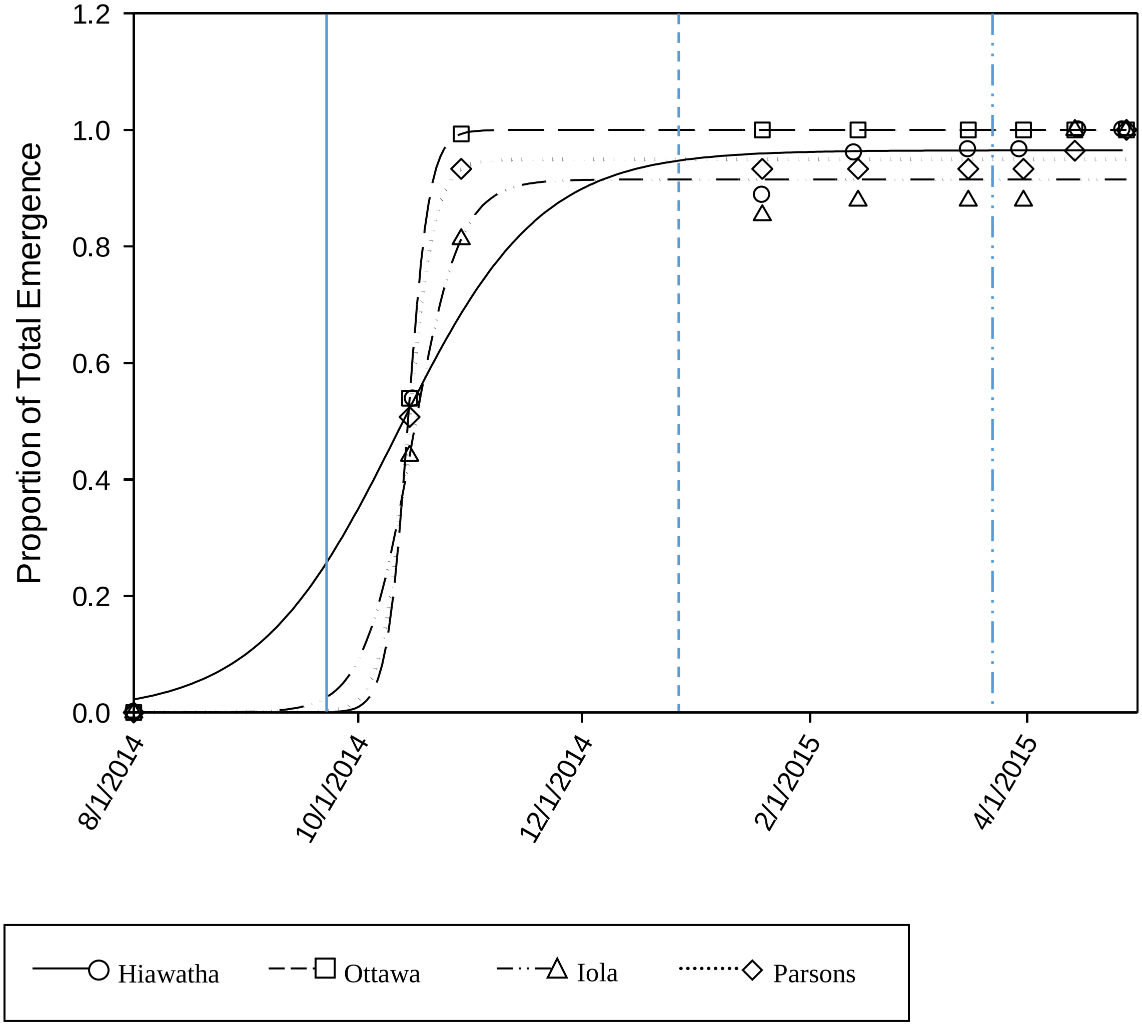


Figure 2.6 Cumulative proportion of total horseweed emergence by calendar date in the absence of competition in 2015-2016. Data points are the average of each pull ring at each day of observation. Regression lines are predicted fit of Equation 2.2. Vertical lines represent the beginning of fall (solid), winter (dashed), and spring (dot and dash).

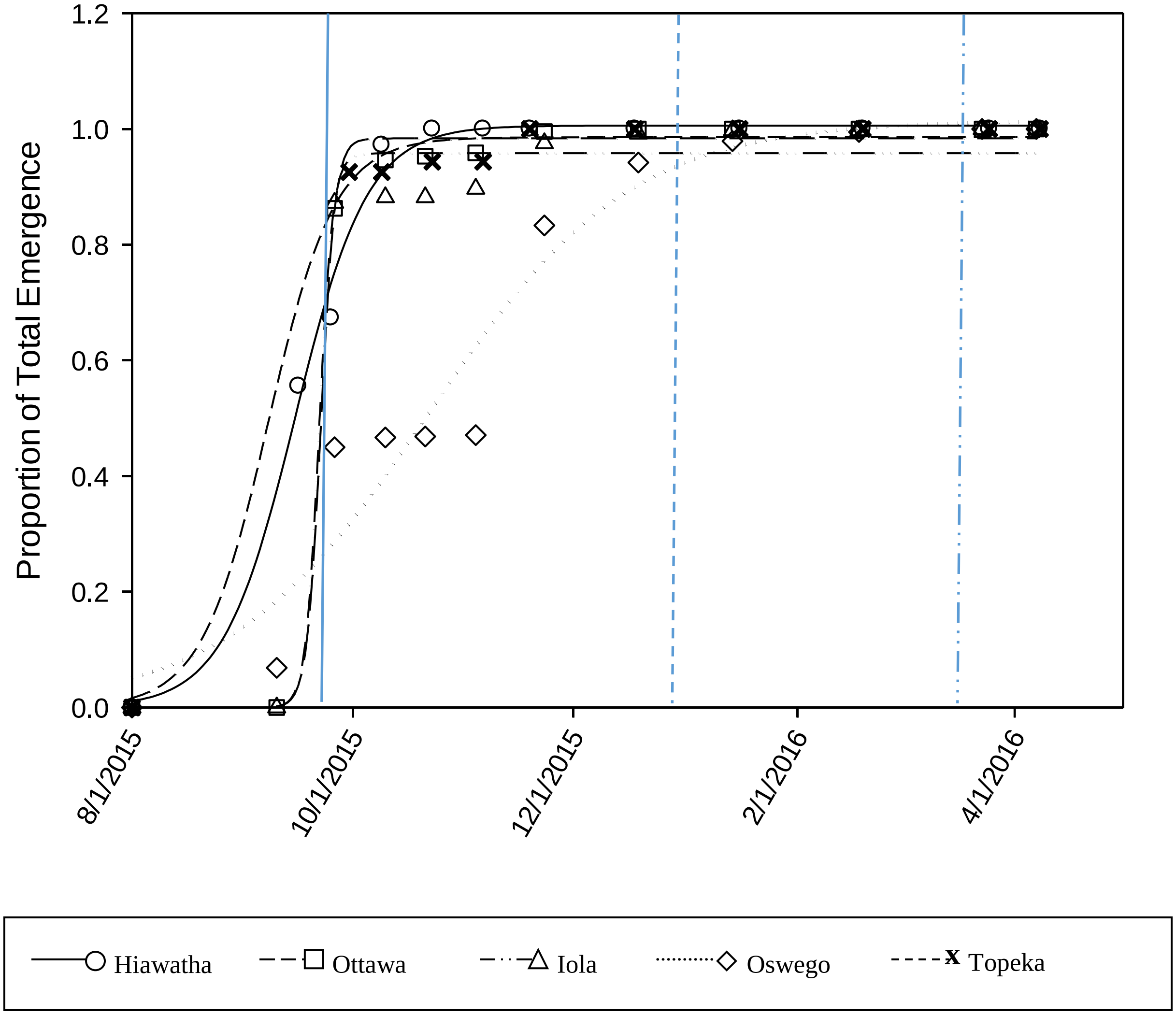
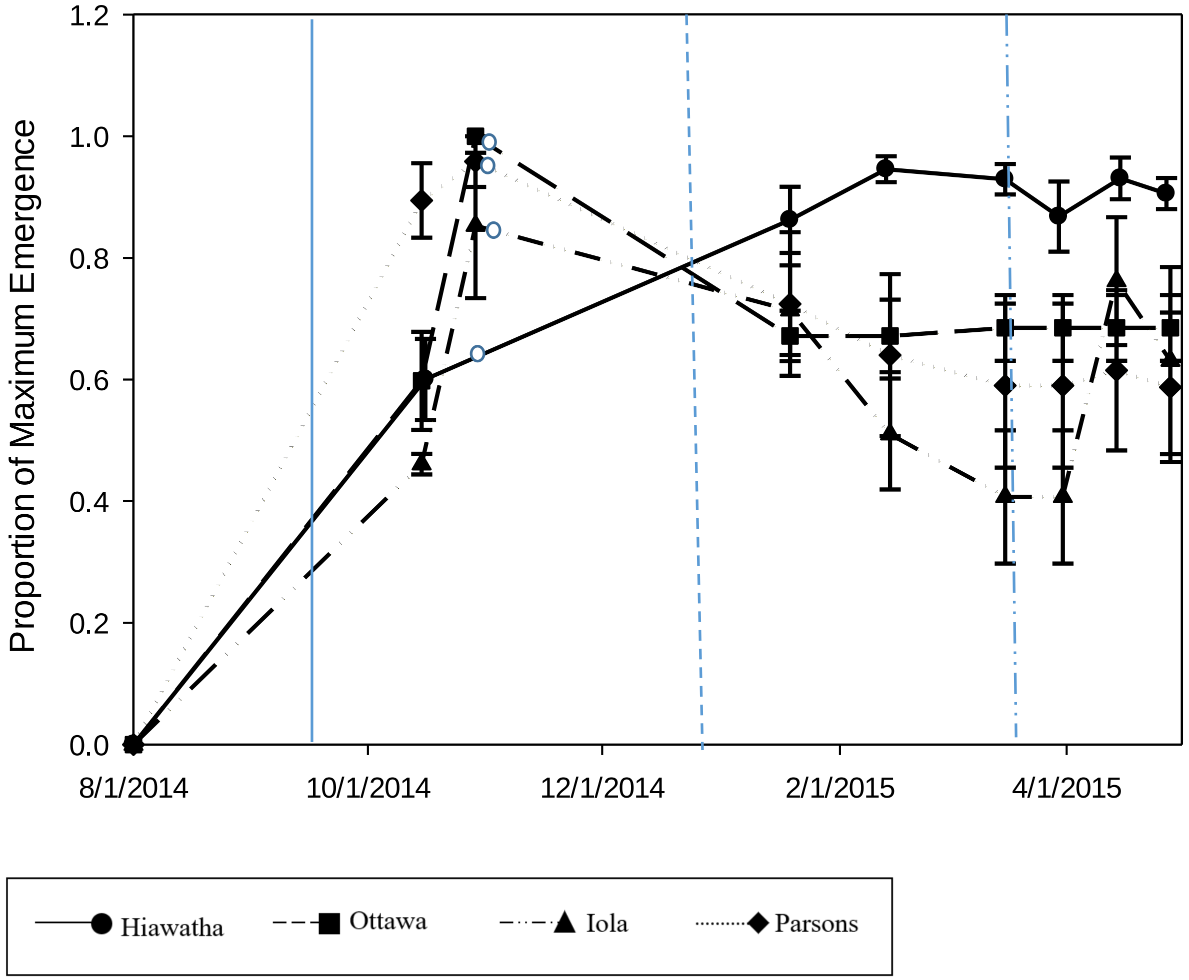


Figure 2.7 Proportion of maximum horseweed emergence in the keep rings by calendar date in 2014-2015. Vertical lines represent the beginning of fall (solid), winter (dashed) and spring (dot and dash). Open circles represent the first frost for each location. Error bars are standard error of the mean.



Chapter 3 - Cover Crops and Herbicide Programs Affect Palmer Amaranth (*Amaranthus palmeri*) Emergence and Development in No-Till Soybean

Abstract

Integrating cover crops and herbicide programs into no-tillage soybean production systems could reduce Palmer amaranth populations in Kansas. Field studies were conducted near Manhattan, KS in 2014-2015 and 2015-2016. Five cover crop treatments included no cover, fall-sown winter wheat, and spring-sown oat, pea, or a mixture of oat and pea. Cover crops were terminated in May with glyphosate and 2,4-D alone or in combination with a residual of flumioxazin and pyroxasulfone. Winter wheat consistently produced the greatest amount of biomass by cover crop termination. Palmer amaranth biomass and density in spring-sown oat were reduced by 98 and 82%, respectively, reduced in the spring-sown mixture of oat and pea by 92 and 54%, respectively, and reduced in winter wheat by 98 and 51%, respectively, in 2014-2015. In the second year, no Palmer amaranth emerged in winter wheat prior to cover crop termination. Weed biomass and density of all species were reduced at least 52 and 62%, respectively, by presence of all cover crops in 2014-2015. By 10 weeks after termination in 2014-2015, use of residual herbicides resulted in 95 and 69% less Palmer amaranth biomass and density, respectively, than treatments with no residual herbicides in the soybean crop. In 2014-2015, winter wheat and spring oat cover crops alone reduced Palmer amaranth biomass by 98 and 91% by 10 weeks after termination. Overall, Palmer amaranth emergence with no residual herbicides was lowest in spring pea in 2014-2015 due to growth of large Palmer amaranth individuals and lowest in winter wheat in 2015-2016 due to cover crop biomass production.

Time to 50% Palmer amaranth emergence was delayed in winter wheat, spring oat, and spring oat/pea mix together with no residual herbicide compared to no cover crop by 51, 37, and 30 GDD, respectively. Soybean yields were 1.5 times greater with residual herbicide and 2 times greater with winter wheat or spring oat cover crop in 2014-2015. Winter wheat or spring oat cover crops with a residual herbicide may increase soybean crop yield and effectively suppress weeds in the absence of a residual herbicide if growing conditions favor cover crop establishment.

Introduction

Integrating cover crops and herbicide programs into no-tillage soybean production systems could reduce Palmer amaranth (*Amaranthus palmeri* S. Watson) populations in Kansas. Palmer amaranth has become a successful weed in soybean because its emergence pattern coincides with soybean planting and is able to adapt its emergence and growth to varying environments (DeVore et al. 2013; Jha et al. 2008, 2010a, 2010b; USDA 2016; Ward et al. 2013). Palmer amaranth can cause 79% yield loss in soybeans at a density of 8 plants m^{-1} row (Bensch et al. 2003). Palmer amaranth has also evolved resistance to numerous important herbicide sites of action in Kansas and surrounding states (Heap 2017; Sweat et al. 1998). Palmer amaranth management must take an integrated approach, which includes understanding how to use cover crops and a diversity of herbicides as tools to suppress Palmer amaranth biomass and densities in no-tillage soybean production.

Cover crops are plants grown between main crops that are not harvested for profit. Benefits of planting cover crops include pest suppression, soil and water quality improvements, nutrient cycling efficiency, and cash crop productivity (Snapp et al. 2005). Specifically, cover crops can suppress weeds by competing for resources, interrupting life cycles, producing allelopathic chemicals, changing the soil environment, enhancing weed seed decay, and maintaining surface residues (Rueda-Ayala et al. 2015; Snapp et al. 2005; Tribouillois et al. 2015). The more cover crop biomass that is produced, the more weed biomass is reduced (Nord et al. 2011; Petrosino et al. 2015; Westgate et al. 2005; Williams et al. 1998). Cover crops differ in their ability to compete with weeds. Grass crops seem to capture resources more efficiently and produce biomass more quickly than legume cover crop species (Brainard et al. 2011). Some cover crops that have been studied include winter wheat (*Triticum aestivum*), spring oat (*Avena sativa*), and spring field pea (*Pisum sativum*).

