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# EMERGENCE PATTERNS OF COMMON WATERHEMP AND PALMER AMARANTH IN SOUTHERN ILLINOIS

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by

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The continued spread of glyphosate-resistant common waterhemp [*Amaranthus tuberculatus* (Moq.) Sauer (syn. *rudis*)] and Palmer amaranth [*Amaranthus palmeri* (S. Wats.)] have complicated weed control efforts in soybean and corn production in Illinois. A thorough understanding of the weed biology of these species is fundamental in developing effective weed management strategies. The determination of emergence patterns as well as the influence of tillage practices on soil microclimate and soil seed bank will allow control strategies to be implemented at the most effective timing.

Field experiments were conducted in southern Illinois throughout the growing season of 2013 and 2014 on two separate sites with populations of common waterhemp and Palmer amaranth. Three tillage treatments were evaluated: no-tillage; early tillage, preferably performed around a recommended soybean planting date of May 1$^{st}$; and late tillage, preferably performed on June 1$^{st}$ to simulate a late soybean planting. *Amaranthus* seedlings were identified and enumerated in the center 1 $m^2$ quadrat of each plot within a 7-day interval from April through November or first frost. All weed seedlings were removed from the plot area after each enumeration. Soil temperature and soil moisture were recorded hourly throughout the experiment using data loggers established in the plot area.

First emergence of common waterhemp occurred earlier in the season than did Palmer amaranth. In 2013, initial emergence of common waterhemp and Palmer amaranth was observed

at the first and second week of May, respectively. In 2014, initial common waterhemp emergence was observed in late April, while Palmer amaranth initial emergence was similar to previous year. Palmer amaranth emerged over a longer period compared to waterhemp. By the end of June, 90% of common waterhemp had emerged regardless of tillage or year. By the same measure, Palmer amaranth emergence was extended to the third week of July and second week of August in 2013 and 2014, respectively. Soil temperature did not differ across tillage treatments in both years. On the other hand, differences in soil moisture were observed, mostly over two weeks following each tillage operation.

The single best predictor for common waterhemp emergence was soil temperature (weekly highs and lows) followed by soil moisture. For Palmer amaranth emergence the single best predictor was spikes in soil moisture (high for the week). In 2013, common waterhemp emergence was initially positively and later in the growing season negatively interacted with maximum temperature 13 days prior to counts, with temperatures above 30 C observed with decreased emergence ($R^2$ = 0.35). In the same year spikes in soil moisture interacted with Palmer amaranth emergence were those observed 11 days before each seedling enumeration date ($R^2$ = 0.30). In 2014, with first common waterhemp emergence in April, a positive interaction to high soil temperature was initially observed followed by a positive interaction to minimum temperatures later in the season ($R^2$ = 0.55). Spikes in soil moisture observed 2 weeks prior to emergence and weekly high temperatures 8 days prior to emergence were the best predictors of Palmer amaranth emergence in 2014 ($R^2$ =0.37). Soil seed bank depletion was also estimated by comparing field emergence with greenhouse experiment results of soil seed bank estimation. Greater emergence of common waterhemp from the soil seed bank was observed in early tillage in 2013 and no-tillage in 2014 than late tillage, respectively; for Palmer amaranth, the greatest emergence from the soil seed bank was observed in no-tillage and late tillage in 2013, and no-tillage, in 2014.

The emergence patterns observed in this research suggest that although common waterhemp and Palmer amaranth exhibit discontinuous emergence throughout the growing season, greater attention should be placed on managing peaks of emergence from late April to late July, which is critical to provide a foundation for early-season weed management. Furthermore, knowledge regarding the emergence patterns of common waterhemp and Palmer amaranth combined with monitoring environmental factors such as soil moisture and soil temperature may assist efforts for scouting fields to determine the likely presence of these weed species. The timing of viable postemergence herbicide options for control of glyphosate-resistant waterhemp and Palmer amaranth is critical and monitoring weather patterns to direct scouting efforts may improve the timeliness of these postemergence applications.

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# CHAPTER 1

# REVIEW OF LITERATURE

The introduction of glyphosate-resistant (GR) crops shifted weed management practices to postemergence herbicide applications and the near exclusive use of glyphosate. With the commercialization of soybeans (*Glycine max* L.) resistant to glyphosate in 1996 the number of hectares treated with glyphosate increased dramatically (USDA 2008). Growers rapidly adopted GR soybeans due to the limited soybean injury observed from glyphosate applied postemergence (Shaw and Arnold 2002), the flexibility of application timing, and the simplicity of a weed control system based on a single herbicide (Young 2006). In 2008, glyphosate was used on more soybean hectares than any other herbicide with over 90% of soybean production area receiving at least one application (USDA 2008).

As reliance on glyphosate increased, the use of different herbicides and association with herbicide modes of action decreased (Givens et al. 2009; Young 2006). Multiple applications of glyphosate in GR soybeans, corn (*Zea mays* L.) and cotton (*Gossypium hirsutum* L.) have been typical. In soybeans, 62% of continuous GR soybean producers apply at least two postemergence applications of glyphosate (Givens et al. 2009). Normally, when producers experience inconsistencies in the efficacy of glyphosate applications they tend to increase the rate of the herbicide being applied instead of using alternate herbicide modes of action (Owen 2000). Reducing the use of alternative herbicides while increasing the use of glyphosate has triggered a selection pressure event shifting the frequency of weed species towards those that are inherently tolerant or have evolved resistance to glyphosate (Reddy 2001). Prior to the introduction of GR crops there were no weed species confirmed resistant to glyphosate in the U.S. (Heap 2011). The evolution of GR weeds has been suggested to occur slowly through multiple gene mutations that may affect herbicide uptake, metabolism, or translocation (Gressel 2009). However, the first glyphosate-resistant weed biotype was confirmed in Australia in 1996 in a population of Italian ryegrass (*Lolium rigidum* L.) located in an orchard. The ramped use of glyphosate in GR crops had only accelerated the selection of glyphosate-resistant weed biotypes with 31 weed species, to date, that have been confirmed resistant to glyphosate worldwide with 14 confirmed in the U.S. (Heap 2014).

Two problematic weed species in row crops are common waterhemp (*Amaranthus tuberculatus* Moq. Sauer) and Palmer amaranth (*Amaranthus palmeri* S.Wats.). Among all the *Amaranthus* species Palmer amaranth, common waterhemp, spiny amaranth (*Amaranthus spinosus* L.) and smooth pigweed (*Amaranthus hybridus* L.) are the only members with biotypes expressing resistance to glyphosate (Legleiter and Bradley 2008; Heap 2015). Normally, susceptible biotypes of Palmer amaranth are very sensitive to glyphosate, although in Georgia certain GR populations have been found to survive glyphosate applications at 10 times the recommended field use rate (Culpepper et al. 2006).

**Weedy *Amaranthus* Species**

The genus *Amaranthus* belongs to the family Amaranthaceae and contains approximately 75 species worldwide. *Amaranthus* became one of the most notable plant groups, in part because of the success of many of its members as fellow travelers of mankind (Sauer 1956). The number of *Amaranthus* species native of North America is extensive. At least nine annual *Amaranthus spp*. have adapted to farm practices to become weedy pests across the Midwestern United States. However, few species are as detrimental to row crop production as common waterhemp and Palmer amaranth. Common waterhemp is native to the Midwest United States and has been historically found mainly in the western part of the Mississippi River, ranging from Nebraska to Texas, spread over a large geographical area containing Illinois, Iowa and Missouri (Hager et al. 2002; Sauer 1955); Palmer amaranth is native from the area encompassing northwestern Mexico to southern California and New Mexico to Texas (Sauer 1957). Both common waterhemp and Palmer amaranth are dioecious, erect branching, summer annuals that utilize the $C_4$ photosynthetic pathway (Bell and Tranel 2010; Ehleringer 1983). For being dioecious both species use outcrossing to reproduce, this ensures large genetically variable populations and can also serve to produce more adaptive traits between fields and across agricultural landscape. Previous researchers have reported that Palmer amaranth was the first to emerge and grew the fastest and the tallest when compared to common waterhemp and two other *Amaranthus* species grown in Kansas (Horak and Loughin 2000). Furthermore, at four weeks after planting Palmer amaranth was 48 and 600% taller than redroot pigweed (*Amaranthus retroflexus* L.) and common waterhemp, respectively, in Missouri (Sellers et al. 2003).

**Herbicide Resistance**

The dioecious nature of common waterhemp and Palmer amaranth has likely contributed to the rapid spread of glyphosate-resistant *Amaranthus.* In 1995, Palmer amaranth was the most troublesome weed of cotton in North Carolina and South Carolina, but not a major problem in any other state; although by 2009, Palmer amaranth was ranked as the most troublesome cotton weed in the southern U.S. (Dowler 1995; Webster and Coble 1997). Glyphosate-resistant Palmer amaranth infests more than 60% of soybean fields in Arkansas and alone has been responsible for the loss of millions of dollars to Midsouth soybean production in the United States (Norsworthy et al. 2012). Palmer amaranth is also listed among the toughest weeds to control in corn (Webster and Nichols 2012). As a result of intense application of glyphosate and failure to control the GR populations, excessive selection pressure has been placed on PPO-inhibiting herbicides, making resistance to this site of action more likely to occur. To this date, Palmer amaranth populations have evolved resistance to five different herbicides sites of action (SOA): EPSPS-inhibiting herbicides; ALS-inhibiting herbicides; photosystem II-inhibiting herbicides; microtubule-inhibiting herbicides; and HPPD-inhibiting herbicides (Wise et al. 2009). According to a state-wide survey in Arkansas in 2011, consultants reported that soybean yield was reduced by 5% from uncontrolled GR Palmer amaranth, causing an estimated loss of US$71,000,000. Furthermore, US$11,000,000 was estimated as spent on hand-weeding labor in soybean fields (Norsworthy 2009). The actual scenario shows that GR Palmer amaranth is now widespread across the south and moving towards the Midwestern U.S. (Heap 2012; Nandula et al. 2012).

Common waterhemp populations also have developed resistance to multiple herbicide sites of action, mostly used in soybeans, such as: EPSPS-inhibiting herbicides; ALS-inhibiting herbicides; PPO-inhibiting herbicides; photosystem II-inhibiting herbicides; synthetic auxins; and HPPD-inhibiting herbicides (Heap 2010). Glyphosate-resistant common waterhemp and Palmer amaranth have been confirmed in Illinois since 2006 and 2010, respectively (Heap 2010). The increase of herbicide resistance and the presence of weed biotypes with multiple resistance mechanisms to several herbicide sites of action have complicated weed management. Herbicides that inhibit the 4-hydroxyphenylpyruvate dioxygenase (HPPD) enzyme constitute the most recently commercialized herbicide site of action in agronomic crops. Nevertheless, common waterhemp populations resistant to HPPD herbicides were reported in Iowa in 2011 (Heap 2011). Common waterhemp was the first weed to evolve resistance to HPPD-inhibiting herbicides (Heap 2011).

**Seed Production**

Palmer amaranth and common waterhemp are also known for being prolific seed producers, with female plants being capable of producing more than 600,000 seeds (Keeley et al. 1987; Hartzler et al. 2004). Most of *Amaranthus* seeds are predominantly dispersed by gravity, but can also be spread by irrigation, water flow, movement of birds and mammals, and through agricultural practices such as plowing, mowing and harvesting (Costea et al. 2004; Norsworthy et al. 2009).

Normally, at high weed densities common waterhemp seed production is higher than Palmer amaranth. In contrast, at low weed density Palmer amaranth seed production is higher than common waterhemp (Bensch et al. 2003). Common waterhemp can produce from 300,000 to 2.3 million seeds per female plant depending on the location, and over 400,000 seeds per female plant under reduced light conditions (Nordby and Hartzler 2004; Steckel et al. 2004). Common waterhemp and Palmer amaranth seeds are characterized for being small (1 to 2 mm), smooth and round or disc-shaped (Sauer 1955). Research conducted in Georgia have reported that seed production of Palmer amaranth was 312,000 seeds per female plant when female plants competed with cotton, and 446,000 seeds per female plant in absence of crop (Webster and Grey 2015). In a similar study conducted in Missouri, female Palmer amaranth plants produced an average of 250,000 seeds per plant (Sellers et al. 2003).

**Competition with Row Crops**

Common waterhemp and Palmer amaranth readily compete with crops for light, water, nutrients, and therefore have a negative impact on yield. Bensch et al. (2003) reported soybean yield reduction of 56% when a population of 8 common waterhemp plants $m^{-1}$ of soybean row was allowed to compete with the crop. Low effectiveness in controlling common waterhemp in a soybean field may result in yield reductions up to 43% (Hager et al. 2002). Grain yield loss of 74% was reported when 270 common waterhemp plants $m^{-1}$ of corn row were allowed to compete with the crop beyond V10 growth stage (Steckel et al. 2004). Common waterhemp has also shown to be a problematic weed in grain sorghum (*Sorghum bicolor* L.). Feltner et al. (1969) reported a yield reduction of 45% when 3 common waterhemp plants $m^{-1}$ of grain sorghum row were allowed to compete for 10 weeks.

Palmer amaranth is capable of being as much or even more competitive to row crops than common waterhemp. Soybean yield reduction varied from 17 to 64% when Palmer amaranth density ranged from 0.3 to 10 plants $m^{-1}$ of soybean row, respectively (Klingaman and Oliver 1994). Palmer amaranth competition reduced corn yield from 11 to 91% as Palmer amaranth density increased from 0.5 to 8 plants $m^{-1}$ of corn row. When compared to common waterhemp and redroot pigweed, Palmer amaranth was responsible for the highest soybean yield reduction (78.7%) at a density of 8 plants $m^{-1}$ of soybean row (Massinga et al. 2001; Bensch et al. 2003). In addition to the competition for light, water, and nutrients Palmer amaranth has also interfered with mechanical harvest efficiency. Smith et al. (2000) reported that 3,260 Palmer amaranth plants per hectare reduced cotton yield by 22% and mechanical harvesting efficiency by 2.4%. In addition, Palmer amaranth biomass has shown to have allelopathic chemicals that reduce seedling vigor of several crops and weeds (Menges 1987).

**Germination Characteristics**

Information on germination rates and emergence patterns of common waterhemp and Palmer amaranth, along with factors that may influence their persistence in the soil seed bank is critical in selecting effective management strategies. There are numerous factors that can influence seed germination, such as soil moisture, oxygen availability and quality, temperature, light exposure, and microbial activity (Leon et al. 2004). These factors are correlated to the level of seed dormancy observed in populations of common waterhemp, green pigweed (*Amaranthus powellii* S. Wats), and redroot pigweed (Oryokot et al. 1997). Normally, seed germination of a particular weed in the field occurs when the dormancy level of the population is minimum (Probert 1992). Bewley et al. (2012) reported that annual dormancy is deeply dependent on temperature and light exposure, which implies that seeds in the soil seed bank undergo changes in germination in response to temperature and light over time. Moreover, the physiological and genetic characteristics of seeds play major roles in seed dormancy. Nevertheless, the interaction between all these characteristics is what determines whether seed dormancy will occur or not (Murdoch and Ellis 1992).

**Seed Dormancy**

Seed dormancy is an innate seed property that defines under which environmental conditions the seed is able start germination (Finch-Savage and Leubner-Metzger 2006). Dormancy is determined by genetic factors with a substantial environmental influence and provides plant adaptation to a diversity of habitats. When determined by genetic factors seed dormancy is classified as primary dormancy; and secondary dormancy, when unfavorable conditions related to the environment are the main cause influencing factor (Graeber et al. 2012). Different classes of seed dormancy have been reported among plant species, and can be divided in physiological dormancy, morphological dormancy, morphophysiological dormancy, and combinational dormancy (Baskin and Baskin 2004; Finch-Savage and Leubner-Metzger 2006). Among all these classes, physiological and morphological dormancies are the most common mechanisms of weed seed persistence in the soil seed bank (Omami et al. 1999). Previous research has defined dormancy as one of the most important component of plant fitness (Donohue et al. 2005; Huang et al. 2010). Seed dormancy levels that are too high may delay germination and reduce the length of the growing season for certain species. In contrast, seed dormancy levels that are too low can lead to germination before the start of a favorable growing season, which may increase the risks of seedling mortality (Graeber et al. 2012). Therefore, seed dormancy is often considered an important adaptive trait of weed species that are characterized for prolonged seed germination, such as common waterhemp and Palmer amaranth. Previous research has reported that major differences in common waterhemp and Palmer amaranth seed dormancy are due to variability in seed physiology, and that these differences arose in response of some kind of selection, such as tillage practices and herbicide applications (Jha et al. 2014; Leon et al. 2006). The timing of tillage and the use of herbicides work as selective forces increasing the level of seed dormancy and consequently, delayed seedling emergence (Ghersa et al. 1994). Tillage is also one of the most important causes of seasonal seed dormancy observed in common waterhemp and Palmer amaranth (Leon et al. 2006; Jha et al. 2008). Nevertheless, depending on how tillage acts, whether burying seeds deeper in the soil profile or bringing them closer to the upper surface, it may relocate and expose seeds to areas where favorable environmental conditions for emergence are more predominant which may break seed dormancy.

Exposure to light breaks seed dormancy in many species, especially small-seeded broadleaves (Dyer 1995). As small-seeded broadleaves may not survive germination from deeper in the soil profile, the necessity of light is thought to be an evolutionary advantage for this type of seeds (Pons 1991). Research has shown that light can only penetrate a few mm in the soil profile; thus, for light-requiring seeds even a shallow burial may induce seed dormancy (Pons 1991; Wesson and Wareing 1969). The quality and quantity of light reaching the soil surface is deeply affected by the presence of crop residues and crop canopy. Generally, when crop canopy is present the light passing through the green leaves is filtered and depleted in red light and enriched in far-red wavelengths, which has shown to inhibit germination of many small-seeded broadleaf species (Taylorson and Borthwick 1969). The primary plant and seed systems responsible for perceiving these wavelengths are the phytochrome family of photoreceptors. *Amaranthus* species that can emerge only from shallow depths, such as common waterhemp and Palmer amaranth, often require light for dormancy breaking and germination (Baskin and Baskin 1987; Benech-Arnold et al. 2000; Gallagher and Cardina 1998; Leon and Owen 2003).

**Temperature and Moisture**

Small differences on soil microclimate conditions may have large effects on weed seed germination and emergence. *Amaranthus* species have shown to be sensitive to environmental variations in the soil microclimate (Buhler et al. 1996; Teasdale and Mohler 1993; Oryokot et al. 1997). The role of temperature on seed germination has been studied in hundreds of species. The temperature factor can be studied as an energy source and as an environmental signal. When taken as an energy source temperature affects seed germination rates, whereas a temperature signal can determine when dormancy ceases and germination initiates (Benech-Arnold et al. 2000). Common waterhemp and Palmer amaranth may have different optimal temperature ranges for growth and development. Wright et al. (1999) reported that Palmer amaranth responds negatively to low temperatures and positively to high temperatures. In presence of natural light or red light, the optimum temperature range for Palmer amaranth germination is between 25 and 35 C in normal summer conditions; however in the fall, germination of few Palmer amaranth seeds may occur when the temperature is higher than 3 C (Jha and Norsworthy 2009).

Light, fluctuating soil temperature, and moisture are thought to be the most important factors that determine the germination and dormancy rate in seed buried under field conditions (Batlla and Benech-Arnold 2010). Temperature is considered to be one of the greatest factors interacting with the hydration level of the soil. Soil temperature ranging from 22 to 34 C, and high soil moisture conditions are known to favor germination of common waterhemp and Palmer amaranth (Wright et al. 1999). The importance of moisture is often related to seed embryo hydration and germination stimulation. Research has reported that under restricted moisture conditions the onset and completion of seed germination may be delayed (Schonbeck and Egley 1998).

**Tillage Effects on Soil Seed bank**

The number of weed seed species present in the soil seed bank is vast. Understanding seedling emergence from the soil seed bank is critical to improve weed management strategies (Buhler et al. 1996; Forcella et al. 1992, 2000; Myers et al. 2004). Mechanical disruption of the soil profile can affect weed seedling emergence patterns by modifying seed burial depth, dormancy, and viability. Benech-Arnold et al. (2000) reported that soil mechanical disruption modifies environmental factors, such as temperature, oxygen, and moisture that are essential to germination.

Soil temperature and soil moisture conditions in the seedbed zone, i.e. the top 5 cm in the soil profile, can promote or delay seed germination and seedling emergence (Kaspar et al. 1990; Schneider and Gupta 1985). Research has shown that soil temperature is lower and soil moisture is higher in reduced tillage systems compared to conventional tillage (Addae et al. 1991; Leon and Owen 2006). Fortin (1991) reported that conventional tillage systems had lower water content compared to no-tillage from planting to emergence of corn. In no-tillage systems seeds are more concentrated in the upper 5 cm of the soil profile which is favorable to small-seeded weed species, such as *Amaranthus* (Buhler et al. 1996; Oryokot et al. 1997). Tillage is also considered to be the main cause of seed burial in arable soils. In no-till systems seed burial may result from sowing implements; wheel and animal traffic; soil shrinking, swelling, and sloughing; and natural burial via structural characteristics of the seeds, e.g. seed shape and weight (Forcella et al. 2000).

Depending on weed seed species and environmental conditions, seed burial can be positive or negative for seedling emergence. Mahboudi and Lal (1998) indicated that tillage improves seedbed conditions and soil structure, resulting in improved drainage and higher soil temperature in the spring. However, the most obvious negative consequence is that seeds are buried so deep that germination is prevented. Small-seeded weed species are more likely to use the red:far red (R:FR) ratio as a germination cue than large-seeded broadleaves (Tiansawat and Dalling 2013). Seed burial as well as crop canopy can have a suppressive effect on weed seedling emergence because they reduce the soil thermal amplitude and alter the quality of the light on the soil surface (Batlla and Benech-Arnold 2000; Fortin and Pierce 1991; Norsworthy 2004).

Research has shown that red light is able to penetrate only a few millimeters through the soil profile, while longer wavelengths penetrate further, which is largely responsible for decreased seed germination (Wooley and Stoller 1978; Benvenuti 1995). Reduced R:FR ratio caused by increased FR has also been shown to be capable of inhibiting seed germination of several *Amaranthus* species such as common waterhemp, redroot pigweed, and smooth pigweed (Fenner 1980; Gallagher and Cardina 1998; Leon and Owen 2003). Perhaps germination occurs with deep burial, but seed reserves may be exhausted before the seedling reaches the soil surface. Weed species have evolved mechanisms that help seedlings break through the soil surface layer. Some seedlings of *Amaranthus* species reflex their cotyledons and their bases form a pointed apex at the top of the hypocotyl, as it extends towards the soil surface (Forcella et al. 2000). This process seems to allow seedlings of this species to elongate even through compacted soils.

Seed burial can also work as a positive event for some weed species. The overlay of soil creates a mulch that maintains high humidity at or near 100%, which allows seed germination relatively rapidly. Moreover, it also provides seed and seedlings protection from abnormal air temperatures as well as granivores and herbivores that feed on or near the soil surface (Tolk et al. 1999; Forcella et al. 2000). Refsell and Hartzler (2009) observed that common waterhemp emergence was three times greater in no-till compared to chisel-till areas in Iowa, although, tillage did not affect the initial time of emergence. Germination of common waterhemp was four times greater in no-till plots compared to chisel and moldboard plow; however, seedling emergence occurred over a longer period in no-till plots (Leon and Owen 2006). Furthermore, the response of Palmer amaranth from a natural seed bank to tillage and soybean canopy showed that tillage had minimum interference in cumulative emergence of Palmer amaranth (Jha and Norsworthy 2009).

**Summary**

As herbicide-resistant biotypes of common waterhemp and Palmer amaranth increase in prevalence, knowledge of germination and emergence patterns of these species is essential in determining effective management tactics. In addition, understanding the effect of soil disturbance on weed seed germination and persistence patterns is critical in determining the influence of tillage systems on common waterhemp and Palmer amaranth management. Considering the large number of environmental factors and weed characteristics inherent to common waterhemp and Palmer amaranth that may influence seed germination and emergence, further information in regard to common waterhemp and Palmer amaranth emergence patterns in different geographies is required to increase the efficacy of management strategies. Furthermore, the interaction of tillage operations with emergence patterns can improve our knowledge base to provide better recommendations to growers on the best management practices to combat these weed species.

**Objectives**

The objectives of my proposed research were to:

1. Characterize the emergence patterns of common waterhemp and Palmer amaranth in southern Illinois.
2. Determine the effect of tillage and the timing of the tillage operation on emergence of common waterhemp and Palmer amaranth throughout the season in southern Illinois.
3. Analyze the interaction between soil temperature and soil moisture with the emergence of common waterhemp and Palmer amaranth in southern Illinois.

# CHAPTER 2

## EMERGENCE PATERNS OF COMMON WATERHEMP

Weed management encompasses an overall strategy with practices designed for depleting the soil seed bank, limiting weed emergence, reducing weed seed production, and preventing interference with crops (Aldrich 1984). The competition between weeds and crops occurs when resources such as water, light, nutrients, and gases are limited in supply. The level of competition is also determined by the variety of cultural practices applied in association with biological and physiological characteristics of the weeds (Morgan et al. 2001).

