

INTEGRATING A CEREAL RYE COVER CROP AND SOYBEAN ROW WIDTH WITH  
HERBICIDES TO MANAGE PALMER AMARANTH IN MICHIGAN

By

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## ABSTRACT

### INTEGRATING A CEREAL RYE COVER CROP AND SOYBEAN ROW WIDTH WITH HERBICIDES TO MANAGE PALMER AMARANTH IN MICHIGAN

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Glyphosate-resistant Palmer amaranth (*Amaranthus palmeri* S. Wats.) is an emerging concern for Michigan farmers. Integrating the use of cultural practices such as cover crops and narrow soybean row width may improve the control of herbicide-resistant Palmer amaranth in Michigan. In 2015 and 2016, field experiments investigated the effects of a cereal rye cover crop, including termination method, and soybean row width as cultural practices to improve Palmer amaranth control with herbicides. Additional pot experiments were conducted to evaluate the effects of cereal rye stage, biomass, and termination method on Palmer amaranth emergence. Cereal rye biomass was greater in 2016 compared with 2015 due to the greater accumulation of growing degree days prior to cereal rye termination. Winter annual weeds were suppressed by more than 75% with cereal rye. However, overall Palmer amaranth emergence and control was not effected by cereal rye. In outdoor pot experiments, cereal rye suppression of Palmer amaranth emergence varied by year with the most consistent suppression with the later stage (Feekes 10.1 or later) cereal rye. In greenhouse pot experiments, total Palmer amaranth emergence was only reduced by cereal rye terminated by cutting compared with chemical termination. Planting soybean in narrow rows reduced the emergence period of Palmer amaranth in both years. Palmer amaranth was effectively controlled by both herbicide management strategies in 2015, while only the high management strategy provided season-long control in 2016. Utilizing an intensive herbicide management program and planting soybean in narrow rows provided the greatest impact on Palmer amaranth management in Michigan soybean production.

Dedicated to my parents, Pat and Deb Rogers

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# CHAPTER 1

## REVIEW OF LITERATURE

### Introduction

Soybean (*Glycine max* (L.) Merr.) is an annual broadleaf crop that is grown primarily for soybean oil and meal. Soybean accounts for about 90% of the oilseed production in the United States with 88% of oil used for human consumption, and 98% of soybean meal used for animal feed (ERS 2016; Wills 2013). After corn (*Zea mays* L.), soybean is the second most planted field crop grown in the United States with the main soybean producing areas in the Midwest and the lower Mississippi Valley (USDA 2010, ERS 2016). Michigan ranks 12<sup>th</sup> in soybean production of the 31 states that produce soybean in the United States (USDA 2016). In 2016, more than 206 million ha<sup>-1</sup> of soybean were planted in the United States with over 5 million ha<sup>-1</sup> planted in Michigan alone (NASS 2016). In 2015, the total soybean production value for the United States was over 34 billion dollars, while Michigan production was over 851 million dollars (NASS 2016).

### Weed Competition in Soybean

Weeds are considered the number one production problem in soybean (Vivian et al. 2013). If not managed they influence soybean growth, development, and yield. Broadleaf weeds tend to be more competitive with soybean than grass species. Cowen et al. (1998) reported that broadleaf weeds, Powell amaranth (*Amaranthus powellii* S. Wats.) and redroot pigweed (*Amaranthus retroflexus* L.), were more competitive than barnyardgrass (*Echinochloa crus-galli* (L.) Beauv.) in soybean across all locations, years, and time of weed emergence relative to crop emergence. Similarly, Weaver (2001) observed that green foxtail (*Setaria viridis* (L.) Beauv.) at low



densities was less competitive and had a lower impact on soybean yield when compared with low densities of common lambsquarters (*Chenopodium album* L.) and common ragweed (*Ambrosia artemisiifolia* L.). Weeds not only impact crop yield but also reduce harvest efficiency by plugging up combines resulting in lower yields from harvest loss. Burnside (1973) observed that in addition to reduced seed quality from plant debris, a predominance of broadleaf weeds at the time of harvest caused 19% greater harvest losses compared with plots that had predominantly grass species. On average, weeds reduce soybean yield almost 50% when no weed control is used (Dille et al. 2016). In the United States, the potential economic loss from weed competition in soybean is over \$15 billion dollars annually (Dille et al 2016). One of the most competitive annual broadleaf weeds is Palmer amaranth (*Amaranthus palmeri* S. Wats.), which was ranked as the most troublesome weed in the United States in a recent survey conducted by the Weed Science Society of America (Van Wychen 2016).

### **Palmer amaranth**

Palmer amaranth is a dioecious summer annual weed species that is a member of the *Amaranthus* family. Palmer amaranth is native to the Sonoran Desert region that spans portions of Mexico, southern Arizona, and California (Ehleringer 1983). It thrived in this region by being able to germinate quickly after a major rainfall and complete its lifecycle under limited soil moisture available at the time of germination (Ehleringer 1983). However, Palmer amaranth populations can now be found in the previously uninhabited areas of the Southern United States and has recently spread into the Midwest (Culpepper et al. 2010; Heap 2016). Palmer amaranth was first identified in Michigan in 2010 in a southwest Michigan county (Sprague 2011). Since 2010, it has spread to eleven counties in the southern half of Michigan's Lower Peninsula (C

Sprague, Weed Scientist, Michigan State University, personal communication). Although Palmer amaranth is native to the southwest region of the United States, research has shown that Palmer amaranth has been able to successfully complete its lifecycle, produce seed that can survive Michigan's cold winters, and become a weed problem the following season (Powell 2014).

Palmer amaranth has become a major weed problem in field crops, due to its rapid and continued emergence, high photosynthetic capacity, and prolific seed production (Keeley et al. 1987; Ward et al. 2013). Palmer amaranth can grow up to 0.21 cm per growing degree day and reach mature heights of over 2 meters (Horak and Loughin 2000). Compared with other *Amaranthus* species, Palmer amaranth produces more biomass at temperatures above 25 C and has up to a 62% greater growth rate per growing degree day (Guo and Al-Khatib 2003; Culpepper et al. 2006). Palmer amaranth that emerges with corn can reduce yield 91% with only 8 plants per meter of corn row (Massinga et al. 2001). In fact, the presence of only one plant per meter of row reduced corn yield by as much as 40%. In a similar study, just one Palmer amaranth plant per meter of row reduced soybean yield by 32% (Klingaman and Oliver 1994). These studies show the importance of managing Palmer amaranth early to prevent serious yield loss.

Palmer amaranth emergence in Michigan typically begins in late May to early June with continued emergence through mid-September (Powell 2014; Kohrt 2017). Depending on soybean planting date, Palmer amaranth emergence occurs two to three weeks after soybean planting, unless weather conditions delay soybean planting until late June (USDA 2010). Reduced soybean growth and yield may occur if Palmer amaranth are not controlled. Monks and Oliver (1988) observed a reduction in soybean biomass when Palmer amaranth was within 50 cm of soybean. Additionally, Palmer amaranth has been documented to reduce soybean canopy closure 55% when 10 plants were present within a meter of row (Klingaman and Oliver 1994).

The rapid and erect growth of Palmer amaranth allows it to compete effectively with soybean for light. Klingaman and Oliver (1994) reported that Palmer amaranth reached heights 60 cm taller than surrounding soybean plants and lead to a soybean yield reduction of up to 64% with just 3.33 plants m<sup>-1</sup>. Palmer amaranth leaves move with the sun and stay perpendicular to the solar rays (Ehleringer and Forseth 1980). This allows the plant to maintain a high photosynthetic rate throughout the day, increasing the plants growth. Palmer amaranth also has an extensive root system. In comparison to soybean, Palmer amaranth has been reported to produce 3.7 times more roots that were 5 times longer (Wright et al. 1999). This root system allows Palmer amaranth to more effectively penetrate compacted soils and provide greater access to water and nutrients, giving it a more competitive edge against the crop, especially in dry conditions (Place et al. 2008).

The presence of large Palmer amaranth seedbanks in agricultural fields can be attributed to its prolific seed production. Keeley et al. (1987) examined individual female Palmer amaranth plants that produced as many as 1 million seeds each and averaged between 200,000 and 600,000 seeds per female plant when no crop competition was present. In Michigan soybean systems, Kohrt (2017) observed individual Palmer amaranth plants that emerged with soybean and grew to maturity produced over 350,000 seeds. Seed production was reduced when Palmer amaranth emergence occurred after crop emergence. However, even Palmer amaranth plants that emerged in August in Michigan were able to produce viable seed prior to a killing frost. Massinga et al. (2001) found that seed production from 0.5 plant per meter of row that emerged with corn produced 140,000 seeds m<sup>-2</sup>, while plants at the same density that emerged at the four-leaf stage of corn produced only 1,800 seeds m<sup>-2</sup>. Due to this high seed production from female plants,

Klingaman and Oliver (1994) stated that, control as great as 99% may not be sufficient in reducing the Palmer amaranth population below the economic threshold.

Palmer amaranth seeds are a smooth, round or disk shape with a black seed coat measuring 1-2 mm in diameter (Sauer 1955). Since these seeds are so small, they must be in a relatively shallow position within the soil profile or on the soil surface in order to establish. Palmer amaranth seeds buried at depths greater than 3.8 cm will not emerge (Ward et al. 2013; Menges 1974). Palmer amaranth seeds fall a short distance from the mother plant by gravity but can be dispersed to greater distances by external forces such as water movement, contaminated farm equipment, manure, seed sources, as well as by birds and other animals (Costea et al. 2004, 2005). It is speculated that Palmer amaranth seed was introduced into Michigan agricultural fields by the spreading of dairy manure from cattle that were fed contaminated cotton seed (Sprague 2013). Contaminated cotton seed and gin trash have been identified as sources of the spread to new areas in the southern United States. Norsworthy et al. (2009) reported that Palmer amaranth was the most prevalent viable broadleaf weed seed in cotton by-products. More recently, Palmer amaranth has spread to additional counties in Illinois, Iowa, and Ohio when seed mixes for Conservation Reserve Program (CRP) fields were found to be contaminated with Palmer amaranth seed (Hager 2016; Hartzler 2016).

In addition to its competitive nature and prolific seed production, Palmer amaranth has shown a remarkable ability to become resistant to several different herbicide sites of action. Palmer amaranth populations have been confirmed resistant to acetolactate synthase inhibitors (ALS) (Group 2); microtubule inhibitors (Group 3); photosystem II inhibitors (PSII) (Group 5); the 5-enolpyruvyl-shikimate-3-phosphate inhibitor (EPSP), glyphosate (Group 9); protoporphyrinogen oxidase inhibitors (PPO) (Group 14); and 4-hydroxyphenylpyruvate

dioxygenase inhibitors (HPPD) (Group 27) (Gossett et al. 1992; Horak and Peterson 1995; Heap 2016). Palmer amaranth populations have also been discovered to be resistant to multiple herbicide sites of action groups. One of the first known multiple-resistant Palmer amaranth populations was identified in Georgia in 2008 with resistance to glyphosate (Group 9) and the ALS-inhibiting (Group 2) herbicide, pyriithiobac (Sosnoskie et al. 2011). The first three-way resistant Palmer amaranth population was confirmed in Kansas in 2009 with resistance to ALS- (Group 2), photosystem II- (Group 5), and HPPD-inhibitors (Thompson 2009). Since then, several other states have reported three-way resistant Palmer amaranth populations, including Michigan, where a population with resistance to glyphosate (Group 9), thifensulfuron an ALS-inhibiting herbicide (Group 2), and atrazine (Group 5) was confirmed in 2013 (Kohrt et al. 2017).

While Palmer amaranth has developed resistance to several different herbicide sites of action, glyphosate resistance has perhaps caused the greatest issues with weed management. The first confirmed case of glyphosate-resistant Palmer amaranth was identified in Georgia in 2005 (Culpepper et al 2006). This population survived glyphosate applications up to 12 times the normal field use rate and was found in a cotton field that relied solely on glyphosate for weed control for seven years. The continuous use of glyphosate throughout the growing season, year after year as the only method of weed control, has led to increased selection pressure for weeds with glyphosate resistance. These resistant weed populations can quickly multiply if left without proper management. Glyphosate-resistant Palmer amaranth has since spread across 23 states including Michigan (Sprague 2011; Heap 2016). The mechanism of glyphosate resistance in Palmer amaranth is by gene amplification of EPSP synthase (Powles 2010; Gaines et al. 2011). Several greenhouse studies have documented that glyphosate-resistant Palmer amaranth

populations have been able to survive glyphosate applications over 10 times the normal field use rate (Culpepper et al. 2006; Norsworthy et al. 2008). Palmer amaranth's ability to develop resistance to glyphosate and multiple herbicide sites of action, along with its physical characteristics makes it challenging for growers to effectively manage this weed in glyphosate-resistant soybean.