Method of cover crop termination may also affect their ability to suppress weeds. Wheat terminated by herbicides and left standing reduced weed biomass more compared to wheat that was rolled with a roller-crimper (Moyer et al. 2000). This was because of the increased shading of the standing crop compared to the rolled crop. The use of herbicides to terminate the cover crop may increase total weed suppression compared to herbicides and cover crops used separately.

To combat herbicide-resistant weeds, the use of pre-emergence and post-emergence herbicides and multiple effective sites of action are encouraged (Davis et al. 2009). One pre-emergence herbicide pre-mix being adopted for use in soybean and that has been found to effectively control Palmer amaranth is flumioxazin and pyroxasulfone (Fierce®, Valent U.S.A. Corporation, Walnut Creek, CA). The use of pre-emergence herbicides with cover crops could increase total weed suppression.

The objectives of this study were to (1) compare biomass accumulation among cover crops at time of termination, (2) determine reduction in Palmer amaranth and other weed biomass and density in response to cover crops and herbicide programs, and (3) quantify the impact of these programs on uncontrolled Palmer amaranth and other weeds on soybean yield.

Materials and Methods

Experimental Design

Field experiments were conducted over two years at the Department of Agronomy Ashland Bottoms Research Farm (39.124651°N, 96.612004°W) near Manhattan, KS. See Table

3.1 for soil information. The experiments were set up in a randomized complete block design with four replications. There were five cover crop treatments and two herbicide termination treatments for a total of ten 4.6 m by 9.1 m plots in each replication. The five cover crop treatments were no cover crop, winter wheat ("Everest"), spring oat ("Jim"), spring pea ("4010"), and a mix of spring oat and spring pea. Winter wheat was drilled with a Crust Buster drill at 45 kg ha^{-1} in 25-cm rows on November 3, 2014 over the entire experiment area. Wheat in plots planned to contain no cover or other cover crops were terminated with an application of glyphosate at 1.1 kg ae ha^{-1} and AMS at 1.25% w/v on March 10, 2015. This was done so that the experiment could be started in 2014 instead of waiting until the next fall to start the study. On October 12, 2015, winter wheat was drilled with a Tye double disk drill at 67 kg ha^{-1} in 20-cm rows. Spring oat (74 kg ha^{-1}), spring pea (74 kg ha^{-1}), and a mix of spring oat (49 kg ha^{-1}) and spring pea (25 kg ha^{-1}) were drilled on March 13, 2015 and March 1, 2016 in 20-cm rows.

Herbicide applications needed to terminate cover crops included glyphosate without or with residual herbicide premix of flumioxazin and pyroxasulfone. All herbicide application dates, products, rates, and company information can be found in Tables 3.2 and 3.3. A majority of the Palmer amaranth present were glyphosate-resistant in 2014-2015 (D.E. Peterson, personal communication), so a second termination treatment was applied on June 4, 2015 with glyphosate and 2,4-D to help control emerged Palmer amaranth and peas that weren't controlled adequately by the previous treatment. 2,4-D was added to the termination treatment the following year. A midseason treatment of glyphosate and lactofen was applied in June both years for general weed control (Tables 3.2 and 3.3). Soybean "Asgrow 3634" were planted with a White 6700 four-row planter in 76-cm rows on June 10, 2015 at 316,000 seeds ha^{-1} and on June 10, 2016 at 321,000 seeds ha^{-1}.

Data collection

Prior to cover crop termination in May of each year, all weed species were identified, counted, and aboveground biomass harvested, as well as cover crop biomass, from two 0.5 by 0.5 m quadrats in each plot. Biomass samples were dried at 70 C for 6 days and weighed.

After termination of cover crops and soybean planting, emergence of Palmer amaranth and other weeds were recorded every two weeks inside four 20-cm diameter PVC rings in 2015 and inside three 0.5 by 0.5-m quadrats in 2016 placed in each plot. In two rings or one half of each quadrat, weeds were counted and left to track plant growth while in the other two rings or half of a quadrat, weeds were counted and pulled to document emergence with no competition from other plants. Aboveground weed biomass was harvested from each undisturbed ring or half of quadrat on June 30, 2015 and June 20, 2016 prior to mid-season herbicide applications. Biomass was dried at 70 C for 6 days and weighed.

Soybean plant biomass, plant counts, and leaf area index were determined to examine the impact of cover crop and herbicide programs and their interaction. Weed emergence counts continued to be recorded through July 31, 2015 and August 4, 2016 when aboveground biomass of soybean and weeds and remaining cover crop residue were harvested from a 0.5 by 0.5-m quadrat in each plot. Soybean plants and weeds were clipped at the soil surface. Soybean plants from each quadrat were counted. Soybean plants were separated into leaves, stems, and reproductive parts. Leaf area for each sample was measured using a leaf area meter (LI-COR 3100, LI-COR Biosciences Inc., Lincoln, NE). All plant parts were bagged separately. Biomass and residue were dried at 70 C for 6 days and weighed. Soybean plant biomass and leaf area were based on a sampling area of 0.76 m by 0.5 m to account for soybean row spacing. Leaf area index (LAI) was calculated as A_l/A_g where A_l was the soybean leaf area (m^2) and A_g was the ground area for the sample (m^2). Soybean seed was harvested from the center two rows using a plot combine on October 19, 2015 and October 17, 2016. Yield was determined at 12% moisture.

Data were analyzed using PROC GLIMMIX in SAS® Studio University Edition (SAS Institute Inc., 100 SAS Campus Dr., Cary, NC). Palmer amaranth biomass and emergence, total weed biomass and emergence, and cover crop biomass prior to cover crop termination were evaluated in response to the five cover crop treatments. After cover crop termination, Palmer amaranth final density and biomass and final total weed density and biomass were analyzed for the effects of the five cover crop treatments, two herbicide programs, and their interaction. After the midseason herbicide treatment, Palmer amaranth density and biomass, total weed density and biomass, remaining cover crop residue, and soybean LAI and yield were evaluated in response to the five cover crop treatments, two herbicide programs, and their interaction. Differences among response variables were significant at $p<0.05$ using the Tukey-Kramer Method.

Proportion of total Palmer amaranth emergence from the rings where seedlings were pulled at each sampling date was calculated by dividing the emergence counts for each ring at each sampling date and location by the total Palmer amaranth emergence count for each ring throughout the study for each year. Emergence counts were plotted over growing degree days (GDD) that were accumulated throughout the study, calculated as follows:

$$GDD = \frac{T_{max}+T_{min}}{2} - T_{base} \qquad \text{Equation 3.1}$$

where T_{max} was the maximum temperature (C) for each day, T_{min} was the minimum temperature for each day, and T_{base} was the base temperature for Palmer amaranth emergence (17 C, Steinmaus et al. 2000). Maximum and minimum temperatures for each day were obtained from the Applied Climate Information System (ACIS). Cumulative GDD was initiated after cover crop termination on June 5, 2015 and on May 22, 2016. Regression curves that plotted proportion of total Palmer amaranth emergence counts over cumulative GDDs for year, cover crop, and herbicide program were determined using a nonlinear, 3-parameter sigmoid regression in Sigmaplot v. 12.0 (Systat Software Inc., San Jose, CA):

$$y = \frac{a}{(1+\exp\left(\frac{-(x-x_0)}{b}\right))} \qquad \text{Equation 3.2}$$

where y is the proportion of total emerged Palmer amaranth plants, x is the cumulative GDD, x_o is the cumulative GDD for 50% total emerged Palmer amaranth plants (inflection point), a is the maximum proportion of total emerged, and b is the slope of the line at the inflection point. Differences in regression lines were determined using a pairwise F-test:

$$F = \frac{(SSResid_R - SSResid_F)/(dfResid_R - dfResid_F)}{SSResid_F/dfResid_F} \qquad \text{Equation 3.3}$$

where F is the calculated value, $SSResid_R$ is the residual sum of squares for one line fit to data from two treatments, $SSResid_F$ is the sum of the residual sums of squares for two separate lines fit to the data for each treatment, $dfResid_R$ is the residual degrees of freedom for one line fit to the data, and $dfResid_F$ is the sum of the degrees of freedom for two separate lines fit to the data. The calculated F-value was compared to the distribution of F (Table A 14, Snedecor and Cochran 1989) with df determined using:

$$\frac{df_N}{df_D} = \frac{(dfResid_R - dfResid_F)}{dfResid_F} \qquad \text{Equation 3.4}$$

where df_N is the degrees of freedom in the numerator, df_D is degrees of freedom in the denominator, $dfResid_R$ is the residual degrees of freedom for one line fit to the data, and $dfResid_F$ is the sum of the degrees of freedom for two separate lines fit to the data. If the calculated value of F was greater than the F-value in the Table, two separate lines were different than one line fit to all the data for both treatments.

Results and Discussion

The weather patterns for both years were different. Maximum temperatures were higher than the 30-yr average maximum, and minimum temperatures were lower than the 30-year average minimum for both 2014-2015 and 2015-2016 (Table 3.4). These extremes in temperatures may have affected cover crop, soybean, and weed growth and development. The distribution of rainfall by month was variable (Table 3.4). Little rain fell in November 2014, but the month before (October) and month after (December) received greater rainfall amounts than the 30-yr average, so winter wheat cover crop established well. In the following spring, rainfall amounts were low in March 2015, but timely events at the end of February and the beginning of April aided in spring cover crop and weed establishment. In fall 2015, more than 2.5 times the 30-yr average rainfall was received in November and December, which ensured winter wheat cover crop establishment; however, a lack of sizeable rain events in the first 3.5 months of 2016 led to poor establishment of spring-sown cover crops and resulted in few weeds (Table 3.4). This was followed by 2.2 times more rain than the 30-yr average at the end of April. Also, June 2016 was dry reducing weed establishment.

Palmer amaranth was the main weed of interest in this study, but other weed species observed were ivyleaf morningglory (*Ipomoea hederacea*), henbit (*Lamium amplexicaule*), puncturevine (*Tribulus terrestris*), carpetweed (*Mollugo verticillata*), large crabgrass (*Digitaria sanguinalis*), horseweed (*Conyza canadensis*), stinkgrass (*Eragrostis cilianensis*), foxtail spp. (*Setaria* spp.), velvetleaf (*Abutilon theophrasti*), common lambsquarters (*Chenopodium album*), volunteer winter wheat, volunteer soybean, and mustard species (Brassicacae spp).

Individual cover crops differed in the amount of biomass that was produced (Figure 3.1). In 2014-2015, winter wheat produced the most aboveground biomass, followed by oat and oat/pea mix which were similar, while spring pea produced the least. In 2015-2016, winter wheat produced the most biomass and was greater than the previous year. Little rainfall in spring of 2016 resulted in low and similar amounts of biomass produced by spring-sown cover crops. Even by soybean R2 growth stage, the amount of remaining residue among cover crops was still different (Figure 3.2). In 2014-2015, winter wheat and spring oat residue weights were greater than spring pea. In 2015-2016, winter wheat residue weight was greater than all other cover crops. Fall-sown winter wheat may be a good candidate for use as a cover crop to suppress weeds because it produced the greatest amount of biomass.

Cover crop effects on Palmer amaranth and total weed biomass and density prior to termination

Prior to cover crop termination in 2014-2015, the no cover treatment had the greatest Palmer amaranth aboveground biomass, while winter wheat and spring oat had the least (Figure 3.3). At the time of cover crop termination, winter wheat and spring oat/pea mixture reduced Palmer amaranth aboveground biomass by 98 and 92%, respectively, compared to no cover crop in 2014-2015. No Palmer amaranth biomass was produced in winter wheat crop in 2015-2016, and spring oat/pea mixture reduced biomass by 85% compared to no cover crop. Palmer amaranth pressure was much lower in 2015-2016 compared to 2014-2015.

Density of Palmer amaranth prior to cover crop termination was different between years and among cover crop treatments (Figure 3.4). In 2014-2015, with no cover Palmer amaranth density was greater (221 plant m^{-2}) than spring oat and spring oat/pea mixture (Figure 3.4). In 2015-2016, no Palmer amaranth emerged in the winter wheat cover crop, but there were 23 and 22 plants m^{-2} in spring oat and spring oat/pea mixture, respectively. Winter wheat cover crop can suppress Palmer amaranth biomass and density and spring oat cover crop can suppress Palmer amaranth density at time of cover crop termination prior to planting no-till soybean.

Overall weed biomass was reduced by 84, 72, 59, and 46% in winter wheat, spring oat, spring oat/pea mixture, and spring pea cover crops, respectively, compared to no cover in 2014-2015 (Figure 3.5). The fraction of Palmer amaranth biomass was 10, 5, 29, 55, and 79% of total weed weight in winter wheat, spring oat, spring oat/pea mixture, spring pea, and no cover, respectively. In 2014-2015, weed density was greatest in no cover (282 plants m^{-2}) and ranged from 57 to 134 plants m^{-2} in the other cover crops. Palmer amaranth made up 95, 69, 90, 83, and 79% of total weed density in winter wheat, spring oat, spring oat/pea mixture, spring pea, and no cover, respectively. In 2015-2016, no differences in weed biomass and density were observed among any of the cover crop treatments and ranged from 0 to 7.5 g m^{-2} and 0 to 87 plants m^{-2}.

Cover crop and herbicide program effects on Palmer amaranth and total weed biomass and density in soybean crop

Palmer amaranth aboveground biomass prior to mid-season herbicide application was not different among years, cover crops, or termination methods. However, Palmer amaranth density prior to mid-season herbicide application was greatest when no residual herbicide was used (Table 3.5). More Palmer amaranth emerged in 2014-2015 compared to 2015-2016 prior to the mid-season herbicide application.

After midseason herbicide application in 2014-2015, average Palmer amaranth biomass at soybean R2 growth stage occurring in winter wheat and spring oat cover crops with and without residual herbicides was less than with no cover crop and no residual herbicides (Figure 3.6). In 2015-2016, Palmer amaranth biomass was not different among treatments, and very few weeds other than Palmer amaranth were present. In 2014-2015, the termination method with no residual herbicides had greater Palmer amaranth densities after the midseason treatment compared to the termination method with residual herbicides (Table 3.5). There were no differences in Palmer amaranth density after the midseason treatment in 2015-2016. Remaining cover crop residues of winter wheat and spring oat, after the midseason treatment in 2014-2015, were able to continue to reduce Palmer amaranth biomass compared to no cover with no residual (Figure 3.6). Winter wheat and spring oat may be good options for Palmer amaranth suppression due to persisting effects on Palmer amaranth growth Cover crops may reduce Palmer amaranth biomass throughout the season, but the herbicide treatments used will have a greater effect on Palmer amaranth density later in the season than the cover crops.

Total aboveground weed biomass prior to midseason herbicide application was greater in the absence of residual herbicides than with residual herbicides in 2014-2015 (Table 3.5). After midseason herbicide application, total weed biomass averaged across cover crop treatments with no residual herbicide (180 g m^{-2}) was greater than with residual herbicide (8.5 g m^{-2}). In 2015-2016, no differences in total aboveground weed biomass were found among treatments before and after midseason treatment. Total weed biomass was reduced most when a residual herbicide was used early in the season.