Among all the factors that influence the success of an annual plant, emergence is probably the single most important phenological event. Forcella et al. (2000) defined complete seedling emergence as the point in time when a seedling is weaned from dependence upon nonrenewable seed reserves originally produced by its parent, and when photosynthetic autotrophism begins above soil surface level. Efforts to develop integrated weed management systems for various crops have emphasized that the outcome of crop-weed competition is highly dependent on time of weed seedling emergence relative to that of the crop. The timing of emergence determines whether a plant competes successfully with its neighbors, is consumed by herbivores, infected with diseases, and whether it flowers, reproduces and complete its life cycle by the end of the growing season. Weed emergence timing is one of the most critical factors in weed management. Knowledge of weed emergence timing may assist decisions regard planting date, fertilizer inputs, cultivation, and post-herbicide applications (Dyer 1995; Forcella et al. 2000; Webster et al. 1999).

The timing of weed seedling emergence in the field varies according to environmental conditions, especially soil temperature, soil moisture, and dormancy levels of a weed population (Forcella and Stephen 1993; Cowan et al. 1988; Wiese and Davis 1967). Normally, common waterhemp populations initiate emergence a month later, and emergence occurs over a longer time period compared to many other summer annual weed species from the North Central United States (Hartzler et al. 1999). The discontinuous and prolonged emergence of common waterhemp is advantageous to survival under weed management systems. Seedlings that emerge late during the growing season are more difficult to control because there are fewer tactics that can be implemented at that time. Delayed emergence has been previously associated with difficult-to-control weed species such as common waterhemp, giant ragweed (*Ambrosia trifida* L.) and Italian ryegrass (*Lolium multiflorum* Lam.) (Leon et al. 2006; Hager et al. 1997). Effective residual herbicides early in the growing season and the development of a robust crop canopy alleviate crop-weed competition later in the season. For example, common waterhemp emergence that was delayed from 14 to 28 days after soybean emergence showed a reduction in shoot biomass of 50 to 80%, respectively (Hartzler and Nordby 2004). Stoller et al. (1987) concluded that yield losses decreased considerably as common waterhemp emergence was delayed at least three weeks after soybean emergence.

Along with traditional use in weed control, tillage is also known for being capable of altering environmental factors that are crucial for germination, such as temperature, moisture, and oxygen (Benech-Arnold et al. 2000). Tillage can also affect weed seedling emergence patterns by modifying seed burial depth, dormancy, and mortality (Gallagher and Cardina 1998). Reduced tillage systems reduce soil temperature, increase soil moisture, and concentrate weed seeds near to the soil surface (Clements et al. 1996; Yenish et al. 1992). Leon and Owen (2006) showed that soil temperature was generally at least 2 to 4 C lower in no-tillage system and temperature fluctuations during the growing season was also lower. Temperature is prominent among the cardinal ecological factors that determine weed species growth and productivity (Guo and Al-Khatib 2003). The ability to start germination under a wide temperature range is one of the characteristics that enable common waterhemp and Palmer amaranth to successfully compete with crops (Wright et al. 1999; Guo and Al-Khatib 2003). Common waterhemp had the greatest germination percentage when submitted to alternating temperature conditions compared to giant foxtail (*Setaria faberi* Herrm.) and velvetleaf (*Abutilon theophrasti* Medik.) (Leon and Owen 2004). Determining the favorable temperature range for seed germination is important in the development of weed management tactics that aim to prevent weed-crop competition. Common waterhemp seeds had lower germination rates when seeds were submitted to temperatures above 35 C, and the highest germination rates under cooler temperatures compared to Palmer amaranth and redroot pigweed (Guo and Al-Khatib 2003).

In arable areas, the seeds located on the soil surface may be buried in the soil profile to a depth of 15 to 20 cm (Cardina et al. 2009). As a small-seeded broadleaf, common waterhemp seeds preferably emerge from burial depths of 0.5 to 3 cm; therefore, most tillage operations are thought to bury the seeds deeper into the soil profile making the emergence of common waterhemp seedlings more difficult. Previous research has reported that common waterhemp emergence timing was 2 to 4 times longer and seedling emergence at least 4 times greater in no-tillage conditions when compared to chisel and moldboard plow (Leon and Owen 2006). Similarly, Hartzler et al. (1999) reported that common waterhemp emergence occurred over an extended period in no-tillage compared to tillage conditions. This prolonged emergence pattern creates management problems for farmers because significant emergence events may occur after preemergence herbicides have dissipated or non-residual postemergence herbicides have already been applied.

Characterization of the seed bank dynamics over multiple years is necessary to achieve a greater understanding of weed emergence patterns and the associated environmental drivers. As a summer annual weed, common waterhemp can have multiple emergence flushes in different growing seasons. Buhler and Hartzler (2001) studied the persistence of common waterhemp, velvetleaf, woolly cupgrass (*Eriochloa villosa* T.) and giant foxtail (*Setaria faberi* H.) seeds over a four-year period; they observed that after seed burial, the total emergence of common waterhemp never exceeded 7% within the same year, and a cumulative emergence of 15% from the soil seed bank was observed after the four-year period, with greater emergence in the two first years.

The increase in the number of weed species with resistance to multiple herbicide sites of action resistance (Heap 2015) has complicated weed management and reduced the number of effective alternative herbicides applied on postemergence. This situation requires attention in making herbicide use and cultural practices more percipient, aiming to reduce the selection of herbicide-resistant biotypes and make weed management practices more efficient. Information regarding emergence timing and patterns of common waterhemp, the effect of soil temperature and moisture, as influenced by tillage is essential to improve the effectiveness of weed management strategies. Thus, the objectives of this research are to 1) determine the period of emergence, date for peak emergence, and date for 90% cumulative emergence for common waterhemp in southern Illinois, 2) determine the effect of tillage and the timing of the tillage operation on emergence of common waterhemp compared to no-till, and 3) analyze the relationship of soil temperature and soil moisture with the emergence of common waterhemp.

## MATERIALS AND METHODS

Experiments were conducted throughout the growing seasons of 2013 and 2014 on two separate portions of a single field site at the Belleville Research Center near Belleville, IL. Historically, the field site has been infested with common waterhemp and was managed uniformly. No crop was planted over the two years and corn was the previous crop in 2012. Prior to experiment initiation tillage practices at the sites included tandem disc, field cultivator, and cultimulcher. The soil class found at the site is Bethalto silt loam with sand at 10%, silt at 72%, and clay at 17.5%; soil pH, OM and CEC was 6.3, 2.3%, and 12, respectively. Soil P was 86, and soil K was 320. Prior to study initiation a blanket application of non-residual herbicides, paraquat[1] (1150 g ai $ha^{-1}$) and glyphosate[2] (1240 g ai $ha^{-1}$) was applied to control weeds present in the area. The experiment included three tillage treatments: 1) undisturbed no-till; 2) early tillage, preferably around a typical soybean planting date of May 1$^{st}$; 3) late tillage, preferably performed on June 1$^{st}$ to simulate a late soybean planting. Experiment plots were always counted for emergence immediately prior to tillage operations. Tillage treatments were implemented using a Troy-Bilt Pro-Line CRT Rototiller – Rear Tine Tiller[3], at a depth of 5 to 7 cm. Infestations of grass species were controlled as necessary with blanket applications of clethodim[4] (280 g ai $ha^{-1}$) plus crop oil concentrate[5] at 1% v/v. Broadleaf species that emerged were hand weeded throughout the study duration. All weed species were considered glyphosate-susceptible.

**Data Collection.** Common waterhemp seedlings were identified and enumerated on a 7-day interval starting prior to the first emergence event for each location (most likely March or April) and concluded after the final emergence event (beginning of November or first frost). After each

[1] Gramoxone SL, Syngenta Crop Protection, Inc., P.O. Box 18300, Greensboro, NC 27419-8300.
[2] Roundup WeatherMAX, Monsanto, Inc., P.O. Box 30170, St. Louis, MO 63167.
[3] Troy-Bilt Pro-Line CRT Rototiller, Pro-Bilt LLC, P.O. Box 361131, Cleveland, OH 44136-0019.
[4] Select 2EC, Valent U.S.A., P.O. Box 8025, Walnut Creek, CA 94596.
[5] Prime Oil, Winfield Solutions, LCC, P.O. Box 64589, St. Paul, MN 55164-0589.

data collection, weed seedlings were removed to provide an open vegetative canopy and allow future emergence of new weeds. To avoid overuse of the same soil seed bank and previous tillage effect, the 2014 experiment was re-located to a different area immediately adjacent to the trial area in 2013.

Data Loggers WatchDog 1000 Series[6] equipped with soil probes were used to collect soil temperature and soil moisture hourly at a 2.5 cm depth, from March 15th through November 30th or first frost. Each data logger had four channels, named A, B, C and D. Channels A and C were used for soil temperature, B and D for soil moisture. Six data loggers with four channels each, 24 channels total (12 used by temperature probes and 12 by moisture probes) were established in the area. To protect probe cables from unforeseen problems such as, probes coming out of the soil, animal stepping and rodents feeding on the rubber lines, cables were passed through PVC pipes before being buried in the soil. Once a week data loggers were read using a WatchDog Data Shuttle[7]. Soil temperature and soil moisture data were downloaded in the computer and transferred to Microsoft Excel [8]sheets where were kept organized by date, probe and treatment.

Precipitation and air temperature data was also collected throughout the season. BRC is a site of the Illinois State Water Survey, and also has its own weather station for hourly precipitation and air temperature data collection.

**Experimental Design and Analysis.** Overall field experiment dimensions were 10 m wide by 30 m long with individual plots being 2 m x 2 m arranged in a randomized complete block design consisting in eight replications. A 1 $m^2$ center quadrat was used for emergence data collection in each plot. Due to different weather conditions in the spring of 2013 and 2014, common waterhemp emergence influenced by tillage were analyzed both, separately and combined.

[6] Spectrum Technologies, Inc., P.O. Box 3600, Aurora, IL 60504.
[7] Spectrum Technologies, Inc., P.O. Box 3600, Aurora, IL 60504.
[8] Microsoft Corporation, Inc., P.O. Box 2362, Redmond, WA 98052.

Considering the high emergence contrast across replications and searching for a more homogeneous distribution, original data was log-transformed for tabulation and graphing. Tillage effects on common waterhemp emergence were analyzed using the PROC GLM procedure in SAS[9]. Means were separated using Fisher's protected LSD (α=0.05). The correlation between common waterhemp emergence peaks to soil temperature and soil moisture were analyzed using Stepwise Regression procedure in SAS. Because of differences on weather patterns between years, and the timing of emergence peaks years were analyzed separately.

**Soil Sampling.** Soil samples were collected in the spring of 2013 and 2014 at trial initiation in the area adjacent to each 1 $m^2$ center quadrat to elucidate soil seed bank density. A common soil core with approximately 2.2 cm diameter at the cutting edge was used to collect six soil cores per plot at a depth of 7.6 cm. Soil samples were brought to SIU and placed into a freezer located at the Tree Improvement Center (TIC). Freezer temperature was set at -20 C to avoid any possible germination while the soil samples were still in bags. The greenhouse growouts for the soil samples for each year were completed the following winter/spring (Wilson et al. 2011). Soil cores were placed in a plastic tray with vermiculite on the bottom and a square sheet plant fabric barrier on top. Trays containing soil cores were placed on benches equipped with irrigation system and covered with a sheet of fabric barrier. Automatic irrigation system was set to provide 20 min of irrigation once a day. The greenhouse temperature was 32 C, ranging 5 C more or less throughout the day.

Three growouts periods were conducted for each soil core. Each period was 28 days long separated by one dry week (between the first and second growout) and 28 days with trays in the freezer (between the second and third growout). During each growout common waterhemp seedlings were identified and enumerated. The number of common waterhemp seedlings in the

[9] SAS software, Version 9.3, July 2011, SAS Institute Inc., Cary, NC 27513.

greenhouse growout were considered the viable fraction of the soil seedbank. Thus, these values were used to calculate the total size of the seedbank for waterhemp at the initiation of the field experiment. Growouts from soil samples collected in 2013 and 2014 were used to estimate the density of common waterhemp in the soil seed bank. Based on the amount of common waterhemp seedlings obtained from the 6 soil cores collected per plot, an estimated value $m^{-2}$ was calculated (Table 2.1). No statistical differences were observed when soil seed bank density was separated by treatment in 2013 and 2014 ($P = 0.814$; $P = 0.439$). These results show that common waterhemp seed bank density was uniform across the experimental areas in both years. To calculate common waterhemp seed bank depletion, field data was used to calculate the percent of total cumulative common waterhemp emergence from the soil seed bank. To meet normality assumptions cumulative emergence at each field plot was log-transformed prior to seed bank estimation (Gomez and Gomez 1984).

## RESULTS AND DISCUSSION

Rainfall patterns and early season air temperature were considerably different between 2013 and 2014 (Figure 2.1; Figure 2.2). The precipitation observed in the spring of 2013 was largely greater compared to the same period in 2014. Differences in daily means of air temperature were also perceived, mostly, in the first two weeks of May. These conditions contributed, at least in part, to differences in treatment means of cumulative emergence between years. For this reason, even with a non-significant treatment by year interaction ($P = 0.143$), data are presented for each year independently (Table 2.1).

First emergence of common waterhemp occurred on the first week of May and last week of April in 2013 and 2014, respectively (Figure 2.3). In 2013, common waterhemp emerged from

May 7th through October 8th. Seedling emergence occurred over a period of 22 wk in no-tillage, 21 wk in early tillage, and 19 wk in late tillage. The major emergence peaks in 2013 occurred in May through mid-July. In the same year, regardless of treatment, 90% common waterhemp cumulative emergence was reached in late June (Figure 2.3).

In 2014, common waterhemp emergence started on April 23rd through October 30th. Seedling emergence was observed over 28 wk in no-tillage and 29 wk in both tillage treatments. The major emergence peaks occurred from late April to mid-July and mid-August through late September. The 90% cumulative emergence point for common waterhemp was reached in no-tillage and late tillage by the end of June, while early tillage was 85% at the same time period and reached 90% by mid-August (Figure 2.3). Cumulative emergence of common waterhemp in early tillage remained lower and statistically different from no-tillage and late tillage until mid-September ($P < 0.001$) (Table 2.2). Hartzler et al. (1999) reported discontinuous emergence of common waterhemp over an extended period throughout the growing season, but the majority had emerged through late June. In 2013, total cumulative seedling emergence was greater in early tillage plots compared to no-tillage and late tillage; whereas in 2014, total cumulative emergence was greater and statistically different in no-tillage and late tillage compared to early tillage ($P = 0.005$) (Table 2.1). Previous research has reported that in tillage systems with seeds buried deeply in the soil profile, germination is prevented or seedlings do not have enough energy to emerge (Mohler and Galford 1997). In addition, in no-till systems weed seeds are concentrated closer to the soil surface, where environmental conditions are more favorable for the emergence of small-seeded broadleaves such as common waterhemp (Felix and Owen 1999).

**Tillage Effects.** Unfavorable weather conditions (excess rainfall) forced the tillage treatments to be delayed; thus, the early tillage treatment was performed on May 20th and May

7th and late tillage on June 7th and June 6th in 2013 and 2014, respectively. In both years, initial common waterhemp emergence occurred prior tillage treatment dates, which implies common waterhemp emergence started under similar environmental conditions. Despite the lower cumulative emergence of common waterhemp observed in early tillage in 2014, tillage effects on common waterhemp emergence were mostly temporary, and mainly observed through two weeks following the early tillage and late tillage operations (Table 2.2). To better analyze the effect of tillage, weekly observations of common waterhemp emergence from the total cumulative emergence were analyzed for 2013 and 2014. In 2013, in the week following early tillage emergence of common waterhemp in early tillage plots was lower, and statistically different from late tillage (P = 0.020). Common waterhemp emergence in early tillage continued the lowest (P = 0.419) for one more week, until late tillage was performed. Similar results were observed after late tillage, with lower emergence in late tillage compared to no-tillage and early tillage (P = 0.076). Nevertheless, the period following the third week after late tillage was characterized by greater emergence in late tillage compared to early tillage and no-tillage (P = 0.006). The same scenario persisted until the end of July with means of common waterhemp cumulative emergence in late tillage higher than early tillage and no-tillage, respectively. Precipitation associated with air temperatures ranging from 20 to 25 C, especially in June and July, must have provided favorable conditions required to increase common waterhemp emergence in disturbed soils. Guo and Al-Khatib (2003) reported that the highest occurrences of common waterhemp emergence peaks was at air temperatures ranging from 20 to 25 C.

In 2014, the weeks following early tillage operation were observed with no differences on common waterhemp emergence across treatments (P = 0.194; P = 0.099; P = 0.114; Table 2.2). The month of May 2014 only had 25% of precipitation of May 2013 and three weeks with means of air temperature around 10 C, which may have affected post-tillage emergence on early tillage plots. Differences were observed during the three weeks following late tillage, common waterhemp in late tillage plots was the highest, followed by no-tillage and early tillage, respectively (P = 0.062; P < 0.001; P < 0.001; Table 2.2). Common waterhemp emergence in late tillage plots continued the highest until late August, when no-tillage plots started having the greatest number of seedling emergence. The large number of common waterhemp seeds present in the upper portion of the soil profile is responsible for the increased emergence observed in no-till systems (Hartzler and Refsell 2009). On Figure 2.3, even with all treatments reaching 100% cumulative emergence, it does not necessarily mean that the same number of seedlings was enumerated in each treatment.

**Soil Temperature.** Figure 2.4 displays daily means of soil temperature recorded by soil probes and common waterhemp emergence throughout the seasons of 2013 and 2014. As expected, soil temperature data were less variable compared to air temperature, which can be explained by the lower temperature amplitude observed in the soil microclimate. Soil temperature was not influenced by any treatment, the same soil temperature pattern was observed across treatments along both years.

In 2013, common waterhemp emergence in no-tillage mostly occurred when soil temperature ranged from 20 to 25 C. Soil temperature above 25 C, especially in July and August, was observed along with decreased common waterhemp emergence. Previous research has shown that seed germination of *Amaranthus* species is inhibited by high temperatures (Keeley et al. 1987; Yaacov 1994; Wright et al. 1999). A decrease in the emergence of common waterhemp in early tillage on May 28$^{th}$ and late tillage on June 11$^{th}$ represents the post-tillage effect relative to each tillage treatment; these observations were only observed on the plots that had been tilled and suggest that decreased common waterhemp emergence is more likely to be influenced by a factor that is not variations in soil temperature, e.g. seed burial. Because of that, the dramatic reduction in common waterhemp emergence observed in late tillage in mid-June may be a result of a series of factors, such as seed burial, warmer soil temperatures (daily average of 25 C), and lack of rainfall events during this period. Contrary to soil temperature, soil moisture showed different values between tillage treatments.

In 2014, similarly to previous year soil temperature did not differ across treatments. In mid-May an unexpected decrease of soil temperature, caused by adverse cold weather, was followed by reduced common waterhemp emergence in no-tillage. In early season, especially May and June, variations on common waterhemp emergence were similar to those of soil temperature. Similarly to 2013, values of soil temperatures above 25 C, especially in late July and early August, were observed along with decreased common waterhemp emergence. After early tillage, more specifically on May 13$^{th}$, a reduction in the emergence of common waterhemp was observed (Figure 2.4). In contrast to early tillage, common waterhemp emergence did not decrease after late tillage. On the other hand, an increase in the emergence of common waterhemp was observed in late tillage. Higher germination of lambsquarters (*Chenopodium album* L.) has been reported in tillage systems compared to no-till (Clements et al. 1996). Soil temperature above 25 C observed in late June and July must have contributed to soil warming to a level that compromised common waterhemp emergence; seedling emergence was diminished across all treatments to less than 5 plants m$^{-2}$ on August 6$^{th}$. Soil moisture in no-tillage plots was higher compared to tillage treatments throughout the season; although, discrepant soil moisture differences across treatments were observed even during the first weeks when any tillage treatment had been applied (Figure 2.5).

**Soil Moisture.** In 2013, soil moisture in no-tillage was greater throughout the season compared to tillage treatments. Values of soil moisture were considerably similar in all treatments prior tillage application. Curiously, a decrease in soil moisture in all treatments in mid-June was not followed by a decrease of common waterhemp emergence in no-tillage; in contrast, an increase of soil moisture in no-tillage was followed by decreased common waterhemp emergence. As observed on Figure 2.5, soil moisture in early tillage plots was dramatically reduced after tillage, especially in the two following weeks, but only until the next rainfall event. A similar trend was observed following the late tillage treatment. In this case, soil moisture in no-tillage and early tillage was greater compared to late tillage. Reduction in soil moisture is often attributed to soil disturbance caused by tillage practices. Recent research has reported that tillage practices greatly affect soil hydrologic properties (Salem et al. 2015).

In 2014, common waterhemp emergence and soil moisture in no-tillage showed a similar pattern, mostly, when reductions in soil moisture were observed; for example late May, August 6$^{th}$, and late September. In contrast, small reductions in common waterhemp emergence was observed while there was an increase in soil moisture; for example, early May, mid-June, and late August. A dramatic decrease in soil moisture was observed in early tillage plots after tillage was applied; this event was followed by a decrease in common waterhemp emergence in early tillage plots. After a period of two weeks and occurrence of precipitation, a similar emergence pattern was observed between early tillage and no-tillage.

No decrease in soil moisture was perceived on late tillage plots, even on the week following tillage application. In contrast to what was observed after early tillage, an increase in common waterhemp emergence was observed following the late tillage operation. Nevertheless, soil moisture in no-tillage was still higher compared to late tillage. Large differences in the consistency of soil moisture data may be related to the shallow placement of soil probes in the soil, which makes the sensor more sensitive to minimum differences in ground level and exposure to increased air movement though the soil particles. Despite the differences observed on soil temperature and soil moisture, common waterhemp emergence in no-tillage, early tillage, and late tillage showed a similar pattern throughout the season, which indicates that common waterhemp emergence throughout the season is, in most part, a result of environmental factors acting alternately.

**Regression Analysis of Soil Temperature and Soil Moisture with Emergence.** Based on the values of soil temperature and soil moisture observed in 2013 and 2014, stepwise regressions were used to indicate which environmental factor (soil temperature and/or soil moisture) was more successful in predicting the emergence of common waterhemp throughout the season. As weed seedlings were enumerated every 7 days, each emergence event was more likely to be a result of soil temperature and soil moisture recorded previously. For a more precise analysis, regression was designed to find the strongest factor in predicting common waterhemp emergence within 14 days prior to each emergence event.

In 2013, 99% of common waterhemp seedlings emerged in the period between April 23rd and August 13th (Figure 2.3). In early season, especially April and May, the majority of common waterhemp emergence peaks showed a positive interaction with high values of soil temperature from 13 days before each emergence count ($R^2$ = 0.35; P = <0.001; Table 2.3). A positive interaction was also observed between common waterhemp emergence peaks and high soil moisture values 11 days prior to emergence counts ($R^2$ = 0.35; P = 0.013; Table 2.3). A better understanding of these results can be obtained by analyzing the shape similarity between the predicted emergence of common waterhemp and high soil temperature 13 days prior emergence, especially in early season (April and May), and high values of soil moisture 11 days prior emergence in June, July, and August (Figure 2.6). Based on previous observations, soil temperature above 25 C, in July and August, was observed along with decrease in common waterhemp emergence. During this period the shape pattern of soil moisture 11 days prior emergence and the predicted common waterhemp emergence is similar, which characterizes, especially in late season, the positive interaction between soil moisture 11 days prior and common waterhemp emergence. In other words the predicted emergence can be defined as the common waterhemp emergence originated from the highest values of soil temperature and soil moisture observed 13 and 11 days before each enumeration event. Considering the similarities observed across graph lines, and the fact that the majority of common waterhemp emergence occurred over the selected period (April 23rd and August 13th) for regression, is plausible to say that the interaction between soil temperature and common waterhemp emergence was positive and strong.

In 2014, the number of emerged common waterhemp seedlings throughout the season was considerably higher compared to previous year. The area where the experiment from 2014 was established had a greater common waterhemp infestation (Table 2.1), which must have been a result from more active seed dispersal in that site in 2013. In 2014, common waterhemp emergence reached 99% by the middle of September, showing emergence over a longer period compared to 2013. For this reason, the period used for regression was initiated on April 23rd through October 8th. A negative interaction between common waterhemp emergence and high soil temperature values 10 days prior emergence was observed ($R^2$ = 0.55; P < 0.001; Table 2.3). On the other hand, a positive interaction with minimum soil temperature 8 days before each emergence event was also observed ($R^2$ = 0.55; P < 0.001).

Analyzing Figure 2.7 and the line pattern of each factor and the predicted common waterhemp emergence, a positive interaction between common waterhemp emergence and minimum soil temperature can be observed, especially in early season. For example, in May 21st a notable decrease in common waterhemp emergence and minimum soil temperature was noticed, which can be used to explain the positive interaction between these two factors. The interaction between these two factors becomes even clearer once minimum soil temperature 8 days prior emergence corresponds to May 13th, which is the date when adverse cold weather was present in the site. The negative interaction between high values of soil temperature 10 days before each emergence event and common waterhemp emergence can also be demonstrated by observing the previous graph of soil temperature and common waterhemp emergence (Figure 2.4). In August 2014, high soil temperatures (around 40 C) were observed along with a decrease in common waterhemp emergence, which, considering the regression results, may be a general overview of the negative interaction between common waterhemp emergence and high soil temperature 10 days before emergence. In similar research Guo and Al-Khatib (2003) have reported severe reductions in common waterhemp emergence when temperature was gradually increased, especially above 35 C.