### **Managing Palmer amaranth with Herbicides**

Glyphosate-resistant Palmer amaranth can be difficult to manage in soybean due to the limited number of effective herbicide site of action groups. Several studies have found that in order to manage glyphosate-resistant Palmer amaranth, an effective preemergence (PRE) herbicide with residual activity needs to be included in the herbicide program (Culpepper et al. 2008; Whitaker et al. 2008; Whitaker et al. 2011; Powell 2014; Bell et al. 2016; Norsworthy et al. 2016). Flumioxazin (Group 14) has been observed to be one of the most effective PRE herbicides used to control Palmer amaranth with observed control of up to 100, 99, and 98%, 20, 40, and 60 days after application (Whitaker et al. 2011). Similarly, Powell (2014) observed good control (>85%) of Palmer amaranth with flumioxazin in Michigan; however, the amount of rainfall received after application impacted the herbicide's effectiveness. Powell (2014) also stated that in optimal environmental conditions, soil-applied herbicides may only provide 28 days of control before new Palmer amaranth seedlings emerge.

This lack of season-long control, requires the use of an effective postemergence (POST) herbicide application to manage weeds that are not controlled by the PRE herbicide application alone. Additionally, PRE followed by POST herbicides have been shown to reduce Palmer amaranth population density and seed production when compared to a POST only application

(Norsworthy et al. 2016). Powell (2014) examined the effects of POST applied lactofen, fomesafen, and glufosinate for control of 8 and 15 cm Palmer amaranth. Results of this experiment suggested an inconsistency in Palmer amaranth control with the use of lactofen and fomesafen. Control with fomesafen was only 56% when applied to 15 cm Palmer amaranth, while control with lactofen was 90%. In drought conditions, glufosinate provided the greatest control of Palmer amaranth with up to 86 and 80%, 7 and 14 days after treatment (DAT), respectively. Fomesafen provided less control with only 68% by 14 DAT and lactofen had the least control with 54%. Lastly, Powell (2014) concluded that if Palmer amaranth was greater than 8 cm tall, glufosinate applied at 0.75 kg ha<sup>-1</sup> may provide the greatest control compared with lactofen and fomesafen.

Glufosinate has been of particular interest as it is an effective POST herbicide for control of glyphosate-resistant Palmer amaranth. Glufosinate is a nonselective herbicide that inhibits glutamine synthase (Group 10) and results in an accumulation of ammonium in the plant (Wendler et al. 1990). Braswell et al. (2016) reported that significant increases in Palmer amaranth control were observed when PRE herbicides were followed with glufosinate POST.

*Management in glufosinate-resistant soybean.* Glufosinate can only be applied POST in crops that are glufosinate-resistant. Glufosinate-resistant soybean (LibertyLink®) were first released to the public in 1998 (Carpenter and Gianessi 1999); however, due to the lack of market because of the wide-spread popularity of glyphosate-resistant soybean they were not commercially grown until 2009. Glufosinate-resistant soybean allows growers to use a broad-spectrum herbicide POST with a different site of action than glyphosate. Results from a study conducted by Norris et al. (2002) found that broadleaf weed control with glufosinate was equal to or better than

conventional treatments with sequential high rate applications providing the most consistent control. Control of the *Amaranthus* species, Palmer amaranth, redroot pigweed, and common waterhemp (*Amaranthus rudis* Sauer), with glufosinate was found to be poor with one application. However, with sequential applications the weed population decreased and control exceeded 80% (Coetzer et al. 2002). Similar results were observed by Hoffner et al. (2012) who reported consistent control of Palmer amaranth with the use of an effective PRE followed by POST or sequential POST applications of glufosinate in glufosinate-resistant soybean. The lack of control with one application of glufosinate may be in part due to new weed emergence following the initial POST application, since glufosinate does not provide residual control. However, sequential applications of glufosinate has provided similar control to the use of a PRE herbicide followed by a POST glufosinate application in common waterhemp (Beyers et al. 2002). Additionally, acetochlor (Group 15) has been shown to aid glufosinate in Palmer amaranth control when tank-mixed POST due to its residual properties. Glufosinate alone provided only 85 and 86% control when applied to Palmer amaranth less than 10 cm tall early POST and mid-season POST, while the combination of glufosinate and acetochlor provided 94 and 91% control, respectively (Cahoon et al. 2015).

### **Cultural Weed Control Practices**

*Soybean row width.* Soybean are grown in different row widths and populations depending on the preference and farming practices of the grower. Typically, soybean row widths grown in Michigan include: 76, 38, and 19 cm. Harder et al. (2007) reported weed control was improved in soybean planted in 19 cm rows compared with 76 cm rows. Soybean planted in 38 cm has also been reported to reduce Palmer amaranth biomass and seed production 38 and 65%, respectively,



when compared with soybean planted in 76 cm rows (Butts et al. 2016). This may be due to earlier canopy closure in soybean planted in narrow rows that prevents light from reaching the soil surface earlier than in wide rows, aiding in the prevention of late-season weed emergence (Wax and Pendleton 1968; Murphy and Gossett 1981). Légère and Schreiber (1989) found that by 50 days after emergence, soybean canopy closure in 25 cm row widths progressed rapidly and was complete, while canopy closure in the 76 cm row widths was never quite achieved. Due to the earlier canopy closure, soybean planted in 19 cm narrow rows have been shown to reduce total weed biomass by 30% compared with 76 cm wide rows (Mickelson and Renner 1997). Another study observed that soybean planted in 25 cm rows, reduced the total pigweed biomass by almost 20% and produced significantly more yield than soybean planted in 76 cm rows (Légère and Schreiber 1989).

Jha and Norsworthy (2009) reported Palmer amaranth emergence was reduced in the presence of a soybean canopy compared with plots without soybean. Similarly, DeVore et al. (2013) observed Palmer amaranth emergence was greatly reduced once the soybean canopy closed. *Amaranthus* species display a phytochrome-controlled germination response in which the presence of red light stimulates germination (Gallagher and Cardina 1998; Leon and Owen 2003). An inhibitory effect of far-red light on Palmer amaranth germination was observed by Jha et al. (2010), which explains why germination and emergence primarily occurs early in the season prior to canopy closure and supports previous findings of emergence declining with the presence of a soybean canopy. However, Holden et al. (2015) reported that herbicide programs provided more of distinguishable impact on Palmer amaranth control, density and seed production than soybean row widths.

*Cover crops for weed suppression.* “A cover crop is any living ground cover that is planted into or after a main crop and is then commonly killed before the next crop is planted” (Hartwig and Ammon 2002). In essence, cover crops are short term rotations between cash crops (Reeves 1994). There are three broad categories of cover crops: brassicas, legumes and grasses. These cover crops can be summer annual plants that die during the winter months, winter annuals or perennials. There are many options, combinations and mixtures of cover crops that can be grown depending on the objectives of the grower, the region the cover crops will be grown in, and the time of year the cover crops will be planted. Many benefits can be obtained from the use of cover crops, although these vary between the different crops. These benefits can include nitrogen fixation, prevention of soil erosion and nutrient loss, improved soil conditions, weed and disease suppression, as well as providing a favorable environment for beneficial predators (Unger and Vigil 1998; Hartwig and Ammon 2002; Gallandt et al. 2005; Larkin et al. 2010; Blanco-Canqui et al. 2015).

Winter annual cover crops are established in the late summer or early fall to provide cover during the winter (Teasdale 1996). In the early spring, these cover crops experience rapid growth which produces most of the final biomass. Winter annual cover crops are especially beneficial for preventing erosion on sandy soils that are erodible when left bare during the winter months (Snapp et al. 2005). These cover crops can also be used for weed suppression as reported by Moore et al. (1994) and Korres and Norsworthy (2015), who found that small grain cover crops, such as cereal rye, reduced weed size and biomass. Price et al. (2006) also observed the effect of small grain cover crops on weed suppression and reported 69-73% control on multiple weed species, including Palmer amaranth, in plots with a cereal rye or black oat cover crop that were terminated in early May with a glyphosate application and roller-crimped 3 d later. This

vegetative cover reduces the quantity of light available and heat adsorbed by the soil, which can cause less favorable conditions for weed germination and emergence (Teasdale 1996). Putnam and DeFrank (1983) examined vegetable seed growth in grass cover crop residue and observed that in general larger seeded plants grew normally and sometimes benefited from the residue, while small seeded plants were severely injured when compared with wood shavings as a cover.

Cereal rye (*Secale cereal* L.) is a winter annual grass that provides many benefits that include, but are not limited to, reduced nitrogen loss, erosion control, improved soil quality, and weed suppression (Kinyangi et al. 2001). Debany et al. (2001) stated that, “rye is the most cold tolerant, easiest to establish, most productive, and the earliest to head among temperate region cereal crops.” Cereal rye is planted in the fall, left to overwinter, then terminated in the spring prior to crop planting. Cereal rye has the ability to produce more biomass the farther south it is grown. Cereal rye produced 3600, 5100, and 11,000 kg ha<sup>-1</sup> of biomass when terminated in the early summer in Ohio and the early spring in North Carolina and Alabama, respectively (Yenish et al. 1995; Akemo et al. 2000; Price et al. 2012). In Michigan, cereal rye has been shown to produce between 800 and 2900 kg ha<sup>-1</sup> of shoot biomass (Snapp et al. 2005). However, Hill (2014) reported cereal rye biomass in Michigan ranged from 784 to 12,777 kg ha<sup>-1</sup> when shoots and roots were harvested. Cereal rye planting and termination date is a significant factor in determining how much cover crop biomass will be produced (Mirsky et al. 2009; Webster et al. 2016; Hill 2014). Hill (2014) observed that the lowest amount of biomass was produced when cereal rye was planted in early November and terminated in mid-May, while rye planted in mid-September and terminated in early-June produced the greatest amount of biomass. An earlier planting date provides an extended growing season and increases growing degree day accumulation resulting in greater biomass production prior to termination.

The speed at which cereal rye residue is broken down is influenced by the carbon to nitrogen ratio (C:N) of the residue. The ideal C:N ratio for microbes to consume is 24:1, residue containing a higher ratio will be degraded more slowly compared with ratios below the ideal (Eiland 2001; NRCS 2011). Cereal rye, at or close to maturity, will have higher C:N ratios that allows the residue to remain longer on the soil surface compared with cereal rye in the vegetative stages. Additionally, C:N ratios 25:1 or greater can immobilize soil N preventing the nutrient from being readily available for the subsequent crop and potentially reducing yields (Schomberg et al. 2007; Pantoja et al. 2016).

Cereal rye has a fibrous root system that can help alleviate compacted soil from the root channels left behind after decomposition, while a rye cover left on the soil surface can aid in the conservation of water early in the season (Williams and Weil 2004). A cereal rye cover crop included in a corn/soybean no-till rotation was shown to improve water-aggregate stability and was effective in trapping soil phosphorous compared with a winter fallow (Villamil et al. 2006). When using a cover crop that leaves residue in the spring, growers need to consider the possibility of an increase in the presence of damaging insects along with those that are beneficial. Hammond (1990) found that seed corn maggot (*Delia platura* Miegen) impacted soybean stands when soil contained decaying cereal rye, while Reddy (2001) found that soybean stands displayed better establishment in cover crop residue that had begun to breakdown compared with stands in a fresh layer of residue. This was further demonstrated by Liebl et al. (1992) where yields of soybean planted into cereal rye terminated 2 weeks prior to planting were significantly higher compared with soybean planted into rye terminated at planting. Armyworm (*Psudaletia unipuncta*), a major pest in field corn, lays its eggs on the leaves of small grains. No-till corn planted into cereal rye has been reported to increase armyworm damage compared with

conventionally grown corn (Untung 1978). This pest may be managed by mowing cereal rye residue due to physically harming the insect larvae. Laub and Luna (1991) reported reduced armyworm densities in early stage corn when cereal rye was terminated by mowing compared with chemical termination.

Cover crops have historically been plowed under or terminated with burndown herbicides prior to planting a row crop (Price et al. 2009). There are three common methods used to terminate cover crops, they include: winterkill, mechanical, or herbicide application (Legleiter et al. 2012). Since cereal rye is a winter annual it can only be terminated mechanically or chemically. Tillage is a mechanical termination method that incorporates the rye into the soil profile before planting, however this will not work for no-tillage systems. One method of termination for a no-till system is to mow the standing cereal rye; however, it is suggested to wait until head emergence (Feekes 10.1 or later) for the greatest amount of biomass and minimal regrowth (Wilkins and Bellinder 1996). A flail mower is the recommended tool when mowing cereal rye as it will leave the cover crop residue more uniformly distributed on the soil surface than other mowers; however, this also leaves the residue in smaller pieces that can break down more rapidly (Creamer and Dabney 2002). Another no-till method of termination is the use of a roller-crimper which cuts or crushes the plants stem and lays the residue flat on the ground creating a longer lasting cover compared with mowing. The effectiveness of roller-crimper termination increases as cereal rye matures with consistent control achieved at anthesis (Feekes 10.5) or later (Mirsky et al. 2009; Wayman et al. 2014).