Palmer amaranth cumulative and final emergence

Total Palmer amaranth emergence counts from May to August were different among main effects of cover crop and termination method in 2014-2015 and among main effect of cover crops in 2015-2016 (Table 3.6). Total seasonal emergence was greatest after winter wheat and least after spring pea in 2014-2015 due to the wider row spacing and lower biomass production in wheat that year compared to 2015-2016 and growth of large individual palmer amaranth plants in spring pea with no residual applied (Table 3.6). Between termination methods, total seasonal emergence was greater with no residual than with residual herbicides. Total seasonal emergence was greatest in the no cover crop and least in the winter wheat cover crop in 2015-2016. This may be due to the heavy residue cover that winter wheat produced compared to all other treatments, which reduced available microsites for Palmer amaranth germination and emergence in the second year. Also, reduced Palmer amaranth seedbank and little rainfall in 2015-2016 resulted in reduced total emergence in the second year.

Cumulative emergence of Palmer amaranth after cover crop termination was different between termination methods in 2014-2015 (Figures 3.7 and 3.8). Spring pea and no cover Palmer amaranth cumulative emergence with residual herbicides were not analyzed due to a lack of Palmer amaranth emergence. The regression lines of treatments without residual herbicides for spring pea was different from spring oat/pea mix, spring oat, and winter wheat. Without residual herbicides, the no cover treatment cumulative Palmer amaranth emergence was similar to spring pea since spring pea did not establish well, but was not different from spring oat/pea mix. Based on x_0 in the parameter estimates (Table 3.7), Palmer amaranth reached 50% emergence earliest in spring pea followed by no cover, spring oat/pea mix, spring oat, and winter wheat. In the crops treated with residual herbicides, cumulative emergence regression lines in winter wheat and spring oat/pea mix were different from spring oat. Palmer amaranth reached 50% emergence earliest in spring oat/pea mix and winter wheat followed by spring oat. Palmer amaranth 50% emergence was later in cover crop treated with residual herbicides compared to cover crops without residual herbicides since the residual herbicides prevented Palmer amaranth emergence for a longer period of time after cover crop termination. Palmer amaranth and other weed cumulative emergence was not analyzed in 2015-2016 due to a lack of weed emergence.

In 2014-2015 growing season, a large proportion of the Palmer amaranth population was determined to be resistant to glyphosate (D. Peterson, personal communication). Surviving glyphosate-resistant Palmer amaranth density was greatest in the no cover crop no residual herbicide treatment, and was lowest in all treatments where a residual herbicide was applied (Figure 3.9). Even when no residual was applied, winter wheat and spring oat reduced Palmer amaranth density compared to no cover crop. This may be because of a delay in Palmer amaranth emergence in the winter wheat and spring oat cover crops compared to no cover, and Palmer amaranth plants in winter wheat and spring oat may have been smaller at the time of treatment.

Overall cover crop effects on weed suppression

The cover crops in this study showed some level of weed suppression at different times in the study. Winter wheat reduced Palmer amaranth biomass through the two growing seasons, but varied in its ability to reduce Palmer amaranth densities. Many studies have shown that winter wheat can effectively reduce weed emergence and biomass (Boz 2003; Norsworthy 2004; Moyer et al. 2000; Moore et al. 1994; Reddy 2001). A study by Williams et al. (1998) found that winter wheat cover crop residue reduced pigweed species canopy volume by 58 to 85% and delayed pigweed species emergence through 21 DAP.

Spring oat reduced both Palmer amaranth density and biomass and reduced Palmer amaranth biomass through soybean R2 in 2014-2015. Due to poor establishment, spring oats were not as effective in 2015-2016. Several studies have shown oats successfully reducing weed biomass because of its ability to produce biomass quickly (Blackshaw 2008; Brennan and Smith 2005; Campiglia et al. 2010; Norsworthy 2004; O’Reilly et al. 2011; Reddy 2001), while others have shown oats to have less success suppressing Palmer amaranth in the spring compared to

Italian ryegrass and sorghum sudangrass in the absence of residual herbicides (Burgos and Talbert 1996).

In this study, spring-sown field peas reduced Palmer amaranth biomass prior to cover crop termination (Figure 3.3), but the effects were short-lived. Field pea has been used as a cover crop to add nutrients to the soil, and may have some weed suppression potential since it can produce large amounts of biomass quickly (Dorn et al. 2015; Norsworthy et al. 2010; Rühlemann and Schmidtke 2015). However, legume cover crops typically produce less biomass than cereal cover crops, and their residue degrades quickly, making its suppressive effects short-lived (Silva 2015; Dorn et al. 2015; Norsworthy et al. 2010).

In 2014-2015, spring oat/pea mix did show success suppressing Palmer amaranth biomass and densities prior to cover crop termination. To take advantage of the suppressive ability of cereal crops and the benefits of legumes, mixtures of legumes and cereal crops have been considered as a cover crop. Dorn et al. (2015) found that oat/pea mix cover crop residue lasted longer than only legume residue. However, weed suppression was not studied in their experiment. Brennan and Smith (2005) suggested that an oat/pea mix cover crop would be a poor choice due to problems with pea establishment. Campiglia et al. (2010) showed that a hairy vetch (*Vicia villosa*)/oat mix produced the greatest amount of biomass and increased tomato yield, but weed biomass was also the greatest in that cover crop mix.

All cover crops reduced total weed biomass and density compared to the no cover treatment prior to termination. However, after termination, cover crops did not have an effect on weeds if an effective residual herbicide such as flumioxazin and pyroxasulfone was used. Mahoney et al. (2014) determined that flumioxazin plus pyroxasulfone provided 96% control of pigweed species by 4 weeks after treatment in no-till soybean at the same rate that was used for this experiment. Similarly, Bell et al. (2015) found that no Palmer amaranth emerged within the first 30 days after treatment when plots had flumioxazin plus pyroxasulfone applied pre-emergence in a soybean crop.

Where a residual herbicide was not used, winter wheat and spring oat reduced Palmer amaranth biomass and winter wheat, spring oat, and spring pea reduced total weed biomass compared to no cover. The effects of winter wheat were not consistent between years on total Palmer amaranth emergence after termination. In 2015, winter wheat had the highest Palmer amaranth pull counts, while in 2016 it had the lowest. Again, this may be due to differences in biomass production between years. Spring oat/pea, spring oat, and winter wheat all delayed 50% emergence compared to spring pea and no cover when no residual was used. But, if a residual was used winter wheat and spring oat/pea mix reached 50% earlier than spring oat. Norsworthy (2004) found that oat reduced weed biomass for a longer period of time compared to rye even though rye produced more biomass which may point to allelopathy in spring oat. This may be why Palmer amaranth emergence was delayed further in spring oat after the effects of the residual herbicide had ceased.

Soybean response to cover crop and herbicide programs.

Soybean LAI at soybean R2 growth stage was different among cover crop treatments in 2014-2015 (Figure 3.10). Soybean LAI was greater after winter wheat and spring oat/pea mix cover crops compared to no cover treatments. Since winter wheat reduced Palmer amaranth biomass (Figure 3.6) and spring oat/pea mix reduced Palmer amaranth density (Figure 3.4) in treatments with no residual herbicide, the soybean plants in those treatments had less competition and were able to produce greater leaf area. Spring oats also reduced Palmer amaranth biomass and density. Norsworthy (2004) found that oats possessed allelopathic tendencies that reduced corn yield. The allelopathy in oats may have reduced soybean growth, reducing the benefits of lesser weed competition. There were no differences in LAI in 2015-2016. Soybean plant populations were not different among treatments.

Soybean yields were different among main effects of termination method and cover crop treatments with no interaction (Figure 3.11). The termination treatment with residual herbicides yielded more (3,500 kg ha^{-1}) than the treatment without residual herbicides (2,280 kg ha^{-1}). In the termination treatment with no residual herbicides, winter wheat and spring oat treatments had greater yields than spring pea and no cover treatments. In the termination treatment with residual herbicides, winter wheat and spring oat treatments also had greater yields than spring pea and no cover treatments. Cover crops may increase no-till soybean yield in the absence or presence of residual herbicides. There were no differences in soybean yield in 2015-2016 among termination or cover crop treatments.

Conclusions

In this study, winter wheat consistently produced the greatest biomass out of all the cover crop treatments. The level of Palmer amaranth and total weed suppression was affected by the use of a residual herbicide in the spring prior to soybean planting and the use of cover crops. Prior to termination, spring oat and the mix of spring oat/spring pea in 2014-2015 and winter wheat in 2015-2016 reduced both Palmer amaranth biomass and density compared to no cover. Winter wheat consistently reduced Palmer amaranth biomass. All cover crops reduced total weed biomass and density in 2014-2015. After termination, weed suppression due to cover crops was not seen where residual herbicides were used. If residual herbicides were not used, winter wheat and spring oat reduced Palmer amaranth biomass, and spring pea in 2014-2015 and winter wheat in 2015-2016 reduced total Palmer amaranth emergence. Winter wheat, spring oat, and spring pea reduced total weed biomass when no residual herbicides were used in 2014-2015. When no residual herbicides were used, spring oat/pea mix, spring oat, and winter wheat delayed Palmer amaranth 50% emergence compared to spring pea and no cover, which may give the soybean crop time to develop more of a canopy to suppress emerging Palmer amaranth. When residual herbicides were used, more GDD required for Palmer amaranth to reach 50% emergence compared to treatments without a residual herbicide. Also, GDD for 50% of Palmer amaranth emergence was delayed more in spring oat compared to winter wheat and spring oat/pea mix when no residual herbicide was applied, giving the soybean crop a competitive advantage over Palmer amaranth. In 2014-2015, soybean yield was higher in treatments that used a residual herbicide, and treatments that used winter wheat or spring oat had higher yields as well. With the use of residual herbicides, winter wheat and spring oat cover crops may suppress weeds and encourage increased soybean yield compared to not using a cover crop when Palmer amaranth pressure is high.

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Tables and Figures

Table 3.1 Soil information for experimental plots in 2014-2015 and 2015-2016.

Year	Soil Type	Landform	Parent Material	Water Storage Capacity
2014-2015	Reading silt loam	loamy lowland	alluvium	very high
2015-2016	Wymore silty clay loam	clayey upland	loess	high

Table 3.2 Herbicide name, rate, trade name, product concentration, and manufacturer for the herbicides used in this study.

Herbicide	Rate	Trade name	Manufacturer
glyphosate	1100 g ae ha^{-1}	Roundup Powermax®	Monsanto Company, St. Louis, MO
2,4-D	530 g ae ha^{-1}	2,4-D LV4	Albaugh, Inc., Ankeny, IA
flumioxazin + pyroxasulfone	890 + 112 g ai ha^{-1}	Fierce®	Valent U.S.A. Corporation, Walnut Creek, CA
lactofen	224 g ai ha^{-1}	Cobra®	Valent U.S.A. Corporation, Walnut Creek, CA

Table 3.3 Herbicide treatment, application date, and herbicide mixture for herbicides used in this study.

Treatment	Application Date	Herbicide Mixture
2014-2015		
cover crop termination no residual	May 19, 2015	glyphosate + AMS 1.25% w/v
cover crop termination with residual	May 19, 2015	glyphosate + flumioxazin + pyroxasulfone + AMS 1.25% w/v
herbicide-resistant Palmer amaranth treatment	June 4, 2015	glyphosate + 2,4-D + AMS 1.25% w/v
midseason herbicide application	June 30, 2015	glyphosate + lactofen + AMS 1.25% w/v
2015-2016		
cover crop termination no residual	May 21, 2016	glyphosate + 2,4-D + AMS 1.25% w/v
cover crop termination with residual	May 21, 2016	glyphosate + 2,4-D + flumioxazin + pyroxasulfone + AMS 1.25% w/v
midseason herbicide application	June 20, 2016	glyphosate + lactofen + AMS 1.25% w/v

Table 3.4 Monthly maximum, minimum, and 30-year average temperatures and monthly and 30-year average precipitation totals for the 2014-2015 and 2015-2016 growing seasons for Manhattan, KS.

Month	Temperature						Precipitation		
	2014-2015		2015-2016		30-year Average		2014-2015	2015-2016	30-year Average
	Max	Min	Max	Min	Max	Min	mm		
	C								
October	31.7	-3.9	31.7	-3.9	20.2	6.2	107	15	65
November	21.7	-14.4	26.7	-5.0	12.5	-0.3	3	114	43
December	15.0	-16.1	20.0	-11.7	5.7	-6.1	55	74	28
January	21.7	-19.4	20.6	-17.8	4.5	-7.8	27	15	19
February	22.2	-18.3	25.0	-10.6	7.2	-5.7	18	12	30
March	29.4	-14.4	27.2	-6.7	13.4	-0.5	5	11	62
April	29.4	-1.7	30.6	-2.8	19.2	5.6	70	202	91
May	30.6	2.2	30.0	4.4	24.2	11.7	230	161	118
June	36.1	11.7	38.9	11.7	28.9	16.9	124	32	135
July	37.2	13.3	38.9	17.2	32.1	19.8	146	129	112
August	33.9	8.3	36.1	12.2	31.7	18.6	82	181	112
September	37.2	8.3	34.4	5.0	27.1	13.1	93	143	82
						Totals	960	1089	897

Table 3.5 Palmer amaranth densities and total weed biomass at different points in the season after cover crop termination. Means labeled with same uppercase letters were not different in 2014-2015 and same lowercase letters were not different in 2015-2016.

	Midseason (June 30, 2015; June 20, 2016)		Final (July 31, 2015; August 1, 2016)
Termination	Palmer amaranth density	All weed aboveground biomass	Palmer amaranth density
	plants m^{-2}	g m^{-2}	plants m^{-2}
2014-2015			
No Residual	116.7 A	21.3 A	14.2 A
With Residual	11.9 B	0.6 B	4.4 B
2015-2016			
No Residual	2.9 a	86.4 a	2.6 a
With Residual	0.1 b	0.8 a	0.0 a

Table 3.6 Cumulative total Palmer amaranth emergence from May 20 to July 31, 2015 (2014-2015) and from May 22 to August 4, 2016 (2015-2016). Uppercase letters denote significant differences among cover crop treatments. Lowercase letters denote significant differences between termination treatments. Growing seasons were analyzed separately.

Main effect	Treatment	2014-2015	2015-2016
		plants m^{-2}	
Cover crop	Wheat	225 A	2 c
	Oat	117 AB	9 bc
	Oat/Pea Mix	104 AB	10 abc
	Pea	62 B	25 ab
	No Cover	100 AB	29 a
	SE	35	5
Termination	No Residual	202 A	16 a
	With Residual	42 B	14 a
	SE	23	3

Table 3.7 Parameter estimates for Figure 3.10 and 3.11 describing cumulative Palmer amaranth emergence over GDD in 2014-2015 using Equation 3.2.

Termination	Cover Crop	Parameter Estimates[a]			R^2
		a (SE)	b (SE)	x_0 (SE)	
		Proportion		GDD	
No Residual	No Cover	0.96 (0.02)	23.1 (6.0)	77 (7)	0.95 (0.07)
	Pea	0.95 (0.02)	17.7 (11.8)	79 (14)	0.94 (0.08)
	Oat/Pea Mix	0.97 (0.04)	36.3 (11.7)	106 (12)	0.80 (0.17)
	Oat	0.95 (0.04)	34.7 (10.3)	114 (11)	0.82 (0.16)
	Wheat	0.96 (0.04)	53.7 (12.4)	128 (14)	0.82 (0.15)
With Residual	Oat/Pea Mix	1.01 (0.08)	47.8 (16.4)	206 (16)	0.82 (0.19)
	Oat	1.21 (0.31)	82.4 (30.6)	370 (58)	0.75 (0.20)
	Wheat	0.98 (0.05)	61.8 (11.5)	208 (12)	0.90 (0.12)

[a] a is maximum proportion of total Palmer amaranth emergence, b is slope at the inflections point, and x_0 is cumulative GDD for 50% Palmer amaranth emergence.