**Emergence from Soil Seed Bank.** Soil seed bank density for common waterhemp was estimated in both years. For the 2013 site, Palmer amaranth seed bank density was estimated at 946 seeds $m^{-2}$. In 2014, the amount of common waterhemp seeds in the soil seed bank was greatly higher, with a seed density of 44,541 seeds $m^{-2}$.

In 2013, total common waterhemp cumulative emergence from the soil seed bank was 33, 36, and 31% in no-tillage, early tillage, and late tillage, respectively ($P = 0.915$; Table 2.1). The lack of differences across treatments may be attributed to similarity in seed distribution within the soil profile, and soil temperature and moisture (Buhler and Daniel 1988; Buhler et al. 1996).

In 2014, common waterhemp emergence from the soil seed bank was 24, 12, and 19% in no-tillage, early tillage, and late tillage, respectively (P = 0.005; Table 2.1). In reason of the large soil seed bank density observed in the site of 2014, a potential intraspecific competition for common waterhemp germination might be the cause of a lower cumulative emergence from the soil seed bank. Previous research has reported that annual emergence of common waterhemp from the soil seed bank may vary from 10 to 35% (Wu and Owen 2014). In similar research, Hartzler et al. (1999) have reported a 15% common waterhemp cumulative emergence from soil seed bank under no-tillage condition. The shallow placement of common waterhemp seedlings on the soil surface may have provided favorable conditions for greater germination in no-tillage plots. Cardina et al. (2009) have reported that weed seed density on the top portion of the soil profile was four times greater than at 5 to 10 cm depth.

**Conclusions.** Common waterhemp emergence is discontinuous throughout the crop growing season, with the greatest emergence spikes in May, June, and July. In both years, 90% common waterhemp cumulative emergence was observed between late April and the end of June, which emphasizes the need for effective weed management in the early to mid-growing season, preferably with the use of soil residual herbicides. The emergence pattern of common waterhemp was mostly affected in the following three weeks after tillage. In both years, after early tillage a decrease in common waterhemp emergence was observed, while after late tillage there was an increase in the number of emerged common waterhemp seedlings; although, the total cumulative emergence was higher in early tillage in 2013, and no-tillage in 2014. These results suggest that soil disturbance operated in late season may increase the emergence of common waterhemp, which at this time in the growing season has reduced control options, which encourages common waterhemp seed dispersal and compromises crop production. Total common waterhemp seedling emergence was greater in early tillage and no-tillage in 2013 and 2014, respectively.

The interaction between common waterhemp emergence and high and low soil temperature was strong and associated to the major common waterhemp emergence peaks. Furthermore, common waterhemp seed bank depletion was greater in no-tillage compared to early tillage treatment in 2014, which suggests that the shallow burial of common waterhemp may lead to a less persistent seed bank.  These results suggest that weed management efforts in controlling common waterhemp should focus in early season, mainly in May and June; and the use of tillage, especially in late season, may increase the emergence of common waterhemp for a period where alternate weed control options are more difficult considering crop presence. Furthermore, monitoring environmental factors, most importantly soil temperature, may assist the development of weed management strategies based on the prediction of common waterhemp emergence.

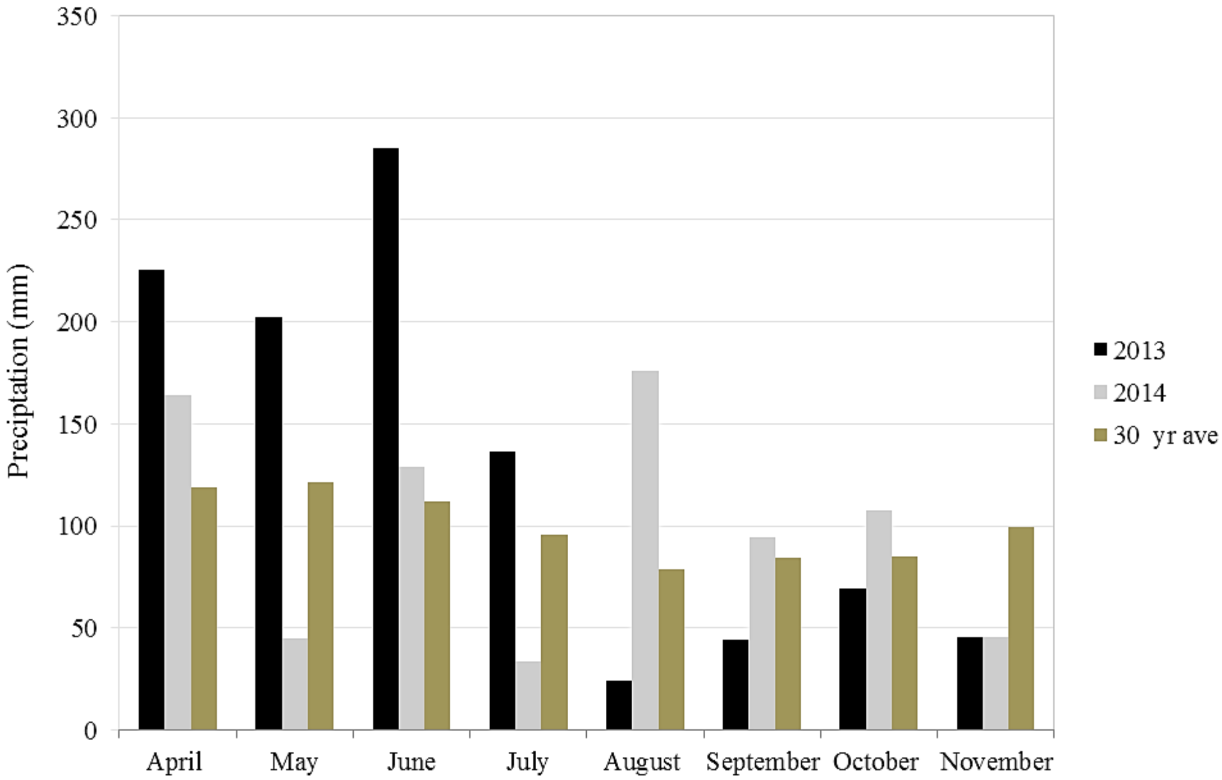


Figure 2.1. Monthly precipitation received during the experimental period and 30-year rainfall average in Belleville, IL.

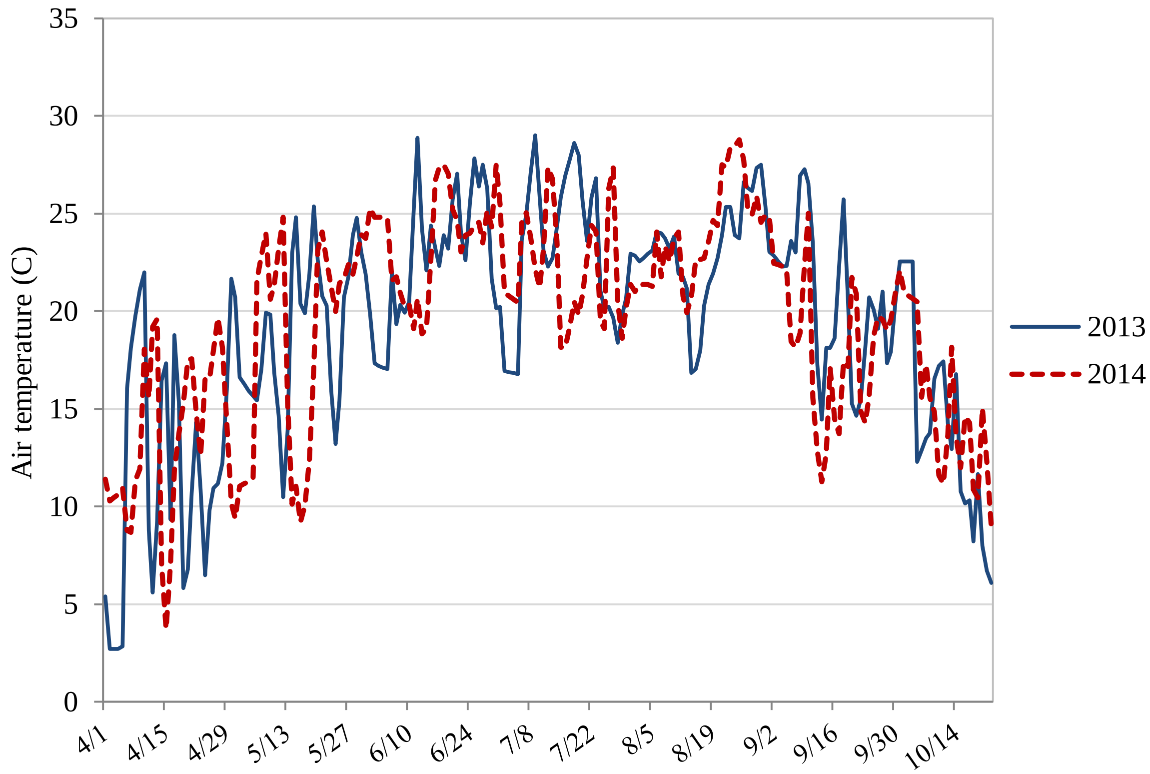


Figure 2.2. Daily means of air temperature throughout the experiment period in 2013 and 2014.

Table 2.1. Total cumulative and soil seed bank emergence of common waterhemp throughout the season for no-tillage, early tillage and late tillage in 2013 and 2014.

| | 2013 | | 2014 | |
|---|---|---|---|---|
| Treatment | Cumulative emergence | Seed bank emergence | Cumulative emergence | Seed bank emergence |
| | no. seedlings $m^{-2}$ | % emerged seedlings $m^{-2}$ | no. seedlings $m^{-2}$ | % emerged seedlings $m^{-2}$ |
| No-tillage | 312[a] a[b] | 33 a | 10,487 a | 24 a |
| Early tillage | 341 a | 36 a | 5,552 b | 12 b |
| Late tillage | 297 a | 31 a | 8,459 a | 19 a |

[a] Numbers presented are the back-transformed of total emergence. Data were log-transformed and back-transformed for clarity.

[b] Numbers within each row and for each year followed by the same letter do not differ significantly according to Fisher's protected LSD ($\alpha = 0.05$).

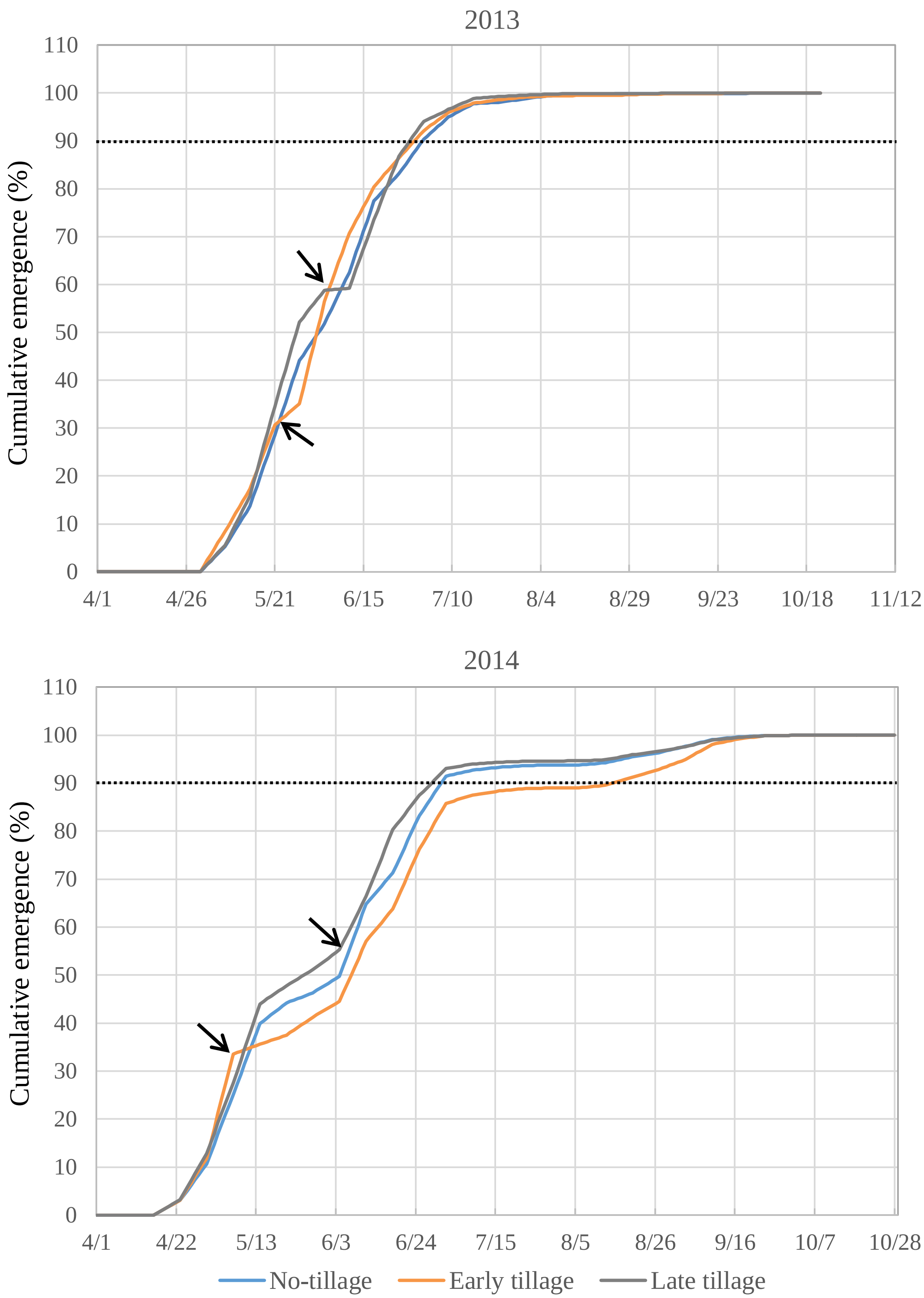


Figure 2.3. Cumulative emergence of common waterhemp for no-tillage, early tillage and late tillage in Belleville, IL in 2013 and 2014. Arrows represent early tillage and late tillage dates.

Table 2.2. Statistical analysis of weekly cumulative emergence of common waterhemp for no-tillage, early tillage, and late tillage in Belleville, IL in 2013 and 2014.

| Year | Date | $R^2$ | F value | $p$ | Tillage | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | No-tillage | | Early tillage[a] | | Late tillage[b] | |
| | | | | | ---% cumulative emergence[c]--- | | | | | |
| 2013 | 5/07 | 0.78 | 6.77 | 0.419 | 5 | a[d] | 8 | a | 6 | a |
| | 5/14 | 0.80 | 0.57 | 0.579 | 14 | a | 17 | a | 16 | a |
| | 5/21 | 0.70 | 0.81 | 0.464 | 29 | a | 31 | a | 35 | a |
| | **5/28** | **0.74** | **5.17** | **0.020** | **44** | **ab** | **35** | **b** | **52** | **a** |
| | 6/4 | 0.59 | 0.92 | 0.419 | 52 | a | 56 | a | 59 | a |
| | **6/11** | **0.64** | **3.11** | **0.076** | **62** | **ab** | **71** | **a** | **59** | **b** |
| | 6/18 | 0.60 | 1.81 | 0.199 | 77 | a | 80 | a | 74 | a |
| | 6/25 | 0.78 | 2.63 | 0.107 | 83 | a | 86 | a | 87 | a |
| | **7/2** | **0.85** | **7.31** | **0.006** | **90** | **b** | **92** | **ab** | **94** | **a** |
| | 7/9 | 0.68 | 1.67 | 0.223 | 95 | a | 96 | a | 97 | a |
| | 7/16 | 0.52 | 2.23 | 0.144 | 98 | a | 98 | a | 99 | a |
| | **7/23** | **0.65** | **4.30** | **0.035** | **98** | **b** | **98** | **ab** | **99** | **a** |
| | 7/30 | 0.40 | 2.15 | 0.153 | 98 | a | 99 | a | 100 | a |
| | 8/6 | 0.45 | 1.66 | 0.225 | 99 | a | 99 | a | 100 | a |
| | 8/13 | 0.46 | 2.37 | 0.130 | 100 | a | 99 | a | 100 | a |
| | 8/20 | 0.46 | 1.97 | 0.176 | 100 | a | 100 | a | 100 | a |
| | 8/27 | 0.46 | 2.07 | 0.163 | 100 | a | 100 | a | 100 | a |
| | 9/3 | 0.40 | 0.76 | 0.486 | 100 | a | 100 | a | 100 | a |
| | 9/10 | 0.63 | 1.47 | 0.263 | 100 | a | 100 | a | 100 | a |
| | 9/17 | 0.68 | 1.35 | 0.290 | 100 | a | 100 | a | 100 | a |
| | 9/24 | 0.68 | 1.05 | 0.376 | 100 | a | 100 | a | 100 | a |
| | 10/01 | 0.40 | 1.09 | 0.363 | 100 | a | 100 | a | 100 | a |
| 2014 | 4/23 | 0.60 | 0.00 | 0.995 | 3 | a | 3 | a | 3 | a |
| | 4/30 | 0.63 | 0.24 | 0.790 | 11 | a | 12 | a | 13 | a |

Table 2.2 (Continued)

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 5/07 | 0.64 | 2.11 | 0.158 | 25 | a | 34 | a | 28 | a |
| 5/14 | 0.69 | 1.85 | 0.194 | 40 | a | 36 | a | 44 | a |
| 5/21 | 0.71 | 2.74 | 0.099 | 44 | ab | 38 | b | 48 | a |
| 5/28 | 0.71 | 2.54 | 0.114 | 46 | ab | 41 | b | 51 | a |
| 6/4 | 0.70 | 3.12 | 0.075 | 50 | ab | 45 | b | 55 | a |
| 6/11 | 0.66 | 3.40 | 0.062 | 65 | ab | 57 | a | 66 | a |
| **6/18** | **0.77** | **12.02** | **<0.001** | **71** | **b** | **64** | **c** | **80** | **a** |
| **6/25** | **0.79** | **14.13** | **<0.001** | **83** | **a** | **76** | **b** | **87** | **a** |
| **7/2** | **0.78** | **15.29** | **<0.001** | **91** | **a** | **86** | **b** | **93** | **a** |
| **7/9** | **0.78** | **14.43** | **<0.001** | **93** | **a** | **88** | **b** | **94** | **a** |
| **7/16** | **0.78** | **14.00** | **<0.001** | **93** | **a** | **88** | **b** | **94** | **a** |
| **7/23** | **0.78** | **13.94** | **<0.001** | **94** | **a** | **89** | **b** | **95** | **a** |
| **7/30** | **0.78** | **13.84** | **<0.001** | **94** | **a** | **89** | **b** | **95** | **a** |
| **8/6** | **0.78** | **13.79** | **<0.001** | **94** | **a** | **89** | **b** | **95** | **a** |
| **8/13** | **0.78** | **14.73** | **<0.001** | **94** | **a** | **90** | **b** | **95** | **a** |
| **8/20** | **0.77** | **14.01** | **<0.001** | **95** | **a** | **91** | **b** | **96** | **a** |
| **8/27** | **0.73** | **11.46** | **0.001** | **97** | **a** | **93** | **b** | **97** | **a** |
| **9/3** | **0.72** | **10.80** | **0.001** | **98** | **a** | **95** | **b** | **98** | **a** |
| **9/10** | **0.72** | **9.63** | **0.002** | **99** | **a** | **98** | **b** | **99** | **a** |
| **9/17** | **0.55** | **4.54** | **0.030** | **100** | **a** | **99** | **b** | **100** | **ab** |
| 9/24 | 0.50 | 0.72 | 0.503 | 100 | a | 100 | a | 100 | a |
| 10/01 | 0.23 | 0.11 | 0.896 | 100 | a | 100 | a | 100 | a |
| 10/08 | 0.24 | 0.43 | 0.659 | 100 | a | 100 | a | 100 | a |
| 10/15 | 0.32 | 0.68 | 0.524 | 100 | a | 100 | a | 100 | a |
| 10/22 | 0.34 | 0.76 | 0.487 | 100 | a | 100 | a | 100 | a |
| 10/29 | - | - | - | 100 | a | 100 | a | 100 | a |

[a] Early tillage performed on May 20th and May 7th in 2013 and 2014, respectively.

[b] Late tillage performed on June 7$^{th}$ and June 6$^{th}$ in 2013 and 2014, respectively.

[c] Degrees of freedom: main effect = 9; error = 14

[d] Means within each column for the same year followed by the same letter do not differ significantly according to Fisher's protected LSD ($\alpha = 0.05$).

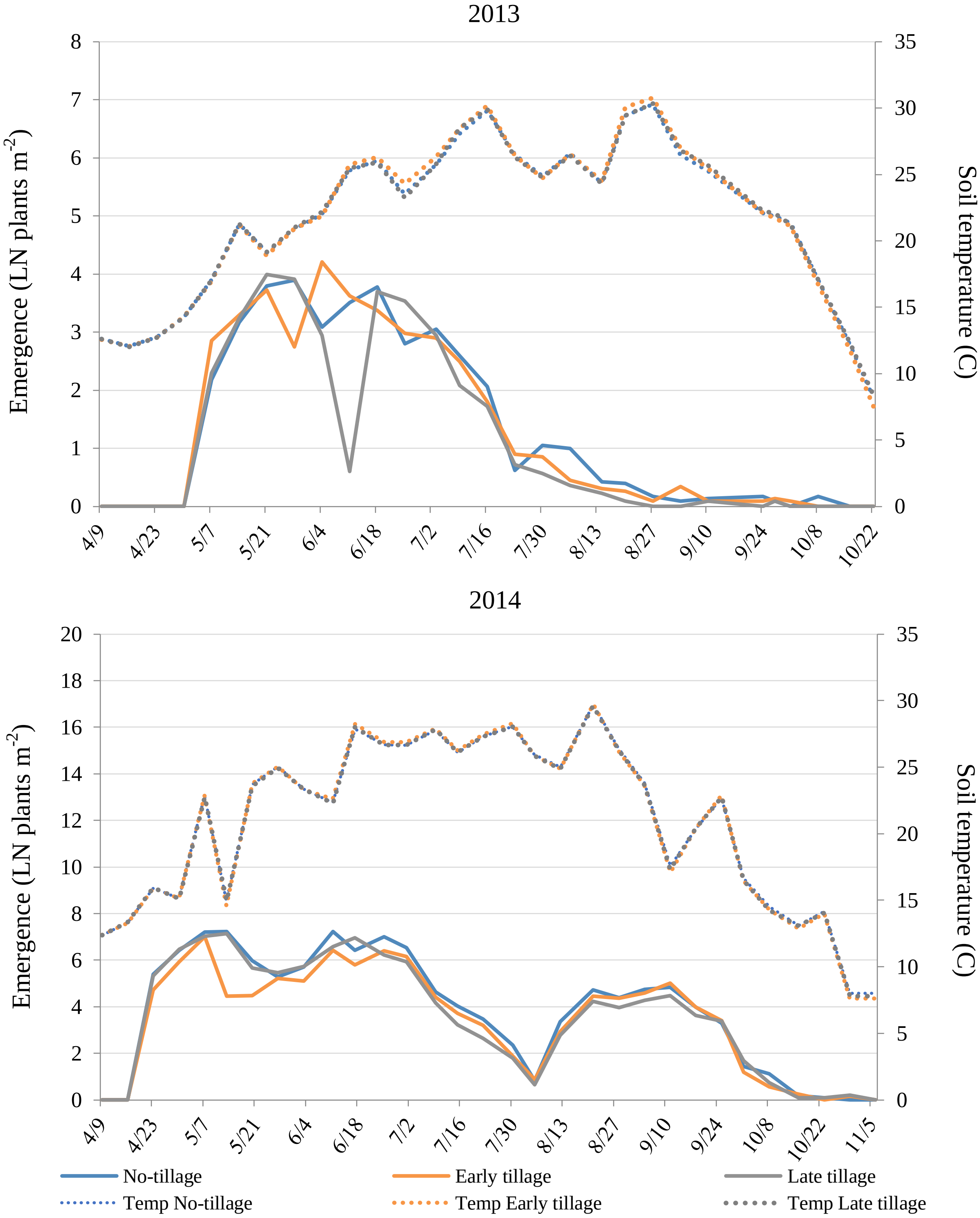


Figure 2.4. Daily means of soil temperature recorded by soil probes and common waterhemp emergence for no-tillage, early tillage, and late tillage in 2013 and 2014.