Of the different termination methods, an application of herbicide alone or in combination with mechanical termination is the most commonly used method of terminating cereal rye in studies (Moore et al. 1994; DeVore et al. 2013; Wiggins et al. 2016). Cereal rye termination with

a roller-crimper or glyphosate was 85% effective while adding glyphosate with the roller-crimper provided greater than 97% termination (Price et al. 2009). In the presence of weed interference, cereal rye termination method, whether it was rolled or chemically terminated, had little effect on no-till soybean yield (Davis 2010). Other studies have reported varying effects on soybean yield grown with a cereal rye cover crop when compared with no cover crop controls. Results ranged from increased yield (Atech and Doll 1996), decreased yield (Reddy 2001), to having no effect on yield (Liebl et al. 1992; Koger et al. 2002).

The effect of weed suppression by a cereal rye cover crop can be due to a combination of physical and chemical factors (Kruse et al. 2000). The presence of a cereal rye cover crop mulch has been shown to reduce weed density by 50% and weed biomass by 75% without the use of herbicides (Malik et al. 2008; Bernstein et al. 2011). However, the degree of weed suppression depends upon the amount of biomass that can be produced. Increases in total cereal rye biomass have been shown to correlate with greater weed suppression and reduced weed biomass (Ryan et al. 2011; Smith et al. 2011; Finney et al. 2016). Early suppression of *Amaranthus* species has been observed with the presence of high cereal rye residue levels on the soil surface, demonstrating the potential benefit of using the cover crop for early-season weed control (Price et al. 2006, 2012; Mirsky et al. 2011; Saini et al. 2006). DeVore et al. (2013) observed in Arkansas, as much as a 51% reduction in Palmer amaranth emergence with the presence of a cereal rye cover crop terminated with glyphosate two weeks prior to soybean planting in a full-season soybean production system. A study conducted by Price et al. (2006) found that a cereal rye cover crop in conjunction with a PRE herbicide was able to provide similar weed control to a PRE followed by POST herbicide management system with no cereal rye. The use of this management strategy may allow for a reduction in the number of herbicide applications made

during the growing season for weed control depending upon the amount of rye biomass produced.

In addition to high biomass production, cereal rye produces allelochemicals that are toxic to certain plant species reducing plant germination, growth, and development. This chemical interference of other plants is known as allelopathy (Barnes and Putnam 1983; Kruse et al. 2000). Allelopathic effects have been of great interest to researchers and growers for the possibility of aiding in weed management while also providing other cover crop benefits. The concentration of allelochemicals depend on the density and age of the allelopathic plant along with soil factors such as pH, organic matter content, moisture content and availability of other carbon sources to microorganisms (Blum et al. 1993; Blum 1996; Kruse et al. 2000). Cereal rye residues have been shown to reduce the emergence of lettuce (*Lactuca sativa* L.) by 58% and proso millet (*Panicum miliaceum* L.) by 35% when compared with a control of a wood shavings mulch (Barnes and Putnam 1986). Cereal rye shoot tissue inhibited lettuce germination more than root tissue. This demonstrates that there can be more that may inhibit the germination and growth of plants when using a cereal rye cover crop than just a physical barrier.

The effects of weed suppression has been shown to last as long as 63 days after cereal rye was terminated, depending on the amount of biomass produced and environmental conditions (Masiunas et al. 1995). However, the maximum concentration of allelochemicals from cereal rye occurs within 20 days of rye decomposition (Chou and Patrick 1976). Cereal rye residues have been shown to inhibit early-season weed growth by at least 75%, while cereal rye residues with no-tillage reduced weed growth by 63% (Putnam and DeFrank 1983).

Several studies have observed the effect of integrating a cereal rye cover crop into the crop rotation to try and suppress Palmer amaranth. In Arkansas, Bell et al. (2016) reported that the

combination of moldboard plowing in the fall followed by a cereal rye cover crop terminated with glyphosate two weeks prior to soybean planting, reduced Palmer amaranth emergence and density. Palmer amaranth and redroot pigweed suppression, from a cereal rye cover crop terminated with a roller-crimper and glyphosate application, was observed in Alabama with reported rye biomass of 4177 kg ha<sup>-1</sup> from a late planting date and up to almost 11,000 kg ha<sup>-1</sup> from an early planting date (Price et al. 2012). Norsworthy et al. (2011) collected cereal rye biomass terminated with glyphosate that averaged from 7880 to 8460 kg ha<sup>-1</sup> in Arkansas, which provided up to 91% control of Palmer amaranth. These studies along with another study conducted by Aulakh et al. (2012) who terminated cereal rye with a roller crimper and glyphosate application, observed that the presence of a cereal rye cover crop reduced Palmer amaranth density in no-till cotton with no negative effect on crop yield. Culpepper et al. (2010b) similarly reported a reduction in Palmer amaranth emergence from cereal rye by 94% in the middle of the cotton row and an improvement of late-season control by 18% compared with no cereal rye. In addition to reduced Palmer amaranth emergence, cotton yield was 15% higher with the use of a cereal rye cover crop (Culpepper et al. 2010b). Suppression of Palmer amaranth depends on the amount of cover crop biomass produced. Webster et al. (2013) predicted Palmer amaranth control in cotton would be 25, 50, and 75% with a cereal rye biomass of 2950, 4900, and 8600 kg ha<sup>-1</sup>. Wiggins et al. (2016) reported that 2440 kg ha<sup>-1</sup> of cereal rye biomass in combination with a PRE herbicide, provided 87% control of Palmer amaranth in cotton. However, the use of a cover crop with no herbicide application provided less than 65% control of Palmer amaranth.

Although cover crops may contribute to weed control during the early spring, additional management practices, including herbicides, are still needed to provide optimum season-long



control (Teasdale 1996; Masiunas et al. 1995; Aulakh et al. 2012; Wiggins et al. 2016). Since Palmer amaranth is a relatively new weed to Michigan, we wanted to determine if seeding a cereal rye cover crop and planting soybean in narrow rows would suppress Palmer amaranth emergence and improve control compared with a herbicide management strategy alone.

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## CHAPTER 2

### INTEGRATING A CEREAL RYE COVER CROP AND SOYBEAN ROW WIDTH WITH HERBICIDES TO MANAGE PALMER AMARANTH IN MICHIGAN

#### Abstract

Integrating the use of narrow row widths and cover crops may improve management of herbicide-resistant Palmer amaranth in Michigan soybean production systems. A field experiment was established in the fall of 2014 and 2015 near Middleton, Michigan in a field with a glyphosate-resistant Palmer amaranth population. This experiment determined if a cereal rye cover crop in conjunction with a standard or high herbicide program improved control of Palmer amaranth in soybean planted in 76- and 19-cm rows. Additionally, pot experiments determined the effects of cereal rye stage, biomass, and termination method on Palmer amaranth emergence. Cereal rye biomass was 1200 and 2186 kg ha<sup>-1</sup> at spring termination in 2015 and 2016, respectively. Cereal rye reduced winter and early summer annual weed biomass by 77 and 84% in 2015 and 2016, respectively, compared with the no cover control. Cereal rye was successfully terminated in plots terminated with glyphosate. However, cereal rye was not completely terminated by flail mowing in either year and produced an additional 580 to 1291 kg ha<sup>-1</sup> of dry biomass, before being terminated with glyphosate prior to soybean planting. Palmer amaranth emergence began in early- to mid-June, 2-3 weeks after soybean planting. Cereal rye had little effect on Palmer amaranth emergence in 2015; however, a delay in emergence was observed with mowing in 2016 that may affect the timing of postemergence herbicide applications. Soybean canopy closure affected Palmer amaranth emergence in both years, with prolonged emergence in soybean planted in 76 cm rows compared with 19 cm rows. In 2015, Palmer amaranth was controlled with both the high and standard herbicide management programs;

however, a lack of precipitation in 2016 resulted in poor control in the standard management program. Cereal rye and soybean row width had little effect on soybean yield. However, the use of a herbicide management strategy significantly increased yield in both years compared with no herbicide management. In 2016, soybean yield was 574 kg ha<sup>-1</sup> higher in the high herbicide management compared with the standard management program. In outside pot experiments, cereal rye biomass at Feekes 10.1 or later suppressed Palmer amaranth emergence in both years, while all covers, regardless of cereal rye stage and biomass, suppressed Palmer amaranth emergence in 2015. In the greenhouse, cereal rye terminated by cutting reduced Palmer amaranth emergence compared with termination by glyphosate. Soybean planted in narrow rows aided in preventing late-season Palmer amaranth emergence. Planting a cereal rye cover crop that had a maximum biomass of 2180 kg ha<sup>-1</sup> was not effective in suppressing Palmer amaranth in Michigan. However, applying a PRE followed by a POST herbicide program and planting soybean in narrow rows reduced the duration of Palmer amaranth emergence and provided effective control.

**Nomenclature:** Palmer amaranth, *Amaranthus palmeri* S. Wats.; soybean, *Glycine max* (L.) Merr.; cereal rye, *Secale cereal* L.; acetochlor; flumioxazin; glufosinate; glyphosate.

**Key words:** Glyphosate-resistant; biomass; cover crop; row width; emergence; herbicide management.

## Introduction

Palmer amaranth (*Amaranthus palmeri* S. Wats.) is a dioecious summer annual weed species that exhibits season-long emergence, rapid biomass accumulation and prolific seed production (Ehleringer 1983; Keeley et al. 1987; Culpepper et al. 2010a; Ward et al. 2013). Native to the southwest region of the United States, Palmer amaranth populations can now be found in

previously uninhabited areas of the southern and Midwest United States (Culpepper et al. 2010a; Heap 2016). First identified in Michigan in 2010 (Sprague 2011), Palmer amaranth can successfully complete its lifecycle and produce seed that survives Michigan's cold winters, thus becoming a weed problem the following season (Kohrt 2017; Powell 2014). In Michigan, Palmer amaranth typically emerges from late-May through September (Powell 2014). In soybean, Kohrt (2017) observed individual plants that emerged in May, grew to maturity, and produced over 350,000 seeds per plant. When Palmer amaranth emerged after the crop, seed production was reduced. However, even Palmer amaranth plants that emerged in August were able to produce viable seed prior to a killing frost.

Managing Palmer amaranth with herbicides poses several challenges. Kohrt (2017) reported that Palmer amaranth emergence in Michigan continued through mid-September. Continued emergence throughout the season makes Palmer amaranth difficult to control with preemergence (PRE) herbicide applications alone. Palmer amaranth can grow up to 0.21 cm per growing degree day and reach a mature height over 2 meters (Horak and Loughin 2000). Compared with other *Amaranthus* species, Palmer amaranth can produce more biomass at temperatures above 25 C, and its growth rate is 62% greater per growing degree day (Gou and Al-Khatib 2003; Culpepper et al. 2006). Rapid growth makes timing of postemergence (POST) herbicide applications difficult for effective Palmer amaranth control. Finally, Palmer amaranth has a remarkable ability to develop resistance to herbicides (Klingaman and Oliver 1994; Heap 2016). To date, populations are confirmed are resistant to acetolactate synthase inhibitors (ALS) (Group 2); microtubule inhibitors (Group 3); photosystem II inhibitors (PSII) (Group 5); the 5-enolpyruvylshikimate-3-phosphate inhibitor (EPSP), glyphosate (Group 9); protoporphyrinogen oxidase

inhibitors (PPO) (Group 14); and 4-hydroxyphenylpyruvate dioxygenase inhibitors (HPPD) (Group 27) (Gossett et al. 1992; Horak and Peterson 1995; Heap 2016).

While Palmer amaranth has developed resistance to multiple herbicide sites of action, glyphosate resistance has perhaps caused the greatest issues with weed management. The first confirmed case of glyphosate-resistant Palmer amaranth was identified in 2005 in a Georgia cotton field that was sprayed with glyphosate for seven straight years as the sole means of weed control (Culpepper et al. 2006). This population survived glyphosate applications up to 12 times the normal field use rate. Glyphosate-resistant Palmer amaranth has since spread across 23 states, including Michigan (Sprague 2011; Heap 2016).