Figure 3.1 Average cover crop biomass (g m^{-2}) prior to termination at Manhattan, KS in 2014-2015 (black bars) and 2015-2016 (grey bars). Error bars represent the standard error of the mean. Bars labeled with same uppercase letters were not different in 2014-2015 and same lowercase letters were not different in 2015-2016.

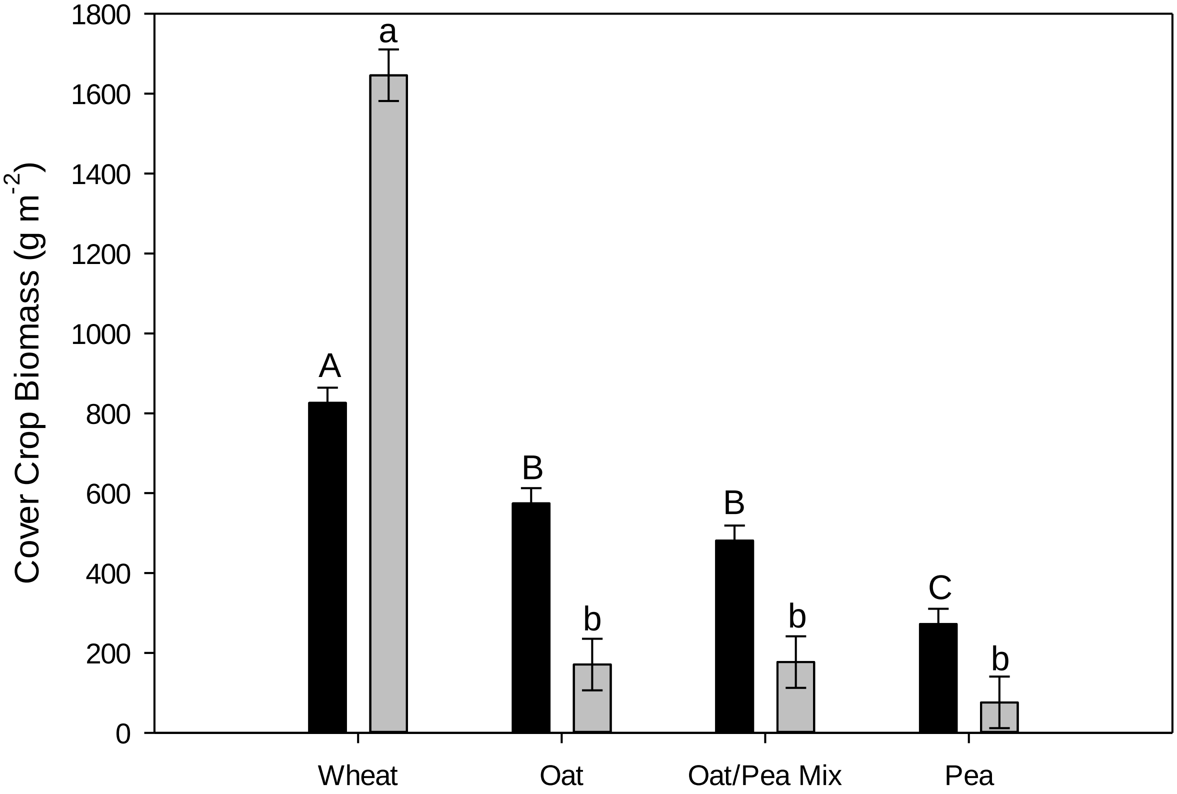


Figure 3.2 Cover crop residue mass (g m^{-2}) remaining by soybean R2 growth stage. Uppercase letters denote significant differences among cover crop treatments in 2014-2015 and lowercase letters denote significant differences among cover crop treatments in 2015-2016.

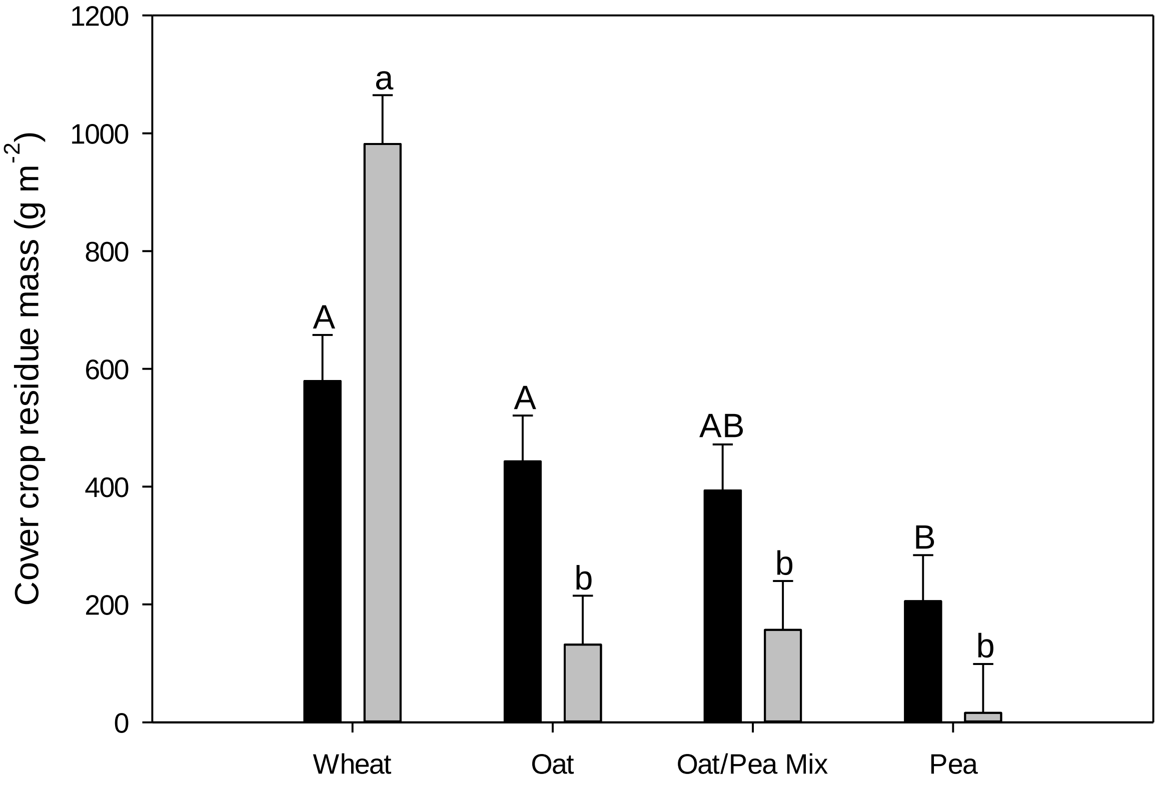


Figure 3.3 Palmer amaranth biomass (g m^{-2}) prior to cover crop termination at Manhattan, KS in 2014-2015 (black bars) and 2015-2016 (grey bars). Error bars represent the standard error of the mean. Bars labeled with same uppercase letters were not different in 2014-2015 and same lowercase letters were not different in 2015-2016.

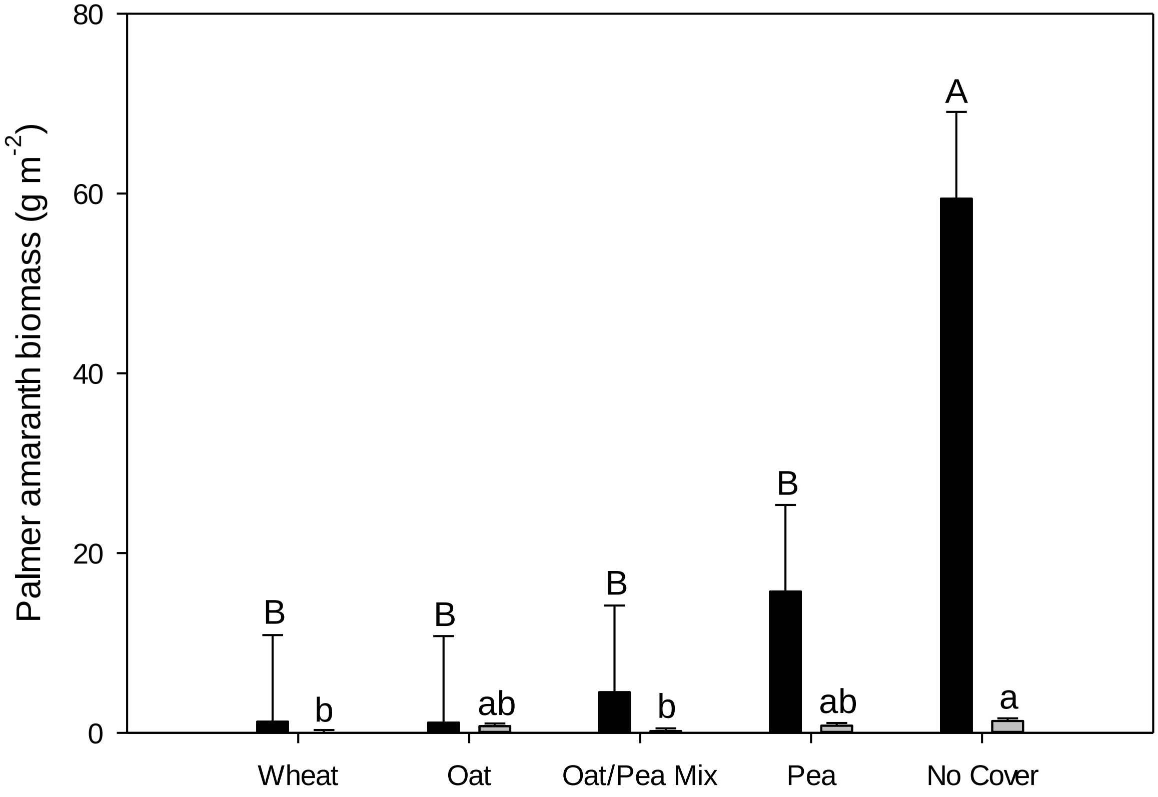


Figure 3.4 Palmer amaranth density (plants m^{-2}) prior to cover crop termination at Manhattan, KS in 2014-2015 (black bars) and 2015-2016 (grey bars). Error bars represent the standard error of the mean. Bars labeled with same uppercase letters were not different in 2014-2015 and same lowercase letters were not different in 2015-2016.

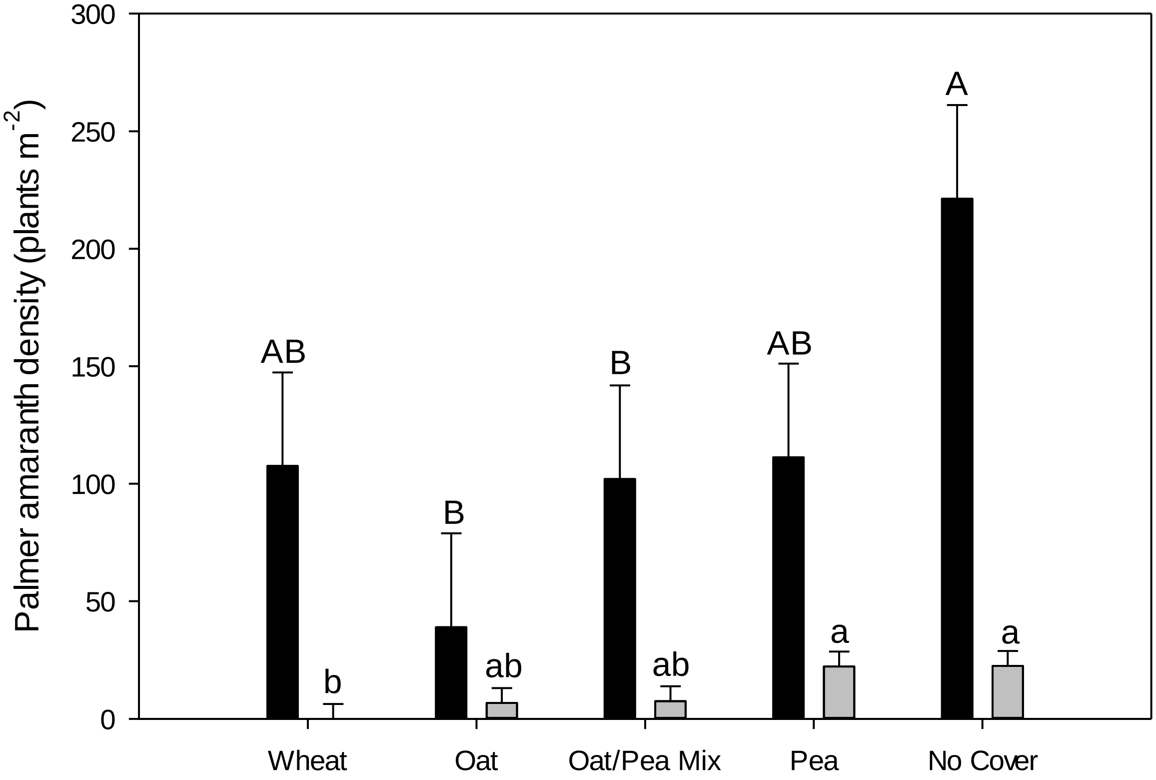


Figure 3.5 Aboveground biomass for all weed species (g m^{-2}) prior to cover crop termination in 2014-2015. Palmer amaranth biomass (black bars) and other weed biomass (grey bars) made up total weed biomass. Letters denote differences among cover crop treatments. Standard error was ±9.9.

