EMERGENCE PATTERN OF *AMARANTHUS* SPP. AND IMPACT ON GROWTH AND REPRODUCTION

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by
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Chapter I

Literature Review

Introduction

Palmer amaranth (*Amaranthus palmeri* S. Wats) and common waterhemp (*Amaranthus rudis* Sauer) are troublesome, dioecious weeds in agronomic crops, reducing yields and restricting harvest efficiency (Klingaman and Oliver 1994; Rowland et al. 1999). Researchers in the Midwest have observed increased densities of waterhemp and Palmer amaranth in row crops (Massinga et al. 2001; Steckel and Sprague 2004a). Additionally, Palmer amaranth continues to be problematic in corn (*Zea mays* L.), cotton (*Gossypium barbadense* L.) and soybean (*Glycine max* (L.) Merr) throughout the mid-south and is now spreading northward across the mid-west (Horak and Loughin 2000).

Factors influencing increased frequency of waterhemp and Palmer amaranth include: decreased levels of in-season tillage, which benefits small-seeded species; decreased use of residual herbicides; and escalation of populations resistant to one or more herbicide mode of action (Buhler 1992; Nordby et al. 2007). In the U.S., the number of no-till hectares increased from 6.6 million in 1990 to 26.3 million by 2008 (Anonymous 2008).

Palmer amaranth originated in the southwestern United States and Mexico (Sauer 1957). Of all the *Amaranthus* species, Palmer amaranth has spread the farthest from its center of origin, expanding from southern California to Oklahoma, Kansas, Nebraska and Missouri (Horak 2000). Recently, Palmer amaranth was reported in Indiana and Illinois (Legleiter and Johnson 2013; Riggins et al. 2013). Waterhemp is indigenous to areas west of the Mississippi River from Nebraska to Texas, but now spans the Great Plains region and east into the Ohio River Valley (Steckel et al. 2004; 2007). Murray (1940) first reported *Amaranthus* species introgressing with one another. Pratt and Clark (2001) furthered Murray's research by theorizing that tall waterhemp (*Amaranthus tuberculatus* (Moq.) J.D. Sauer) and common waterhemp have crossed, resulting in a polymorphic waterhemp species referred to as *A. tuberculatus.*

***Amaranthus* Biology**

There are approximately 75 species in the genus *Amaranthus*; of which ten are dioecious (separate male and female plants. Some have become significant weedy species; all are native to North America (Steckel 2007). Dioecious *Amaranthus* spp. are in the subgenus *Acnida* under the genus *Amaranthus* (Mosyakin and Robertson 1996; Sauer 1955).

To the untrained eye, Palmer amaranth and waterhemp appear similar and may be difficult to distinguish. Identification of seedling plants is possible using leaf, stem and floral parts. According to Steckel et al. (2007) and Pratt et al. (1999), stems can range from green to red and variations of both colors. Mature Palmer amaranth leaves are hairless and egg-shaped, typically notched at the tip, with petioles often exceeding the leaf length (Sauer 1955). Leaves are arranged alternately along the stem and have long petioles, often appearing in a poinsettia (*Euphorbia pulcherrima* Willd.) like formation. Palmer amaranth flowering structures are 30 to 60 cm long. Waterhemp generally exhibits lanceolate (widest at the center) leaves with a notch in the tip. Waterhemp petioles are shorter compared to Palmer amaranth. Waterhemp inflorescences are 3 to 35 cm in length and often branched (Horak et al. 1994). For both species, mature seed is circular and shiny, as well as dark brown to black in color (Bell and Tranel 2010). Under

Missouri conditions, waterhemp and Palmer amaranth are reported to produce in excess of 250,000 seeds plant^{-1} on average, but some waterhemp plants generated up to 1,000,000 seeds (Sellers et al. 2003; Steckel et al. 2003).

Emergence

Waterhemp and Palmer amaranth both exhibit a prolonged emergence period. Leon and Owen (2006) noted that no-tillage plots exhibited 4-fold greater waterhemp seedling emergence and the emergence period was 4 to 6 weeks longer compared to chisel and moldboard plow plots. This suggests that seeds exposed to moldboard plowing are buried too deep for consistent emergence because seedlings do not have sufficient resources to emerge. Palmer amaranth emergence was drastically reduced from 36.4 to 7.2% when seed burial depth increased from 2.5 to 5.1 cm, respectively (Keeley et al. 1987). Other studies support that seeds in no-tillage systems are on or adjacent to the soil surface encouraging more consistent emergence, especially for small seeded species such as pigweeds (Felix and Owen 1999; Hoffman et al. 1998; Yenish et al. 1992).