The use of an effective herbicide management program is important in controlling Palmer amaranth and reducing future emergence. Flumioxazin (Group 14) is one of the most effective PRE herbicides, with observed control of up to 98% at 60 days after application (Whitaker et al. 2011). In Michigan, Powell (2014) observed good control (>85%) of Palmer amaranth with flumioxazin 28 days after planting; however, the amount of rainfall after application impacted herbicide effectiveness. Flumioxazin alone does not provide season-long control. Thus, an effective POST herbicide application is needed to manage weeds that are not controlled by the PRE herbicide application alone. Glufosinate is an effective POST herbicide for control of glyphosate-resistant Palmer amaranth. Barnett et al. (2013) observed over 90% control when glufosinate was applied to Palmer amaranth under 13 cm in height. When glufosinate was applied to 26 cm tall Palmer amaranth, control was reduced to 59%, demonstrating the importance of timely POST applications. Acetochlor (Group 15) aids glufosinate in Palmer amaranth control when tank-mixed POST due to its residual properties. Glufosinate alone provided only ~86% control when applied to Palmer amaranth less than 10 cm tall early POST



and mid-season POST, while the combination of glufosinate and acetochlor provided 94 and 91% control, respectively (Cahoon et al. 2015).

Planting soybean in narrow row widths is a cultural practice that many growers use to improve weed suppression. Narrow row soybean forms a closed canopy earlier than soybean planted in wide rows, reducing the amount and quality of light that reaches the soil surface and, in turn reducing late-season weed germination and emergence (Wax and Pendleton 1968; Murphy and Gossett 1981). By 50 days after emergence, soybean canopy closure in 25 cm rows was complete, while canopy closure in the 76 cm rows was never quite achieved (Légère and Schreiber 1989). *Amaranthus* species display a phytochrome-controlled germination response in which the presence of red light stimulates germination (Gallagher and Cardina 1998; Leon and Owen 2003). Since the soil surface under a plant canopy receives more far-red light than red light due to adsorption by the plant, soybean planted in narrow rows reduces late-season Palmer amaranth emergence. An inhibitory effect of far-red light on Palmer amaranth germination was observed by Jha et al. (2010). This explains why the majority of germination occurs prior to crop canopy closure, and supports observations that emergence declines in the presence of a soybean canopy.

DeVore et al. (2013) reported Palmer amaranth emergence was greatly reduced once the soybean canopy closed, providing late-season control. Jha and Norsworthy (2009) similarly reported that Palmer amaranth emergence was reduced by 73% from the presence of a soybean canopy. Soybean planted in narrow rows also reduced the growth of weeds after emergence compared with wide rows. Mickelson and Renner (1997) reported that total weed biomass in 19 cm rows was reduced by 30% compared with biomass in 76 cm rows, due to earlier canopy closure. Another study observed that planting soybean in 25 cm rows, reduced total pigweed

biomass by almost 20% and produced more yield than soybean planted in 76 cm rows (Légère and Schreiber 1989).

Cover crops are an additional tool to aid in weed management and reduce herbicide use for weed control (Mortensen et al. 2012). Cereal rye in particular, has been of interest as it provides ground cover during the winter months, produces high amounts of biomass, reduces soil erosion and has the potential to provide early-season weed control (Kinyangi et al. 2001). Cereal rye is terminated chemically with herbicides or mechanically prior to the planting of a cash crop in the spring. Flail mowing is one mechanical termination method used in no-till systems to leave residue more uniformly distributed across the soil surface. However, it is suggested to wait until head emergence (Feekes 10.1 or later) for the greatest amount of biomass and minimal regrowth (Wilkins and Bellinder 1996).

When using a cover crop that leaves residue in the spring, growers need to consider the possibility of an increase in the presence of damaging insects along with those that are beneficial. Crop damaging insects such as armyworm (*Psudaletia unipuncta*) and black cutworm (*Agrotis ipsilon*) lay their eggs on spring plant vegetation, such as cover crops and weeds, while seed corn maggot (*Delia platura* Miegen) feeds on plant residues in the soil. Earlier termination of the cover crop compared with crop planting may reduce the presence of these pests due to the early removal of their food source which forces them to find alternative sources. Reddy (2001) observed better establishment of soybean stands in cover crop residue that had begun to breakdown compared with stands in a fresh layer of residue. Physical termination of the cover crop, such as mowing, may kill armyworm and black cutworm larvae reducing the population (Laub and Luna 1991).

Cereal rye mulches left on the soil surface reduce the quality of available light and heat adsorbed by the soil, causing less favorable conditions for germination and a reduction of early-season weed growth (Moore et al. 1994; Teasdale 1996). DeVore et al. (2013) reported that in Arkansas, a cereal rye cover crop reduced Palmer amaranth emergence in soybean by up to 71%. In no-till cotton production, cereal rye reduced Palmer amaranth emergence by 94% and improved late-season control by 18%, compared with no cover crop (Culpepper et al. 2010b). However, cover crop residues typically do not provide season-long weed control, so additional cultural methods or herbicide applications are needed.

The search for management practices that can be integrated with herbicides to improve the management of Palmer amaranth in Michigan soybean production led to the following research objectives: 1) determine if a cereal rye cover crop and planting soybean in narrow rows reduce Palmer amaranth emergence and growth in Michigan, and 2) determine the effect of above- and belowground cereal rye biomass and termination method on Palmer amaranth emergence.

## **Materials and Methods**

**Field Experiment.** Field experiments were conducted in 2015 and 2016 in a commercial field near Middleton, MI (43.2616°N; -84.7609°W). This field was in a corn-soybean rotation. In 2013, two years following a dairy cattle manure application to this field, Palmer amaranth was identified and confirmed glyphosate-resistant. The soil type at this location was a Metea loamy sand (loamy, mixed, active, mesic Arenic Hapludalfs) with pH of 7.0 and 2.5% soil organic matter.

The experiment was conducted as a split-split plot arranged in a randomized complete block design with 18 treatments, each replicated four times. Each plot measured 3 m wide by 9 m long.

The main plot factor was a cereal rye cover crop, the subplot factor soybean row width, and the sub-subplot factor was herbicide management strategy. The main plots consisted of three cover crop factors: 1) a cereal rye cover crop terminated with 1.26 kg a.e. ha<sup>-1</sup> glyphosate (Roundup PowerMAX, Monsanto Co., St. Louis, MO) + 2% w w<sup>-1</sup> spray grade ammonium sulfate (AMS) (Actamaster, Loveland Products Inc., Loveland, CO) (RG), 2) a cereal rye cover crop terminated by a flail mower (RM), and 3) no rye cover crop (NC). The subplots consisted of two row-width factors, soybean planted in 76- and 19-cm rows. The sub-subplot factors consisted of three herbicide management factors: 1) high herbicide management (HH), 2) standard herbicide management (SH), and 3) no herbicide management (NH) (Table 2.1).

‘Wheeler’ cereal rye was sown in 19 cm rows at a rate of 100 kg ha<sup>-1</sup> on October 23, 2014 and September 30, 2015 using a no-till drill (Great Plains, Salina, KS). Cereal rye was terminated on May 14, 2015 and May 11, 2016 when it was 30 cm tall at Feekes 6 and 58 cm tall at Feekes 9, respectively. Prior to termination, percent ground cover was measured using line-transects (Laflen et al. 1981) laid diagonally across each main cereal rye and no cover crop plots. Incidents of cereal rye, weed or no vegetation were recorded every 30 cm along a 23 m transect. Aboveground cereal rye and weed biomass was harvested at this time from three random 0.25 m<sup>2</sup> subsamples in each main plot. Annual bluegrass (*Poa annua* L.), common chickweed (*Stellaria media* (L.) Vill.), and shepherd’s purse (*Capsella bursa-pastoris* (L.) Medik.) were present at the time of biomass collection in both years. Common lambsquarters (*Chenopodium album* L.) and field pennycress (*Thlaspi arvense* L.) were also present in 2015. Biomass samples were dried for approximately 7 d at 65 C and weighed. Seven to 10 d after termination, cereal rye was evaluated for percent control from termination method. Cereal rye regrowth occurred in the plots that were terminated with the flail mower and regrowth biomass was harvested, dried, and weighed from

three 0.25 m<sup>2</sup> samples. Cereal rye subsamples of initial and regrowth biomass were analyzed for C:N ratios using a ECS 4010 CHNSO Analyzer (Costech Analytical Technologies Inc., Valencia, CA). After sampling, the RM and NH plots were treated with 1.26 kg a.e. ha<sup>-1</sup> glyphosate + 2% w w<sup>-1</sup> AMS.

Glufosinate-resistant soybean ‘DF 9221 LL’ (D.F. Seeds, Dansville, MI) was planted on May 27, 2015 and May 24, 2016, approximately 2 weeks after initial rye termination, in 76 and 19 cm rows. Soybean seeding rates for the 76 and 19 cm row widths were based on local MI recommendations of 370,500 and 494,000 seeds ha<sup>-1</sup>, respectively. At planting, percent ground cover of terminated vegetation was reassessed in the main plots using the line-transect method described above. Soil moisture was also measured at this time with a FieldScout TDR 300 Soil Moisture Meter (FieldScout, Spectrum Technologies, Aurora, IL) by collecting nine measurements per main plot at depths of 7.6 and 11.9 cm.

Preemergence (PRE) herbicides in the SH and HH plots were applied immediately after planting (Table 2.1). Postemergence (POST) and late postemergence (LPOS) herbicide applications were made when emerged Palmer amaranth was approximately 7.5 cm tall. All herbicide applications were made using a tractor-mounted, compressed air sprayer or CO<sub>2</sub> pressurized backpack sprayer calibrated to deliver 177 L ha<sup>-1</sup> at 207 kPa of pressure through 11003 AIXR flat-fan nozzles (TeeJet, Spraying Systems Co., Wheaton, IL).

*Palmer amaranth measurements.* Palmer amaranth control was evaluated at the POST application, 21 d after POST treatment (DAT), and at harvest. Evaluations were based on a scale of 0 to 100% with 0 representing no control and 100 indicating complete control. Two permanent 0.25 m<sup>2</sup> quadrats were established in each plot to measure Palmer amaranth emergence

throughout the growing season. Each week, newly emerged Palmer amaranth seedlings were counted and removed from these quadrats. At Palmer amaranth maturity when peak biomass occurred, plants were counted and aboveground biomass was harvested from two random 0.25 m<sup>2</sup> subsamples in the NH plots. Palmer amaranth biomass was dried and weighed to assess biomass reduction from cover crop and row width treatments. The number of Palmer amaranth plants from the middle 76 cm by 9 m area in the SH and HH plots was also recorded at the time of peak biomass.

*Soybean measurements.* Light interception was measured weekly or biweekly only in the HH plots using a SunScan Canopy Analysis system (Delta-T Devices Ltd, Burwell, Cambridge, UK). Three measurements were taken above and below the soybean canopy at corresponding locations. Soybean canopy closure was calculated using Equation 1.

$$\text{Canopy closure (\%)} = \frac{[(\text{above canopy measurement} - \text{below canopy measurement}) / (\text{above canopy measurement})] \times 100}{\text{[Eq.1]}}$$

Final soybean populations were assessed in all plots at maturity. Soybean was harvested by hand from a 1.5 m wide by 3 m long area in the center of each plot on October 19, 2015 and October 21, 2016. Harvested plants were threshed through an ALMACO stationary thresher (Allan Machine Company, Nevada, IA) to separate the beans from other plant material and debris. Cleaned samples were weighed, and grain moisture and test weight were measured using a Grain Analysis Computer (GAC®) 2100 Agri (Dickey-john, Auburn, IL). Yields were calculated by adjusting to 13% moisture.

Precipitation and temperature data was obtained from Michigan State University Enviro-weather Automated Weather Station Network located in Ithaca, MI (MSU Enviro-weather 2016).

**Effects of Cereal Rye on Palmer amaranth Emergence – Pot Experiments.** *Outdoor.* A pot experiment was conducted outside in the summers of 2015 and 2016 to examine the mulching effects of a cereal rye cover on Palmer amaranth emergence. The experimental setup was a completely randomized design with eight treatments in 2015 and five treatments in 2016. All treatments were replicated four times. The treatments consisted of, cereal rye at two different growth stages (early and late; Feekes 6 and 10.5 in 2015 and Feekes 9 and 10.1 in 2016, respectively) applied at three mulching rates, a non-cereal rye cover, and a no cover control. ‘Wheeler’ cereal rye aboveground biomass for the two different growth stages was collected from separate fields. Cereal rye fresh weight per 0.25 m<sup>2</sup> was taken to determine the amount of biomass needed per pot. Dry biomass was 1200 and 3750 kg ha<sup>-1</sup> for the early and late cereal rye stages, respectively. Mulching rates were categorized as low, medium, and high which was equivalent to 1200, 2400 and 3750 kg ha<sup>-1</sup>, respectively. The low rate was the 1X rate for the early stage cereal rye, the medium rate was 2X the rate of the early stage cereal rye and approximately 0.5X the rate of the late stage rye, and the high rate was equivalent to 1X the late stage cereal rye. In 2016, only the low and medium rates were examined for the early stage cereal rye and only the low rate was examined for the late stage rye. In both years, the non-cereal rye cover, a dried raffia palm (Ashland, Irving, Texas), was applied at the low mulching rate. Each treatment was applied to the surface of 10 x 10 cm pots planted with 50 Palmer amaranth seeds 0.75 cm deep in a sandy loam sterilized field soil with a pH of 7.4 and 3% soil organic matter. Pots were watered immediately after planting and were kept moist by rainfall or overhead watering on a daily basis. Emergence counts were recorded twice a week with new seedlings removed at each count until germination ceased. Emergence counts were recorded for 45 d.