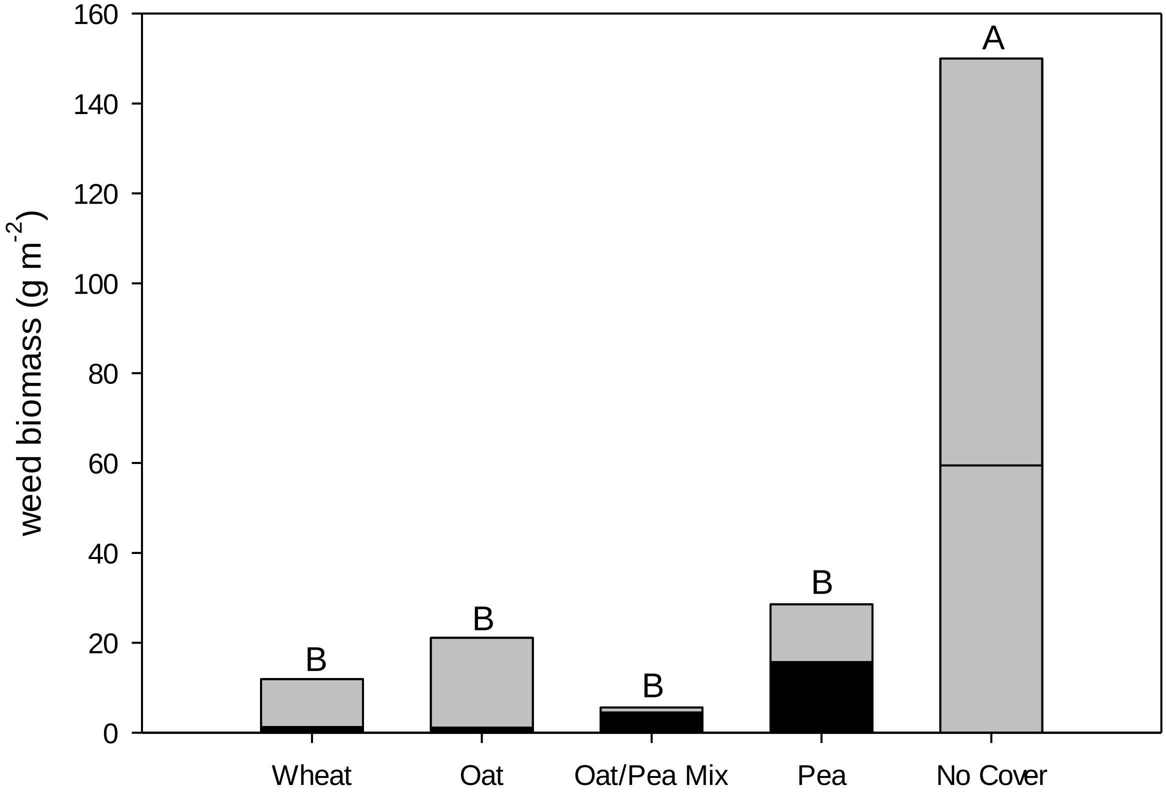


Figure 3.6 Palmer amaranth aboveground biomass (g m^{-2}) at soybean R2 growth stage in 2014-2015 by cover crop treatment without residual herbicides (black bars) and with residual herbicides (grey bars). Letters denote differences among all cover crop termination treatments.

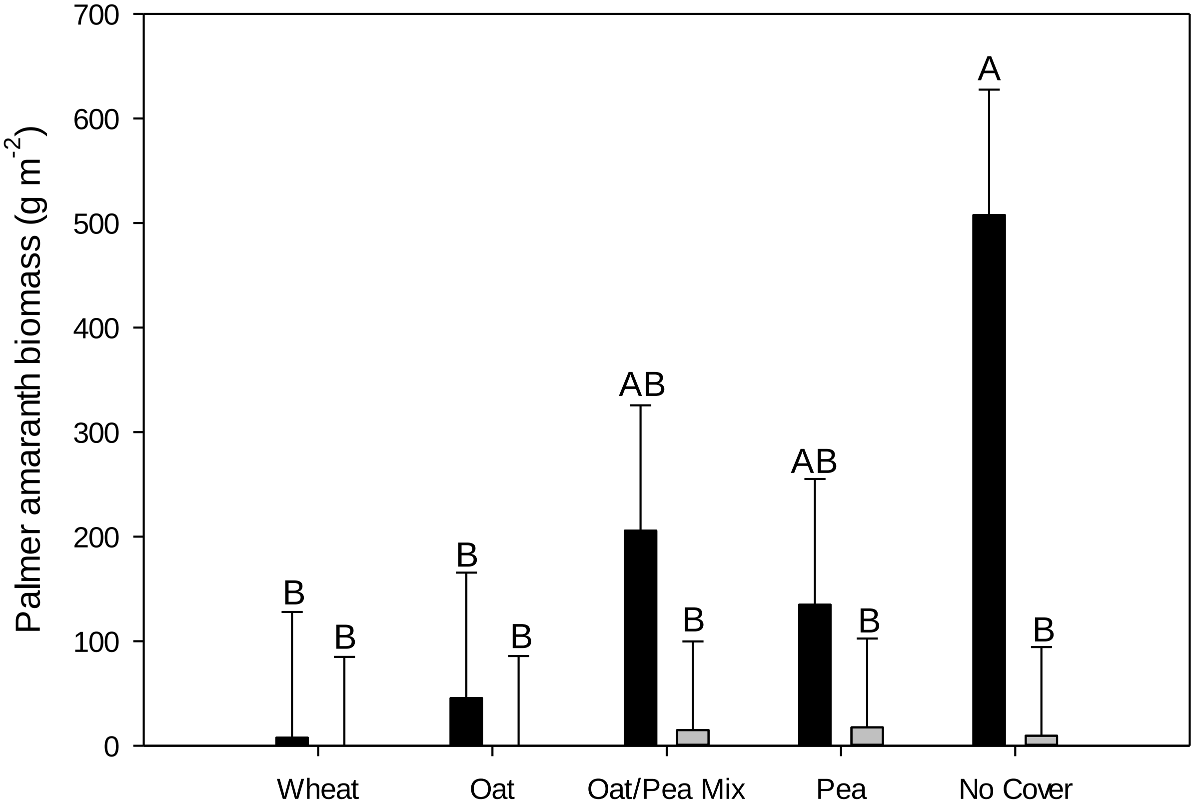


Figure 3.7 Proportion of total Palmer amaranth emergence by cumulative GDD in 2014-2015 when no residual herbicides were applied. See Table 3.7 for the parameter estimates of the regression.

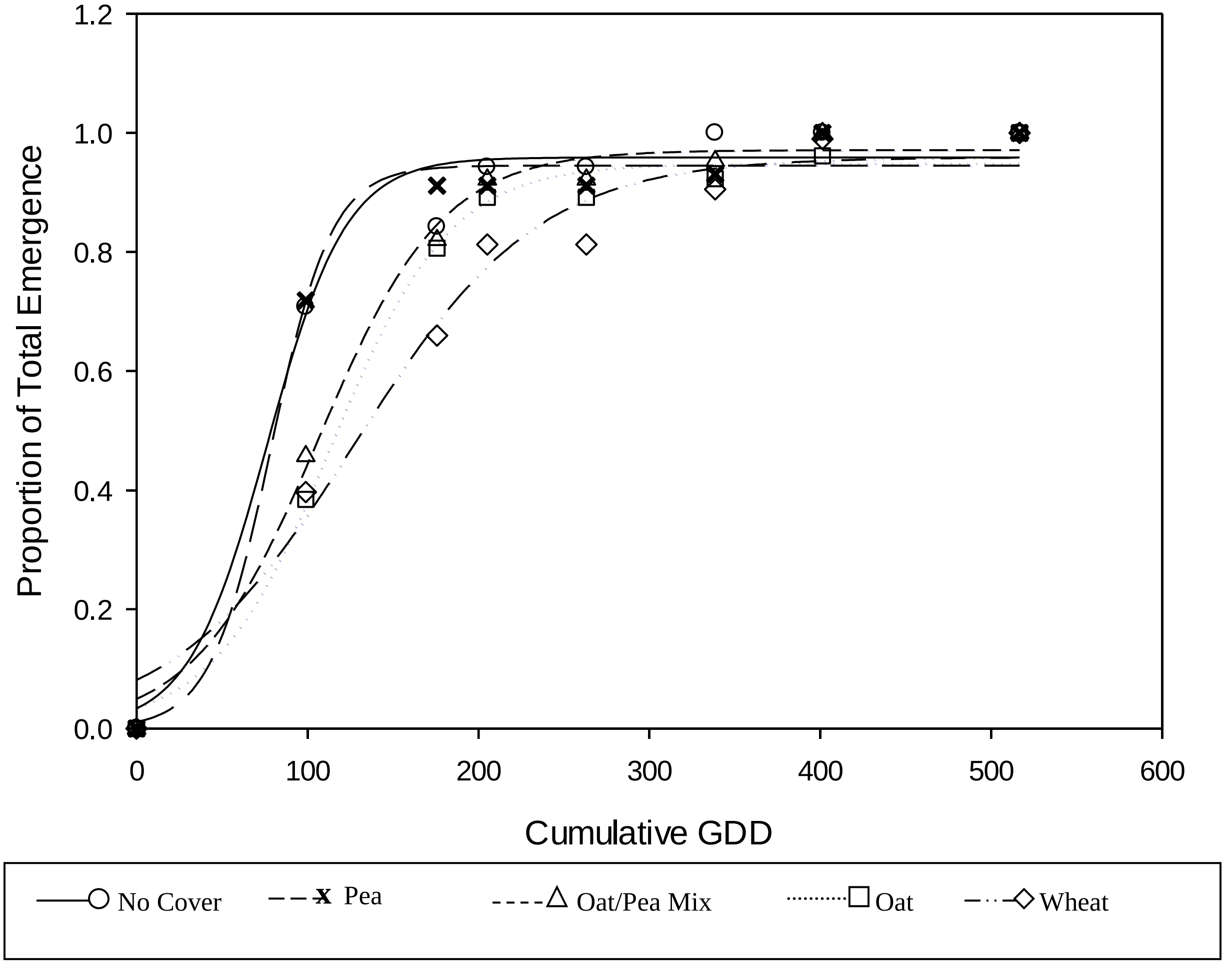


Figure 3.8 Proportion of total Palmer amaranth emergence by cumulative GDD in 2014-2015 when residual herbicides were applied. See Table 3.7 for the parameter estimates of the regression.

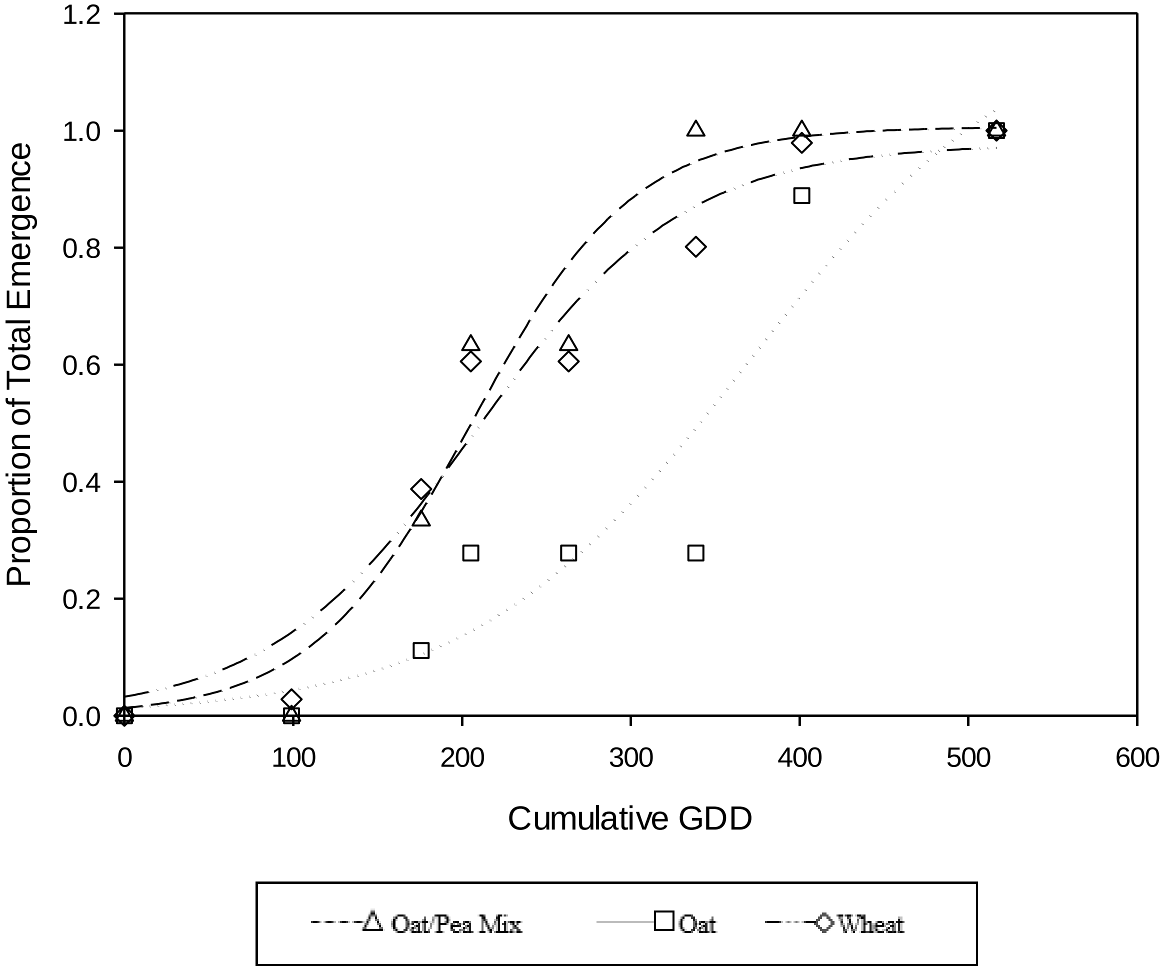


Figure 3.9 Surviving glyphosate-resistant Palmer amaranth density in 2014-2015 growing season by cover crop and termination treatment interaction on June 30, 2015. Same letters are not different among cover crop treatments. Error bars represent standard error of the mean.

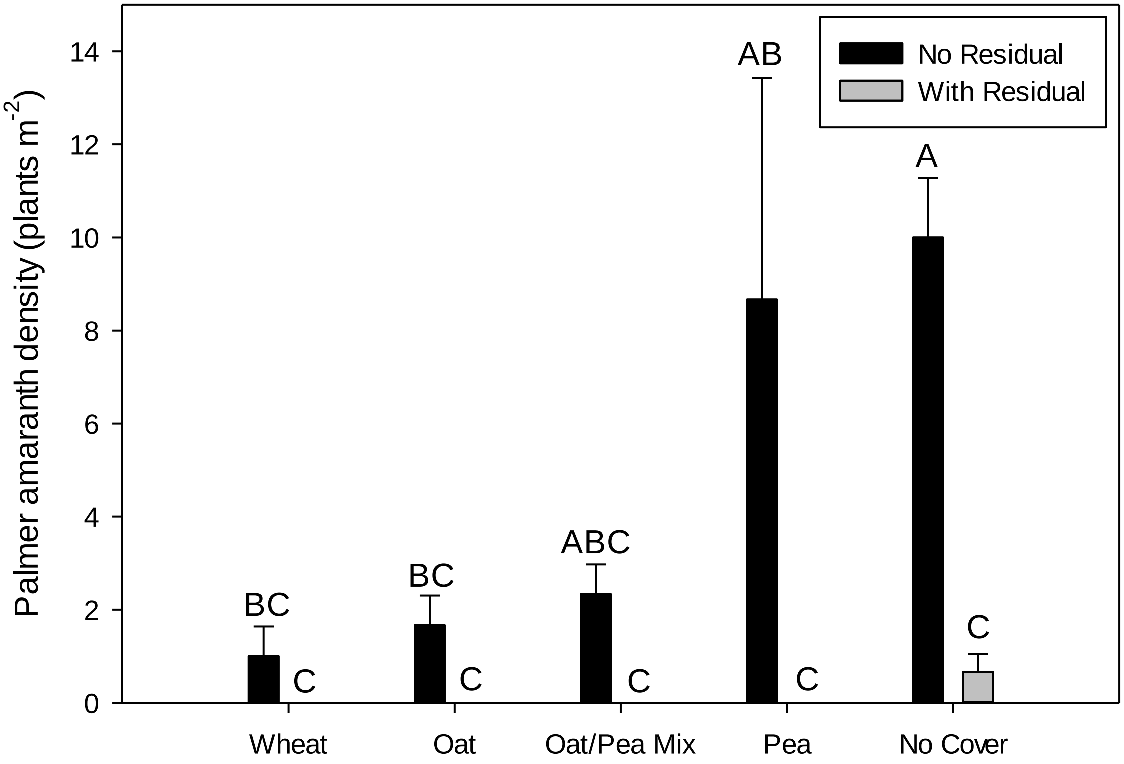


Figure 3.10 Soybean leaf area index at soybean R2 growth stage in 2014-2015 growing season for each cover crop treatment. Letters denote significant differences among cover crop treatments.