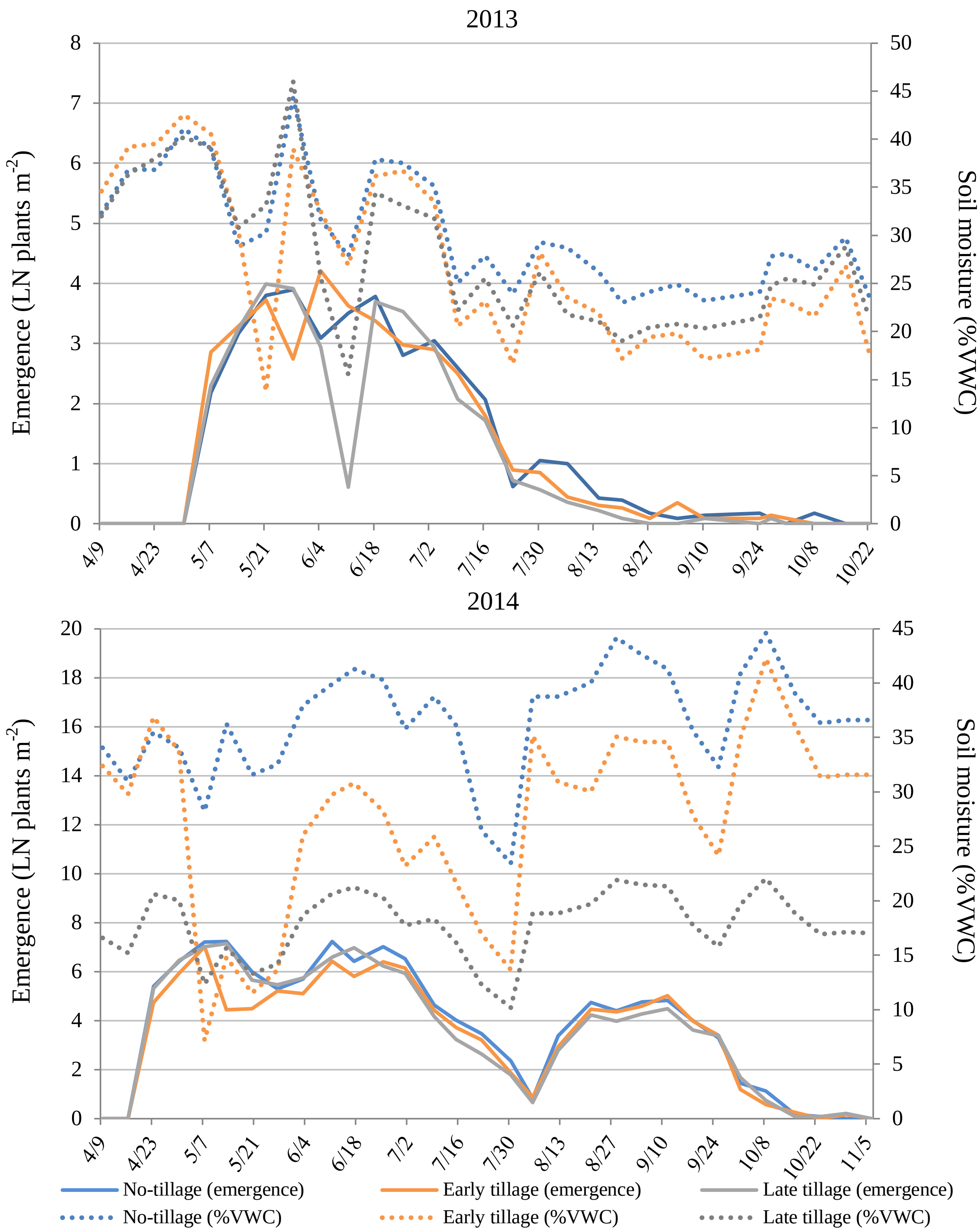


Figure 2.5. Daily means of soil moisture recorded by soil probes and common waterhemp emergence for no-tillage, early tillage, and late tillage in 2013 and 2014.

Table 2.3. Results of stepwise regression testing the interaction of common waterhemp emergence with values of soil temperature and soil moisture in 2013 and 2014. Soil temperature and soil moisture included as factors for germination.

| Year | Variable[a] | $R^2$ | Time prior emergence events | Parameter Estimation | F value | *p*-value |
|---|---|---|---|---|---|---|
| | | | ----------(d)--------- | | | |
| 2013 | High soil temperature | 0.35 | 13[b] | 0.46 | 4.82 | <0.001 |
| | High soil moisture | 0.35 | 11 | 0.07 | 2.57 | 0.013 |
| 2014 | High soil temperature | 0.55 | 10 | -0.20 | -7.55 | <0.001 |
| | Minimum soil temperature | 0.55 | 8 | 0.15 | 6.09 | <0.001 |

[a] Maximum (highest), mean, and minimum (lowest) values of soil temperature and soil moisture up to 14 days prior each emergence event were used as predict variables.

[b] Results show the period (days) after observed environmental factors, that  led to major peaks of common waterhemp emergence.

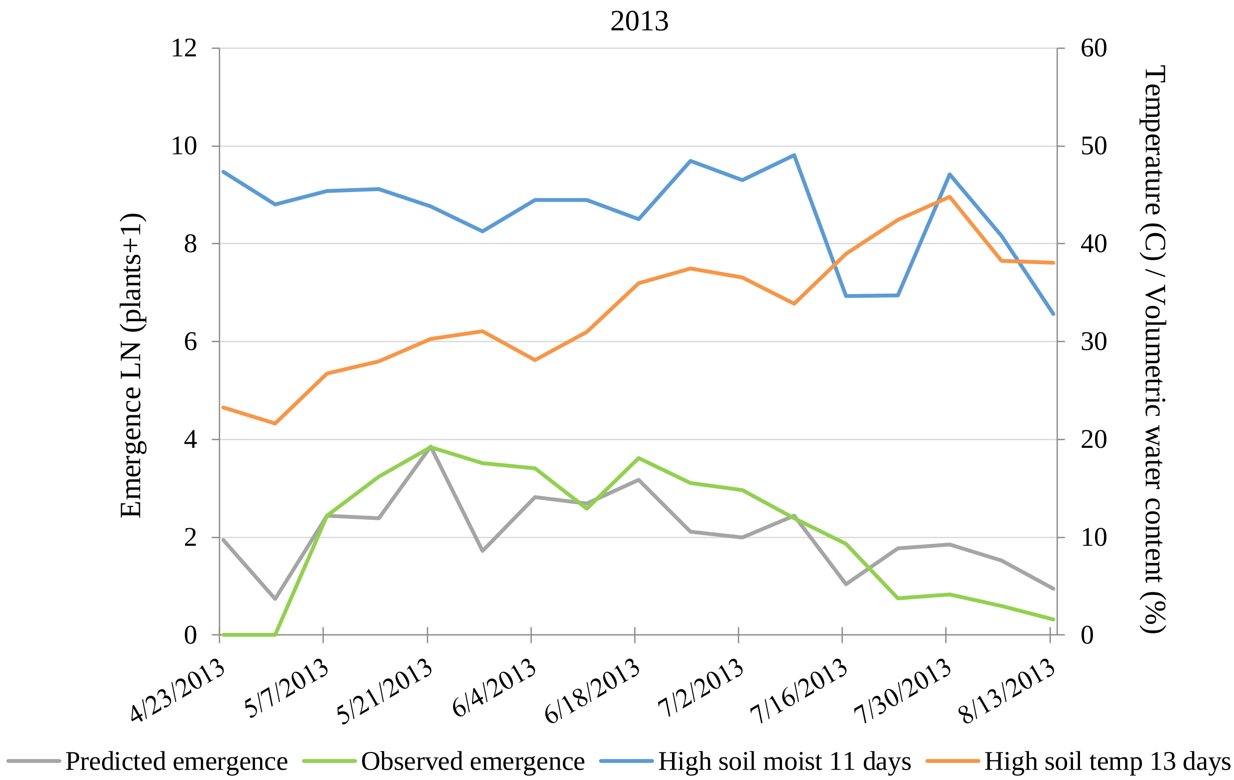


Figure 2.6. Stepwise regression for emergence of common waterhemp predicted by soil temperature and soil moisture in 2013. The blue line represents the highest values of soil moisture observed 11 days before each common waterhemp emergence event, the orange line represents the highest values of soil temperature collected 13 days prior each emergence. The grey line shows the predicted common waterhemp emergence as result of these two variables. The green line shows the mean of common waterhemp emergence throughout the selected period.

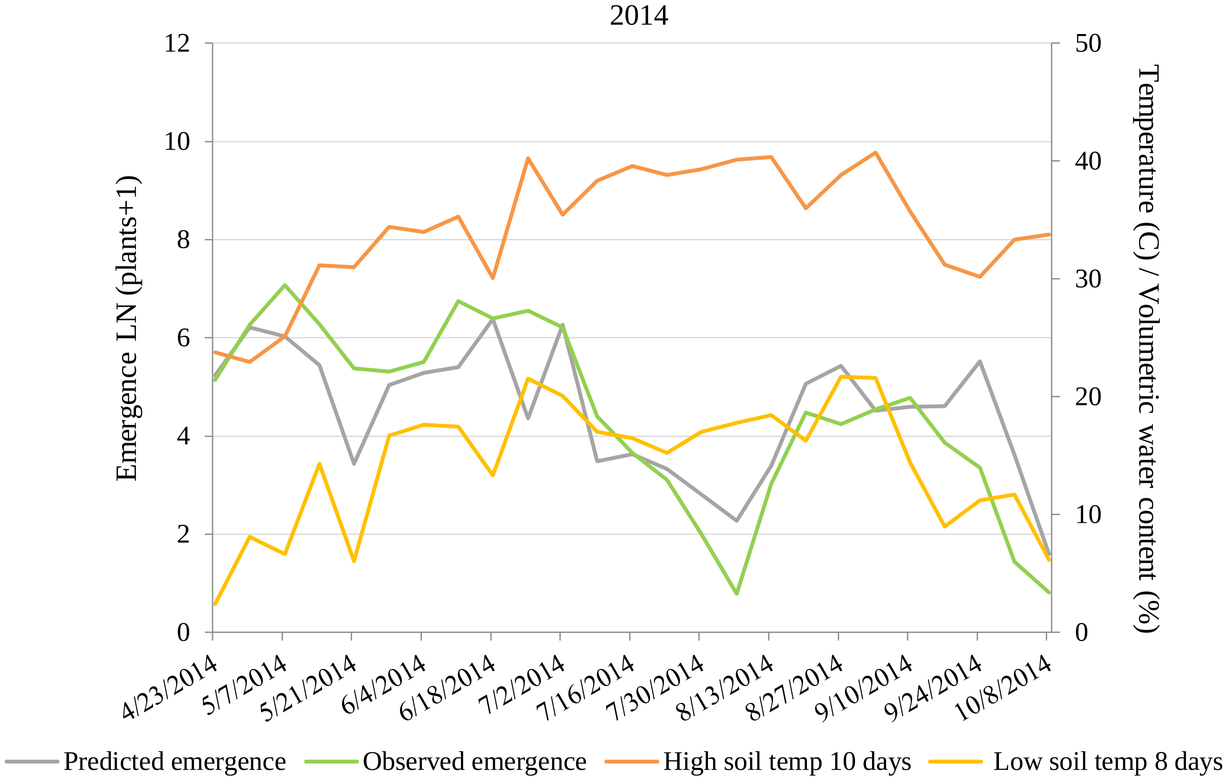


Figure 2.7. Stepwise regression for emergence of common waterhemp predicted by soil temperature and soil moisture in 2014. The orange line represents the highest values of soil temperature observed 10 days before each common waterhemp emergence event, the yellow represents the lowest values of soil temperature collected 8 days prior each emergence. The grey line shows the predicted common waterhemp emergence as result of these two variables. The green line shows the means of common waterhemp emergence throughout the selected period.

# CHAPTER 3

## EMERGENCE PATERNS OF PALMER AMARANTH

Palmer amaranth is listed among the most troublesome weeds in corn, soybeans and cotton and has become one of the most economically damaging glyphosate-resistant (GR) weed species in the United States (Beckie 2009). As any other *Amaranthus* species, Palmer amaranth germination is highly dependent on environmental conditions. Originated in the xeric environment of northern Mexico and southeastern United States, where water is often a limiting factor, Palmer amaranth is naturally opportunistic, and is characterized for rapid germination and complete lifecycle in response to available moisture (Ehleringer 1985). The fast response of Palmer amaranth to favorable germination conditions was characterized when nine *Amaranthus* species were subjected to different temperature amplitudes with a mean of 30 C; all the viable Palmer amaranth and smooth pigweed seeds germinated in the first day, while the other species required three to eight days to reach 50% emergence (Steckel et al. 2004). Despite being capable of germinating under high temperatures, seed production of Palmer amaranth decreased when temperature above 35 C were observed. Moreover, Palmer amaranth seed germination was higher under alternating temperatures compared to constant temperatures (Steckel et al. 2004). Research has reported that low rainfall condition are also responsible for reduced and delayed emergence of pigweed (Hartzler et al. 1999; Oryokot et al. 1997). Forcella et al. (1992) reported that redroot pigweed was sensitive to small changes in rainfall, even those lower than 1 mm, during the growing season.

Weed species that contribute to the formation of persistent soil seed banks shall be taken as a concern for the success of weed management. The percentage of seed that emerges in a given year varies widely among species and environmental conditions (Hartzler et al. 1999). Previous research has shown that Palmer amaranth seeds possess dormancy and are relatively persistent in the seed bank, which explains the extended period of emergence observed for Palmer amaranth throughout the season (Sosnoskie et al. 2013). This characteristic allows Palmer amaranth to become a long-term problem once established. In research conducted in Georgia, Palmer amaranth seed germination was directly related to depth of seed burial (Sosnoskie et al. 2013). Among the effects of seed burial, changes in the light environment is one of the most important in altering seed germination. Research has reported weed seed burial inducing light-sensitivity dormancy in small-seeded *Amaranthus* species (Gallagher and Cardina 1998). Moreover, Jha and Norsworthy (2009) have reported that seed burial and crop canopy were responsible for an increase in the far-red transmitted light, which is known for reducing and delaying the emergence of small-seeded broadleaves (Gallagher and Cardina 1998).

Agronomic practices, such as the absence or presence of crops, crop rotation, and tillage, are crop production practices that influence weed seed dormancy and persistence (Jha et al. 2014). The effect of tillage on weed seed persistence is mainly in the vertical distribution of seeds in the soil profile. Steckel et al. (2007) reported that tillage may bring seeds closer to the soil surface, favoring emergence and seed bank depletion; or buries seeds deeper in the soil profile, favoring seed dormancy and persistence. Previous research has shown that seed burial caused by tillage at depths of 5 cm or more, significantly reduces Palmer amaranth seed germination and increases the required seedling elongation (Ward et al. 2013). Similar results have shown that seed burial, at least 10 cm deep, caused by moldboard plow can provide a 50% reduction in Palmer amaranth emergence (Ward et al. 2013). The presence of glyphosate resistance in a Palmer amaranth population does not affect the longevity of soil seed bank; the same results showed that deep burial of Palmer amaranth seeds can help reduce Palmer amaranth infestation, but only if seeds stay buried below their germination zone longer than 36 months (Sosnoskie et al. 2013).

The emergence of Palmer amaranth coincides with the growing season of most row crops. Seasonal seed dormancy and an extended emergence period allow Palmer amaranth to compete throughout the season contributing to severe yield reductions in soybeans, cotton, and corn. The increase in the number of Palmer amaranth populations with herbicide resistance has reduced the number of herbicides available for Palmer amaranth control in Illinois. Characterizing the emergence patterns of Palmer amaranth under no-tillage and tillage conditions, as well as the interaction between Palmer amaranth emergence and environmental factors, may be useful in implementing a more effective weed management strategy. Thereby, the objectives of this research were to 1) determine the period of emergence, date for peak emergence, and date for 90% cumulative emergence for Palmer amaranth in southern Illinois, 2) determine the effect of tillage and the timing of the tillage operation on emergence of Palmer amaranth compared to no-till, 3) analyze the relationship of soil temperature and soil moisture with the emergence of Palmer amaranth.

## MATERIALS AND METHODS

Experiments were conducted throughout the growing seasons of 2013 and 2014 on two separate portions of a single field site at the Belleville Research Center near Belleville, IL. Historically, the field site has been infested with Palmer amaranth and was managed uniformly. No crop was planted over the two years and soybean was the previous crop in 2012. Prior to experiment initiation tillage practices at the sites included tandem disc, field cultivator, and cultimulcher. The soil class present at the site is a Bethalto silt loam with sand at 10%, silt at 72.5%, and clay at 17.5%; soil pH, OM and CEC was 6.2, 2.0%, and 11, respectively. Soil P was 72, and soil K was 275. Prior to study initiation a blanket application of non-residual herbicides, paraquat[1] (1150 g ai $ha^{-1}$) and glyphosate[2] (1240 g ai $ha^{-1}$) was applied to control weeds present in the area. The experiment included three tillage treatments: 1) undisturbed no-till; 2) early tillage, preferably around a typical soybean planting date of May 1st; 3) late tillage, preferably performed on June 1st to simulate a late soybean planting. Experiment plots were always counted for emergence immediately prior to tillage operations. Tillage treatments were implemented using a Troy-Bilt Pro-Line CRT Rototiller – Rear Tine Tiller[3], at a depth of 5 to 7 cm.

Infestations of grass species were controlled as necessary with blanket applications of clethodim[4] (280 g ai $ha^{-1}$) plus crop oil concentrate[5] at 1% v/v. Broadleaf species that emerged were hand weeded throughout the study duration. All weed species were considered glyphosate-susceptible.

**Data Collection.** Palmer amaranth seedlings were identified and enumerated on a 7-day interval starting prior to the first emergence event for each location (most likely March or April) and concluded after the final emergence event (beginning of November or first frost). After each data

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[1] Gramoxone SL, Syngenta Crop Protection, Inc., P.O. Box 18300, Greensboro, NC 27419-8300.
[2] Roundup WeatherMAX, Monsanto, Inc., P.O. Box 30170, St. Louis, MO 63167.
[3] Troy-Bilt Pro-Line CRT Rototiller, Pro-Bilt LLC, P.O. Box 361131, Cleveland, OH 44136-0019.
[4] Select 2EC, Valent U.S.A., P.O. Box 8025, Walnut Creek, CA 94596.
[5] Prime Oil, Winfield Solutions, LCC, P.O. Box 64589, St. Paul, MN 55164-0589.

collection, weed seedlings were removed to provide an open vegetative canopy and allow future emergence of new weeds. To avoid overuse of the same soil seed bank and previous tillage effect, the 2014 experiment was re-located to a different area immediately adjacent to the trial area in 2013.

Data Loggers WatchDog 1000 Series[6] equipped with soil probes were used to collect soil temperature and soil moisture hourly at a 2.5 cm depth, from March 15th through November 30th or first frost. Each data logger had four channels, named A, B, C and D. Channels A and C were used for soil temperature, and B and D for soil moisture data collection. Six data loggers with four channels each, 24 channels total (12 used by temperature probes and 12 by moisture probes) were established in the area. To protect probe cables from unforeseen problems such, probes coming out of the soil, animal stepping and rodents feeding on the rubber lines, cables were passed through PVC pipes before buried in the soil. Once a week data loggers were read using a WatchDog Data Shuttle[7]. Soil temperature and soil moisture data were downloaded in the computer and transferred to Microsoft Excel [8]sheets where were kept organized by date, probe and treatment.

Precipitation and air temperature data was also collected throughout the season. BRC is a site of the Illinois State Water Survey, and also has its own weather station for hourly precipitation and air temperature data collection.

**Experimental Design and Analysis.** Overall field experiment dimensions were 10 m wide by 30 m long with individual plots being 2 m x 2 m arranged in a randomized complete block design consisting in eight replications. In the center of each plot a 1 $m^2$ quadrat was used for emergence data collection. Due to different weather conditions in the spring of 2013 and 2014, Palmer

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[6] Spectrum Technologies, Inc., P.O. Box 3600, Aurora, IL 60504.
[7] Spectrum Technologies, Inc., P.O. Box 3600, Aurora, IL 60504.
[8] Microsoft Corporation, Inc., P.O. Box 2362, Redmond, WA 98052.

amaranth emergence influenced by tillage were analyzed both, separately and combined. Considering the high emergence contrast across replications and searching for a more homogeneous distribution, original data was log-transformed for tabulation and graphing. Tillage effects on Palmer amaranth emergence were analyzed using the PROC GLM procedure in SAS[9]. Means were separated using Fisher's protected LSD ($\alpha$=0.05). The interaction of Palmer amaranth emergence peaks with soil temperature and soil moisture was analyzed using Stepwise Regression procedure in SAS. Due to differences on weather patterns and timing of emergence peaks, years were analyzed separately.

**Soil Sampling.** Soil samples were collected in the spring of 2013 and 2014 at trial initiation in the area adjacent to each 1 $m^2$ center quadrat to elucidate soil seed bank density. A common soil core with approximately 2.2 cm diameter at the cutting edge was used to collect six soil cores per plot at a depth of 7.6 cm. Soil samples were brought to SIU and placed into a freezer located at the Tree Improvement Center (TIC). Freezer temperature was set at -20 C to avoid any possible germination while the soil samples were still in bags. The greenhouse growouts for the soil samples for each year were completed the following winter/spring (Wilson et al. 2011). Soil cores were placed in a plastic tray with vermiculite on the bottom and a square sheet plant fabric barrier on top. Trays containing soil cores were placed on benches equipped with irrigation system and covered with a sheet of fabric barrier. Automatic irrigation system was set to provide 20 min of irrigation once a day. The greenhouse temperature was 32 C, ranging 5 C more or less throughout the day.

Three growouts periods were conducted for each soil core. Each period was 28 days long separated by one dry week (between the first and second growout) and 28 days with trays in the freezer (between the second and third growout). During each growout Palmer amaranth seedlings

[9] SAS software, Version 9.3, July 2011, SAS Institute Inc., Cary, NC 27513.

were identified and enumerated. The number of Palmer amaranth seedlings in the greenhouse growout were considered the viable fraction of the soil seedbank. Thus, these values were used to calculate the total size of the seedbank for Palmer amaranth at the initiation of the field experiment. Palmer amaranth emergence from the soil seed bank was estimated based on growouts from soil samples collected at the experiment initiation in 2013 and 2014. Based on the amount of Palmer amaranth seedlings enumerated from the 6 soil cores collected per plot, an estimated value $m^{-2}$ was calculated (Table 3.1). No statistical differences were observed when soil seed bank estimation was grouped by treatment (P = 0.793; P = 0.305), which suggests a homogenous seed bank density across the experimental area. Palmer amaranth field emergence in no-tillage, early tillage and late tillage was used to calculate the respective soil seed bank depletion.

## RESULTS AND DISCUSSION

Precipitation events were notably different between the experimental period in 2013 and 2014 (Figure 3.1). Predominant rainfall events in the spring and in the fall characterize precipitation in 2013 and 2014, respectively. Differences in air temperature were also observed throughout the experiment duration but mostly in the beginning of May (Figure 3.2). These conditions contributed, at least in part, to large differences across means of Palmer amaranth emergence between years. Thus, even with non-significant treatment interaction between years (P = 0.188), data is presented for each year independently (Table 3.1).

First emergence of Palmer amaranth occurred on May 14th in both years (Figure 3.3). During 2013, Palmer amaranth emerged from May 14th through October 22nd. Seedling emergence was observed over a period of 23 wk in no-tillage, 21 wk in early tillage, and 19 wk in late tillage. Emergence peak periods were observed from late May through mid-July. Cumulative emergence of Palmer amaranth in no-tillage and early tillage reached 90% by the third week of July, while late tillage reached 90% cumulative emergence in the first week of July (Figure 3.4) The increase in Palmer amaranth emergence observed after late tillage operation allowed late tillage to reach 90% cumulative emergence before no-tillage and early tillage.

In 2014, seedling emergence occurred from May $14^{th}$ through October $16^{th}$. Palmer amaranth emergence in no-tillage occurred over 22 wk, while emergence in early tillage and late tillage occurred over 21 wk. Major emergence peaks were observed from late May through late July, and mid-August through late September. In the same year, regardless of treatment 90% cumulative emergence was reached by mid-August (Figure 3.3).

The period of Palmer amaranth emergence was largely dependent on rainfall in both years. Peaks of Palmer amaranth emergence observed from May through July may be explained by the wet spring observed in 2013. Similarly, rainfall events concentrated in June, August, and September were observed along with peaks of Palmer amaranth emergence in 2014. Jha and Norsworthy (2009) have reported that peaks of Palmer amaranth emergence occurred along with the largest precipitation events. Furthermore, research has reported the effect of low precipitation events in delaying pigweed emergence (Hartzler et al. 1999; Oryokot et al. 1997).

**Tillage Effects.** Tillage treatments had to be delayed due to excessive rainfall; thus, the early tillage treatment was performed on May $20^{th}$ and May $7^{th}$ and late tillage on June $7^{th}$ and June $6^{th}$ in 2013 and 2014, respectively. The effect of tillage on Palmer amaranth emergence was temporary, and mostly observed through three weeks after early tillage and late tillage had been applied (Table 3.2). To better analyze possible effects of tillage on Palmer amaranth emergence,

emergence data was analyzed weekly, throughout the season using Palmer amaranth cumulative emergence (not transformed) from the total.

In 2013, in the two weeks following early tillage Palmer amaranth emergence in no-tillage was greater and statistically different from early and late tillage (P = 0.002); although, by the third week after early tillage no differences were observed (P = 0.159). These results are in agreement with those reported by Jha and Norsworthy (2009) in a similar experiment conducted in South Carolina in 2005, where the effect of tillage was evident from two to three weeks following tillage dates. Different results were observed after late tillage; Palmer amaranth emergence in no-tillage and early tillage were greater and statistically different from late tillage (P < 0.001). No differences were observed between treatments in the second week after late tillage (P = 0.392). However, on the third week after late tillage Palmer amaranth emergence in late tillage plots was greater and statistically different from early tillage and no-tillage (P = 0.002). The results remained the same until the end of July, when no significant differences between tillage treatments were observed.