Numerous environmental factors influence *Amaranthus* emergence, including air temperature. Pigweeds germinate in the spring, starting at approximately 350 growing degree days (using a base temperature of 10 C) (Horak and Loughin 2000; Sellers et al. 2003). Temperature fluctuations, coupled with a minimum air temperature of 10 C triggers waterhemp germination (Leon et al. 2004; Steckel et al. 2007). Guo and Al-Khatib (2003) reported peak waterhemp and Palmer amaranth germination when day/night temperatures fluctuated between 25/20 and 35/30 C, respectively. At 15/10 C, waterhemp accumulated greater plant biomass than Palmer amaranth 2 to 5 weeks after seedling emergence. However, at 25/20 and 35/30 C Palmer amaranth consistently had higher biomass. Total chlorophyll content decreased slightly in both species when air temperature exceeded 15/10 C. Using fluctuating temperatures, Steckel et al. (2004) found Palmer amaranth and smooth pigweed (*Amaranthus hybridus* L.) reached 100% germination within the first day of a germination study investigating nine *Amaranthus* spp. The remaining species required as long as 3 to 8 days to reach 50% germination.

In addition to temperature, seed depth within the soil profile also affects emergence of small seeded annuals. Tillage can affect soil temperature, soil moisture and weed seed distribution within the soil profile, ultimately influencing pigweed germination (Oryokot et al. 1997). No-till versus tilled fields commonly exhibit lower soil temperatures but, in turn have higher soil moisture compared to tilled fields (Addae et al. 1991; Johnson and Lowery 1985). Conservation tillage has been adopted to decrease soil erosion, losses in soil moisture, and overall crop production costs, however there are concomitant impacts on weed populations. Weed species shifts and increased weed density is possible when no-till systems are not managed correctly due to decreased weed seed burial (Buhler et al. 1996). In turn, weed density was more influenced by tillage (decreased seed burial) than by increased surface residue. Yenish et al. (1992) found that approximately 60 and 30% of the total weed seeds found in the soil profile were located in the upper 1 cm for non-tilled versus chisel plowed soils, respectively. In controlled environments, Keeley et al. (1987) noted 36 to 40% of Palmer amaranth seed emerged at depths of 0.6 to 2.5 cm. Emergence drastically decreased to 7 and 2% at depths of 5.1 and 7.6 cm, respectively.

Comparing conventional and no-till fields, weed emergence patterns may differ. Redroot pigweed (*Amaranthus retroflexus* L.), had the highest emergence pattern in no-till systems without crop residue; the presence of residues delayed the timing of emergence by almost 50% (Buhler et al. 1996). Initial and mean time to emergence was compared among common watrehemp, velvetleaf (*Abutilon theophrasti* Medik), woolly cupgrass (*Eriochloa villosa* (Thunb.) Kunth) and giant foxtail (*Setaria faberi* Herrm.) (Hartzler et al. 1999). Waterhemp was delayed beyond other species and overall emergence was lower.

Plant Growth

Once established, pigweed seedlings rapidly develop. Mature Palmer amaranth and waterhemp average ~2 m in height (Steckel 2007). Among six *Amaranthus* spp. in Missouri, Sellers et al. (2003) ranked Palmer amaranth first in season-long biomass accumulation, followed by redroot pigweed, smooth pigweed, spiny amaranth (*Amaranthus spinosus* L.), waterhemp, and prostrate pigweed (*Amaranthus albus* L.). Maximum growth rates occurred for Palmer amaranth and waterhemp emerging in June (Horak and Loughin 2000). High photosynthetic rates underlie rapid growth rates for Palmer amaranth, exceeding 5 cm/day under non-competitive conditions in full sunlight. Palmer amaranth grew 0.21 and 0.18 cm growing degree day^{-1} (GDD^{-1}) in 1994 and 1995, respectively. Waterhemp grew 0.16 and 0.11 cm GDD^{-1} in 1994 and 1995, respectively. Horak and Loughin (2000) reported Palmer amaranth and waterhemp emerging in mid-June grew to a final height of 231 and 221 cm while generating 69 and 47 lateral branches, respectively. Plants emerging in mid-July grew only to a final height of 23 and 22 cm and produced 26 and 19 lateral branches for Palmer amaranth and waterhemp, respectively. Nordby and Hartzler (2004) recorded waterhemp biomass and seed production emerging at the V3, V5 and V8 corn stages. Biomass and fecundity of waterhemp decreased quickly with delayed emergence in corn. Waterhemp emerging with corn exhibited 20% mortality. Plants emerging in V3 and V5 corn expressed 56 and 97% mortality while 99% of waterhemp plants emerging in V8 corn did not survive. At season's end, waterhemp emerging at the VE corn stage averaged 140 cm in height, decreasing by 40, 80 and 95% as emergence was delayed (V3, V5 and V8, respectively). Corn row spacing did not affect waterhemp height or mortality. Nordby and Hartzler (2004) suggested corn should be planted early to suppress late emerging waterhemp, taking advantage of higher seedling mortality later in the season.