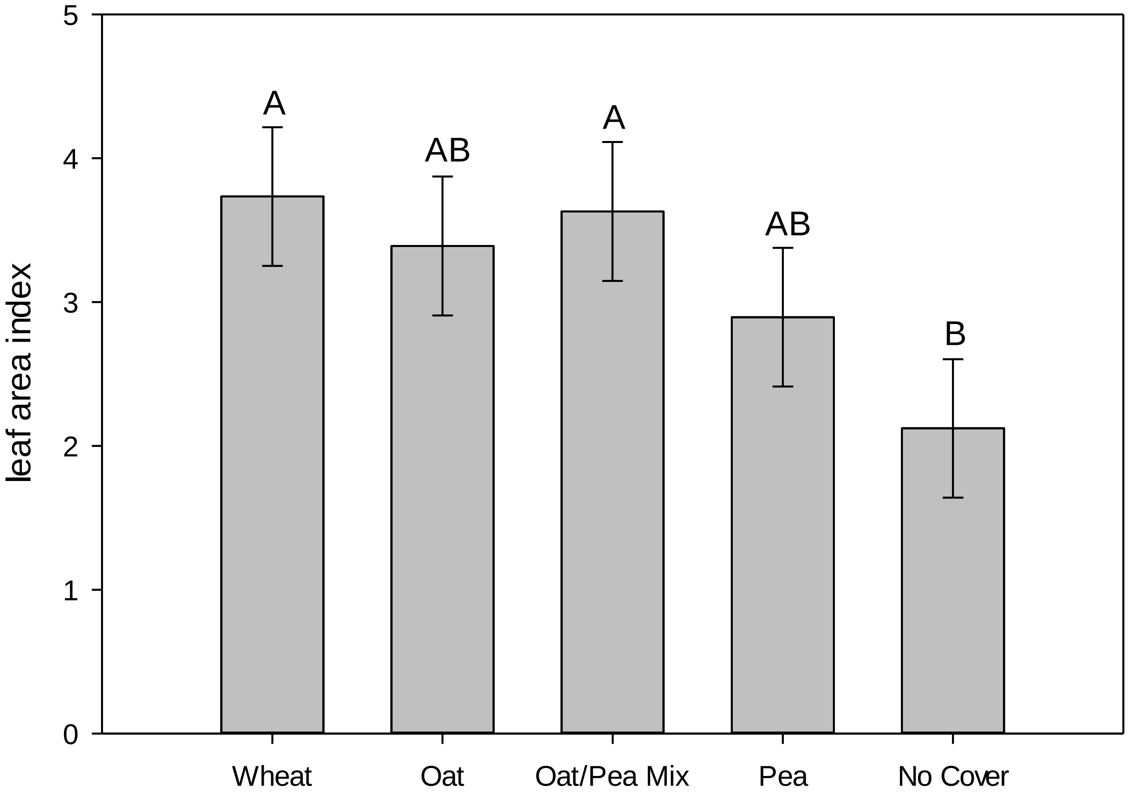
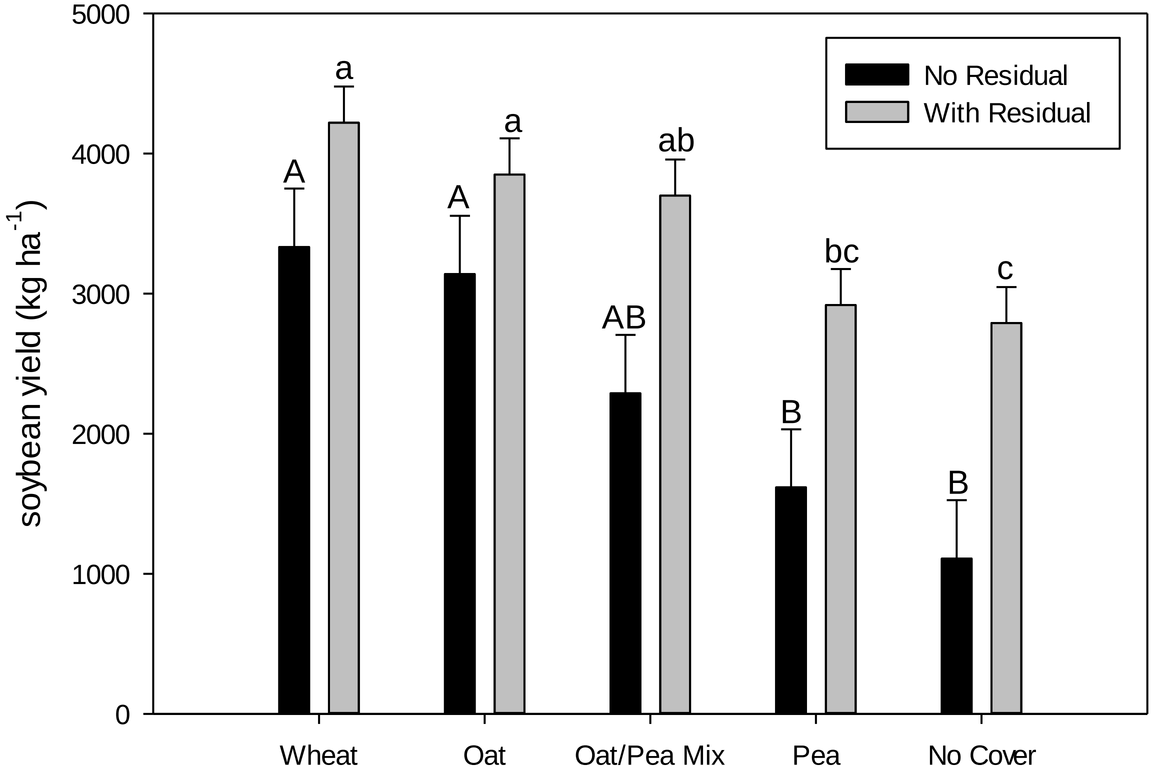


Figure 3.11 Soybean yield (kg ha^{-1}) as affected by cover crops and herbicide treatments in 2014-2015. Uppercase letters denote significant differences among cover crop treatments and termination with no residual herbicide and lowercase letters denote significant differences among cover crop treatments and termination with residual herbicides.



Chapter 4 - Rye Cover Crop and Herbicide Programs Affect Horseweed (*Conyza canadensis*) and Palmer Amaranth (*Amaranthus palmeri*) in No-Till Soybean

Abstract

Integrating cover crops and herbicide programs into no-tillage soybean production systems could reduce horseweed and Palmer amaranth populations in Kansas. A field study was conducted near Manhattan, KS in 2015-2016. Three fall treatments included fall-sown rye cover crop, a November residual herbicide application, and no fall weed control. Four spring treatments included no herbicide, burndown with no residual, burndown with full residual, and split burndown with 2/3 split residual preplant and 1/3 residual at soybean planting. Horseweed density and biomass and total weed biomass were reduced 92% or more by either fall residual or rye treatments compared to no fall weed control when assessed prior to application of spring treatments. Horseweed suppression was similar as long as some control measure was used in the fall or spring. Palmer amaranth biomass and density were reduced as long as any spring herbicide was used. In rye cover crop, total weed biomass was reduced 97% or more across spring treatments even when no herbicide was used. Rye could serve as an alternative to spraying residual herbicides in the fall or the spring to suppress horseweed, Palmer amaranth, and other weeds in a no-till soybean crop. Total weed biomass was reduced most when an herbicide was used in the spring with no rye cover crop. Soybean yield loss was greatest when no herbicide treatment was used in the spring. The use of spring herbicides can protect soybean yields more than relying on fall rye cover crop or residual herbicide.

Introduction

Horseweed [*Conyza canadensis* (L.) Cronq.] and Palmer amaranth [*Amaranthus palmeri* S. Watson] are annual weed species that can cause large yield losses in no-till soybean production if not properly controlled. Horseweed can reduce no-till soybean yields by 83% (Bruce and Kells 1990), and glyphosate-resistant horseweed reduced no-till soybean yields by 83 to 93% when no control measures were used (Byker et al. 2013b). Horseweed has become a problematic weed species in no-tillage production systems because it does not emerge well from soil depths over 0.5 cm and seeds are not buried by tillage (Bhowmik and Bekech 1993; Nandula et al. 2006). Horseweed has evolved resistance to numerous important herbicide sites of action in Kansas and surrounding states (Heap 2017). Palmer amaranth can cause 79% soybean yield loss at a density of 8 plants m^{-1} row (Bensch et al. 2003). Palmer amaranth has become a successful weed in soybean because its emergence pattern coincides with soybean planting and is able to adapt its emergence and growth to varying environments (DeVore et al. 2013; Jha et al. 2008, 2010a, 2010b). Palmer amaranth has also evolved resistance to numerous important herbicide sites of action in Kansas and surrounding states (Heap 2017; Horak and Peterson 1995; Sweat et al. 1998).

To manage both horseweed and Palmer amaranth in a soybean crop requires an integrated approach. This includes understanding how to integrate the use cover crops and a diversity of herbicides at different timings to suppress both horseweed and Palmer amaranth densities and biomass in soybean. Horseweed can complete its life cycle as either a winter annual or a summer annual depending on the region (Buhler and Owen 1997; Davis et al. 2007; Regehr and Bazzaz 1979; Weaver 2001). In eastern Kansas, horseweed primarily completes its life cycle as a winter annual (See Chapter 2). Palmer amaranth is a summer annual with a life cycle that matches soybean cropping (Keeley et al. 1987; USDA 2016; Ward et al. 2013). As a result, the management plan for both weeds within a no-till soybean crop must contain different approaches at different times of the year.

Cover crops are plants grown between main crops and are not harvested for profit. Cover crops can suppress weeds by competing for resources, interrupting life-cycles, producing allelopathic chemicals, changing the soil environment, reducing dispersal of propagules, enhancing weed seed decay, and maintaining surface residues (Snapp et al. 2005). The more cover crop biomass that is produced, the more weed biomass is reduced (Nord et al. 2011; Petrosino et al. 2015; Westgate et al. 2005; Williams et al. 1998). Grass cover that compete well with weeds because of their ability to capture resources more efficiently and produce biomass quickly (Brainard et al. 2011).

One pre-emergence herbicide that has been found to effectively suppress Palmer amaranth is a mixture of flumioxazin and pyroxasulfone (Fierce®, Valent U.S.A. Corporation Walnut Creek, CA). The use of a tankmix of dicamba, glyphosate, flumioxazin, and pyroxasulfone, together with a cereal rye cover crop could suppress horseweed and Palmer amaranth in no-till soybean production.

The objectives of this study were to (1) determine the level of horseweed, Palmer amaranth, and total weed suppression, and impact on soybean growth in response to cover crop, herbicide programs, and an integrated weed management program, and (2) quantify soybean yield in response to cover crop, herbicide programs, and horseweed and Palmer amaranth competition.

Materials and Methods

Experimental Design

A field experiment was conducted during the 2015-2016 growing season at the Department of Agronomy Ashland Bottoms Research Farm (39.124651°N, 96.612004°W) near Manhattan, KS. Soil type was a Muir silt loam formed in a floodplain from calcareous alluvium which has a very high available water storage capacity. The experiment was set up in a split plot design with three replications. The main plots consisted of three fall treatments and the subplots were four spring treatments with a total of twelve 3.0 m by 12.1 m subplots per replication. The three fall treatments were fall residual herbicide, winter rye cover crop variety “Elbon”, and no treatment. The four spring cover crop termination treatments were burndown with no residual, burndown with full residual, burndown with split 2/3 residual preplant and 1/3 applied at soybean planting, and no treatment. Information on herbicide mixtures, rates, manufacturers, and application dates can be found in Tables 4.1 and 4.2. Rye was seeded with a Tye experimental plot drill at 67 kg ha^{-1} in 22.5-cm rows on October 12, 2015. Soybean variety ASGROW 3634 was planted with four-row planter (White 6700) in 76-cm rows on May 23, 2016 at 321,000 seeds ha^{-1}. A POST herbicide was applied in June 2016 for general weed control (Tables 4.1 and 4.2).

Data collection

Weed density was recorded on November 14, 2015 and February 22 and April 5, 2016 within three 20-cm diameter PVC rings established in each subplot prior to application of spring treatments. Weed and rye aboveground biomass were collected on May 4, 2016 from one 0.5 m by 0.5 m quadrat per subplot. Biomass samples were dried at 70 C for 6 days and then weighed. After spring treatments were applied, weed emergence by species was recorded every two weeks within two 0.5 m by 0.5 m quadrats established in each subplot. In one half of each quadrat the weeds were counted and left to track plant growth while in the other half the weeds were counted and then pulled to see effects on emergence in the absence of intraspecific competition.

Prior to the midseason POST herbicide application, weed and soybean aboveground biomass were collected from one 0.5 m by 0.5 m quadrat per subplot on June 16, 2016. Biomass samples were dried at 70 C for 6 days and then weighed. Weed and soybean aboveground biomass and cover crop residue were collected from one 0.5 m by 0.5 m quadrat per subplot on August 2, 2016. The soybean plants were separated into leaves, stems, and reproductive structures, leaf area was determined using a leaf area meter (LiCOR 3100, Lincoln NE), and parts were bagged and dried separately. All biomass and cover crop residue samples were dried at 70 C for 6 days and weighed. Soybean seed was harvested from the middle two rows in each subplot using a plot combine on October 25, 2016. Yield was determined at 12% moisture.

Weed and cover crop biomass and densities were averaged over samples per plot and calculated to g or plants m^{-2}. Soybean plant biomass and leaf area were calculated based on a sampling area of 0.76 m by 0.5 m rather than 0.5 m by 0.5 m quadrat to account for soybean row spacing. Leaf area index (LAI) was determined as the ratio of area of the leaves over the ground area sampled. The relationship of horseweed individual plant biomass in response to horseweed density was described using a 3-parameter exponential decay regression curve:

$$y = y0 + a * \exp(-b * x) \qquad \text{Equation 4.1}$$

where y is horseweed biomass in g plant^{-1}, y0 is the initial biomass at the lowest density, a is the difference between the maximum biomass and the initial biomass, b is the decay constant, and x is horseweed density in plants m^{-2}.

Data were analyzed using PROC GLIMMIX in SAS® Studio University Edition (SAS Institute Inc., 100 SAS Campus Dr., Cary, NC). Horseweed biomass and density, total weed biomass and density, and cover crop biomass documented before spring herbicide treatments were compared to evaluate effectiveness of fall treatments. Palmer amaranth biomass and density, horseweed biomass and density, and total weed biomass and density documented at 10 and 13 weeks after application of the spring treatments were analyzed for the combined effects of fall treatments, spring treatments, and their interactions. Palmer amaranth biomass and density, horseweed biomass and density, total weed biomass and density, cover crop dry residue, and soybean LAI and yield documented after the midseason POST herbicide treatment were analyzed for the combined effects of the fall treatments, spring treatments, and their interactions. Data were determined to be significant at $\alpha<0.05$ using the Tukey-Kramer method.