*Greenhouse.* A greenhouse experiment determined the effects of cereal rye termination method and biomass on Palmer amaranth emergence. Ten seeds of ‘Wheeler’ cereal rye were planted at a depth of 1.4 cm in 10 x 10 cm pots filled with a sandy loam sterilized field soil with a pH of 7.4 and 3% soil organic matter. Approximately two weeks later, additional pots of cereal rye were planted to ensure two levels of cereal rye biomass. The first planting date was used for the high biomass treatments, while the second planting date was used for the low biomass treatments. Cereal rye was grown in the greenhouse at  $25 \pm 5$  C and sunlight was supplemented to provide a total midday light intensity of  $1,000 \mu\text{mol m}^{-2} \text{s}^{-1}$  photosynthetic photon flux at plant height in a 16 h day. Plants were watered and fertilized to promote optimum plant growth.

Cereal rye was terminated one month after the initial planting when plants were 36 and 25 cm tall. The average aboveground dry biomass weighed 3.5 and 0.4 g pot<sup>-1</sup> for the high and low biomass treatments, respectively. The high biomass weight was equivalent to 3500 kg ha<sup>-1</sup> while the low rate was equivalent to 400 kg ha<sup>-1</sup> of dry biomass. Treatments for the two different sizes of cereal rye included: 1) cereal rye terminated with glyphosate with the biomass left in place (roots and shoots), 2) cereal rye terminated with glyphosate and aboveground biomass harvested 3 d later to leave only the roots in place (roots only), 3) aboveground cereal rye biomass from the previous treatment where only the roots were left in place (shoots only), 4) cereal rye terminated by cutting with scissors to simulate mowing, and 5) a non-rye cover. A dried raffia palm (Ashland, Irving, Texas) was used as the non-rye cover, applied at weights that matched the average dry weight of the high and low aboveground cereal rye biomass treatment. A no cover treatment was also included as a control. Cereal rye that was terminated by cutting regrew and was subsequently treated with glyphosate 3 d after cutting. Glyphosate applications applied at



1.68 kg a.e. ha<sup>-1</sup> + 2% w w<sup>-1</sup> AMS were made using a single nozzle track sprayer calibrated to deliver 187 L ha<sup>-1</sup> at 193 kPa of pressure through an 8001E nozzle (TeeJet Technologies, Wheaton, IL). Five days after initial cereal rye termination, aboveground biomass was removed and 50 Palmer amaranth seeds pot<sup>-1</sup> were planted at a depth of 0.75 cm before the mulch was replaced. Glyphosate treatments containing above- and belowground biomass had seeds planted on the soil surface and 0.75 cm of soil added to cover the seeds so as to not disturb the cereal rye residue. Pots were watered daily. Emergence was recorded every 2-3 d for 14 d from each pot, with the newly emerged seedlings removed. All treatments were replicated six times and the experiment was repeated in time.

**Data Analysis.** Statistical analysis was conducted using SAS® 9.4 (SAS Institute Inc., Cary, NC). Assumptions of normality of residuals and homogeneity of variances were confirmed using PROC UNIVARIATE. Analysis of variance was conducted using PROC MIXED. The statistical model for the field experiment included the main effects of cereal rye cover crop, soybean row width, herbicide management system, and their interactions as fixed effects and replication was considered a random effect. Due to significant year interactions, data were analyzed separately by year. Data were combined over main effects when significant interactions did not occur. The statistical model for both pot experiments, included treatment and year or repetition in time as fixed effects and replication as a random effect. Data were analyzed separately by year for the outside experiments due to differences in treatment structure and differences between the growing seasons. Data were combined over repetition in time for greenhouse experiment. For all experiments, treatment means were separated using Fisher's protected LSD at  $\alpha \leq 0.05$  level of significance.

Cumulative weekly Palmer amaranth emergence from no herbicide management plots was regressed against days after planting (DAP) using the Gompertz equation (Equation 1; Forcella et al. 2000) in SigmaPlot version 11.0 (Systat Software Inc., San Jose, CA).

$$Y = 100 \times \exp[-B \times \exp(-K \times X)] \quad [\text{Eq.2}]$$

Where Y is the cumulative emergence, B is the DAP prior to emergence, K is the rate of emergence, and X is d accumulations. Curves were separated using the extra sum-of-squares principle for non-linear regression analysis (Lindquist et al. 1996).

## Results and Discussion

**Field Experiment.** *Cereal rye cover, biomass, and effects on early-season weeds.* In early May, at the time of cover crop termination, cereal rye provided 88 and 80% ground cover in 2015 and 2016, respectively (Table 2.3). Cereal rye dry biomass was greater in 2016 compared with 2015 with 2180 and 1250 kg ha<sup>-1</sup>, respectively (Table 2.3) due to an earlier cereal rye sowing date (~3 weeks) and warmer spring temperatures in 2016. Growing degree day (GDD) accumulations between cereal rye planting and termination were 400 and 640 GDD (base 4.4 C) for the 2014/2015 and 2015/2016 growing seasons, respectively. An earlier planting date resulted in an increase in cereal rye growth. The variability in cereal rye biomass at the time of termination was similar to findings by Snapp et al. (2005) who reported fall-sown cereal rye in Michigan produced between 800 and 2900 kg ha<sup>-1</sup> of dry aboveground biomass; however, Hill (2014) reported up to 12,777 kg ha<sup>-1</sup> of dry above- and belowground biomass when rye was planted in mid-September and terminated in early-June. Cereal rye planting and termination date is a significant factor in determining how much cover crop biomass will be produced (Mirsky et al. 2009; Hill 2014).

Warmer temperatures in 2016 also resulted in greater winter and early-summer annual weed growth in the no cover controls. Weed ground cover and biomass were 66% and 1315 kg ha<sup>-1</sup> in 2016, compared with only 33% and 104 kg ha<sup>-1</sup> in 2015 (Table 2.3). Early-season weeds present at the time of termination included annual bluegrass, common chickweed, and shepherd's purse in 2015 and 2016. Common lambsquarters and field pennycress were also present in 2015. Cereal rye reduced early-season weed growth by 74 and 84% in 2015 and 2016, respectively, compared with the no cover control (Table 2.3). Putnam and DeFrank (1983) reported similar early-season weed growth reductions (75%) in the presence of a cereal rye cover crop.

Cereal rye was terminated at Feekes stage 6 in 2015 and Feekes stage 9 in 2016. The carbon to nitrogen (C:N) ratios for cereal rye were 12:1 and 31:1 at these stages (Table 2.3). Flail mowing did not effectively terminate cereal rye. Cereal rye regrew in both years due to the early stage at which the rye was terminated and produced an additional 1290 kg ha<sup>-1</sup> of dry biomass one week after mowing in 2015 and 580 kg ha<sup>-1</sup> of dry biomass two weeks after mowing in 2016. Mowed plots were then treated with glyphosate to terminate regrowth. Cereal rye should be at head emergence or near anthesis (Feekes 10 or later) for effective termination; mowing at earlier growth stages results in significant regrowth (De Bruin et al. 2005; Wilkins and Bellinder 1996). Cereal rye terminated by mowing provided 12% more ground cover compared with termination by glyphosate alone in 2016 (Table 2.3). This was most likely due to the additional 580 kg ha<sup>-1</sup> of cereal rye regrowth plus a more uniform distribution of the cover created by the flail mower.

Soil moisture at soybean planting was greater at the 11.9 cm compared with the 7.6 cm depth in 2015 (Table 2.4). Cereal rye had no effect on soil moisture in 2015, but increased soil moisture at both 11.9 and 7.6 cm in 2016 (Table 2.4). In 2015, a lower amount of rainfall in the 26 days prior to soybean planting, combined with the low amount of cereal rye biomass, was not

sufficient to prevent soil moisture evaporation from the rye treatments. In 2016, the 71 cm of rain accumulated in the month of May prior to soybean planting, in conjunction with greater cereal rye biomass, resulted in higher soil moisture retention in the rye cover treatments.

*Palmer amaranth emergence.* Palmer amaranth emergence in the no herbicide management (NH) plots began two to three weeks after soybean planting. Initial emergence was on June 16, 2015 (392 GDD) and June 6, 2016 (306 GDD) (base 10 C) and ceased by July 21, 2015 and August 10, 2016. Similar Palmer amaranth emergence dates were reported by Kohrt (2017) in Michigan in 2014 and 2015. The cereal rye cover crop, regardless of termination method, did not affect cumulative Palmer amaranth emergence in 2015 (Figure 2.1a). However, cereal rye terminated by mowing significantly delayed weed emergence in 2016 when compared with rye terminated by glyphosate or no cover crop (Figure 2.1b). The delayed emergence in mowed plots may be attributed to more evenly distributed ground cover created by mowing as well as higher residue levels produced by the rye regrowth. The result was a reduction in the amount of sunlight reaching the soil surface to delay initial emergence. Although there was a delay in cumulative emergence in the mowed plots, there was no difference in total Palmer amaranth emergence by the end of the season (data not shown). In fact, neither cereal rye nor soybean row width had any effect on total Palmer amaranth emergence. Only herbicide management significantly reduced total emergence.

Soybean planted in wide rows extended Palmer amaranth emergence in both years (Figure 2.2). Emergence lasted an additional 10 d in 2015 and 17 d in 2016, for Palmer amaranth to reach 100% emergence when soybean was planted in 76 versus 19 cm rows. The extended emergence period in 76 cm rows corresponded with a delay in reaching 80% soybean canopy

closure compared with 19 cm rows of 7 d in 2015 and 30 d in 2016 (Figure 2.3). The yearly difference in the amount of time it took to reach 80% soybean canopy closure may be explained by the early-season drought conditions experienced in 2016 (Table 2.2). The reduced canopy in 2016 encouraged an environment for additional weed emergence later in the season. An open soybean canopy increases red light hitting the soil surface and promotes Palmer amaranth germination, while a closed canopy increases the amount of far-red light which inhibits germination (Jha et al 2010). In 2016 soybean planted in the 76 cm rows never exceeded 80% canopy closure because of a lack of soil moisture in the six weeks after soybean planting, similar to what Bell et al. (2015) reported; under dry conditions soybean planted in wide rows never reached 90% ground cover, while soybean planted in narrow rows reached 90% cover in 85 d.

*Palmer amaranth control, biomass, and density.* Planting a cereal rye cover crop, regardless of termination method, had no influence on Palmer amaranth control at any evaluation timing, except at the POST application timing in 2016 (Table 2.5). Palmer amaranth control was greater at this point in time where cereal rye was terminated by mowing compared with cereal rye terminated with glyphosate or no cover. There was a delay in Palmer amaranth emergence when cereal rye was terminated by mowing in 2016 (Figure 2.1b); greater ground cover and cereal rye biomass in this treatment may have resulted in slower degradation of the cereal rye residue (Table 2.3). A C:N ratio of 24:1 is ideal for a microbial diet (NRCS 2011); the C:N ratios were 31:1 and 23:1 for the initial and regrowth cereal rye in 2016, respectively (Table 2.3). Residues that have ratios higher than 24:1 will decompose more slowly, whereas residues with C:N ratios lower than 24:1 will decompose more rapidly (Odhiambo and Bomke 2001). The C:N ratio in

2015 for both the initial and regrowth cereal rye was 12:1 because the cereal rye was terminated at an earlier vegetative stage (Feekes 6).

In the absence of herbicides, cereal rye did not reduce Palmer amaranth density or biomass in 2015 compared with no cover crop (Table 2.6). In 2016 the number, but not the biomass, of Palmer amaranth plants  $\text{m}^{-2}$  was lower when cereal rye was terminated by mowing compared with no cover (Table 2.6). Creamer and Dabney (2002) reported that flail mowing cereal rye provided more uniform distribution of residue, and more rapid break down, which could account for the lack of significant effects on Palmer amaranth biomass and control later in the season.

In the absence of herbicides, Palmer amaranth density and biomass was lower in soybean planted in 76 compared with 19 cm rows in 2015 (Table 2.6). However, in 2016 soybean planted in 19 cm rows reduced Palmer amaranth biomass by 46%, even though there was no difference in weed density between the two row widths. Narrow row soybeans effectively suppressed Palmer amaranth in 2016 due to the quicker canopy closure, reducing light from reaching the soil surface earlier in the season (Figure 2.3).