In 2014, the three weeks following early tillage showed no differences on the emergence of Palmer amaranth across treatments (P = 0.522; P = 0.349; P = 0.325; Table 3.2). Similar to the same period of previous year an increase in Palmer amaranth emergence was observed after late tillage. On the first week after late tillage no statistical differences were observed between treatments. However, the period from the second week after late tillage through late July was characterized by greater emergence of Palmer amaranth on late tillage compared to early tillage and no-tillage (P = 0.041).

**Soil Temperature.** Daily means of soil temperature recorded by soil probes and Palmer amaranth emergence throughout the season of 2013 and 2014 are displayed on Figure 3.4. No differences were observed in soil temperature across treatments in both years. In 2013, Palmer amaranth emergence in no-tillage was mostly observed when temperature ranged from 20 to 30 C. Peaks of Palmer amaranth in no-tillage coincided with means of soil temperature around 25 C in June and July. However, consecutive days with soil temperature above 25 C were observed with decreased Palmer amaranth emergence. A decrease in the emergence of Palmer amaranth in early tillage on May 28$^{th}$ and late tillage on June 11$^{th}$ shows the post-tillage effect relative to each tillage treatment. As these observations were not noticed in no-tillage, it seems that decreased emergence of Palmer amaranth after early tillage and late tillage are more related to seed burial, caused by tillage, than soil temperature in 2013.

In 2014, similarly to 2013 means of soil temperature did not differ across tillage treatments. In mid-May, a decreased Palmer amaranth emergence in no-tillage was observed when soil temperature decreased to 15 C. From late May through June 18$^{th}$ an increase in soil temperature was observed along with an increased Palmer amaranth emergence in no-tillage. Daily means of soil temperature above 25 C associated with low precipitation in July must have contributed to the dramatic decrease in Palmer amaranth emergence on August 6$^{th}$, when Palmer amaranth emergence was reduced to less than three plants $m^{-2}$. Nevertheless, rainfall in late August and early September must have stimulated the dormant portion of the soil seed bank. Steckel et al. (2004) reported that Palmer amaranth and smooth pigweed had higher seed germination under alternated temperature compared to constant temperatures.

**Soil Moisture.** Values of soil moisture between treatments were not as similar as those observed in soil temperature. Similarities were observed between the pattern for Palmer amaranth emergence and soil moisture in no-tillage, and peaks of soil moisture were concomitant with peaks of Palmer amaranth emergence, most importantly in mid-June, late July and mid-

September (Figure 3.5). A decrease in soil moisture was observed one week after early tillage and late tillage operations; these events were observed along with a reduced followed by an increased emergence of Palmer amaranth, but only for a period not longer than two weeks (Figure 3.5).

In 2014, soil moisture in no-tillage was generally greater compared to early tillage and late tillage. Throughout the year, peaks of soil moisture were observed with increased Palmer amaranth emergence, especially in May, June, and late August. The lack of rainfall in July associated with high soil temperature must have been associated with the reduction in soil moisture in all treatments at the end of July. Overall, peaks of Palmer amaranth emergence were observed along with peaks in soil moisture, and soil moisture in no-tillage was higher than early and late tillage. However, differences on Palmer amaranth emergence were restricted, to a period not longer than 4 weeks, after tillage operations (Table 3.2).

**Environmental Factors Influencing Emergence Peaks.** Based on soil temperature and soil moisture data of 2013 and 2014, stepwise regressions were used to indicate which environmental factor (soil temperature and/or soil moisture) was more successful at predicting the emergence of Palmer amaranth throughout the growing season. With weed seedlings being enumerated every 7 days, each emergence event was more likely to be a result of recent soil temperature and soil moisture values. To increase the precision of the analysis, regression was set to find the strongest factor in predicting Palmer amaranth emergence within 14 days prior to each Palmer amaranth emergence event.

During 2013, 99% Palmer amaranth had emerged between May 14$^{th}$ and August 8$^{th}$ (Figure 3.3); thus, regression was used to find the best predictors of Palmer amaranth emergence in the selected period. A positive interaction with high soil moisture values observed 11 days prior emergence events and the prediction of Palmer amaranth emergence was observed ($R^2$ = 0.30; P < 0.001; Table 3.3). Conversely, a negative interaction between Palmer amaranth emergence peaks and high values of soil temperature observed 14 days prior each count date was also observed ($R^2$ = 0.30; P = 0.807; Table 3.3). The positive interaction between high soil moisture 11 days and the prediction of Palmer amaranth emergence is significant and can be observed by the similarity between the two variables in the graph throughout the selected time period (Figure 3.6). These results suggest that most of Palmer amaranth emergence in 2013 could be predicted by the high values of soil moisture observed 11 days apart from each emergence event.

In 2014, Palmer amaranth emergence only reached 99% in all treatments by mid-September (Figure 3.3). Nevertheless, the major emergence peaks of Palmer amaranth were observed from May 14$^{th}$ through August 13$^{th}$. A positive and significant interaction between high values of soil moisture 14 days before each emergence event and the prediction of Palmer amaranth was observed ($R^2$ = 0.37; P < 0.001; Table 3.3). Mutually, there was a positive interaction between high values of soil temperature at 8 days prior and the prediction of Palmer amaranth ($R^2$ = 0.37; P = 0.022; Table 3.3). The positive interaction between high soil moisture 14 days and the prediction of Palmer amaranth through the selected period is evident comparing the regression lines. High and low values of soil moisture 14 d throughout the season were observed with increased and decreased predicted emergence of Palmer amaranth, respectively (Figure 3.7). The positive interaction between high soil temperature 8 days prior count dates and predicted Palmer amaranth emergence seems to be stronger from May through late June. In July, peaks of high values of soil temperature 8 days prior emergence, especially those above 35 C, were contrary to reduction in Palmer amaranth emergence. These results suggest that Palmer amaranth emergence in 2014 was better predicted by high values of soil moisture observed 14 days before each emergence event. Furthermore, high values of soil temperature 8 days showed to have a positive interaction to Palmer amaranth emergence; although, long periods of high values of soil temperature can reduce soil moisture to a level that compromises seed germination, which could characterize a negative interaction.

**Emergence from Soil Seed Bank.** Based on greenhouse growouts, soil seed bank density for Palmer amaranth was calculated for 2013 and 2014. For the 2013 site, Palmer amaranth seed density in the soil seed bank was 1073 seeds $m^{-2}$. In 2014, the amount of Palmer amaranth seeds in the soil seed bank was greater, with 3092 seeds $m^{-2}$.

In 2013, Palmer amaranth emergence from soil seed bank was 39, 33, and 39% in no-tillage, early tillage, and late tillage, respectively ($P = 0.426$). The similar Palmer amaranth cumulative emergence across treatments in 2013 may be explained by a uniform Palmer amaranth seed distribution within the soil profile at the site. Licht and Al-Kaisi (2005) have reported that tillage can provide better seedbed conditions to buried seeds, such as higher temperature, light exposure, soil aeration, and less penetration resistance for germination and emergence. Moreover, Jha and Norsworthy (2009) have reported that the tillage effect for improving Palmer amaranth germination may be expected if seeds were buried after dispersal in the previous fall and were exposed to light by soil disturbance in the spring.

In 2014, the total cumulative emergence of Palmer amaranth from the soil seed bank was 1.7 greater in no-tillage compared to late tillage (Table 3.1). Palmer amaranth cumulative emergence from the total seed bank was 50, 32, and 30% in no-tillage, early tillage and late tillage, respectively ($P = 0.079$; Table 3.1). In similar study, Keeley et al. (1987) have reported that Palmer amaranth emergence from the soil seed bank was higher, 36 to 44% emergence, when seeds were found at a depth of 2.5 cm or less, which simulates seed burial in no-till systems.

**Conclusions.** The results presented suggest that peaks of Palmer amaranth emergence in southern Illinois mostly occur from early May through late July; in case of crop presence an extended weed management program may be required to reduce late season competition. Normally, the period between emergence and 90% Palmer amaranth cumulative emergence is shorter than the period required by row crops, such as soybean, corn, and cotton to start showing canopy effect. Aiming to reduce the period of competition between the crop and Palmer amaranth, tillage practices, especially in early June, should be avoided. Palmer amaranth emergence responded positively to soil disturbance in early June, with late tillage treatment reaching 90% cumulative emergence before no-tillage and early tillage, which increase the need for a more effective burndown followed by a soil residual herbicide program that assures reduced crop-weed competition. Furthermore, monitoring soil moisture levels, may aid the prediction of Palmer amaranth emergence flushes that may occur after 11 to 14 days throughout the season, which contributes to the development of weed management strategies focused on reduce postemergence competition of the weed to the crop.

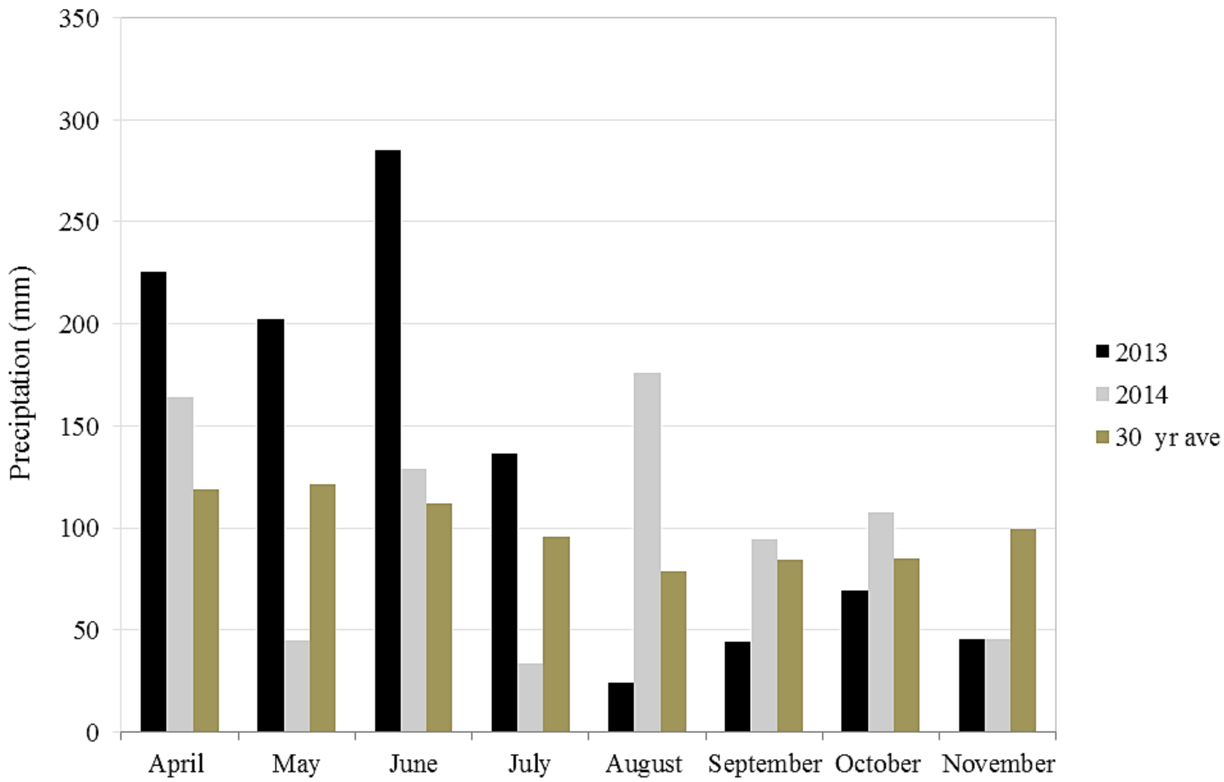


Figure 3.1. Monthly precipitation received during the experimental period and 30-year rainfall average in Belleville, IL.

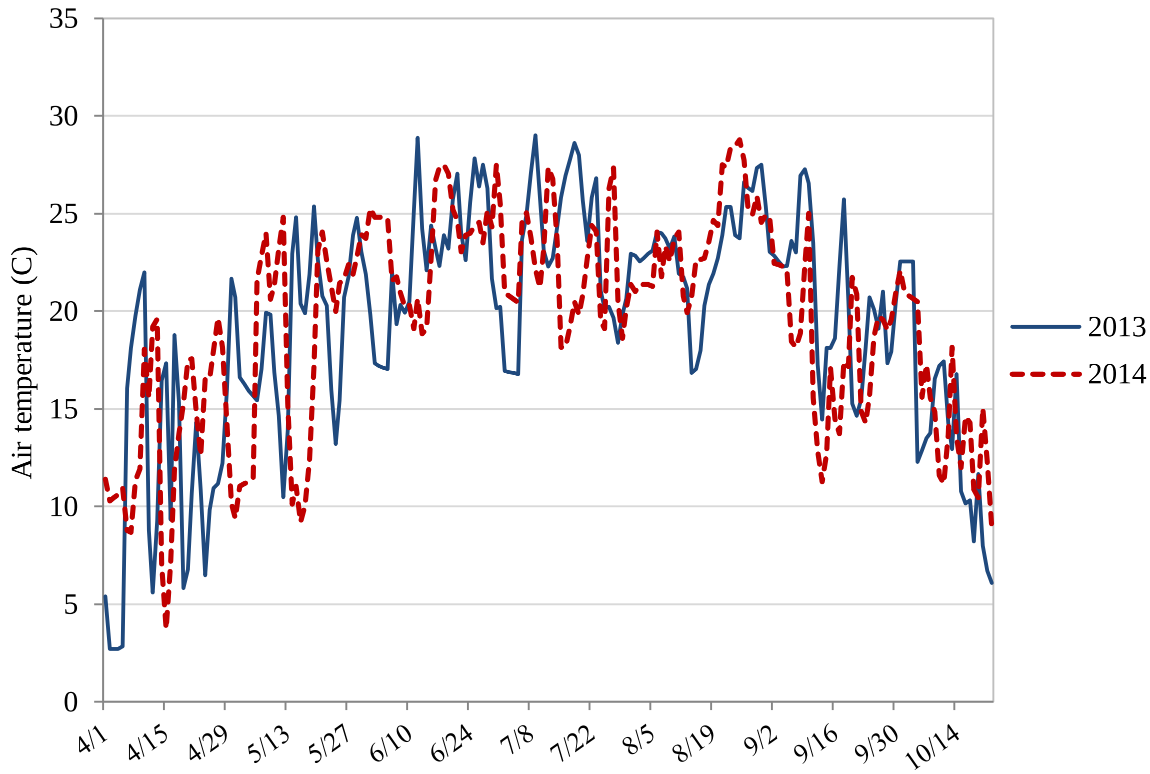


Figure 3.2. Daily means of air temperature throughout the experiment duration in 2013 and 2014.

Table 3.1. Total cumulative and soil seed bank emergence of Palmer amaranth throughout the season for no-tillage, early tillage and late tillage in 2103 and 2014.

| | 2013 | | 2014 | |
|---|---|---|---|---|
| Treatment | Cumulative emergence | Seed bank emergence | Cumulative emergence | Seed bank emergence |
| | no. seedlings $m^{-2}$ | % emerged seedlings $m^{-2}$ | no. seedlings $m^{-2}$ | % emerged seedlings $m^{-2}$ |
| No-tillage | 416[a] a[b] | 39 a | 1,550 a | 50 a |
| Early tillage | 350 a | 33 a | 982 ab | 32 ab |
| Late tillage | 415 a | 39 a | 933 b | 30 b |

[a] Numbers presented are the back-transformed of total emergence. Data were log-transformed and back-transformed for clarity.

[b] Numbers within each row and for each year followed by the same letter do not differ significantly according to Fisher’s protected LSD ($\alpha = 0.05$).

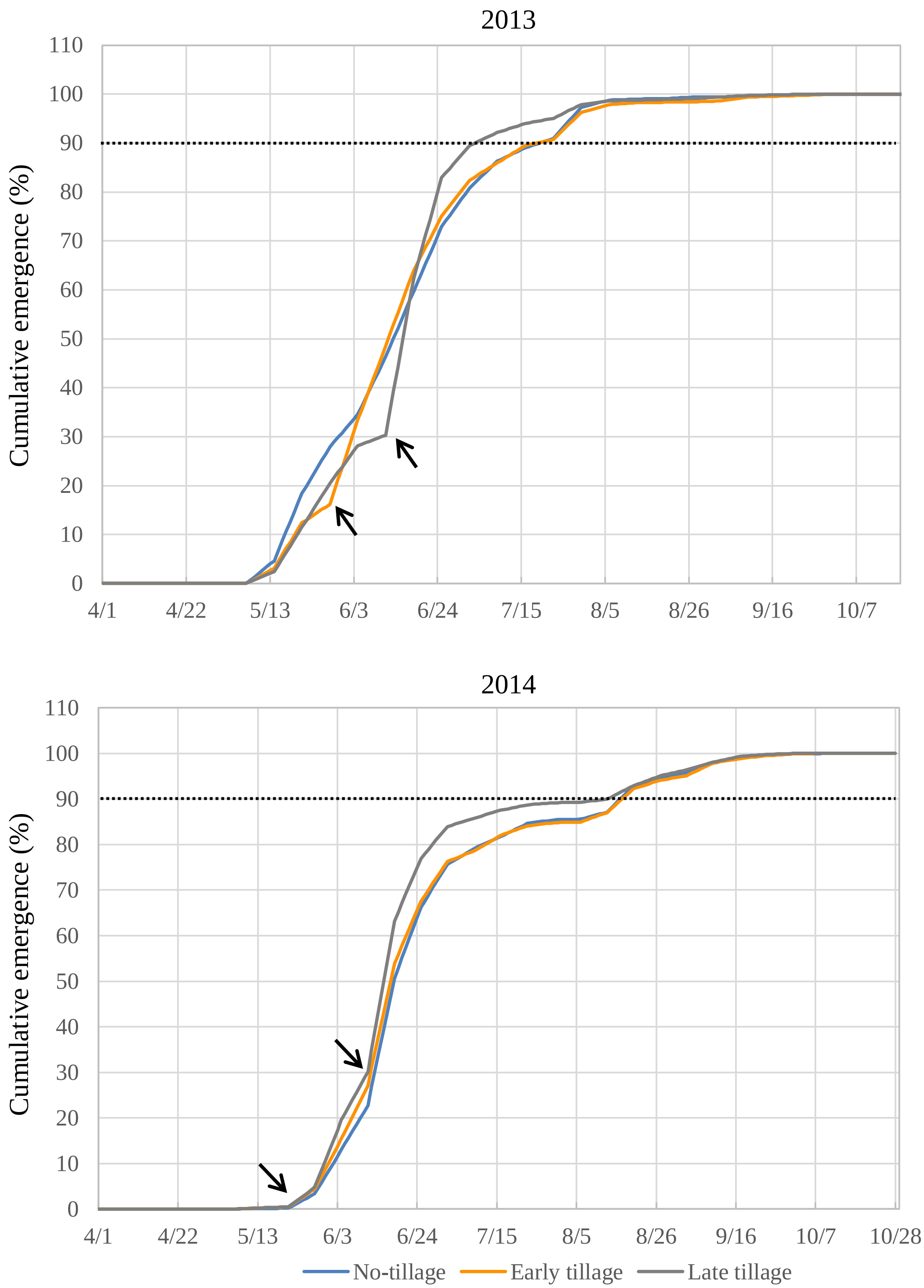


Figure 3.3. Cumulative emergence of Palmer amaranth for no-tillage, early tillage and late tillage in Belleville, IL in 2013 and 2014. Arrows represent early tillage and late tillage dates.

Table 3.2. Statistical analysis of weekly cumulative emergence of Palmer amaranth for no-tillage, early tillage, and late tillage in Belleville, IL in 2013 and 2014.

| | | | | | Tillage | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Year | Date | $R^2$ | F value | *p* | No-tillage | | Early tillage[a] | | Late tillage[b] | |
| | | | | | --------------% cumulative emergence[c]-------------- | | | | | |
| 2013 | 5/14 | 0.62 | 0.50 | 0.616 | 5 | a | 3 | a | 2 | a |
| | 5/21 | 0.57 | 4.17 | 0.038 | 18 | a | 12 | a | 12 | a |
| | **5/28** | **0.70** | **9.93** | **0.002** | **28** | **a** | **16** | **b** | **20** | **b** |
| | 6/4 | 0.57 | 2.10 | 0.159 | 35 | a | 33 | a | 28 | a |
| | **6/11** | **0.77** | **15.76** | **<0.001** | **46** | **a** | **49** | **a** | **30** | **b** |
| | 6/18 | 0.40 | 1.00 | 0.392 | 60 | a | 64 | a | 62 | a |
| | **6/25** | **0.67** | **9.70** | **0.002** | **73** | **b** | **75** | **b** | **83** | **a** |
| | **7/2** | **0.80** | **7.69** | **0.005** | **81** | **b** | **82** | **b** | **89** | **a** |
| | **7/9** | **0.79** | **5.44** | **0.017** | **86** | **b** | **86** | **b** | **92** | **a** |
| | **7/16** | **0.75** | **4.15** | **0.038** | **89** | **b** | **89** | **b** | **94** | **a** |
| | **7/23** | **0.76** | **3.96** | **0.043** | **91** | **b** | **91** | **b** | **95** | **a** |
| | **7/30** | **0.62** | **3.36** | **0.064** | **97** | **ab** | **96** | **b** | **99** | **a** |
| | **8/6** | **0.72** | **3.28** | **0.067** | **99** | **a** | **98** | **b** | **99** | **ab** |
| | **8/13** | **0.71** | **3.01** | **0.081** | **99** | **a** | **98** | **b** | **99** | **ab** |
| | **8/20** | **0.70** | **2.66** | **0.105** | **99** | **a** | **98** | **b** | **99** | **ab** |
| | 8/27 | 0.46 | 2.33 | 0.134 | 99 | a | 98 | a | 99 | a |
| | 9/3 | 0.47 | 3.08 | 0.077 | 99 | a | 98 | a | 99 | a |
| | 9/10 | 0.19 | 0.72 | 0.502 | 100 | a | 99 | a | 100 | a |
| | 9/17 | 0.29 | 0.72 | 0.504 | 100 | a | 99 | a | 100 | a |
| | 9/24 | 0.59 | 1.34 | 0.293 | 100 | a | 100 | a | 100 | a |
| | 10/1 | 0.53 | 1.34 | 0.293 | 100 | a | 100 | a | 100 | a |
| | 10/8 | 0.45 | 2.23 | 0.144 | 100 | a | 100 | a | 100 | a |
| | 10/15 | 0.45 | 2.23 | 0.144 | 100 | a | 100 | a | 100 | a |
| | 10/22 | - | - | - | 100 | a | 100 | a | 100 | a |

Table 3.2 (Continued)

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 2014 | 5/14 | 0.42 | 0.68 | 0.522 | 1 | a | 1 | a | 1 | a |
| | 5/21 | 0.29 | 1.13 | 0.349 | 1 | a | 1 | a | 1 | a |
| | 5/28 | 0.80 | 1.22 | 0.325 | 3 | a | 4 | a | 5 | a |
| | **6/4** | **0.79** | **4.51** | **0.030** | **13** | **b** | **15** | **ab** | **19** | **a** |
| | **6/11** | **0.76** | **4.52** | **0.030** | **23** | **b** | **27** | **b** | **30** | **a** |
| | **6/18** | **0.50** | **4.74** | **0.026** | **51** | **b** | **54** | **b** | **63** | **a** |
| | **6/25** | **0.62** | **7.34** | **0.006** | **66** | **b** | **68** | **b** | **77** | **a** |
| | **7/2** | **0.55** | **6.45** | **0.010** | **76** | **b** | **76** | **b** | **84** | **a** |
| | **7/9** | **0.47** | **4.72** | **0.027** | **79** | **b** | **79** | **b** | **86** | **a** |
| | **7/16** | **0.45** | **4.01** | **0.041** | **82** | **b** | **82** | **b** | **87** | **a** |
| | **7/23** | **0.39** | **2.78** | **0.095** | **85** | **ab** | **84** | **b** | **89** | **a** |
| | 7/30 | 0.38 | 2.40 | 0.126 | 85 | a | 85 | a | 89 | a |
| | 8/6 | 0.37 | 2.38 | 0.128 | 85 | a | 85 | a | 89 | a |
| | 8/13 | 0.40 | 1.61 | 0.234 | 87 | a | 87 | a | 90 | a |
| | 8/20 | 0.37 | 0.13 | 0.875 | 93 | a | 92 | a | 93 | a |
| | 8/27 | 0.49 | 0.40 | 0.679 | 95 | a | 94 | a | 95 | a |
| | 9/3 | 0.47 | 1.21 | 0.326 | 96 | a | 95 | a | 96 | a |
| | 9/10 | 0.57 | 0.07 | 0.936 | 98 | a | 98 | a | 98 | a |
| | 9/17 | 0.59 | 1.91 | 0.184 | 99. | a | 99 | a | 99 | a |
| | 9/24 | 0.61 | 2.10 | 0.159 | 100 | a | 99 | a | 100 | a |
| | 10/1 | 0.53 | 1.83 | 0.196 | 100 | a | 100 | a | 100 | a |
| | 10/8 | 0.49 | 3.17 | 0.07 | 100 | a | 100 | a | 100 | a |
| | 10/15 | - | - | - | 100 | a | 100 | a | 100 | a |
| | 10/22 | - | - | - | - | - | - | - | - | - |

[a] Early tillage performed on May 20th and May 7th in 2013 and 2014, respectively.