Results and Discussion

Maximum temperatures were higher than the 30-yr average maximum, and minimum temperatures were lower than the 30-year average minimum for the 2015-2016 growing season (Table 4.3). Total rainfall was 1089 mm for 2015-2016, which was greater than the 30-yr average of 899 mm, however, the distribution of rainfall by month was variable with more than normal in November and December, which ensured winter rye cover crop and fall weed establishment. In early 2016, few rain events led to no new emergence of spring-emerging weeds. This was followed by more rain at the end of April that was 2.2 times the 30-yr average. Also, June 2016 was a dry month reducing summer weed establishment.

The main weeds of interest for this study were horseweed and Palmer amaranth but other weed species included blue mustard (*Chorispora tenella*), velvetleaf (*Abutilon theophrasti*), ivyleaf morningglory (*Ipomoea hederacea*), stinkgrass (*Eragrostis cilianensis)*, downy brome (*Bromus tectorum*), large crabgrass (*Digitaria sanguinalis*), and volunteer soybeans. A majority of the weeds that emerged at this site were winter annual species. Horseweed emerged at high levels throughout the field site. Downy brome occurred in thick patches, but only in certain areas of the site. Blue mustard also made up a large portion of the emerging winter annual species. Fewer summer annuals such as Palmer amaranth and large crabgrass emerged compared to winter annual species.

Horseweed density after planting rye but prior to applying the fall residual on November 14, 2015 was fewest in rye (Table 4.4). Spring horseweed density in established rings was zero in the fall residual treatment, while densities in rye were the same as no treatment on April 5, 2016 (Table 4.4). By May 3, 2016, horseweed biomass and density from harvested quadrats prior to spring herbicide treatments was much greater with no fall treatment compared to rye cover crop and fall residual (Table 4.5). Winter rye and fall residual herbicides both reduced horseweed biomass and density similarly. The differences in the effects of the rye between April and May are because of abundant rye growth that competed with the horseweed and choked it out. With no fall treatment, individual horseweed plant biomass decreased as horseweed density increased (Figure 4.1). This relationship explains why the presence of rye further reduced horseweed biomass and density as there was only a limited capacity available for plant occurrence in the field.

After spring treatment and prior to midseason POST herbicide application, horseweed biomass and density were greatest in the no fall treatment with no spring herbicide (Table 4.6). Horseweed biomass and density were affected similarly by all other treatments, however, fall residual with no spring herbicide reduced horseweed biomass and density 93 and 87%, respectively, while all other treatments caused 98% or more reduction compared to the no control measures treatment (Table 4.6). Samples harvested from quadrats with soybeans on August 2 and between soybean rows on August 4, 2016 were averaged across sampling dates to determine plant responses after the midseason treatment POST herbicide application. Horseweed biomass and density were reduced similarly among all other treatments compared to the no control treatment, however, the fall residual with no spring herbicide reduced horseweed biomass 76% while all other treatments reduced horseweed biomass by 99% or more (Table 4.7). Similarly, horseweed density was reduced by 83% by rye cover crop or fall residual with no spring herbicide while all other treatments reduced horseweed density by 89% or more. Even though both fall residual and rye cover crop treatments suppressed horseweed populations by the following spring, the effects of the rye cover crop on horseweed lasted longer into the growing season and was comparable to other control treatments even when no herbicide was applied in the spring. A rye cover crop could provide control of horseweed similar to the use of a residual herbicide applied in the spring.

Few Palmer amaranth plants had emerged by May 3, 2016, so biomass and density prior to spring herbicide treatments were not different among fall treatments (Table 4.5). After spring treatment and prior to the midseason POST herbicide application, Palmer amaranth biomass from quadrats harvested on June 16, 2016 was greatest in the fall residual with no spring herbicide treatment, and not different from fall residual with no spring residual or rye cover crop with no spring residual (Table 4.6). These plots had less vegetative cover and a lack of residual herbicides to suppress subsequent Palmer amaranth emergence and growth. If the rye cover crop was not terminated with a spring herbicide, Palmer amaranth biomass and density were reduced 100% compared to fall residual with no spring herbicides. Where no control measures were used, Palmer amaranth biomass and density were reduced due to the presence of large populations of established horseweed (Table 4.6). The use of spring residual herbicides provided 91% or more control of Palmer amaranth across fall treatments compared to the fall residual treatment with no spring herbicide (Table 4.6). Palmer amaranth biomass and density averaged across samples taken on August 2 and August 4, 2016 were not different (Table 4.7). Spring residual herbicides applied to a no-till soybean crop can suppress Palmer amaranth populations early in the season more than relying on other control programs without spring residual herbicides unless a rye cover crop was not terminated with a spring herbicide.

Because horseweed and Palmer amaranth were the main weeds of interest, other weed species were combined, and their density after planting rye (Table 4.4). After the fall residual treatment was applied, the density of other weeds was not different among fall treatments (Table 4.4). Prior to spring herbicide application, biomass of other weeds were reduced by both fall residual (6 g m^{-2}) and rye cover crop (20 g m^{-2}) compared to no fall treatment (217 g m^{-2}) (data not shown). After spring herbicide application and prior to midseason POST herbicide application, biomass of other weeds was greatest in the fall residual treatment with no spring herbicide (49 g m^{-2}) and all other treatments ranged from 12 to 0 g m^{-2} (data not shown). Greater growth of other weeds in this treatment was allowed because of the reduction of horseweed biomass from the fall residual treatment. Where no control measures were used in the fall or spring, biomass of other weeds was reduced because of the high biomass of horseweed which prevented the growth of other weeds. The presence of the rye cover crop residue reduced other weed biomass by 99% even when no spring herbicide was applied and horseweed and Palmer amaranth biomass was low. The presence of spring residual herbicides reduced other weed biomass by 93% or more across all fall treatments. After midseason POST, biomass of other weeds, averaged across August 2 and August 4, 2016 samples was not different among treatments (data not shown). However, density of other weeds' in the quadrats established between soybean rows was greatest in the rye cover crop with no spring herbicide (31 plants m^{-2}) followed by no fall treatment with no spring herbicide (15 plants m^{-2}) and fall residual with no spring residual (11 plants m^{-2}) (data not shown). The use of a fall control treatment suppressed other weeds, but the effects of the rye cover crop lasted longer into the following growing season than the fall residual treatment. A rye cover crop could suppress biomass production of other weeds similarly to treatments containing spring herbicides, but densities of these other weeds may not be reduced.

Prior to spring herbicide treatment, total weed biomass was greatest in the no fall treatment (Table 4.5). Rye cover crop and fall residual herbicides reduced total weed biomass similarly. Prior to and after midseason POST herbicide application, total weed biomass was greatest where no control measures were used followed by fall residual with no spring herbicide (Table 4.6 and 4.7). Total weed density averaged across fall treatments from established quadrats between soybean rows was greatest where no spring herbicide was applied (50 plants m^{-2}) compared to other spring treatments. If a no fall treatment or a fall residual is used, spring herbicide applications should be used to suppress early weed biomass in soybeans. However, if a rye cover crop is used, a spring herbicide treatment does not need to be used to suppress weed growth, but the use of spring herbicides could reduce total weed density more than rye cover crop alone.

Soybean growth and yield were affected by the spring treatment but was not affected by fall treatments (Table 4.8). Soybean biomass on June 16, 2016 averaged across fall treatments was greatest where a residual herbicide was used followed by no spring residual treatment.

Soybean leaf area and seed yield averaged across fall treatments was greatest among spring herbicide treatments. Soybean yield with no spring herbicide was reduced by 44% compared to split residual. As long as a spring herbicide was used, soybean yield was greater than not using an herbicide. Even though winter rye suppressed weeds without the use of a spring herbicide, the continued growth of rye when no herbicide was applied in the spring also reduced soybean yield. However, a rye cover crop could be used instead of a spring residual herbicide as long as a spring herbicide is used to terminate the cover crop.

Rye biomass averaged 693 g m^{-2} on May 3, 2016 (data not shown). Residue left from the cover crops on August 2, 2016 was different among spring herbicide treatments. Rye residue in plots that did not receive spring herbicides had the greatest residue cover (823 g m^{-2}) followed by no residual (475 g m^{-2}), residual split (395 g m^{-2}), and full residual (357 g m^{-2}) spring herbicide applications (data not shown). Since no herbicide was sprayed on the rye in the no spring herbicide treatments, the rye was allowed to grow for a longer period of time and produce more biomass while the other treatments killed the rye at spring herbicide application. With no spring herbicides applied, the greater production in rye biomass reduced total weed biomass compared to the no control measures fall treatments (Table 4.7). However, soybean yield was lowest when no spring herbicide was applied (Table 4.8).

Rye has been a common choice as a cover crop used to suppress weeds due to its vigorous growth, competitive ability, and allelopathic compounds (Boz 2003; Dhima et al. 2006; Didon et al. 2014; Nord et al. 2011). Fall-seeded rye has been shown to reduce weed biomass further with the application of herbicides (Blackshaw 2008). Palmer amaranth emergence was delayed compared to treatments with no cover crop (DeVore et al. 2013). However, some studies have shown variable results on weed biomass and density reduction with the use of rye as a cover crop (O'Reilly et al. 2011). This study supports the claim that a rye cover crop does effectively reduce weed biomass (Table 4.7), even without the application of herbicides, though total weed density was not reduced.

To combat herbicide-resistant weeds, the use of pre-emergence and post-emergence herbicides and multiple modes of action are encouraged (Davis et al. 2009). The greatest returns on investment were seen when both post-emergence and pre-emergence herbicides were used to control horseweed (Reddy 2001). The control of horseweed and effectiveness of herbicide treatments is dependent on when horseweed emerges. Residual herbicides applied in the fall or spring with glyphosate applied post-emergence in-crop reduced horseweed density and seedbank densities more than glyphosate alone, and spring-applied treatments tended to be more effective than fall-applied treatments because 90% of horseweed emerged in the spring at the study location in Indiana (Davis et al. 2007). In this study, horseweed populations were affected by both fall and spring treatments, with greatest horseweed biomass and density where no control measures were used (Table 4.7). All combinations of cover crop, fall residual, no spring residual, and spring residual affected horseweed populations similarly.

The pre-emergence application of flumioxazin plus pyroxasulfone in the spring was chosen due to its effectiveness as a residual herbicide. Flumioxazin plus pyroxasulfone provided 96 to 99% control of pigweed species by 4 weeks after treatment in no-till soybean when higher rates were used (Mahoney et al. 2014). Within the first 30 days after treatment no Palmer amaranth emerged where plots had flumioxazin plus pyroxasulfone applied pre-emergence in a soybean crop (Bell et al. 2015). In a study containing treatments with rye and wheat cover crops and different herbicide programs, the treatments that contained flumioxazin and pyroxasulfone applied pre-emergence provided 95% or greater control of Palmer amaranth through harvest regardless of cover crop, soybean cultivar, or tillage method (Bell et al. 2016). Horseweed was not effectively controlled by a tank mix of glyphosate with flumioxazin and pyroxasulfone (Byker et al. 2013a). However, adding dicamba to that mix may increase herbicide effectiveness (Kruger et al. 2010).

Conclusions

In this study, horseweed suppression was similar among treatments as long as some control measure was used in the fall or spring. Palmer amaranth suppression was greatest if a residual herbicide was used in the spring. If a fall residual herbicide or no fall treatment was used, total weed suppression was greatest when a residual herbicide was included in the spring treatment. If winter rye was used, not using a residual herbicide was just as effective at suppressing total weed biomass as using a residual herbicide, but total weed density was less affected when no spring herbicide was used in rye. Soybean growth and yield was reduced when no herbicide treatments were used in the spring. Overall, winter rye could be used to suppress horseweed, Palmer amaranth, and other weeds in a no-till soybean crop as long as a non-residual or residual spring herbicide was used.

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Tables and Figures

Table 4.1 Herbicide active ingredient, rate, trade name, product concentration, and manufacturer for herbicides used in this study.

Herbicide	Rate used	Trade name	Product concentration	Manufacturer
	g ai or ae ha^{-1}		g ai or ae L^{-1} or %	
glyphosate	868 or 1300 or 1100	Roundup Powermax®	540	Monsanto Company, St. Louis, MO
dicamba	280	Clarity®	480	BASF, Research Triangle Park, NC
chlorimuron ethyl + tribenuron methyl	14 + 4	DuPont™ Canopy® EX	22.7 + 6.8	E. I. du Pont de Nemours and Company, Wilmington, DE
flumioxazin + pyroxasulfone	89 + 112	Fierce®	33.5 + 42.5	Valent U.S.A. Corporation, Walnut Creek, CA
lactofen	224	Cobra®	240	Valent U.S.A. Corporation, Walnut Creek, CA

Table 4.2 Herbicide treatment, application date, and mixture for herbicides used in this study.

Season	Treatment	Application Date	Herbicide Mixture[1]
Fall	Residual	11/23/2015	glyphosate + dicamba + chlorimuron ethyl + tribenuron methyl
Spring	Burndown with split 2/3 and 1/3 residual	5/5 and 5/23/2016	glyphosate + dicamba + flumioxazin + pyroxasulfone
	Burndown and full residual	5/5/2016	glyphosate + dicamba + flumioxazin + pyroxasulfone
	Burndown	5/5/2016	glyphosate + dicamba
Summer	midseason POST	6/17/2016	glyphosate + lactofen

[1] All applications included AMS at 1.25% w/v

Table 4.3 Monthly average, maximum, minimum, and 30-yr average temperatures (C), and monthly, total, and 30-year average precipitation for the 2015-2016 growing season for Manhattan, KS.

Month	Temperature				Precipitation	
	2015-2016		30-year Average		2015-2016	30-year Average
	Maximum	Minimum	Maximum	Minimum	mm	
	C					
October	31.7	-3.9	20.2	6.2	15	65
November	26.7	-5.0	12.5	-0.3	114	43
December	20.0	-11.7	5.7	-6.1	74	28
January	20.6	-17.8	4.5	-7.8	15	19
February	25.0	-10.6	7.2	-5.7	12	30
March	27.2	-6.7	13.4	-0.5	11	62
April	30.6	-2.8	19.2	5.6	202	91
May	30.0	4.4	24.2	11.7	161	118
June	38.9	11.7	28.9	16.9	32	135
July	38.9	17.2	32.1	19.8	129	112
August	36.1	12.2	31.7	18.6	181	112
September	34.4	5.0	27.1	13.1	143	82
Total					1089	899

Table 4.4 Horseweed and other weed density (plants m^{-2}) and standard error from established rings prior to fall treatment (11/14/2015), after fall herbicide treatment (2/22/2016), and prior to spring herbicide treatment (4/5/2016). Means with same letters within a column are not different at α=0.05.

Fall Treatment	Horseweed Density			Other Weed Density		
	11/14/2015	2/22/2016	4/5/2016	11/14/2015	2/22/2016	4/5/2016
	plants m^{-2} (SE)					
No Fall Treatment	378 (68) a	256 (53) a	235 (47) a	290 (110) a	65 (46) a	78 a (45) a
Fall Residual		0 (0) b	0 (0) b		51 (46) a	29 a (21) a
Rye Cover Crop	233 (24) b	180 (26) a	169 (23) a	63 (18) b	10 (4) a	26 a (6) a

Table 4.5 Density of horseweed and Palmer amaranth and biomass of horseweed, Palmer amaranth, and total weeds in response to fall treatment prior to spring herbicide treatments on 5/3/2016. Means with same letters in a column are not different at α=0.05.