Herbicides had the greatest impact on Palmer amaranth control in both years. In 2015, timely rainfall (Table 2.2) after the PRE application effectively incorporated flumioxazin into the soil resulting in early-season Palmer amaranth control for up to 42 DAP at the time of POST application (Table 2.5). Palmer amaranth control 21 d after POST (DAT) and at harvest was similar between the SH and HH herbicide programs. At peak biomass, Palmer amaranth density was  $<1$  plant  $\text{m}^{-2}$  in these treatments (data not shown). Since Palmer amaranth control was greater than 95% 21 DAT, the LPOS treatment of glufosinate was not applied.

In contrast, in 2016 low rainfall (Table 2.2) following soybean planting resulted in only 14 d of Palmer amaranth control with flumioxazin PRE in 2016 (Table 2.5). Therefore, POST

glufosinate and glufosinate plus acetochlor applications in the SH and HH strategies, respectively, were applied earlier in 2016 compared with 2015. Flumioxazin provides good control (>85%) of Palmer amaranth (Powell 2014). However, rainfall after application can impact the effectiveness and length of weed control, which helps explain the differences in PRE herbicide activity between 2015 and 2016. Palmer amaranth control was 67% and 95% in the SH and HH plots, respectively, 21 DAT in 2016 (Table 2.5). Others reported consistent Palmer amaranth control with the use of an effective PRE herbicide followed by POST application of glufosinate (Hoffner et al. 2012). However, these treatments are not always consistent over years. The addition of acetochlor to the POST glufosinate treatment in the HH strategy was beneficial for late-season Palmer amaranth control. Palmer amaranth emergence continued 30 DAT in the HH plots, so an additional application of glufosinate was needed for season-long weed control (Figure 2.4). The benefit of the HH strategy was also evident at the time of soybean harvest; Palmer amaranth control was 94% in the HH plots and only 62% in the SH plots. An extended emergence period due to the continuing rain events following POST application caused difficulty in controlling Palmer amaranth with a single POST herbicide application.

*Soybean yield.* Row spacing had no effect on soybean yield in either year, when averaged over cover crop and herbicide treatment (Table 2.7). Cereal rye had no effect on soybean yield in 2015; soybean yield was greater in 2016 in cereal rye treatments when herbicides were not applied (Table 2.8). Some studies have reported increases (Ateh and Doll 1996), decreases (Reddy 2001), or no effect (Liebl et al. 1992; Koger et al. 2002; Pantoja et al. 2015) on soybean yield in the absence of herbicides when compared with no cover crop. Soybean yield was reduced in the absence of a herbicide in both years (Tables 2.7; 2.8). The greatest difference

between herbicide management strategies occurred in 2016. Soybean yield was 36% higher in the HH plots than the NH control, but only 23% higher in the SH plots. This was likely due to the lower Palmer amaranth control in the SH system.

**Effects of Cereal Rye on Palmer amaranth Emergence – Pot Experiments.** *Outdoor.* Any cover applied to the soil surface, whether it was early or late-stage cereal rye or the non-rye cover, reduced initial and total Palmer amaranth emergence in 2015 (Table 2.9). Only the late-stage cereal rye and the non-rye cover reduced Palmer amaranth emergence in 2016; however, the non-rye cover was not different in total emergence from the early-stage cereal rye treatments (Figure 2.9). The high C:N ratio (34:1) may be the reason Palmer amaranth emergence was reduced with the late-stage cereal rye compared with a no cover control. These results mirror those observed in the field study when cereal rye had a greater amount of biomass and a high C:N ratio that may have reduced the rate at which cereal rye decomposed.

*Greenhouse.* Significant reductions (at least 70%) in initial and total Palmer amaranth emergence occurred in pots where cereal rye was terminated by cutting to simulate mowing (Table 2.10). The high rate of the non-rye cover also effectively reduced Palmer amaranth emergence, but only at initial emergence. Again, this may be due to the presence of both above- and belowground cereal rye biomass in addition to a uniform residue distribution over the soil surface provided by the cutting. From this study, we can conclude that cereal rye terminated by cutting was more effective at reducing Palmer amaranth emergence than a non-rye cover and termination with glyphosate. This suggests that physically injuring the cereal rye by cutting may release allelochemicals, such as the benzoxazinoid 2,4-dihydroxy-1,4 (2H)-



benzoxazin-3-one (DIBOA), that suppressed Palmer amaranth emergence. Weed suppression from cereal rye containing DIBOA was studied by Tabaglio et al. (2008) who reported up to 52% suppression of redroot pigweed from seven cereal rye cultivars compared with a no cover control.

Cereal rye had little impact on Palmer amaranth emergence or control in either year of our field research, with the exception of delayed emergence in 2016 when cereal rye was terminated by mowing. The lack of cover crop effect may be due to the low (less than 3000 kg ha<sup>-1</sup>) amounts of cereal rye biomass produced at termination in addition to the amount of time between rye termination and Palmer amaranth emergence. Palmer amaranth suppression with a cereal rye cover crop has been reported by Price et al. (2012) and Norsworthy et al. (2011) in cotton. However, the cereal rye biomass in these studies ranged from 4177 to almost 11,000 kg ha<sup>-1</sup>, 2-5 times more than the highest amount of biomass produced in this study. Furthermore, multiple studies found that while cover crops contributed to weed control in early spring, additional management practices, including herbicides, are needed for effective season-long control (Teasdale 1996; Masiunas et al. 1995; Aulakh et al. 2012; Wiggins et al. 2016).

Soybean planted in narrow rows reduced the duration of Palmer amaranth emergence compared with wide rows, likely due to the earlier canopy closure. When no herbicide was applied, and in the presence of a high Palmer amaranth population, narrow row soybean reduced weed growth and biomass, while having no negative effect on soybean yield.

Herbicides had the greatest impact on Palmer amaranth management in both years. The high and standard management strategies performed similarly in 2015, in Palmer amaranth control and soybean yield due to the consistent and prolonged weed control from PRE flumioxazin. Under drought conditions in 2016, the effectiveness of PRE flumioxazin was less, resulting in an

earlier POST application timing. Later-season rainfall in 2016 also promoted late Palmer amaranth emergence that was controlled with the LPOS application in the high management strategy. As a result, there was an increase of 574 kg ha<sup>-1</sup> in soybean yield with the use of the HH strategy compared with the SH strategy in 2016.

The goal of this study was to determine which (if any) cultural practices to recommend with herbicides to manage Palmer amaranth in Michigan soybean production. The use of a cereal rye cover crop terminated at Feekes stage 9 with 2180 kg ha<sup>-1</sup> of biomass, regardless of termination method, had less of an impact on Palmer amaranth emergence and growth than planting soybean in narrow rows. In Mississippi, Koger et al. (2002) also observed that cereal rye had no effect on Palmer amaranth control and that planting soybean in narrow rows was a more effective cultural method for reducing weed pressure. However, other studies have reported that cereal rye suppressed and helped provide control of Palmer amaranth (Norsworthy et al. 2011; DeVore et al. 2012; Korres and Norsworthy 2015). Cereal rye biomass in these studies ranged from 5352 to 8460 kg ha<sup>-1</sup>.

In our study, flail mowing did not effectively terminate cereal rye. Previous studies have reported that cereal rye should be terminated at Feekes stage 10.1 or later to produce the most biomass while having minimal regrowth (Wilkins and Bellinder 1996; Mirsky et al. 2009; Wayman et al. 2014). Planting cereal rye earlier in the fall in combination with a later cereal rye stage at the time of termination, may improve Palmer amaranth suppression by increasing biomass and providing a longer lasting mulch. However, this is difficult to accomplish in a Michigan corn-soybean rotation due to the late timing of corn harvest in October through November. Additionally, corn is planted in late-April and soybean in May which leads to earlier rye termination. Palmer amaranth emergence in Michigan began four weeks after cereal rye

termination and two weeks after soybean planting. During this time, the cereal rye may lose some its suppressive effect due to decomposition of the residue by the time Palmer amaranth emergence would begin. One way to potentially increase biomass and extend the cover crop growing season is to interseed into the cash crop. Growers may also to choose to terminate cereal rye closer to or after cash crop planting. Even though cereal rye did not impact Palmer amaranth control in this study, winter annual weeds were suppressed and there is the potential for additional ecosystem services (Finney et al. 2016). In Michigan, the recommended method of controlling Palmer amaranth and preventing late-season emergence is planting soybean in narrow rows to reduce the period of Palmer amaranth emergence in addition to an intensive herbicide management program.

## **APPENDIX**

**APPENDIX**  
**CHAPTER 2 TABLES AND FIGURES**

*Table 2.1.* Herbicide application timings, active ingredients, and product information for three different herbicide strategies used for management of glyphosate-resistant Palmer amaranth in Middleton, MI (2015-2016).

Management	Timings <sup>a</sup>	Active ingredient	Rate kg ai ha <sup>-1</sup>	Trade name	Manufacturer <sup>b</sup>
High	PRE	flumioxazin	0.07	Valor	Valent Co.
	POST <sup>c</sup>	glufosinate + acetochlor	0.6 + 1.26	Liberty 280SL + Warrant	Bayer CropScience + Monsanto
	LPOS <sup>d</sup>	glufosinate	0.6	Liberty	Bayer CropScience
Standard	PRE	flumioxazin	0.07	Valor	Bayer + Monsanto
	POST	glufosinate	0.6	Liberty	Bayer CropScience
No herbicide	--	--	--	--	--

<sup>a</sup> Abbreviations: PRE, preemergence application, POST, postemergence application, LPOS, late-postemergence application.

<sup>b</sup> Manufacturer information: Bayer CropScience, Research Triangle Park, NC, [www.cropscience.bayer.com](http://www.cropscience.bayer.com); Monsanto Co., St. Louis, MO, [www.monsanto.com](http://www.monsanto.com); Valent Co., Walnut Creek, CA, [www.valent.com](http://www.valent.com).

<sup>c</sup> Spray grade ammonium sulfate (AMS) (Actamaster, Loveland Products Inc., Loveland, CO, [www.lovelandproducts.com](http://www.lovelandproducts.com)) at 2% w w<sup>-1</sup> was added to all POST and LPOS applications.

<sup>d</sup> The LPOS herbicide application was if needed and was only used in 2016

Table 2.2. Monthly precipitation and the 30-year average for Middleton, MI in 2015 and 2016.

Month	Precipitation <sup>a</sup> (mm)		
	2015	2016	30 yr. <sup>c</sup>
April	68	41	77
May	60 (35) <sup>b</sup>	78 (71) <sup>b</sup>	88
June	78	16	87
July	56	95	70
August	93	127	87
September	82	72	87

<sup>a</sup> Precipitation data collected from the Enviro-weather Automated Weather Station Network (<https://mawn.geo.msu.edu/>)

<sup>b</sup> Rainfall accumulation up to the date of soybean planting.

<sup>c</sup> 30-year average precipitation data collected from the National Oceanic and Atmospheric Administration (<https://www.ncdc.noaa.gov/cdo-web/datatools/normal>s)

Table 2.3. Cereal rye and weed dry biomass at cover crop termination and cover crop regrowth from cereal rye plots in Middleton, MI (2015-2016). Cereal rye biomass was analyzed for C:N ratio.

Cover crop	2015					2016					
	Ground cover		Dry biomass			Ground cover		Dry biomass			
	Cereal rye	Weed <sup>b</sup>	Cereal rye	Weed	Cereal rye	Cereal rye	Weed	Cereal rye	Weed	Cereal rye	
<i>At termination<sup>a</sup></i>	%		kg ha <sup>-1</sup>			%		kg ha <sup>-1</sup>			C:N ratio
Cereal rye	88	4 b <sup>d</sup>	1249	27 b	12:1	80	9 b	2186	206 b	31:1	
No cover	--	33 a	--	104 a	--	--	66 a	--	1315 a	--	
<i>At planting</i>	Cereal rye regrowth <sup>c</sup>					Cereal rye regrowth					
			kg ha <sup>-1</sup>					kg ha <sup>-1</sup>			C:N ratio
Rye glyphosate	92 a	0 b	0 b	--	--	71 b	3 b	0 b	--	--	
Rye mowed <sup>c</sup>	83 a	4 b	1291 a	--	12:1	83 a	2 b	582 a	--	23:1	
No cover	--	34 a	--	--	--	--	43 a	--	--	--	

<sup>a</sup> Cereal rye was terminated at Feekes stage 6 (30 cm) on May 14, 2015 and at Feekes stage 9 (58 cm) on May 11, 2016.

<sup>b</sup> Weed species present were: annual bluegrass, common chickweed, and shepherd's purse. Common lambsquarters and field pennycress were also present in 2015.

<sup>c</sup> Cereal rye regrowth occurred in plots terminated by flail mowing. Regrowth biomass was collected one week after mowing in 2015 and two weeks after mowing in 2016. Regrowth was then terminated with glyphosate at 1.26 kg ae ha<sup>-1</sup> + 2% w w<sup>-1</sup> spray grade ammonium sulfate (AMS).