Part of the competitiveness of pigweeds may result because they are C4 plants. Palmer amaranth has one of the highest photosynthetic rates of C4 plants (81 $\mu mol/m^2/s$ at 42 C) (Ehleringer 1983), which is up to 4-fold higher than row crops like C4 corn and C3 cotton and soybeans (Gibson 1998). C4 versus C3 plants decrease photorespiration and increase use efficiency of nitrogen, water, and, in some cases, light (Leegood 2002). Also, C4 plants have higher light-saturated photosynthetic rates and are able to function better at higher levels of irradiance versus C3 plants (Stoller and Meyers 1989). Approximately a 90% peak photosynthetic rate of Palmer amaranth occurred between 36 and 46 C (Ehleringer 1983).

Reproduction

The timing and duration of flowering correlates to the time of seed maturity and total seed production potential (Adamsen and Coffelt 2005). Four major flowering components contribute to the success of seed production: timing of first flowering plants; flowering duration period; flowering patterns/flowering peak; and flowering synchrony between individual plants within a population, especially for dioecious species (Ollerton and Lack 1998). According to Keeley et al. (1987), female Palmer amaranth plants contain 23% more inflorescences than do male plants (894 versus 689). The average ratio of Palmer amaranth male:female plants was 47:53. Wu and Owen (2014) reported that flowering synchronization between male and female plants varied for waterhemp emerging early versus late emergence timings and changed from year to year. Also, male plants tended to flower earlier than females, making wind pollination more efficient since viable pollen is available as soon as female plants begin to flower. Photoperiod and air temperature heavily influence the physiological and morphological events that lead to flowering, fruiting and eventually mature seed production (Goyne and Schneiter 1988). Wu and Owen (2014) recorded 7 and 8 waterhemp flowering peaks over 40 and 60 d periods for 2009 and 2010, respectively. Flowering duration lasted from 17 to 57 d for plants emerging throughout the season. Flowering timing near the summer solstice results in longer reproductive and seed maturity periods, ultimately resulting in higher seed production (Cooper 2003).

Pollen grain germinability determines the successfulness of female fertilization. Waterhemp pollen can remain viable up to 5 days following anthesis of male plants and can fertilize females up to 800 m from the original source (Liu et al. 2012). Using seed production as an indicator of pollen dispersal, Liu et al. (2012) reported seed production was highest at the pollen source (17,500 seeds plant^{-1}). Most pollen dispersal occurred within 25 m of the source and seed production decreased over 90% at 50 m (1,260 seeds plant^{-1}). Sosnoskie et al. (2012) reported 50 to 60% of Palmer amaranth offspring from females pollinated by a glyphosate-resistant male 1 to 5 m from the pollen source were also glyphosate-resistant. However, female plants 250 m away from a pollen source produced 20 to 40% glyphosate-resistant progeny.

Complex biochemical signaling between the stigma and pollen grain initiates an increase in water, nutrients, and other small molecules in the pollen grain. This influx activates metabolism, stored RNA, proteins, and bioactive small molecules to establish a pollen tube on a receptive stigma (Becker and Feijo 2007; Taylor and Helper 1997). As a result, the pollen tube grows through the transmitting tract of the pistil and the pollen tube delivers two gamete cells within the embryo sac for fertilization. The process is very specialized to ensure the embryo is fertilized by gametes of the proper species.