Fall Treatment	Density				Biomass					
	Horseweed		Palmer Amaranth		Horseweed		Palmer Amaranth		Total Weed	
	plants m^{-2} (SE)				--------------------g m^{-2} (SE)----------------------					
No Fall Treatment	363 (91)	a	0 (0)	a	74.2 (15)	a	0 (0)	a	290.7 (36)	a
Fall Residual	0 (0)	b	1.5 (1)	a	0 (0)	b	0.1 (0)	a	6.1 (4)	b
Rye Cover Crop	15 (8)	b	0 (0)	a	1.8 (1)	b	0 (0)	a	22.0 (11)	b

Table 4.6 Biomass of horseweed, Palmer amaranth, and total weeds, and horseweed and Palmer amaranth density on 6/16/2016 in response to fall and spring treatments prior to midseason POST herbicide application. Means followed by the same letters in a column were not different at α=0.05.

Fall Treatment	Spring Treatment	Density				Biomass					
		Horseweed		Palmer Amaranth		Horseweed		Palmer Amaranth		Total Weed	
		plants m^{-2}				--------------------g m^{-2}------------------					
No Fall Treatment	No Herbicide	141.3	a	6.7	a	322.6	a	0.0	b	323.8	a
	Burndown	0.0	b	9.3	a	0.0	b	2.2	b	8.9	b
	Full Residual	0.0	b	4.0	a	0.0	b	2.1	b	2.7	b
	Split Residual	0.0	b	1.3	a	0.0	b	0.0	b	0.0	b
Fall Residual	No Herbicide	18.7	b	109.3	a	21.2	b	22.2	a	92.1	ab
	Burndown	2.7	b	12.0	a	0.5	b	6.1	ab	18.6	b
	Full Residual	1.3	b	1.3	a	0.0	b	0.6	b	3.9	b
	Split Residual	0.0	b	0.0	a	0.0	b	0.0	b	0.0	b
Rye Cover Crop	No Herbicide	0.0	b	0.0	a	0.0	b	0.0	b	0.6	b
	Burndown	0.0	b	9.3	a	0.0	b	4.9	ab	5.2	b
	Full Residual	0.0	b	1.3	a	0.0	b	0.4	b	0.4	b
	Split Residual	0.0	b	0.0	a	0.0	b	0.0	b	0.5	b

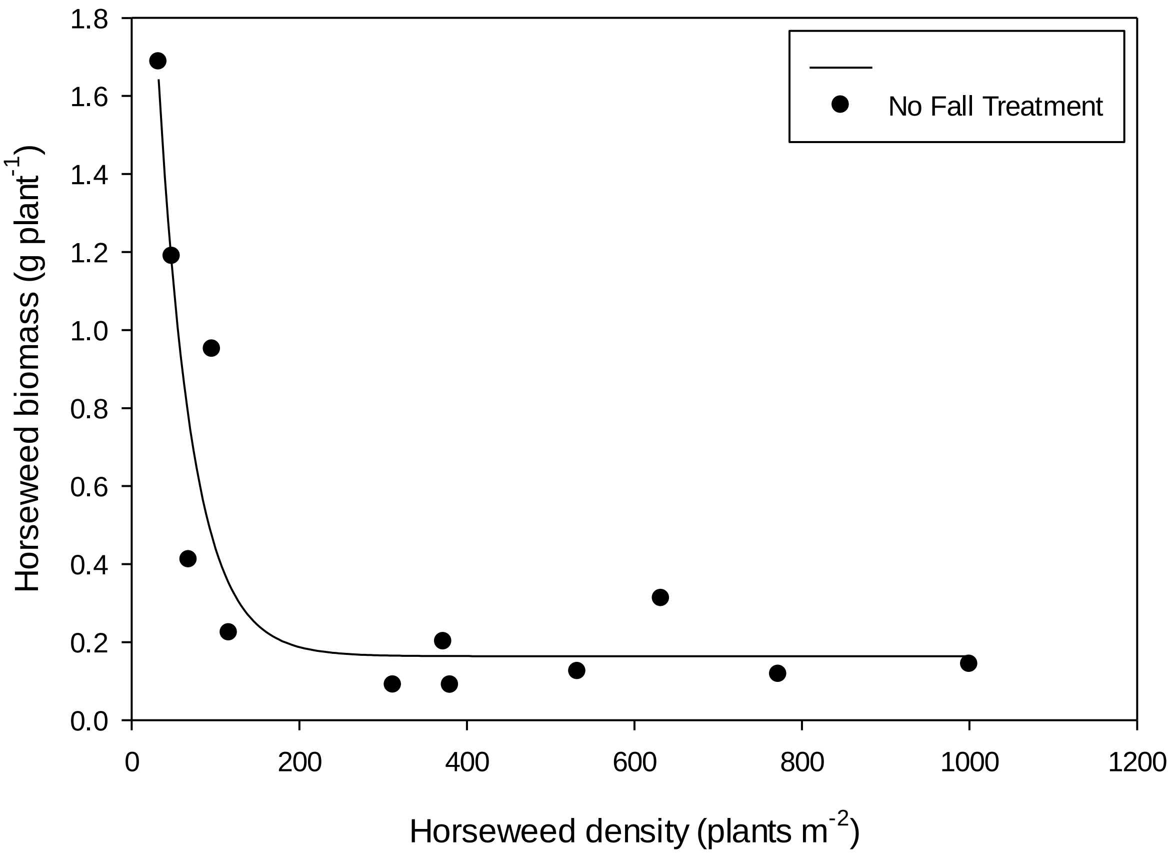
Table 4.7 Density of horseweed and Palmer amaranth, and biomass of horseweed, Palmer amaranth, and total weeds in response to fall and spring treatments 6 weeks after midseason POST herbicide averaged across quadrats with (8/2/2016) and without (8/4/2016) soybean plants. Means followed by the same lowercase letters in a column are not different at α=0.05.

Fall Treatment	Spring Treatment	Density				Biomass					
		Horseweed		Palmer Amaranth		Horseweed		Palmer Amaranth		Total Weed	
		plants m^{-2}				g m^{-2}					
No Fall Treatment	No Herbicide	62.3	a	0.7	a	310.6	a	0.5	a	363.3	a
	Burndown	2.7	b	4.0	a	4.1	b	114.3	a	120.0	b
	Full Residual	5.0	b	3.0	a	0.8	b	1.5	a	21.5	b
	Split Residual	0.0	b	0.0	a	0.0	b	0.0	a	22.0	b
Fall Residual	No Herbicide	10.7	b	3.7	a	74.8	b	71.6	a	191.5	ab
	Burndown	2.7	b	4.3	a	1.9	b	56.1	a	66.0	b
	Full Residual	4.7	b	3.7	a	0.7	b	108.5	a	110.3	b
	Split Residual	6.7	b	0.3	a	0.0	b	0.1	a	0.4	b
Rye Cover Crop	No Herbicide	10.3	b	3.0	a	0.8	b	4.2	a	12.6	b
	Burndown	1.7	b	0.0	a	0.5	b	0.0	a	0.9	b
	Full Residual	1.3	b	0.7	a	0.4	b	5.9	a	6.9	b
	Split Residual	6.0	b	0.3	a	0.3	b	0.2	a	0.7	b

Table 4.8 Soybean biomass, leaf area index (LAI), and yield averaged across fall treatments and harvested from quadrats on June 16, August 2, and October 25, 2016, respectively. Means followed by the same lowercase letters in a column were not different at α=0.05.

Spring Treatment	Biomass		LAI		Yield	
	$g\ m^{-2}$ (SE)		$cm^2\ cm^{-2}$ (SE)		$kg\ ha^{-1}$ (SE)	
No Herbicide	5.6 (0.6)	b	3.9 (0.5)	b	3650 (291)	b
Burndown	8.6 (1.2)	ab	6.7 (0.4)	a	5760 (330)	a
Full Residual	10.3 (1.2)	a	7.2 (0.5)	a	6220 (170)	a
Split Residual	9.9 (1.0)	a	8.1 (0.6)	a	6460 (108)	a

Figure 4.1 Horseweed individual plant biomass in response to changes in horseweed density. See Equation 4.1 for 3-parameter exponential decay regression curve equation.



Appendix A - Chapter 4 F values and two-way ANOVAs

Table B.1 F values of two-way ANOVAs of the effects of fall treatments and spring treatments on horseweed, Palmer amaranth, other weed, and total weed density before (6/16/2016) and after (8/2/2016 and 8/4/2016) the midseason herbicide treatment.

Source of Variation	df	Horseweed Density	df	Palmer Amaranth Density	df	Other Weed Density	df	Total Weed Density
				6/16/2016				
Fall Treatment	2, 22	5.44*	2, 22	1.05	-	-	-	-
Spring Treatment	3, 22	7.92***	3, 22	1.04	-	-	-	-
Fall Treatment x Spring Treatment	6, 22	5.61**	6, 22	1.03	-	-	-	-
				8/2/2017 and 8/4/2017 Samples Combined				
Fall Treatment	2, 24	2.23	2, 6	0.99	-	-	-	-
Spring Treatment	3, 24	5.16**	3, 18	2.49	-	-	-	-
Fall Treatment x Spring Treatment	6, 24	2.80*	6, 18	1.36	-	-	-	-
				8/2/2017 Samples Only				
Fall Treatment	2, 22	4.22*	2, 6	0.28	-	-	-	-
Spring Treatment	3, 22	4.80*	3, 18	1.80	-	-	-	-
Fall Treatment x Spring Treatment	6, 22	3.34*	6, 18	2.03	-	-	-	-
				8/4/2017 Samples Only				
Fall Treatment	2, 24	0.54	2, 4	11.55*	2, 4	0.22	2, 24	0.48
Spring Treatment	3, 24	3.55*	3, 18	2.59	3, 18	14.46***	3, 24	9.88***
Fall Treatment x Spring Treatment	6, 24	1.57	6, 18	3.68*	6, 18	4.12**	6, 24	2.25

Table B.2 F values of two-way ANOVAs of the effects of fall treatments and spring treatments on horseweed, Palmer amaranth, other weed, and total weed biomass before (6/16/2016) and after (8/2/2016 and 8/4/2016) the midseason herbicide treatment.

Source of Variation	df	Horseweed Biomass	df	Palmer Amaranth Biomass	df	Other Weed Biomass	df	Total Weed Biomass
6/16/2016								
Fall Treatment	2, 24	3.61*	2, 4	2.76	2, 4	5.11	2, 22	3.16
Spring Treatment	3, 24	4.37*	3, 18	2.72	3, 18	5.37**	3, 22	6.11**
Fall Treatment x Spring Treatment	6, 24	3.62*	6, 18	3.19*	6, 18	5.24**	6, 22	3.11*
8/2/2017 and 8/4/2017 Samples Combined								
Fall Treatment	2, 22	3.03	2, 6	1.30	2, 22	1.22	2, 4	6.97*
Spring Treatment	3, 22	5.54**	3, 18	1.92	3, 22	1.70	3, 18	7.94**
Fall Treatment x Spring Treatment	6, 22	2.94*	6, 18	2.00	6, 22	0.35	6, 18	2.98*
8/2/2017 Samples Only								
Fall Treatment	2, 22	3.20	2, 24	2.97	2, 22	1.43	2, 24	11.34***
Spring Treatment	3, 22	4.25*	3, 24	5.07**	3, 22	1.36	3, 24	10.48***
Fall Treatment x Spring Treatment	6, 22	3.11*	6, 24	5.19**	6, 22	0.30	6, 24	3.45*
8/4/2017 Samples Only								
Fall Treatment	2, 22	2.23	2, 6	1.37	2, 22	1.19	2, 4	1.84
Spring Treatment	3, 22	7.57**	3, 18	0.90	3, 22	1.05	3, 18	2.10
Fall Treatment x Spring Treatment	6, 22	2.17	6, 18	0.92	6, 22	1.40	6, 18	1.35

Appendix B - Herbicide Resistance in Horseweed Populations in Eastern Kansas

Materials and Methods

In the fall of 2014 and 2015, seeds were harvested from mature horseweed plants at Hiawatha, Topeka, Ottawa, Iola, Parsons, and Oswego (See Chapter 2). Seeds were used in a greenhouse study to assess occurrence of herbicide resistance in the populations. Seed from an additional horseweed population was collected at the Dept of Agronomy Ashland Bottoms Experiment Field (39.124651°N, 96.612004°W) near Manhattan, KS in the fall of 2015.

Horseweed seeds were liberally sprinkled over the surface of 50.8 by 35.6 by 10.2-cm flats filled with commercial potting mix (Metro-Mix 360, Hummert International, 1415 NW Moundview Dr., Topeka, KS 66618). Flats were kept watered as needed. Two sets of horseweed seedlings were transplanted when they reached between the 3-leaf to 10-leaf stage on April 25, 2016 and May 11, 2016 into 7.6 by 7.6 by 8.9-cm pots filled with same potting mix.

Two weeks after transplanting, the horseweed plants were sprayed with herbicide treatments. Since horseweed emergence was uneven and minimal in some populations, one plant from each transplant date and population was kept back as a control. The herbicide treatments included: (1) 868 g ae ha^{-1} glyphosate (Monsanto Roundup Powermax®) with 2.3 kg L^{-1} AMS; (2) 17.5 g ai ha^{-1} chlorsulfuron (Dupont™ Glean XP) with 0.5% NIS v/v; (3) 841 g ai ha^{-1} paraquat (Syngenta® Gramoxone Inteon®) with 0.25% NIS v/v; (4) 2243 g ai ha^{-1} atrazine (Syngenta® Aatrex 4L®) with 1% COC v/v; and (5) 561 g ae ha^{-1} dicamba (BASF Corporation Clarity®).

On May 11, 2016, the first set of transplanted horseweeds was sprayed two weeks after transplanting. A minimum of 6 plants were sprayed per treatment. Glyphosate was sprayed on

Hiawatha, Ottawa, Iola, Oswego, and Ashland Bottoms plants. Chlorsulfuron was sprayed on Ottawa, Iola, Oswego, and Ashland Bottoms plants. Paraquat was sprayed on Iola, Oswego, and Ashland Bottoms plants. Atrazine was sprayed on Iola and Ashland Bottoms plants. Dicamba was sprayed on Iola plants only on this treatment date.

On May 26, 2016, the second set of transplanted horseweed plants was sprayed. Chlorsulfuron was sprayed on Hiawatha and Topeka plants. Paraquat was sprayed on Hiawatha, Ottawa, and Oswego plants. Dicamba was sprayed on Hiawatha, Ottawa, Oswego, and Ashland Bottoms plants. Percent herbicide resistant plants was determined at 4 weeks after treatment based on a scale of 1 to 10 where 1 was no effect and 10 was plant death.

Results and Discussion

Many of the populations used in the herbicide experiment were found to be resistant to certain herbicides. Seed collected from Topeka and Parsons had poor germination, so Topeka was only treated with a few treatments and Parsons had none. Since emergence was uneven, some locations were treated and planted on different days. Glyphosate resistance was found in 100% of the plants from Hiawatha and Ottawa and 33.3%, 50%, and 71.4% of plants from Topeka, Iola, and Ashland Bottoms respectively. Considering that this was a very small sampling of horseweed populations and that many plants were found to be resistant, glyphosate alone cannot be relied on for effective control of horseweed populations in Eastern Kansas. Ashland Bottoms had 37.5% of the population resistant to chlorsulfuron. No tests for multiple resistance were conducted. No resistance was found for dicamba, paraquat, and atrazine.