<sup>d</sup> Means followed by the same letter at each evaluation timing within a column are not statistically different at  $\alpha \leq 0.05$ .

Table 2.4. Soil moisture<sup>a</sup> at 7.6 and 11.9 cm depths measured at the time of soybean planting in the cereal rye and no cover plots in 2015 and 2016.

Prong length	Cover crop termination	2015	2016
		% moisture	
7.6 cm	Cereal rye – <i>glyphosate</i>	10.4 a <sup>b</sup>	16.8 a
	Cereal rye – <i>mowed</i>	10.3 a	18.0 a
	No cover	9.2 a	12.3 b
11.9 cm	Cereal rye – <i>glyphosate</i>	21.3 b	17.9 a
	Cereal rye – <i>mowed</i>	20.7 b	18.3 a
	No cover	20.4 b	13.7 b

<sup>a</sup> Soil moisture reported as volumetric water content and measured with a TDR 300 Soil Moisture Meter (FieldScout, Spectrum Technologies, Aurora, IL).

<sup>b</sup> Means followed by the same letter within a column are not statistically different at  $\alpha \leq 0.05$ .



Table 2.5. Main effects of cereal rye cover crop, soybean row width and herbicide management strategy on Palmer amaranth control in 2015 and 2016 at Middleton, MI.

Main effects	2015			2016		
	at POST	21 DAT	at Harvest	at POST	21 DAT	at Harvest
	% control			% control		
<i>Cover crop</i>						
Rye glyphosate	88	93	95	83 b <sup>a</sup>	80	77
Rye mowed	89	96	97	98 a	80	73
No cover	86	97	96	93 b	83	84
<i>Row width</i>						
76 cm	87	94	95	93	78	76
19 cm	89	97	98	89	84	80
<i>Herbicide strategy</i>						
High management	86	96	97	88	95 a	94 a
Standard management	90	95	95	95	67 b	62 b
<i>Effects</i>						
	p-value					
Cover crop	0.5215	0.1906	0.5030	0.0158	0.7829	0.2410
Row width	0.4602	0.1759	0.0568	0.3067	0.1802	0.4051
Herbicide management	0.0891	0.5267	0.1666	0.0824	<0.0001	<0.0001

<sup>a</sup> Means followed by the same letter for each main effect within a column are not statistically different at  $\alpha \leq 0.05$ .

Table 2.6. Main effects of cover crop and soybean row width on Palmer amaranth density and biomass in the no herbicide management plots at peak biomass in 2015 and 2016 at Middleton, MI.

Main effects	Density		Biomass	
	2015	2016	2015	2016
	plants m <sup>-2</sup>		g m <sup>-2</sup>	
<i>Cover crop</i>				
Rye glyphosate	14.7	38.5 ab	13.9	89.9
Rye mowed	14.0	20.0 b	17.4	76.2
No cover	13.2	57.4 a	30.9	123.8
<i>Row width</i>				
76 cm	9.5 b <sup>a</sup>	38.1	11.4 b	125.8 a
19 cm	18.5 a	39.1	30.1 a	67.5 b
<i>Effects</i>				
	p-value			
Cover crop	0.9055	0.0288	0.1547	0.2192
Row width	0.0022	0.9329	0.0187	0.0183
Cover crop*Row width	0.3521	0.6570	0.9153	0.7347

<sup>a</sup> Means followed by the same letter for each main effect within a column are not statistically different at  $\alpha \leq 0.05$ .

Table 2.7. Main effects and interactions of cereal rye cover crop, soybean row width, and herbicide management strategy on soybean yield in 2015 and 2016 at Middleton, MI.

Main effects	Yield	
	2015	2016
	kg ha <sup>-1</sup>	
<i>Cover crop</i>		
Rye glyphosate	3324	2739
Rye mowed	3419	3037
No cover	3235	2502
<i>Row width</i>		
76 cm	3321	2616
19 cm	3331	2902
<i>Herbicide management</i>		
High herbicide	3718 a <sup>a</sup>	3358 a
Standard herbicide	3607 a	2784 b
No herbicide	2649 b	2135 c
<i>Effects</i>		
	p-value	
Cover crop	0.6856	0.4234
Row width	0.9126	0.1542
Herbicide management	<0.0001	<0.0001
Cover crop*Row width	0.1436	0.2400
Cover crop*Herbicide management <sup>b</sup>	0.0018	0.1964
Row width*Herbicide management	0.1352	0.3728
Cover crop*Row width*Herbicide management	0.8258	0.9687

<sup>a</sup> Means followed by the same letter for each main effect within a column are not statistically different at  $\alpha \leq 0.05$ .

<sup>b</sup> The cover crop by herbicide management interaction data is presented in Table 2.8.

Table 2.8. Effect of cover crop by herbicide management strategy interaction on soybean yield in 2015 and 2016.

Cover crop - Termination	Herbicide strategy	Soybean yield	
		2015	2016
		kg ha <sup>-1</sup>	
Cereal rye - <i>glyphosate</i>	High	3570 a <sup>a</sup>	3453
	Standard	3574 a	2724
	None	2829 b	2039
Cereal rye - <i>mowed</i>	High	3780 a	3364
	Standard	3532 a	2960
	None	2945 b	2786
No cover	High	3809 a	3258
	Standard	3718 a	2667
	None	2178 c	1581
<i>Effects</i>		p-value	
Cover crop		0.6856	0.4234
Herbicide management		<0.0001	<0.0001
Cover crop*Herbicide management		0.0018	0.1964

<sup>a</sup> Means followed by the same letter are not statistically different at  $\alpha \leq 0.05$ .

Table 2.9. Effect of a cereal rye or non-rye cover on the initial and total emergence of Palmer amaranth in outside pots in 2015 and 2016.

Treatment	Rate <sup>d</sup>	2015		2016	
		Initial emergence	Total emergence	Initial emergence	Total emergence
		plants pot <sup>-1</sup>		plants pot <sup>-1</sup>	
Early stage- cereal rye <sup>a</sup>	Low	8 bc <sup>c</sup>	14 bc	36 a	40 ab
	Medium	5 cd	13 bc	37 a	40 ab
	High	4 cd	16 bc	-	-
Late stage- cereal rye <sup>b</sup>	Low	10 bc	21 b	19 b	28 c
	Medium	6 cd	12 c	-	-
	High	1 d	9 c	-	-
Non-rye cover <sup>e</sup>		14 b	21 b	25 b	31 bc
No cover		21 a	32 a	41 a	43 a

<sup>a</sup> Early stage cereal rye was Feekes 6 and 9 in 2015 and 2016.

<sup>b</sup> Late stage cereal rye was Feekes 10.5 and 10.1 in 2015 and 2016.

<sup>c</sup> Means followed by the same letter within a column are not statistically different at  $\alpha \leq 0.05$ .

<sup>d</sup> Rates of cereal rye biomass were 1200 kg (low), 2400 kg (medium), and 3750 kg (high) ha<sup>-1</sup>.

<sup>e</sup> Non-rye cover was raffia palm (Ashland, Irving, Texas).

Table 2.10. Effect of termination method and cereal rye cover on initial and total Palmer amaranth emergence in the greenhouse.

Cover	Termination method	Initial emergence	Total emergence
		plants pot <sup>-1</sup>	
Cereal rye - High biomass <sup>a</sup>	Glyphosate - above & below <sup>b</sup>	16 bc <sup>f</sup>	18 cde
	Glyphosate – above <sup>c</sup>	21 a	24 a
	Glyphosate – below <sup>d</sup>	19 ab	19 bcde
	Cutting <sup>e</sup>	3 e	3 f
Cereal rye - Low biomass <sup>a</sup>	Glyphosate - above & below	15 cd	17 de
	Glyphosate - above	21 a	24 ab
	Glyphosate - below	21 a	23 abc
	Cutting	3 e	5 f
Non-rye cover - High biomass		11 d	15 e
Non-rye cover - Low biomass		21 a	22 abcd
No cover		17 abc	17 de

<sup>a</sup> Rates of cereal rye biomass were 3500 kg (high) and 400 kg (low) ha<sup>-1</sup>.

<sup>b</sup> The above- and belowground treatment included cereal rye shoots and roots.

<sup>c</sup> The aboveground treatment included only cereal rye shoots.

<sup>d</sup> The belowground treatment included only intact cereal rye roots where aboveground shoot biomass was removed.

<sup>e</sup> The cutting treatment contained cereal rye shoots cut into pieces and spread out on soil surface and roots left intact.

<sup>f</sup> Means followed by the same letter within a column are not statistically different at  $\alpha \leq 0.05$ .

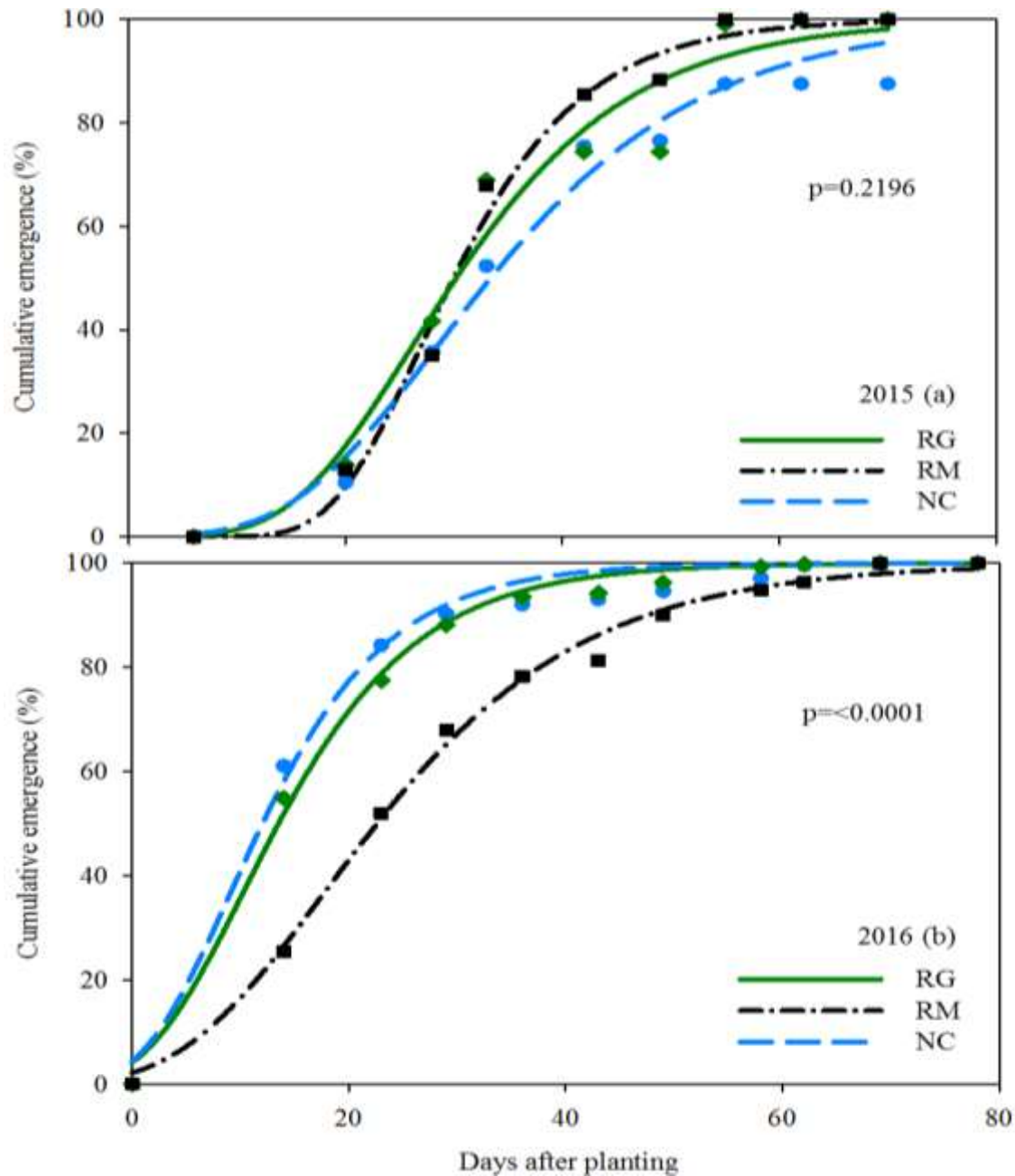


Figure 2.1. Cumulative Palmer amaranth emergence as a percent of total emergence combined across all soybean row widths with cereal rye terminated by glyphosate (RG) (◆), cereal rye terminated by mowing (RM) (■) and no cover (NC) (●) in 2015 (a) and 2016 (b). There was no difference between the treatments in 2015; however, RM was significantly different from RG and NC in 2016. Fitted lines were calculated with the Gompertz equation: NC,  $y=100*\exp(-8.25*\exp(-0.07*x))$ ,  $R^2 = 0.53$ ; RG,  $y=100*\exp(-10.57*\exp(-0.09*x))$ ,  $R^2 = 0.74$ ; RM,  $y=100*\exp(-26.87*\exp(-0.12*x))$ ,  $R^2 = 0.78$ .