Pollen viability is dependent on several environmental conditions. Upon anthesis, pollen is partially dehydrated to increase tolerance to environmental stresses during transport by wind, water, insects and animals (Lin and Dickinson 1984). The degree of dehydration is species specific (Kerhoas et al. 1987). Successful rehydration determines pollen germination. Humidity and temperature heavily influences pollen vitality. Extreme fluctuations in humidity and temperature during pollen dispersal can cause damage to the membrane and decrease viability (Crowe et al. 1989; Kerhoas et al. 1987).

Various researchers suggest that dioecious *Amaranthus* species can cross with monoecious species. Trucco et al. (2006) supported Murray (1940) and Tranel et al. (2002) by demonstrating hybrids of female tall waterhemp x male smooth pigweed (a monoecious species) are dioecious. Hybrids appeared healthy with variable branching and apical dominance similar to female waterhemp plants. Male hybrids rarely released viable pollen while female hybrids produced very few seeds. Using transfer of resistnace to ALS (Acetolactate synthase) inhibitor herbicides from male ALS-resistant Palmer amaranth to ALS-susceptible female waterhemp plants in the greenhouse, Franssen et al. (2001) identified 0.02 to 4.03% seed production from flowers; the majority of seeds were aborted. Of 22,000 seeds examined, only 35 hybrid plants were produced, suggesting that interspecific hybridization between Palmer amaranth and waterhemp in nature is very low.

Amaranthus species produce viable seed quickly after flowering. Bell and Tranel (2010) stored waterhemp seed post-harvest at -20 or 30 C for 48 hours following multiple harvest time intervals from 0 to 62 days after pollination. Seed proved to be viable 11 and 9 days after pollination when stored at -20 and 30 C, respectively. Maximum germination was 78% for 30 C treatments and occurred 12 days after pollination. For -20 C treatments at 24 days after pollination, 80% germination was measured.

There are varying reports about the duration of seed viability under field conditions. Steckel et al. (2007) reported 10% survival of waterhemp seed after three years under Tennessee conditions; viability dropped below 1% after four years. Egley and Williams (1990) saw similar weed seed decreases in a five year study. Several *Amaranthus* spp. seed banks were exhausted within three years when seed production was prevented. Waterhemp seed in the upper soil profile in no-till systems may be less persistent than in tilled treatments due to an increased likelihood of germination (Steckel et al. 2007). Buhler and Hartzler (2001) compared seed viability of waterhemp, velvetleaf, woolly cupgrass and giant foxtail and determined that only velvetleaf and waterhemp emerged four years after initial establishment under field conditions. Approximately 12% of the originally sown waterhemp seed was recorded as viable after four years of burial. This conflicts with Egley and Williams (1990) who claimed no viability after three years under Mississippi field conditions.

Both crop maturity stage and row spacing influence pigweed seed production. Steckel and Sprague (2004b) recorded 26,000 and 23,000 waterhemp seeds produced on plants emerging with soybean spaced in narrow (19 cm) and wide (76 cm) rows, respectively. Waterhemp emerging at V4 to V5 soybean produced 500 and 4,300 seeds for narrow and wide row spacing, respectively at season's end. In contrast, Hartzler et al. (2004) at four locations, recorded 309,000 seeds plant^{-1} for waterhemp emerging with soybean. This stark contrast with Steckel and Sprague (2004b) could be due to differences in environmental factors. Hartzler et al. (2004) also reported 64,000, 17,000, and 3,000 seeds plant^{-1} for waterhemp emerging 27, 40, and 50 days after soybean planting, respectively. Nordby and Hartzler (2004) suggested that waterhemp seed production is greatly impacted by corn row spacing. In wide rows (76 cm), waterhemp emerging at the same time as corn resulted in higher seed production compared to waterhemp growing in narrow rows (38 cm).

Similar to waterhemp, Palmer amaranth can also produce large quantities of seed when grown in crop fields. Massinga et al. (2001) estimated 140,000 and 514,000 seeds m^{-2} at 0.5 and 8 plants m^{-1} of row, respectively, when Palmer amaranth emerged in VE corn. Approximately 1,800 and 91,000 seeds m^{-2} were produced at the same densities for Palmer amaranth emerging in V4 to V7 corn. Bensch et al. (2003) reported that at a density of eight Palmer amaranth plants m^{-1} of row, 9,300 and 32,300 pigweed seeds m^{-2} were produced in Topeka and Manhattan, KS, respectively.