[b] Late tillage performed on June 7th and June 6th in 2013 and 2014, respectively.

[c] Degrees of freedom: main effect = 9; error = 14

[d] Means within each column for the same year followed by the same letter do not differ significantly according to Fisher's protected LSD ($\alpha = 0.05$).

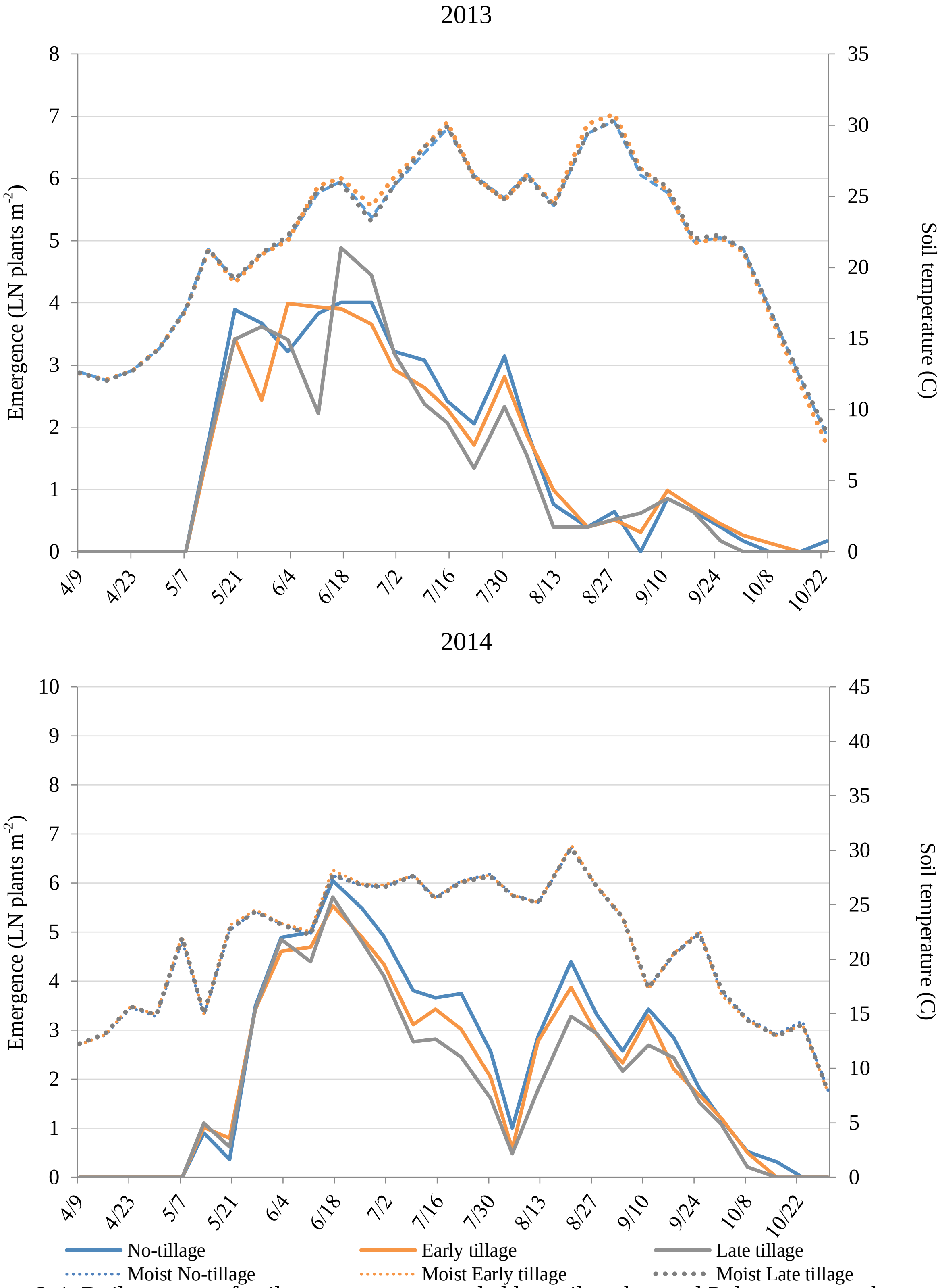


Figure 3.4. Daily means of soil temperature recorded by soil probes and Palmer amaranth emergence in 2013 and 2014.


Figure 3.5. Daily means of soil moisture recorded by soil probes and Palmer amaranth emergence in 2013 and 2014.

Table 3.3. Results of stepwise regression testing the interaction of Palmer amaranth emergence with soil temperature and soil moisture in 2013 and 2014. Soil temperature and soil moisture included as factors for germination.

| Year | Variable[a] | $R^2$ | Time prior emergence events | Parameter Estimation | F value | *p*-value |
|---|---|---|---|---|---|---|
| | | | ----------(d)--------- | | | |
| 2013 | High soil moisture | 0.30 | 11[b] | 0.084 | 3.61 | <0.001 |
| | High soil temperature | 0.30 | 14 | -0.004 | -0.25 | 0.807 |
| 2014 | High soil moisture | 0.37 | 14 | 0.132 | 5.01 | <0.001 |
| | Minimum soil temperature | 0.37 | 8 | 0.077 | 2.37 | 0.022 |

[a] Maximum (highest), mean, and minimum (lowest) values of soil temperature and soil moisture up to 14 days prior each emergence event were used as predict variables.

[b] Results show the period (days) after observed environmental factors, that led to major peaks of Palmer amaranth emergence.

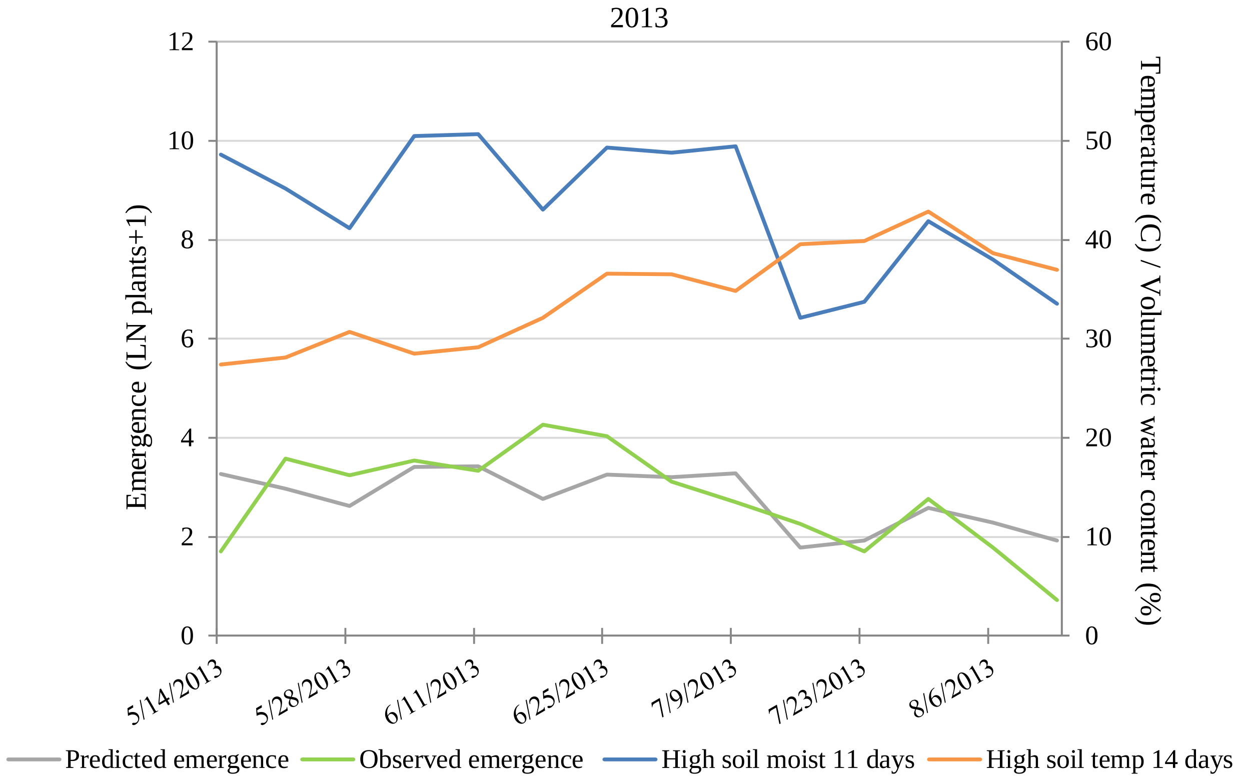


Figure 3.6. Stepwise regression for emergence of Palmer amaranth predicted by soil temperature and soil moisture in 2013. The blue line represents the highest values of soil moisture observed 11 days before each Palmer amaranth emergence event, the orange line represents the highest values of soil temperature collected 14 days prior each emergence. The grey line shows the predicted Palmer amaranth emergence as result of these two variables. The green line shows the mean of Palmer amaranth emergence throughout the selected period.

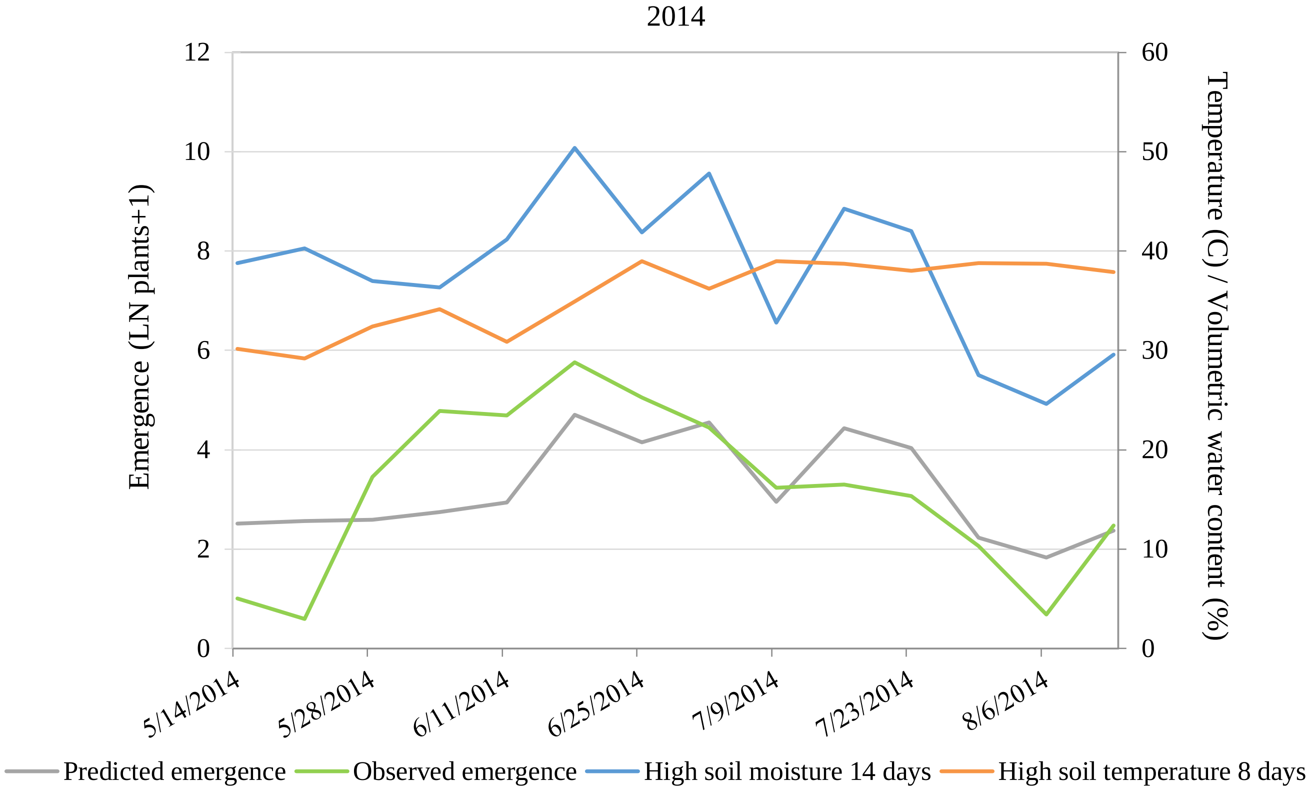


Figure 3.7. Stepwise regression for emergence of Palmer amaranth predicted by soil temperature and soil moisture in 2014. The blue line represents the highest values of soil temperature observed 14 days before each Palmer amaranth emergence event, the orange represents the highest values of soil temperature collected 8 days prior each emergence. The grey line shows the predicted Palmer amaranth emergence as result of these two variables. The green line shows the means of Palmer amaranth emergence throughout the selected period.

# CHAPTER 4

# CONCLUSIONS

The increase in the number of herbicide-resistant weeds has complicated common waterhemp and Palmer amaranth management practices in agricultural fields worldwide. The extended period of emergence observed on common waterhemp and Palmer amaranth promotes the indiscriminate use of postemergence herbicides for weed control. Over the last two decades, several herbicides used to control common waterhemp and Palmer amaranth have lost partial or total effectiveness. This scenario has made growers turn their attention to alternative control tactics that do not only rely on postemergence herbicides, such as tillage practices, and residual herbicides. The literature of the effects of tillage on weed species germination, seed burial, emergence, and soil microclimate is vast. Nevertheless, research on the emergence patterns of common waterhemp and Palmer amaranth under no-tillage and tillage conditions in southern Illinois is lacking.

In southern Illinois, common waterhemp emergence started earlier than did Palmer amaranth in both years; although, Palmer amaranth emerged through a longer time period compared to common waterhemp. Cumulative emergence of common waterhemp reached 90% in almost all treatments by the end of June in both years. In contrast, Palmer amaranth 90% emergence in late tillage was reached by mid-July and late August in 2013 and 2014, respectively. In no-tillage and early tillage treatments, Palmer amaranth cumulative emergence only reached 90% by mid-August and late August in 2013 and 2014, respectively. These results show that common waterhemp and Palmer amaranth may have different period of competition with row crops in southern Illinois. Furthermore, tillage timing may increase common waterhemp and more importantly Palmer amaranth emergence when performed in June. Thereby, weed management tactics for controlling common waterhemp shall focus on early season, whereas for Palmer the period of competition may extend through late season.

Common waterhemp and Palmer amaranth emergence was largely contingent on environmental events throughout the growing season in both years. Strong interaction was observed between common waterhemp emergence dates and variations on soil temperature. A positive interaction between common waterhemp emergence and high soil temperature was observed, especially in early season (May and June), which may be related to high temperature amplitudes usually observed in the spring. A positive interaction was also observed between the emergence of common waterhemp and soil moisture, but mostly in late season when soil temperature is above 35 C. The emergence of Palmer amaranth was strong and positively correlated to high values of soil moisture throughout the season. Peaks of Palmer amaranth emergence were concomitant to those observed on soil moisture. Considering the natural origin of common waterhemp and Palmer amaranth, high soil temperature and soil moisture may stimulate the dormant portion of the seed bank. Control tactics that aim to reduce the soil seed bank have also been adopted by growers as an alternative to control common waterhemp and Palmer amaranth. In both years, Palmer amaranth emergence from a natural soil seed bank was greater in no-tillage compared to tillage treatments. Similar results were observed for common waterhemp in 2014. Shallow-buried seeds of common waterhemp and Palmer amaranth favors seed germination, and consequently, reduce seed persistence in the soil through recruitment.

The results of this research emphasize the importance of an early-season weed control management for common waterhemp and Palmer amaranth in southern Illinois. The emergence patterns of common waterhemp and Palmer amaranth reflect the potential competitiveness with crops that may occur, especially in May and June, in case weed control is not satisfactory. The use of tillage, when applied in May can reduce the emergence of common waterhemp. However, if applied in June, a temporary but increasing, emergence of common waterhemp and Palmer amaranth may be observed. Given the large number of factors that may affect weed seed germination of these two species, high values of soil temperature and soil moisture may assist the prediction of common waterhemp and Palmer amaranth emergence. Moreover, the monitoring of soil temperature and soil moisture may aid growers to make decisions in regard to field operations, such as fertilization, cultivation, pre and post emergence applications. As a result, by adopting the use of a burndown followed by an effective residual herbicide program that overlaps the emergence period of common waterhemp and Palmer amaranth combined with crop canopy effect, growers should be able enhance the control levels of common waterhemp and Palmer amaranth.

# LITERATURE CITED

[USDA] United States Department of Agriculture (2008) National Agricultural Statistics Service. Agricultural Chemical Use Database: Web page: http://www.pestmanagement.info/nass/app_statcs3_crop.cfm. Accessed November 21, 2011.

Addae PC, Collis-George N, Pearson CJ (1991) Over-riding effects of temperature and soil strength on wheat seedling under minimum and conventional tillage. Field Crop Res 28:103-116.

Aldrich RJ, ed (1984) Weed-Crop Ecology:  Principles in Weed Management. North Scituate, MA:  Breton Publishers.

Baskin JM, Baskin CC (1987) Temperature requirements for after-ripening in buried seeds of four summer annual weeds. Weed Res 27:397-402.

Baskin JM, Baskin CC (2004) A classification system for seed dormancy. Seed Sci Res 14:1-16.

Batlla D, Benech-Arnold RL (2010) Predicting changes in dormancy level in natural seed soil banks. Plant Mol Biol 73:3–13.

Batlla D, Kruk BC, Benech-Arnold RL (2010) Very early detection of canopy presence by seeds through perception of subtle modifications in R : FR signals. Funct Ecol 14:195-202.

Beckie HJ (2009) Herbicide-Resistant Weeds: Management Tactics and Practices. Weed Technol 20:793-814.

Bell MS, Tranel PJ (2010) Time requirement from pollination to seed maturity in waterhemp (*Amaranthus tuberculatus)*. Weed Sci 58:167-173.

Benech-Arnold RL, Sánchez RA, Forcella F, Kruk BC, Ghersa CM (2000) Environmental control of dormancy in weed seed banks in soil. Field Crop Res 67(2)105–122.

Bensch CN, Horak MJ, Peterson D (2003) Interference of Redroot Pigweed (*Amaranthus retroflexus*), Palmer Amaranth (*A. palmeri*), and Common Waterhemp (*A. rudis*) in Soybean. Weed Sci 51:37–43.

Benvenuti S (1995) Soil light penetration and dormancy of jimsonweed (*Datura stramonium*) seeds. Weed Sci 43:389-393.

Bewley JD, Bradford K, Hilhorst H, Nonogaki H (2012) Seeds: Physiology of Development, Germination and Dormancy. Springer Science & Business Media.

Buhler DD, Daniel TC (1986) Influence of tillage systems on giant foxtail (*Setaria faberi*) and velvet leaf (*Abutilon theophrasti*) density and control in corn (*Zea mays*). Weed Sci 36:642-647.

Buhler DD, Hartzler RG (2001) Emergence and persistence of seed of velvetleaf, common waterhemp, woolly cupgrass, and giant foxtail. Weed Sci 49:230-235.

Buhler DD, Mester TC, Kohler KA (1996) The effect of maize residues and tillage on emergence of *Setaria faberi, Abutilon theophrasti, Amaranthus retroflexus* and *Chenopodium album*. Weed Res 36:153–165.

Cardina J, Herms CP, Doohan DJ (2009) Crop rotation and tillage system effects on weed seedbanks. Weed Sci 39:186-194.

Clements DR, Benoit D, Murphy SD, Swanton CJ (1996) Tillage effects on weed seed return and seedbank composition. Weed Sci 44:314-322.

Costea MS, Weaver SE, Tardif FJ (2004) The biology of Canadian weeds. Can J Plant Sci 84:631-668.

Cowan P, Weaver SE, Swanton CJ (1998) Interference between pigweed (*Amaranthus spp.*), barnyardgrass (*Echinochloa crus-galli*), and soybean (*Glycine max*). Weed Sci 533-539.

Culpepper AS, Grey TL, Vencill WK, Kichler JM, Webster TM, Brown SM, York AC, Davis JW, Hanna WW (2006) Glyphosate-resistant palmer amaranth (*Amaranthus palmeri)* confirmed in Georgia. Weed Sci 54:620-626.

Donohue K, Dorn L, Griffith C, Kim E, Aguilera A, Polisetty CR, Schmitt J (2005) Environmental and genetic influences on the germination of *Arabidopsis thaliana* in the field. Evolution 59:740-757.

Dowler CC (1995) Weed survey – southern states – broadleaf crops subsection. Proceedings of the Southern Weed Science Society. Las Cruces, NM. WSSA.

Dyer WE (1995) Exploiting weed seed dormancy and germination requirements through agronomic practices. Weed Sci 498-503.

Ehleringer J (1983) Ecophysiology of *Amaranthus palmeri*, a sonoran desert summer annual. Oecologia (Berlin) 57:107-112.

Ehleringer J (1985) Annuals and perennials of warm deserts. Physiological Ecology of North American Plant Communities 162-180.

Felix J, Owen MDK (1999) Weed population dynamics in land removed from the conservation reserve program. Weed Sci 511-517.

Feltner KC, Hurst HR, Andrserson LE (1969) Tall Waterhemp Competition in Grain Sorghum. Weed Sci 17:214-216.

Fenner M (1980) The induction of a light requirement in *Bidens pilosa* seeds by leaf canopy shade. New Phytol 84:103-106.

Finch-Savage WE, Leubner-Metzger G (2006) Seed dormancy and the control of germination. New Phytol 171:501-523.

Forcella F, Benech-Arnold RL, Sanchez R, Ghersa CM (2000) Modeling seedling emergence. Field Crop Res 67:123–139.

Forcella F, Stephen H (1993) Vernal seedling emergence model for common lambsquarters (*Chenopodium album*). Weed Sci 309-316.

Forcella F, Wilson RG, Renner KA, Dekker J, Harvey RG, Alm DA, Buhler DD, Cardina J (1992) Weed seedbanks of the US corn belt: magnitude, variation, emergence, and application. Weed Sci 636-644.

Fortin MC, Pierce FJ (1991) Timing and nature of mulch retardation of corn vegetative development. Agron J 83:258-263.

Gallagher RS, Cardina J (1998) Phytochrome-mediated *Amaranthus* germination I: effect of seed burial and germination temperature. Weed Sci 48-52.

Ghersa CM, Martinez-Ghersa MA, Brewer TG, Roush ML (1994) Selection pressures for diclofop-methyl resistance and germination time of Italian ryegrass. Agron J 86:823-828.

Givens WA, Shaw DR, Johnson WG, Weller SC, Young BG, Wilson RG, Owen MDK, Jordan D (2009) A grower survey of herbicide use patterns in glyphosate-resistant cropping systems. Weed Technol 23:156-161.

Gomez KA, Gomez AA (1984) Statistical Procedures for Agricultural Research. NY Wiley J 7-83.

Graeber KAI, Nakabayashi K, Miatton E, Leubner-Metzger GE, Rhard and Soppe WJ (2012) Molecular mechanisms of seed dormancy. Plant cell environ 35:1769-1786.

Gressel J (2009) Evolving understanding of the evolution of herbicide resistance. Pest Manag Sci 65:1164-1173.

Guo P, Al-Khatib K (2003) Temperature Effects on Germination and Growth of Redroot Pigweed (*Amaranthus retroflexus*), Palmer Amaranth (*A. palmeri*), and Common Waterhemp (*A. rudis*). Weed Sci 51:869–875.

Hager AG, Wax LM, Simmons FW, Stoller EW (1997) Waterhemp management in agronomic crops. U Illinois Bul 12.

Hager AG, Wax LM, Stoller EW, Bollero GA (2002) Common waterhemp (*Amaranthus rudis)* interference in soybean. Weed Sci 50:607-610.

Hartzler RG, Battles BA, Nordby D (2004) Effect of common waterhemp (*Amaranthus rudis)* emergence date on growth and fecundity in soybean. Weed Sci 52:242 245.

Hartzler RG, Buhler DD, Stoltenberg DE (1999) Emergence characteristics of four annual weed species. Weed Sci 578-584.

Heap IM (2010) The International survey of herbicide-resistant weeds. Available at: www.weedscience.org. Accessed: December 10, 2013.

Heap IM (2011) The International survey of herbicide-resistant weeds. Available at: www.weedscience.org. Accessed: December 4, 2013.

Heap IM (2012) The International survey of herbicide-resistant weeds. Available at: www.weedscience.org. Accessed: December 10, 2013.

Heap IM (2014) The International survey of herbicide-resistant weeds. Available at: www.weedscience.org. Accessed: December 13, 2014.

Heap IM (2015) The International survey of herbicide-resistant weeds. Available at: www.weedscience.org. Accessed: January 12, 2015.

Horak MJ, Loughin TM (2000) Growth analysis of four *Amaranthus* species. Weed Sci 48:347-355.

Huang X, Schmitt J, Dorn L, Griffiths C, Effgen S, Takao S, Koornneef M, Donohue K (2010) The earliest stages of adaptation in an experimental plant population: strong selection on QTLs for seed dormancy. Mol Ecol 19:1335-1351.

Jha P, Norsworthy JK (2009) Soybean Canopy and Tillage Effects on Emergence of Palmer Amaranth (*Amaranthus palmeri*) from a Natural Seed Bank. Weed Sci 57: 644–651.