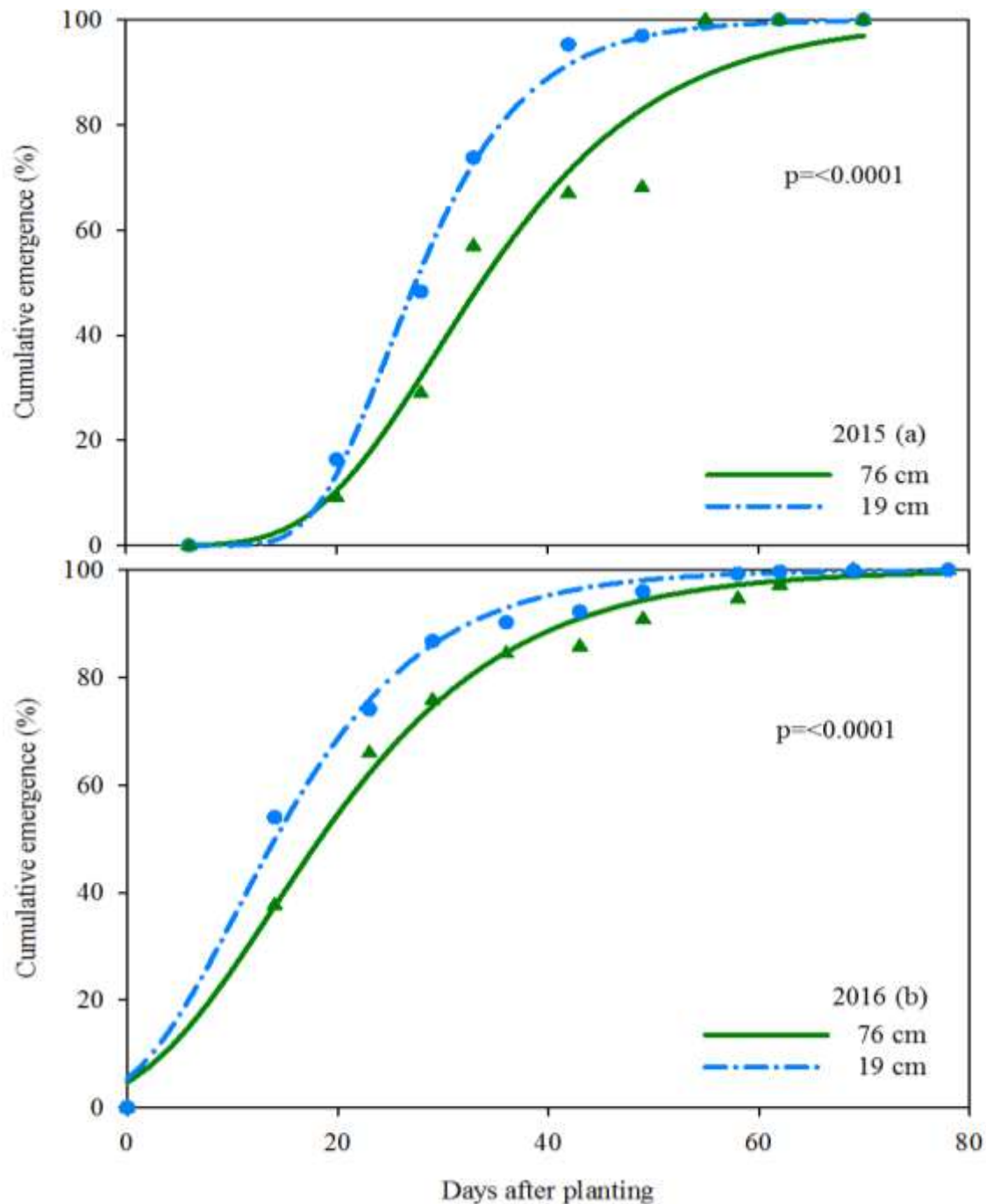


Figure 2.2. Cumulative Palmer amaranth emergence in 2015 (a) and 2016 (b) as a percent of total emergence combined across all cover crop treatments in 19 (●) and 76 cm (▲) rows. Soybean row widths were significantly different from each other in both years. Fitted lines were calculated with the Gompertz equation: 76 cm rows,  $y=100*\exp(-12.67*\exp(-.08*x))$ ,  $R^2 = 0.74$ ; 19 cm rows,  $y=100*\exp(-33.93*\exp(-0.14*x))$ ,  $R^2 = 0.86$ .



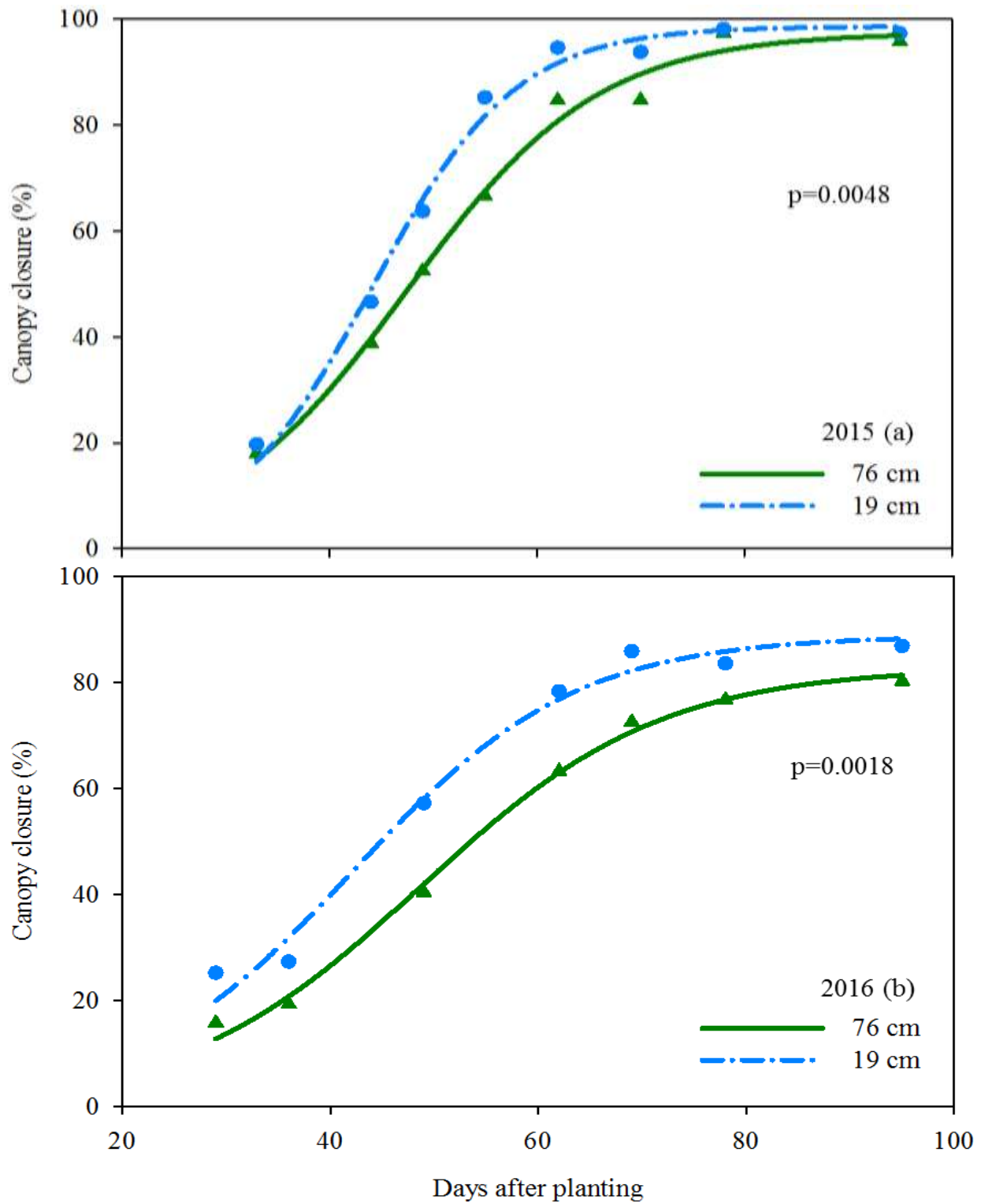


Figure 2.3. Percent soybean canopy closure in 19 (●) and 76 cm (▲) rows in 2015 (a) and 2016 (b). Soybean row widths were significantly different from each other in both years.

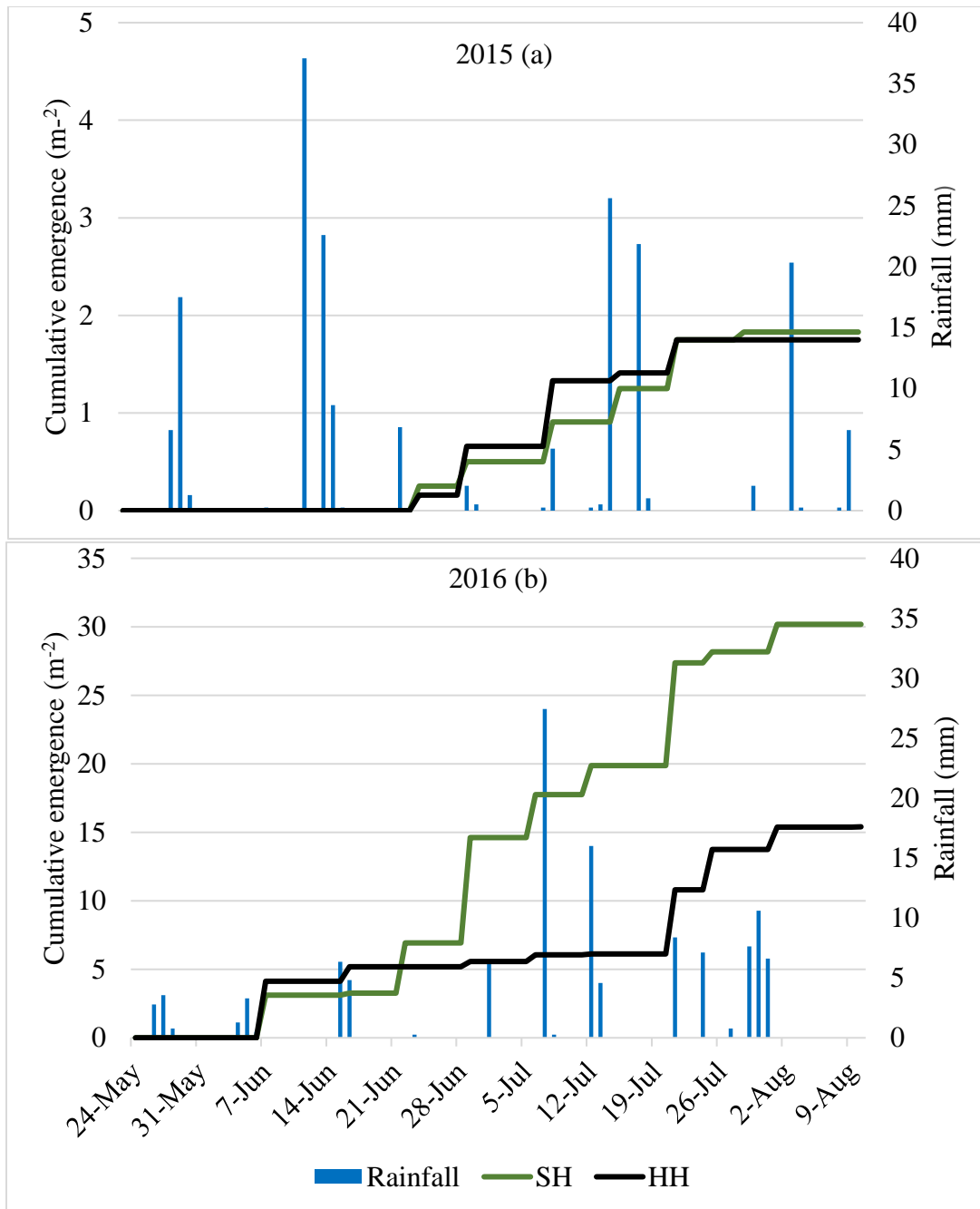


Figure 2.4. Effect of rainfall on cumulative Palmer amaranth emergence in the standard and high herbicide management strategies in 2015 (a) and 2016 (b). POST applications were made on July 15, 2015 and June 10, 2016. LPOST application was applied on July 8, 2016.

## **LITERATURE CITED**

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