Continuous emergence of *Amaranthus* species throughout the growing season allows for an extended period for plants to contribute significantly to soil seed bank levels. Later-emerging pigweeds may have reduced influence on crop yield but may still contribute to the soil seed bank (Nordby et al. 2007). In California, Palmer amaranth plants emerging from July through September produced 115 to 80,000 seeds compared to 200,000 to 600,000 seeds for March through June plants (Keeley et al. 1987).

Waterhemp seed production is also prolific, perhaps greater than Palmer amaranth. Under Missouri conditions, Sellers et al. (2003) observed optimum seed production when inter- and intraspecies competition was eliminated. Waterhemp produced 535 seeds g^{-1} plant dry weight, greater than five other *Amaranthus* species. Redroot and smooth pigweed seed production was comparable with 28% fewer seeds g^{-1} plant dry weight than waterhemp. Palmer amaranth produced approximately half as many seeds as waterhemp, 261 seeds g^{-1} plant dry weight.

Depletion of weed seed in the soil is a desired control tactic but has proven difficult to accomplish. Germination, decay and predation within the soil profile and physical movement out of the field contributes to weed seed loss from the soil seed bank (Buhler et al. 1997; Steckel et al. 2007). Seed predation is normally less prominent in agricultural systems using tillage because of limited predator habitats and seed burial (Buhler et al. 1997). Approximately 69% of *Ambrosia artemisiifolia* L., *Amaranthus retroflexus, Cassia obtusifolia* L., and *Datura stramonium* L. seed was lost to predation in no-till soybean versus only 27% in conventional tillage; 128 more pigweed seeds were consumed by beetles and mice in no-till versus conventional till treatments (Brust and House 1988).

Seed Dormancy and Persistence

One factor permitting seed persistence in the seed bank and also influencing emergence timing is seed dormancy. Seed dormancy for a population is influenced by genetics and surrounding environmental conditions (Murdoch and Ellis 1992). Altering the level of dormancy/sensitivity to environmental signals may influence emergence patterns (Baskin and Baskin 1985). Two general types of dormancy are primary and secondary. Primary dormancy develops while seeds mature and is generally short lived if germination is not triggered; secondary dormancy is induced after seed drop (Murdoch and Ellis 1992). Light exposure, temperature and oxygen regiments required to break secondary dormancy varies by weed species (Steckel et al. 2007). Primary dormancy in *Amaranthus* allows for extended germination over a longer period compared to other species, maximizing seedling survival. Leon and Owen (2006) speculated that tillage may affect the level of waterhemp seed dormancy. Using three biotypes with differing levels of dormancy under three tillage conditions, no consistent differences in emergence patterns were recorded between biotypes. This suggests that multiple factors play a role in waterhemp seed dormancy. In a separate study, Leon et al. (2006) observed differences in the dormancy alleviation of three waterhemp biotypes when exposed to temperature fluctuations and differing moisture conditions. When analyzing protein profiles, protein number and type were different across all biotypes, suggesting that differences in dormancy may be due to the differences in seed physiology. They also hypothesized that seed dormancy may be an adaptive trait influenced by agricultural practices just as waterhemp populations differ in their tolerance and resistance to herbicides (Patzoldt et al. 2002). Results from Steckel et al. (2007) and Egley and Williams (1990) suggest that the use of continuous no-till maximizes weed emergence; precluding seed production will reduce total seed in the soil seed bank over time.

In addition to seed dormancy, seed persistence in the soil permits *Amaranthus* species to emerge despite the lack of seed production the previous year. Buhler and Hartzler (2001) recorded yearly emergence of four species over four years. In the first year after seed establishment, velvetleaf, woolly cupgrass, and giant foxtail all exhibited greater emergence than waterhemp when compared by percent of the original planted seed bank. By the fourth year, 1, 0, 0 and 2% of the original seed bank emerged for velvetleaf, woolly cupgrass, giant foxtail, and waterhemp, respectively. However, 5 and 12% of the original seed bank for velvetleaf and waterhemp seeds were recovered after four years, respectively. Viability for waterhemp over the four year study ranged from 71 to 95%.