Jha P, Norsworthy JK, Bridges Jr, W and Riley MB (2008) Influence of glyphosate timing and row width on Palmer amaranth (*Amaranthus palmeri*) with cotton (*Gossypium hirsutum*). Weed Sci 37:326-334.

Jha P, Norsworthy JK, Garcia J (2014) Depletion of an artificial seed bank of Palmer amaranth (*Amaranthus palmeri*) over four years of burial. Am J Plant Sci 5:1599-1606.

Jha P, Norsworthy JK, Riley MB, Jr WB (2010) Annual changes in temperature and light requirements for germination of Palmer amaranth (*Amaranthus palmeri*) seeds retrieved from soil. Weed Sci 58:426-432.

Kaspar TC, Erbach DC, Cruse RM (1990) Corn response to seed-row residue removal. Soil Sci Soc Am J 54:1112-1117.

Keeley PE, Carter CH, Thullen HJ (1987) Influence of Planting Date on Growth of Palmer Amaranth (*Amaranthus Palmeri)*. Weed Sci 35:199-204.

Klingaman TE, Oliver LR (1994) Palmer amaranth (*Amarantus palmeri)* interference in soybean (*Glycine max)*. Weed Sci 42:523-527.

Legleiter TR, Bradley KW (2008) Glyphosate and Multiple Herbicide Resistance in common waterhemp (*Amaranthus rudis*) populations from Missouri. Weed Sci 56:582–587.

Leon RG, Bassham DC, Owen MD (2006) Germination and proteome analyses reveal intraspecific variation in seed dormancy regulation in common waterhemp (*Amarathus tuberculatus*). Weed Sci 54:305-315.

Leon RG, Knapp AD, Owen MDK (2004) Effect of temperature on germination of common waterhemp (*Amaranthus tuberculatus*), giant foxtail (*Setaria faberi*), and velvetleaf (*Abutilon theophrasti*). Weed Sci 52.1:67-73.

Leon RG, Owen MDK (2003) Regulation of weed seed dormancy through light and temperature interactions. Weed Sci 51:752-758.

Leon RG, Owen MDK (2006) Tillage systems and seed dormancy effects on common waterhemp (*Amaranthus tuberculatus*) seedling emergence. Weed Sci 54:1037–1044.

Licht MA, Al-Kaisi M (2005) Strip-tillage effect on seedbed soil temperature and other soil physical properties. Soil Till Res 80:233-249.

Mahboubi AA, Lal R (1998) Long-term tillage effects on changes in structural properties of two soils in central Ohio. Soil Til Res 45:107-118.

Massinga RA, Currie RS, Horak MJ, Boyer JrJ (2001) Interference of Palmer amaranth in corn. Weed Sci 49:202-208.

Menges RM (1987) Allelopathic effects of Palmer amaranth (*Amaranthus palmeri*) and other plant residues in soil. Weed Sci 35:339-347.

Mohler CL, Galford AE (1997) Weed seedling emergence and seed survival: separating the effects of seed position and soil modification by tillage. Weed Res 147-155.

Morgan GD, Baumann PA, Chandler JM (2001) Competitive impact of Palmer amaranth (*Amaranthus palmeri*) on cotton (*Gossypium hirsutum*) development and yield. Weed Technol 15:408-412.

Murdoch AJ, Ellis RH (1992) Longevity, viability and dormancy. Seeds: The Ecology of Regeneration in Plant Communities 193–229.

Myers MW, Curran WS, VanGessel MJ, Calvin DD, Mortensen DA, Majek BA, Roth G W (2004) Predicting Weed Emergence for Eight Annual Species in the Northeastern United States. Weed Sci 52:913–919.

Nandula VK, Reddy KN, Kroger CH, Poston DH, Rimando AM, Duke SO, Bond JA, Ribeiro DN (2012) Multiple resistance to glyphosate and pyrithiobac in Palmer amaranth (*Amaranthus palmeri*) from Mississippi and response to flumiclorac. Weed Sci 60:179-188.

Norsworthy JK (2004) Soybean canopy formation effects on pitted morningglory (*Ipomoea lacunosa*), common cocklebur (*Xanthium strumarium*), and sicklepod (*Senna obtusifolia*) emergence. Weed Sci 52:954-960.

Norsworthy JK (2009) Use of Soybean Production Surveys to Determine Weed Management Needs of South Carolina Farmers. Weed Sci 17:195-201.

Norsworthy JK, Smith LK, Steckel LE, Koger CH (2009) Weed seed contamination of cotton gin trash. Weed Technol 23:574-580.

Norsworthy JK, Ward SM, Shaw DR, Llewellyn RS, Nichols RL, Webster TM, Barrett M (2012) Reducing the Risks of Herbicide Resistance: Best Management Practices and Recommendations. Weed Sci 60:31–62.

Omami EN, Haigh AM, Medd RW, Nicol HI (1999) Changes in germinability, dormancy and viability of *Amaranthus retroflexus* as affected by depth and duration of burial. Weed Res 39:345-354.

Oryokot JOE, Hunt LA, Murphy S, Swanton CJ (1997) Simulation of Pigweed (*Amaranthus spp.*) Seedling Emergence in Different Tillage Systems. Weed Sci 45:684–690.

Owen MDK (2000) Current use of transgenic herbicide-resistant soybean and corn in the USA. Crop Prot 19:765–771.

Pons TL (1991) Induction of dark dormancy in seeds: its importance for the seed bank in the soil. Funct Ecol 5:669-675.

Probert RJ (1992) The role of temperature in germination ecophysiology. In: Fenner, M. (Ed.), Seeds: The Ecology of Regeneration in Plant Communities. CAB Internation Wallingford, UK. 285-325.

Reddy KN (2001) Glyphosate-resistant soybean as a weed management tool: Opportunities and challenges. Weed Biol Manag 1:193-202.

Refsell DE, Hartzler RG (2009) Effect of tillage on common waterhemp (*Amaranthus rudis*) emergence and vertical distribution of seed in the soil. Weed Technol 23.1:129-133.

Salem HM, Valero C, Muñoz MA, Rodriguez MG, Silva LL (2015) Short-term effects of four tillage practices on soil physical properties, soil water potential, and maize yield. Geoderma 237:60-70.

Sauer J (1956) Recent migration and evolution of the dioecious amaranths. Evolution 11:11-31.

Sauer JD (1955) Revision of the dioecious amaranths. Madrono 13:5-46.

Schneider EC, Gupta SC (1985) Corn emergence as influenced by soil temperature, matric potential, and aggregate size distribution. Soil Sci Soc 49:415-422.

Schonbeck MW, Egley GH (1988) Effects of ethylene and some environmental factors on different stages of germination in redroot pigweed (*Amaranthus retroflexus* L.) seeds. Plant Cell Environ 11:189-197.

Sellers BA, Smeda R, Johnson WG, Kendig JA, Ellersieck MR (2003) Comparative growth of six *Amaranthus* species in Missouri. Weed Sci 51:329–333.

Shaw DR, Arnold JC (2002) Weed control from herbicide combinations with glyphosate. Weed Technol 16:1-6.

Smith DT, Baker RV, Steele GL (2000) Palmer amaranth (*Amarantus palmeri* )Impacts on Yield, Harvesting, and Ginning in Dryland Cotton (*Gossypium hirsutum*). Weed Technol 14:122–126.

Sosnoskie LM, Webster TM, Culpepper AS (2013) Glyphosate resistance does not affect Palmer amaranth (*Amaranthus palmeri*) seed bank longevity. Weed Sci 61:283-288.

Steckel LE, Sprague CL (2004) Common waterhemp *(Amaranthus rudis)* interference in corn. Weed Sci 52:359-364.

Steckel LE, Sprague LC, Stoller EW, Wax LM, Simmons FW (2007) Tillage, Cropping System, and Soil Depth Effects on Common Waterhemp (*Amaranthus rudis*) Seed Bank Persistence. Weed Sci 55:235-239.

Stoller EW, Harrison SK, Wax LM, Regnier EE, Nafziger ED (1987) Weed interference in soybeans (*Glycine max*). Weed Sci 3:155-181.

Taylorson RB, Borthwick HA (1969) Light infiltration by foliar canopies: significance for light-controlled weed seed germination. Weed Sci 17:48-51.

Teasdale JR, Mohler CL (1993) Light Transmittance, Soil Temperature, and Soil Moisture under Residue of Hairy Vetch and Rye. Agron J 85:673.

Tiansawat P, Dalling JW (2013) Differential seed germination responses to the ratio of red to far-red light in temperate and tropical species. Plant Ecol 214:751-764.

Tolk JA, Howell TA, Evett SR (1999) Effect of mulch, irrigation, and soil type on water use and yield of maize. Soil Til Res 50:137-147.

Ward SM, Webster TM, Steckel LE (2013) Palmer amaranth (*Amaranthus palmeri*): a review. Weed Technol 27:12-27.

Webster EP, Kelly JB, Larry DE (1999) Weed control and economics in nontransgenic and glyphosate-resistant soybean (*Glycine max*). Weed Technol 586-593.

Webster TM, Coble HD (1997) Changes in the Weed Species Composition of the Southern United States: 1974 to 1995. Weed Technol 11:167-174.

Webster TM, Grey TL (2015) Glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) morphology, growth, and seed production in Georgia. Weed Sci 63:264-272.

Webster TM, Nichols RL (2012) Changes in the prevalence of weed species in the major agronomic crops of the Southern United States. Weed Sci 60:145-157.

Wesson G, Wareing PF (1969) The induction of light sensitivity in weed seeds by burial. J Exp Bot 20:414-425.

Wiese AF, Davis RG (1967) Weed emergence from two soils at various moistures, temperatures and depths. Weeds 118-121.

Wilson RG, Young BG, Matthews JL, Weller SC, Johnson WG, Jordan DL, Owen MD, Dixon PM, Shaw DR (2011) Benchmark study on glyphosate-resistant cropping systems in the United States. Part 4: Weed management practices and effects on weed populations and soil seedbanks. Pest Manag Sci 67:771-800.

Wise AM, Grey TL, Prostko EP, Vencill WK, Webster TM (2009) Establishing the geographical distribution and level of acetolactate synthase resistance of Palmer amaranth (*Amaranthus palmeri*) accessions in Georgia. Weed Technol 23:214-220.

Wooley JT, Stoller EW (1978) Light penetration and light induced seed germination in soil. Plant Physiol 61:597-600.

Wright SR, Coble HD, Raper CDJr, Rufty TWJr (1999) Comparative Responses of Soybean (*Glycine max*), Sicklepod (*Senna obtusifolia*), and Palmer Amaranth (*Amaranthus palmeri*) to Root Zone and Aerial Temperatures. Weed Sci 47:167–174.

Wu C, Owen MD (2014) When Is Time to Emerge: Reproductive Phenology and Success of Natural Common Waterhemp (*Amaranthus rudis*) Cohorts in the Midwest United States? Weed Sci 62:107-117.

Yaacov G, Kigel J (1994) Differential sensitivity to high temperature of stages in the reproductive development of common bean (*Phaseolus vulgaris* L.) Field Crops Res 201-212.

Yenish JP, Doll JD, Buhler DD (1992) Effects of tillage on vertical distribution and viability of weed seed in soil. Weed Sci 429-433.

Young BG (2006) Changes in herbicide use patterns and production practices resulting from glyphosate-resistant crops. Weed Technol 20:301-307.

# APPENDICES

# APPENDIX A

## Table A.1

Test of treatment by year interaction for common waterhemp and Palmer amaranth considering log-transformed cumulative data during the experimental period in 2013 and 2014.

| Dependent variable | Source | $R^2$ | Var. | DF | Root MSE | Mean Square | F value | *p* |
|---|---|---|---|---|---|---|---|---|
| common waterhemp cumulative | | | | | | | | |
| | year | 0.95 | 7.15 | 1 | 0.53 | 124.28 | 447.95 | <0.001 |
| | rep(year) | 0.95 | 7.15 | 14 | 0.53 | 0.69 | 2.47 | 0.020 |
| | trt | 0.95 | 7.15 | 2 | 0.53 | 0.30 | 1.08 | 0.354 |
| | trt*year | 0.95 | 7.15 | 2 | 0.53 | 0.58 | 2.08 | 0.143 |
| Palmer amaranth cumulative | | | | | | | | |
| | year | 0.93 | 5.88 | 1 | 0.38 | 13.29 | 91.13 | <0.001 |
| | rep(year) | 0.93 | 5.88 | 14 | 0.38 | 3.05 | 20.96 | <0.001 |
| | trt | 0.93 | 5.88 | 2 | 0.38 | 0.44 | 3.05 | 0.063 |
| | trt*year | 0.93 | 5.88 | 2 | 0.38 | 0.26 | 0.18 | 0.188 |

Table A.2

ANOVA of data analysis for common waterhemp seed density in the seed bank per $m^{-2}$.

| Year | Cumulative common waterhemp emergence from soil seed bank | *Sum* | Average | Standard error | F value | *p* |
|---|---|---|---|---|---|---|
| 2013 | No-tillage | 8611 | 1076 | 564 | 0.20 | 0.814 |
| | Early tillage | 7320 | 915 | 628 | 0.20 | 0.814 |
| | Late tillage | 6890 | 861 | 861 | 0.20 | 0.814 |
| 2014 | No-tillage | 428838 | 53605 | 28,319 | 0.85 | 0.439 |
| | Early tillage | 285892 | 35736 | 32,368 | 0.85 | 0.439 |
| | Late tillage | 368990 | 46124 | 20,247 | 0.85 | 0.439 |

Table A.3

ANOVA of data analysis for Palmer amaranth seed density in the seed bank per $m^{-2}$.

| Year | Cumulative Palmer amaranth emergence from soil seed bank | *Sum* | Average | Standard error | F value | *p* |
|---|---|---|---|---|---|---|
| 2013 | No-tillage | 7750 | 969 | 502 | 0.23 | 0.793 |
| | Early tillage | 9472 | 1184 | 681 | 0.23 | 0.793 |
| | Late tillage | 8611 | 1077 | 690 | 0.23 | 0.793 |
| 2014 | No-tillage | 34875 | 4359 | 2,260 | 1.25 | 0.305 |
| | Early tillage | 22389 | 2799 | 3,230 | 1.25 | 0.305 |
| | Late tillage | 19375 | 2422 | 2,146 | 1.25 | 0.305 |

# APPENDIX B

## Table B.1

Test of weekly common waterhemp cumulative emergence per treatment in 2013.

| Dependent variable[a] | 2013 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | $R^2$ | F value | *p* | No-tillage | | Early tillage | | Late tillage | |
| | | | | ---------------------emergence[b]------------------- | | | | | |
| 5/07 | 0.78 | 6.77 | 0.419 | 5.298 | a | 8.399 | a | 5.513 | a |
| 5/14 | 0.80 | 0.57 | 0.579 | 13.700 | a | 17.278 | a | 15.857 | a |
| 5/21 | 0.70 | 0.81 | 0.464 | 28.535 | a | 30.648 | a | 34.527 | a |
| 5/28 | 0.74 | 5.17 | 0.020 | 44.156 | ab | 35.132 | b | 52.198 | a |
| 6/4 | 0.59 | 0.92 | 0.419 | 51.792 | a | 56.401 | a | 58.771 | a |
| 6/11 | 0.64 | 3.11 | 0.076 | 62.464 | ab | 70.681 | a | 59.212 | b |
| 6/18 | 0.60 | 1.81 | 0.199 | 77.463 | a | 80.402 | a | 73.505 | a |
| 6/25 | 0.78 | 2.63 | 0.107 | 83.113 | a | 86.458 | a | 86.802 | a |
| 7/2 | 0.85 | 7.31 | 0.006 | 90.326 | b | 92.117 | ab | 94.031 | a |
| 7/9 | 0.68 | 1.67 | 0.223 | 94.999 | a | 95.954 | a | 96.574 | a |
| 7/16 | 0.52 | 2.23 | 0.144 | 97.771 | a | 97.877 | a | 98.837 | a |
| 7/23 | 0.65 | 4.30 | 0.035 | 98.055 | b | 98.587 | ab | 99.251 | a |
| 7/30 | 0.40 | 2.15 | 0.153 | 98.725 | a | 99.091 | a | 99.542 | a |
| 8/6 | 0.45 | 1.66 | 0.225 | 99.440 | a | 99.368 | a | 99.769 | a |
| 8/13 | 0.46 | 2.37 | 0.130 | 99.606 | a | 99.472 | a | 99.886 | a |

Table B.1 (Continued)

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 8/20 | 0.46 | 1.97 | 0.176 | 99.779 | a | 99.545 | a | 99.914 | a |
| 8/27 | 0.46 | 2.07 | 0.163 | 99.854 | a | 99.579 | a | 99.914 | a |
| 9/3 | 0.40 | 0.76 | 0.486 | 99.856 | a | 99.772 | a | 99.914 | a |
| 9/10 | 0.63 | 1.47 | 0.263 | 99.861 | a | 99.855 | a | 99.971 | a |
| 9/17 | 0.68 | 1.35 | 0.290 | 99.923 | a | 99.924 | a | 100.000 | a |
| 9/24 | 0.68 | 1.05 | 0.376 | 99.930 | a | 99.936 | a | 100.000 | a |
| 10/01 | 0.40 | 1.09 | 0.363 | 99.930 | a | 100.000 | a | 100.000 | a |
| 10/8 | - | - | - | 100.000 | a | 100.000 | a | 100.000 | a |

[a] Degrees of freedom: main effect = 9 ; error = 14

[b] Cumulative common waterhemp emergence per treatment in each week

Table B.2

Test of weekly common waterhemp cumulative emergence per treatment in 2014.

| Dependent variable[a] | 2014 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | $R^2$ | F value | *p* | No-tillage | | Early tillage | | Late tillage | |
| | | | | ----------emergence[b]---------- | | | | | |
| 4/23 | 0.60 | 0.00 | 0.995 | 3.075 | a | 3.092 | a | 3.168 | a |
| 4/30 | 0.63 | 0.24 | 0.790 | 10.583 | a | 11.818 | a | 12.833 | a |
| 5/7 | 0.64 | 2.11 | 0.158 | 25.137 | a | 33.545 | a | 27.528 | a |
| 5/14 | 0.69 | 1.85 | 0.194 | 39.862 | a | 35.571 | a | 43.968 | a |
| 5/21 | 0.71 | 2.74 | 0.099 | 44.185 | ab | 37.511 | b | 47.817 | a |
| 5/28 | 0.71 | 2.54 | 0.114 | 46.306 | ab | 41.241 | b | 51.126 | a |
| 6/4 | 0.70 | 3.12 | 0.07 | 49.799 | ab | 44.553 | b | 55.303 | a |
| 6/11 | 0.66 | 3.40 | 0.06 | 64.851 | ab | 57.097 | a | 66.433 | a |
| 6/18 | 0.77 | 12.02 | <0.001 | 71.246 | b | 63.758 | c | 80.293 | a |
| 6/25 | 0.79 | 14.13 | <0.001 | 83.269 | a | 76.232 | b | 87.462 | a |
| 7/2 | 0.78 | 15.29 | <0.001 | 91.445 | a | 85.789 | b | 93.066 | a |
| 7/9 | 0.78 | 14.43 | <0.001 | 92.709 | a | 87.536 | b | 93.985 | a |
| 7/16 | 0.78 | 14.00 | <0.001 | 93.319 | a | 88.383 | b | 94.356 | a |
| 7/23 | 0.78 | 13.94 | <0.001 | 93.666 | a | 88.885 | b | 94.558 | a |
| 7/30 | 0.78 | 13.84 | <0.001 | 93.772 | a | 88.999 | b | 94.628 | a |
| 8/6 | 0.78 | 13.79 | <0.001 | 93.787 | a | 89.045 | b | 94.645 | a |
| 8/13 | 0.78 | 14.73 | <0.001 | 94.244 | a | 89.548 | b | 94.882 | a |

Table B.2 (Continued)

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 8/20 | 0.77 | 14.01 | <0.001 | 95.464 | a | 91.247 | b | 95.920 | a |
| 8/27 | 0.73 | 11.46 | 0.001 | 96.635 | a | 92.845 | b | 96.635 | a |
| 9/3 | 0.72 | 10.80 | 0.001 | 97.676 | a | 94.899 | b | 97.591 | a |
| 9/10 | 0.72 | 9.63 | 0.002 | 99.066 | a | 98.072 | b | 98.964 | a |
| 9/17 | 0.55 | 4.54 | 0.030 | 99.632 | a | 99.222 | b | 99.511 | ab |
| 9/24 | 0.50 | 0.72 | 0.503 | 99.928 | a | 99.888 | a | 99.898 | a |
| 10/01 | 0.23 | 0.11 | 0.896 | 99.969 | a | 99.967 | a | 99.973 | a |
| 10/08 | 0.24 | 0.43 | 0.659 | 99.995 | a | 99.988 | a | 99.992 | a |
| 10/15 | 0.32 | 0.68 | 0.524 | 99.999 | a | 99.995 | a | 99.993 | a |
| 10/22 | 0.34 | 0.76 | 0.487 | 100.000 | a | 99.995 | a | 99.994 | a |
| 10/29 | - | - | - | 100.000 | a | 100.000 | a | 100.000 | a |

[a] Degrees of freedom: main effect = 9 ; error = 14

[b] Cumulative common waterhemp emergence per treatment in each week

Table B.3

Test of weekly log-transformed common waterhemp cumulative emergence per treatment in 2013.

| Dependent variable[a] | 2013 | | | | | |
|---|---|---|---|---|---|---|
| | $R^2$ | F value | *p* | No-tillage | Early tillage | Late tillage |
| | | | | ----------------------emergence[b] | ---------------- | |
| 5/7 | 0.65 | 0.65 | 0.535 | 2.178 a | 2.855 a | 2.300 a |
| 5/14 | 0.63 | 0.31 | 0.737 | 3.490 a | 3.866 a | 3.732 a |
| 5/21 | 0.58 | 0.08 | 0.924 | 4.435 a | 4.537 a | 4.597 a |
| 5/28 | 0.59 | 0.32 | 0.728 | 4.893 a | 4.702 a | 5.015 a |
| 6/4 | 0.55 | 0.11 | 0.897 | 5.066 a | 5.237 a | 5.145 a |
| 6/11 | 0.56 | 0.41 | 0.670 | 5.257 a | 5.477 a | 5.153 a |
| 6/18 | 0.56 | 0.24 | 0.792 | 5.484 a | 5.611 a | 5.375 a |
| 6/25 | 0.55 | 0.10 | 0.903 | 5.556 a | 5.685 a | 5.550 a |
| 7/2 | 0.53 | 0.08 | 0.927 | 5.640 a | 5.749 a | 5.632 a |
| 7/9 | 0.52 | 0.08 | 0.919 | 5.691 a | 5.790 a | 5.659 a |
| 7/16 | 0.52 | 0.08 | 0.925 | 5.720 a | 5.810 a | 5.682 a |
| 7/23 | 0.52 | 0.08 | 0.921 | 5.723 a | 5.817 a | 5.686 a |
| 7/30 | 0.52 | 0.08 | 0.919 | 5.729 a | 5.823 a | 5.689 a |
| 8/6 | 0.52 | 0.08 | 0.920 | 5.737 a | 5.825 a | 5.691 a |
| 8/13 | 0.52 | 0.08 | 0.920 | 5.738 a | 5.826 a | 5.692 a |
| 8/20 | 0.52 | 0.08 | 0.920 | 5.740 a | 5.827 a | 5.693 a |

Table B.3 (Continued)

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 8/27 | 0.52 | 0.08 | 0.920 | 5.741 | a | 5.827 | a | 5.693 | a |
| 9/3 | 0.52 | 0.09 | 0.917 | 5.741 | a | 5.829 | a | 5.693 | a |
| 9/10 | 0.52 | 0.09 | 0.917 | 5.741 | a | 5.830 | a | 5.693 | a |
| 9/17 | 0.52 | 0.09 | 0.916 | 5.741 | a | 5.831 | a | 5.694 | a |
| 9/24 | 0.52 | 0.09 | 0.916 | 5.741 | a | 5.831 | a | 5.694 | a |
| 10/01 | 0.52 | 0.09 | 0.915 | 5.741 | a | 5.832 | a | 5.694 | a |
| 10/08 | 0.52 | 0.09 | 0.915 | 5.742 | a | 5.832 | a | 5.694 | a |
| 10/15 | 0.52 | 0.09 | 0.915 | 5.742 | a | 5.832 | a | 5.694 | a |
| 10/22 | 0.52 | 0.09 | 0.915 | 5.742 | a | 5.832 | a | 5.694 | a |
| 10/29 | 0.52 | 0.09 | 0.915 | 5.742 | a | 5.832 | a | 5.694 | a |

[a] Degrees of freedom: main effect = 9 ; error = 14

[b] Log-transformed common waterhemp cumulative emergence per treatment in each week

Table B.4

Test of weekly log-transformed common waterhemp cumulative emergence per treatment in 2014.

| Dependent variable[a] | 2014 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | $R^2$ | F value | $p$ | No-tillage | | Early tillage | | Late tillage | |
| | | | | ---------------------emergence[b]---------------- | | | | | |
| 4/23 | 0.60 | 1.14 | 0.347 | 5.430 | a[a] | 4.801 | a | 5.390 | a |
| 4/30 | 0.63 | 1.34 | 0.292 | 6.802 | a | 6.278 | a | 6.837 | a |
| 5/7 | 0.61 | 0.51 | 0.610 | 7.784 | a | 7.498 | a | 7.692 | a |
| 5/14 | 0.69 | 4.71 | 0.027 | 8.290 | a | 7.557 | b | 8.182 | a |
| 5/21 | 0.70 | 5.57 | 0.016 | 8.398 | a | 7.615 | b | 8.268 | a |
| 5/28 | 0.70 | 5.40 | 0.018 | 8.451 | a | 7.710 | b | 8.343 | a |
| 6/4 | 0.70 | 5.70 | 0.015 | 8.531 | a | 7.793 | b | 8.428 | a |
| 6/11 | 0.72 | 6.54 | 0.009 | 8.816 | a | 8.049 | b | 8.623 | a |
| 6/18 | 0.75 | 8.15 | 0.004 | 8.911 | a | 8.161 | b | 8.819 | a |
| 6/25 | 0.75 | 8.46 | 0.003 | 9.072 | a | 8.348 | b | 8.907 | a |
| 7/2 | 0.75 | 8.40 | 0.004 | 9.168 | a | 8.467 | b | 8.970 | a |
| 7/9 | 0.75 | 8.41 | 0.004 | 9.181 | a | 8.487 | b | 8.980 | a |
| 7/16 | 0.75 | 8.41 | 0.004 | 9.188 | a | 8.497 | b | 8.984 | a |
| 7/23 | 0.75 | 8.39 | 0.004 | 9.192 | a | 8.503 | b | 8.986 | a |
| 7/30 | 0.75 | 8.39 | 0.004 | 9.193 | a | 8.504 | b | 8.987 | a |
| 8/6 | 0.75 | 8.39 | 0.004 | 9.193 | a | 8.505 | b | 8.987 | a |

Table B.4 (Continued)

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 8/13 | 0.75 | 8.34 | 0.004 | 9.198 | a | 8.510 | b | 8.990 | a |
| 8/20 | 0.75 | 8.29 | 0.004 | 9.211 | a | 8.529 | b | 9.001 | a |
| 8/27 | 0.75 | 8.14 | 0.004 | 9.220 | a | 8.547 | b | 9.008 | a |
| 9/3 | 0.75 | 8.03 | 0.004 | 9.234 | a | 8.569 | b | 9.018 | a |
| 9/10 | 0.74 | 7.65 | 0.005 | 9.248 | a | 8.602 | b | 9.032 | a |
| 9/17 | 0.74 | 7.57 | 0.005 | 9.254 | a | 8.614 | b | 9.038 | a |
| 9/24 | 0.74 | 7.55 | 0.006 | 9.257 | a | 8.620 | b | 9.042 | a |
| 10/01 | 0.74 | 7.56 | 0.005 | 9.257 | a | 8.621 | b | 9.042 | a |
| 10/08 | 0.74 | 7.56 | 0.005 | 9.257 | a | 8.621 | b | 9.042 | a |
| 10/15 | 0.74 | 7.56 | 0.005 | 9.257 | a | 8.622 | b | 9.042 | a |
| 10/22 | 0.74 | 7.56 | 0.005 | 9.257 | a | 8.622 | b | 9.042 | a |
| 10/29 | 0.74 | 7.56 | 0.005 | 9.257 | a | 8.622 | b | 9.043 | a |

[a] Degrees of freedom: main effect = 9 ; error = 14

[b] Log-transformed common waterhemp cumulative emergence per treatment in each week

# APPENDIX C

Table C.1

Test of weekly Palmer amaranth cumulative emergence per treatment in 2013.

| Dependent variable[a] | 2013 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | $R^2$ | F value | $p$ | No-tillage | | Early tillage | | Late tillage | |
| | | | | ----------------------emergence[b]------------------ | | | | | |
| 5/14 | 0.62 | 0.50 | 0.616 | 4.611 | a | 3.147 | a | 2.417 | a |
| 5/21 | 0.57 | 4.17 | 0.038 | 18.492 | a | 12.420 | a | 11.507 | a |
| 5/28 | 0.70 | 9.93 | 0.002 | 27.962 | a | 16.219 | b | 20.493 | b |
| 6/4 | 0.57 | 2.10 | 0.159 | 34.536 | a | 33.397 | a | 28.173 | a |
| 6/11 | 0.77 | 15.76 | <0.001 | 46.359 | a | 48.550 | a | 30.312 | b |
| 6/18 | 0.40 | 1.00 | 0.392 | 59.722 | a | 64.012 | a | 62.383 | a |
| 6/25 | 0.67 | 9.70 | 0.002 | 72.872 | b | 75.072 | b | 82.917 | a |
| 7/2 | 0.80 | 7.69 | 0.005 | 80.862 | b | 82.371 | b | 89.483 | a |
| 7/9 | 0.79 | 5.44 | 0.017 | 86.304 | b | 86.002 | b | 92.188 | a |
| 7/16 | 0.75 | 4.15 | 0.038 | 89.043 | b | 89.498 | b | 94.011 | a |
| 7/23 | 0.76 | 3.96 | 0.043 | 90.945 | b | 90.688 | b | 95.064 | a |
| 7/30 | 0.62 | 3.36 | 0.064 | 97.324 | ab | 96.233 | b | 97.864 | a |
| 8/6 | 0.72 | 3.28 | 0.067 | 98.778 | a | 97.889 | b | 98.638 | ab |
| 8/13 | 0.71 | 3.01 | 0.081 | 99.013 | a | 98.260 | b | 98.768 | ab |
| 8/20 | 0.70 | 2.66 | 0.105 | 99.065 | a | 98.351 | b | 98.920 | ab |

Table C.1 (Continued)

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 8/27 | 0.46 | 2.33 | 0.134 | 99.396 | a | 98.426 | a | 99.085 | a |
| 9/3 | 0.47 | 3.08 | 0.077 | 99.396 | a | 98.627 | a | 99.424 | a |
| 9/10 | 0.19 | 0.72 | 0.502 | 99.634 | a | 99.437 | a | 99.737 | a |
| 9/17 | 0.29 | 0.72 | 0.504 | 99.756 | a | 99.565 | a | 99.856 | a |
| 9/24 | 0.59 | 1.34 | 0.293 | 99.898 | a | 99.785 | a | 100.000 | a |
| 10/1 | 0.53 | 1.34 | 0.293 | 99.983 | a | 99.991 | a | 100.000 | a |
| 10/8 | 0.45 | 2.23 | 0.144 | 99.983 | a | 100.000 | a | 100.000 | a |
| 10/15 | 0.45 | 2.23 | 0.144 | 99.983 | a | 100.000 | a | 100.000 | a |
| 10/22 | - | - | - | 100.000 | a | 100.000 | a | 100.000 | a |

[a] Degrees of freedom: main effect = 9 ; error = 14

[b] Cumulative Palmer amaranth emergence per treatment in each week

Table C.2

Test of weekly Palmer amaranth cumulative emergence per treatment in 2014.

| | 2014 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Dependent variable[a] | $R^2$ | F value | $p$ | No-tillage | | Early tillage | | Late tillage | |
| | | | | ----------------------emergence[b]------------------- | | | | | |
| 5/14 | 0.42 | 0.68 | 0.522 | 1.000 | a | 1.000 | a | 1.000 | a |
| 5/21 | 0.29 | 1.13 | 0.349 | 1.000 | a | 1.000 | a | 1.000 | a |
| 5/28 | 0.80 | 1.22 | 0.325 | 3.300 | a | 4.400 | a | 4.700 | a |
| 6/4 | 0.79 | 4.51 | 0.030 | 12.900 | b | 15.200 | ab | 19.400 | a |
| 6/11 | 0.76 | 4.52 | 0.030 | 22.700 | b | 27.100 | b | 30.100 | a |
| 6/18 | 0.50 | 4.74 | 0.026 | 50.600 | b | 53.800 | b | 63.200 | a |
| 6/25 | 0.62 | 7.34 | 0.006 | 66.300 | b | 67.600 | b | 76.900 | a |
| 7/2 | 0.55 | 6.45 | 0.010 | 75.600 | b | 76.200 | b | 83.900 | a |
| 7/9 | 0.47 | 4.72 | 0.027 | 79.100 | b | 78.600 | b | 85.800 | a |
| 7/16 | 0.45 | 4.01 | 0.041 | 81.700 | b | 82.000 | b | 87.500 | a |
| 7/23 | 0.39 | 2.78 | 0.095 | 84.600 | ab | 84.000 | b | 88.600 | a |
| 7/30 | 0.38 | 2.40 | 0.126 | 85.400 | a | 84.800 | a | 89.100 | a |
| 8/6 | 0.37 | 2.38 | 0.128 | 85.500 | a | 84.900 | a | 89.200 | a |
| 8/13 | 0.40 | 1.61 | 0.234 | 87.000 | a | 87.000 | a | 89.900 | a |
| 8/20 | 0.37 | 0.13 | 0.875 | 92.800 | a | 92.200 | a | 92.800 | a |
| 8/27 | 0.49 | 0.40 | 0.679 | 94.700 | a | 94.100 | a | 95.000 | a |
| 9/3 | 0.47 | 1.21 | 0.326 | 95.800 | a | 95.100 | a | 96.300 | a |

Table C.2 (Continued)

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 9/10 | 0.57 | 0.07 | 0.936 | 98.000 | a | 97.800 | a | 98.100 | a |
| 9/17 | 0.59 | 1.91 | 0.184 | 99.300 | a | 98.800 | a | 99.300 | a |
| 9/24 | 0.61 | 2.10 | 0.159 | 99.600 | a | 99.400 | a | 99.700 | a |
| 10/1 | 0.53 | 1.83 | 0.196 | 99.900 | a | 99.800 | a | 99.900 | a |
| 10/8 | 0.49 | 3.17 | 0.07 | 99.900 | a | 100.000 | a | 100.000 | a |
| 10/15 | - | - | - | 100.000 | a | 100.000 | a | 100.000 | a |

[a] Degrees of freedom: main effect = 9 ; error = 14

[b] Cumulative Palmer amaranth emergence per treatment in each week

Table C.3

Test of weekly log-transformed Palmer amaranth cumulative emergence per treatment in 2013.

| Dependent variable[a] | 2013 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | $R^2$ | F value | $p$ | No-tillage | | Early tillage | | Late tillage | |
| | | | | ----------------------emergence[b]---------------- | | | | | |
| 5/14 | 0.36 | 0.10 | 0.908 | 1.779 | a | 1.625 | a | 1.713 | a |
| 5/21 | 0.95 | 3.08 | 0.077 | 4.272 | a | 3.775 | b | 3.853 | ab |
| 5/28 | 0.95 | 5.87 | 0.014 | 4.749 | a | 4.012 | b | 4.438 | ab |
| 6/4 | 0.95 | 1.03 | 0.381 | 4.968 | a | 4.735 | a | 4.746 | a |
| 6/11 | 0.96 | 3.24 | 0.069 | 5.257 | a | 5.119 | ab | 4.825 | b |
| 6/18 | 0.96 | 0.42 | 0.668 | 5.512 | a | 5.411 | a | 5.556 | a |
| 6/25 | 0.96 | 1.46 | 0.265 | 5.713 | a | 5.571 | a | 5.841 | a |
| 7/2 | 0.96 | 1.39 | 0.280 | 5.813 | a | 5.660 | a | 5.917 | a |
| 7/9 | 0.96 | 1.29 | 0.306 | 5.879 | a | 5.703 | a | 5.947 | a |
| 7/16 | 0.96 | 1.09 | 0.362 | 5.911 | a | 5.744 | a | 5.967 | a |
| 7/23 | 0.96 | 1.10 | 0.359 | 5.933 | a | 5.758 | a | 5.978 | a |
| 7/30 | 0.96 | 1.02 | 0.387 | 6.002 | a | 5.819 | a | 6.007 | a |
| 8/6 | 0.97 | 0.97 | 0.403 | 6.017 | a | 5.836 | a | 6.015 | a |
| 8/13 | 0.97 | 0.96 | 0.408 | 6.019 | a | 5.840 | a | 6.017 | a |
| 8/20 | 0.97 | 0.96 | 0.408 | 6.020 | a | 5.841 | a | 6.018 | a |
| 8/27 | 0.97 | 0.97 | 0.403 | 6.023 | a | 5.842 | a | 6.020 | a |
| 9/3 | 0.97 | 0.97 | 0.403 | 6.023 | a | 5.844 | a | 6.023 | a |

Table C.3 (Continued)

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 9/10 | 0.97 | 0.92 | 0.421 | 6.026 | a | 5.852 | a | 6.026 | a |
| 9/17 | 0.97 | 0.92 | 0.423 | 6.027 | a | 5.853 | a | 6.027 | a |
| 9/24 | 0.97 | 0.92 | 0.422 | 6.028 | a | 5.855 | a | 6.029 | a |
| 10/1 | 0.97 | 0.91 | 0.426 | 6.029 | a | 5.857 | a | 6.029 | a |
| 10/8 | 0.97 | 0.90 | 0.427 | 6.029 | a | 5.857 | a | 6.029 | a |
| 10/15 | 0.97 | 0.90 | 0.427 | 6.029 | a | 5.875 | a | 6.029 | a |
| 10/22 | 0.97 | 0.90 | 0.426 | 6.029 | a | 5.857 | a | 6.029 | a |

[a] Degrees of freedom: main effect = 9 ; error = 14

[b] Log-transformed Palmer amaranth cumulative emergence per treatment in each week

Table C.4

Test of weekly log-transformed Palmer amaranth cumulative emergence per treatment in 2014.

| | 2014 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Dependent variable[a] | $R^2$ | F value | *p* | No-tillage | | Early tillage | | Late tillage | |
| | | | | ----------------------emergence[b]---------------- | | | | | |
| 5/14 | 0.56 | 0.16 | 0.856 | 0.900 | a | 1.015 | a | 1.097 | a |
| 5/21 | 0.43 | 0.52 | 0.604 | 1.050 | a | 1.268 | a | 1.512 | a |
| 5/28 | 0.73 | 0.03 | 0.972 | 3.579 | a | 3.513 | a | 3.579 | a |
| 6/4 | 0.68 | 0.33 | 0.722 | 5.162 | a | 4.956 | a | 5.110 | a |
| 6/11 | 0.56 | 0.64 | 0.540 | 5.838 | a | 5.531 | a | 5.610 | a |
| 6/18 | 0.47 | 1.11 | 0.355 | 6.659 | a | 6.261 | a | 6.371 | a |
| 6/25 | 0.55 | 1.73 | 0.213 | 6.932 | a | 6.493 | a | 6.574 | a |
| 7/2 | 0.54 | 2.05 | 0.165 | 7.066 | a | 6.617 | a | 6.662 | a |
| 7/9 | 0.54 | 2.21 | 0.146 | 7.110 | a | 6.647 | a | 6.684 | a |
| 7/16 | 0.55 | 2.26 | 0.140 | 7.143 | a | 6.690 | a | 6.704 | a |
| 7/23 | 0.56 | 2.49 | 0.119 | 7.178 | a | 6.715 | a | 6.717 | a |
| 7/30 | 0.57 | 2.52 | 0.116 | 7.187 | a | 6.724 | a | 6.722 | a |
| 8/6 | 0.57 | 2.53 | 0.115 | 7.189 | a | 6.725 | a | 6.723 | a |
| 8/13 | 0.58 | 2.61 | 0.108 | 7.207 | a | 6.749 | a | 6.731 | a |
| 8/20 | 0.60 | 2.97 | 0.083 | 7.271 | a | 6.809 | ab | 6.763 | b |
| 8/27 | 0.61 | 3.03 | 0.080 | 7.290 | a | 6.829 | ab | 6.787 | b |
| 9/3 | 0.61 | 3.05 | 0.079 | 7.302 | a | 6.839 | ab | 6.801 | b |

Table C.4 (Continued)

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 9/10 | 0.61 | 3.03 | 0.080 | 7.325 | a | 6.868 | ab | 6.818 | b |
| 9/17 | 0.61 | 3.05 | 0.079 | 7.338 | a | 6.878 | ab | 6.831 | b |
| 9/24 | 0.61 | 3.05 | 0.079 | 7.342 | a | 6.885 | ab | 6.835 | b |
| 10/1 | 0.60 | 3.05 | 0.079 | 7.345 | a | 6.888 | ab | 6.837 | b |
| 10/8 | 0.60 | 3.05 | 0.079 | 7.345 | a | 6.890 | ab | 6.838 | b |
| 10/15 | 0.60 | 3.05 | 0.079 | 7.345 | a | 6.890 | ab | 6.838 | b |
| 10/22 | 0.60 | 3.05 | 0.079 | 7.345 | a | 6.890 | ab | 6.838 | b |

[a] Degrees of freedom: main effect = 9 ; error = 14

[b] Log-transformed Palmer amaranth cumulative emergence per treatment in each week

# APPENDIX D

Table D.1

Stepwise regression of common waterhemp peaks of emergence and environmental factors in 2013.

| 2013 | | |
|---|---|---|
| *MSE* | $R^2$ | *STD* |
| 1.141 | 0.35 | 7.397 |

| Dependent variable[a] | Parameter estimate[b] | F value | *p* |
|---|---|---|---|
| Max soil moist 11 days | 0.075 | 2.57 | 0.013 |
| Max soil temp 13 days | 0.460 | 4.82 | <0.001 |

| Week | Max soil moist 11 days (%VWC) | Max soil temp 13 days (C) | Predicted emergence (plants.m$^{-2}$) [c] |
|---|---|---|---|
| 4/23/2013 | 47 | 23 | 7 |
| 4/30/2013 | 44 | 22 | 2 |
| 5/7/2013 | 45 | 27 | 11 |
| 5/14/2013 | 46 | 28 | 11 |
| 5/21/2013 | 44 | 30 | 47 |
| 5/28/2013 | 41 | 31 | 6 |
| 6/4/2013 | 44 | 28 | 17 |
| 6/11/2013 | 44 | 31 | 15 |

Table D.1 (Continued)

| | | | |
|---|---|---|---|
| 6/18/2013 | 42 | 36 | 24 |
| 6/25/2013 | 48 | 38 | 8 |
| 7/2/2013 | 46 | 37 | 7 |
| 7/9/2013 | 49 | 34 | 11 |
| 7/16/2013 | 35 | 39 | 3 |
| 7/23/2013 | 35 | 42 | 6 |
| 7/30/2013 | 47 | 45 | 6 |
| 8/6/2013 | 41 | 38 | 5 |
| 8/13/2013 | 33 | 38 | 3 |

[a] Best predictors for common waterhemp emergence according to stepwise regression.

[b] Characteristic of the interaction of common waterhemp emergence with soil temperature and soil moisture.

[c] Number of common waterhemp seedlings as a result of variable factors.

Table D.2

Stepwise regression of common waterhemp peaks of emergence and environmental factors in 2014.

| 2014 | | |
|---|---|---|
| *MSE* | $R^2$ | *STD* |
| 1.243 | 0.55 | 5.246 |

| Dependent variable[a] | Parameter estimate[b] | F value | *p* |
|---|---|---|---|
| Max soil temp 10 days | -0.201 | -7.55 | <0.001 |
| Min soil temp 8 days | 0.158 | 6.09 | <0.001 |

| Week | Max soil temp 10 days (%VWC) | Min soil temp 8 days (C) | Predicted emergence (plants.m$^{-2}$) [c] |
|---|---|---|---|
| 4/23/2014 | 24 | 2 | 187 |
| 4/30/2014 | 23 | 8 | 502 |
| 5/7/2014 | 25 | 7 | 416 |
| 5/14/2014 | 31 | 14 | 231 |
| 5/21/2014 | 31 | 6 | 31 |
| 5/28/2014 | 34 | 17 | 154 |
| 6/4/2014 | 34 | 18 | 199 |
| 6/11/2014 | 35 | 17 | 223 |
| 6/18/2014 | 30 | 13 | 593 |
| 6/25/2014 | 40 | 22 | 78 |

Table D.2 (Continued)

| | | | |
|---|---|---|---|
| 7/2/2014 | 35 | 20 | 528 |
| 7/9/2014 | 38 | 17 | 33 |
| 7/16/2014 | 40 | 16 | 38 |
| 7/23/2014 | 39 | 15 | 28 |
| 7/30/2014 | 39 | 17 | 17 |
| 8/6/2014 | 40 | 18 | 10 |
| 8/13/2014 | 40 | 18 | 30 |
| 8/20/2014 | 36 | 16 | 158 |
| 8/27/2014 | 39 | 22 | 228 |
| 9/3/2014 | 41 | 22 | 91 |
| 9/10/2014 | 36 | 14 | 99 |
| 9/17/2014 | 31 | 9 | 100 |
| 9/24/2014 | 30 | 11 | 249 |
| 10/1/2014 | 33 | 12 | 37 |
| 10/8/2014 | 34 | 6 | 5 |

[a] Best predictors for common waterhemp emergence according to stepwise regression.

[b] Characteristic of the interaction of common waterhemp emergence with soil temperature and soil moisture.

[c] Number of common waterhemp seedlings as a result of variable factors.

# APPENDIX E

Table E.1

Stepwise regression of Palmer amaranth peaks of emergence and environmental factors in 2013.

| 2013 | | |
|---|---|---|
| *MSE* | $R^2$ | *STD* |
| 0.882 | 0.30 | 5.648 |

| Dependent variable[a] | Parameter estimate[b] | F value | *p* |
|---|---|---|---|
| Max soil moist 11 days | 0.084 | 3.61 | <0.001 |
| Max soil temp 14 days | -0.004 | -0.25 | 0.807 |

| Week | Max soil moist 11 days (%VWC) | Max soil temp 14 days (C) | Predicted emergence (plants.m$^{-2}$) [c] |
|---|---|---|---|
| 5/14/2013 | 49 | 27 | 26 |
| 5/21/2013 | 45 | 28 | 20 |
| 5/28/2013 | 41 | 31 | 14 |
| 6/4/2013 | 50 | 29 | 30 |
| 6/11/2013 | 51 | 29 | 31 |
| 6/18/2013 | 43 | 32 | 16 |
| 6/25/2013 | 49 | 37 | 26 |
| 7/2/2013 | 49 | 37 | 25 |

Table E.1 (Continued)

| | | | |
|---|---|---|---|
| 7/9/2013 | 49 | 35 | 27 |
| 7/16/2013 | 32 | 40 | 6 |
| 7/23/2013 | 34 | 40 | 7 |
| 7/30/2013 | 42 | 43 | 13 |
| 8/6/2013 | 38 | 39 | 10 |
| 8/13/2013 | 34 | 37 | 7 |

[a] Best predictors for Palmer amaranth emergence according to stepwise regression.

[b] Characteristic of the interaction of Palmer amaranth emergence with soil temperature and soil moisture.

[c] Number of Palmer amaranth seedlings as a result of variable factors.

Table E.2

Stepwise regression of Palmer amaranth peaks of emergence and environmental factors in 2014.

| 2014 | | |
|---|---|---|
| *MSE* | $R^2$ | *STD* |
| 1.314 | 0.37 | 6.420 |

| Dependent variable[a] | Parameter estimate[b] | F value | *p* |
|---|---|---|---|
| Max soil moist 14 days | 0.132 | 5.01 | <0.001 |
| Max soil temp 8 days | 0.077 | 2.37 | 0.022 |

| Week | Max soil moist 14 days (%VWC) | Max soil temp 8 days (C) | Predicted emergence (plants.m$^{-2}$) [c] |
|---|---|---|---|
| 5/14/2014 | 39 | 30 | 12 |
| 5/21/2014 | 40 | 29 | 13 |
| 5/28/2014 | 37 | 32 | 13 |
| 6/4/2014 | 36 | 34 | 16 |
| 6/11/2014 | 41 | 31 | 19 |
| 6/18/2014 | 50 | 35 | 111 |
| 6/25/2014 | 42 | 39 | 63 |
| 7/2/2014 | 48 | 36 | 95 |
| 7/9/2014 | 33 | 39 | 19 |
| 7/16/2014 | 44 | 39 | 84 |
| 7/23/2014 | 42 | 38 | 57 |

Table E.2 (Continued)

| | | | |
|---|---|---|---|
| 7/30/2014 | 28 | 39 | 9 |
| 8/6/2014 | 25 | 39 | 6 |
| 8/13/2014 | 30 | 38 | 11 |

[a] Best predictors for Palmer amaranth emergence according to stepwise regression.

[b] Characteristic of the interaction of Palmer amaranth emergence with soil temperature and soil moisture.

[c] Number of Palmer amaranth seedlings as a result of variable factors.

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França, L. X.; Coelho, L.; Carvalho, H. P.; Camargo, R. 2010. Evaluation of wildfire risk in Uberlândia-MG. Federal University of Uberlândia Academic Research Symposium.

Franca, L. X.; Young, B.G.; Young, J.M.; Matthews, J.L.; Norsworthy, J.K.; Eubank, T.W.; Loux, M.M.; Steckel, L.E.; Johnson, W.G.; Davis, V.M.; Smeda, R.J.; Kruger, G.R. 2013. Emergence Patterns of Waterhemp and Palmer amaranth in Southern and Midwestern U.S. Page 50 *in* Proceedings of the North Central Weed Science Society. Columbus, OH: North Central Weed Science Society

Franca, L. X.; Young, B.G.; Young, J.M.; Matthews. 2014. Emergence Patterns of Waterhemp and Palmer amaranth under No-till and Tillage Conditions in Southern Illinois. Page 55 *in* Proceedings of the North Central Weed Science Society. Minneapolis, MN: North Central Weed Science Society