***Amaranthus* Competition**

Both shoot/leaf as well as root biomass is extensive for *Amaranthus* resulting in significant depletions of available soil moisture. The magnitude of soil water competition is a result of the relative root volume of each competing species (Aldrich 1984). Davis et al. (1965) described the root moisture extraction profile of Palmer amaranth as a narrow, lateral root distribution, with extensive vertical root distribution and a high density of roots located near the soil surface. Palmer amaranth roots extended to a depth of 1.8 m and up to 3 m wide; the soil moisture extraction zone was 3.34 m^2. This compares with kochia (*Kochia scoparia* (L.); roots 1.2 m deep by 1.8 m wide) where the extraction zone was 1.85 m^2. Competition for available water is a major concern in cropping systems. Rule (2007) studied the effect of dryland versus irrigation on Palmer amaranth and corn development. Palmer amaranth reduced grain yield in irrigated areas by 35 and 43% at densities 1 and 4 plants m^{-1} of row, respectively. At the same densities, dryland corn yield was reduced by 31 and 45%. In comparison, grain yield in dryland corn was reduced 55, 69, and 75% by 0, 1, and 4 Palmer amaranth plants m^{-1} of row, respectively.

The response of *Amaranthus* plants to light is another variable impacting plant competition. Available photosynthetic active radiation (PAR) is reduced by shading (Jha et al. 2008; Steckel et al. 2003). Weeds are able to adapt to light limiting environments such as under crop canopies (Stoller and Meyers 1989). Massinga et al. (2003) studied water use and light interception in Palmer amaranth and corn. Under irrigated conditions, Palmer amaranth had a higher concentration of leaves in the upper canopy, enabling Palmer amaranth plants to intercept more light than corn. The effect of Palmer amaranth density on total light interception was not significant, suggesting individual plants can compensate for available space in the canopy. Palmer amaranth growing in high inter- and intraspecific densities grow more erect. At low plant densities, Palmer amaranth initiates lateral branching, therefore maximizing light interception. Even in irrigated corn, the water use efficiency decreased as Palmer amaranth density increased, but reductions were not linear.

Row spacing in the presence of weed pressure throughout the growing season likely impacts crop yields. Steckel and Sprague (2004b) observed waterhemp interference in soybean. Following the V2 soybean stage, more than 2-fold waterhemp emerged in wide (76 cm) versus narrow (19 cm) rows, likely a result of light availability. Co-emergence of waterhemp with soybeans resulted in crop yield losses of 44 and 37% in wide and narrow rows, respectively. By delaying waterhemp emergence until V2 to V3 soybean, soybean yield losses were only 27 and 15% in wide (76 cm) and narrow (19 cm) row spacings, respectively. Waterhemp plants emerging at the V4 to V5 soybean stage reduced crop yield <10% at both row spacings. Steckel and Sprague (2004b) concluded that the use of narrow row spacings in soybean decreases competitive crop yield losses as well as weed seed production compared to wide rows.

Besides competition for growth factors, *Amaranthus* species may exhibit allelopathic activity that can impact crop plants. Crop interference may come about in several ways and even indirect effects can be problematic. In the presence of *Amaranthus* species, Menges (1988) observed decreased crop seedling vigor. Palmer amaranth residue inhibited grain sorghum (*Sorghum bicolor* (L.) Moench) root growth at 8,000 and 16,000 ppm Palmer amaranth residue; an allelopathic response was inspected. Seedling growth was more inhibited by leaf and stem material than root tissues. A similar study by Bhowmik and Doll (1982) analyzed the effect of redroot pigweed extracts on corn and soybean. After emergence, corn and soybean coleoptile and hypocotyl expansion was inhibited by 19 and 39%, respectively.

Numerous studies have demonstrated the competitiveness of *Amaranthus* species with agronomic crops (Bensch et al. 2003; Massinga et al. 2001; Nordby and Hartzler 2004; Rowland et al. 1999; Steckel and Sprague 2004b). Bensch et al. (2003) as well as Horak and Loughin (2000) ranked Palmer amaranth as highly detrimental to soybean yield followed by waterhemp and redroot pigweed. Palmer amaranth plants also exhibited the highest plant biomass/seed production at low and medium *Amaranthus* densities (0.25 to 4 plants m^{-1} of row). Maximum soybean yield losses were 78.7 and 56.2% following competition with eight Palmer amaranth or waterhemp plants m^{-1} row, respectively, when plants emerged with soybean (Bensch et al. 2003). Soybean yield was not significantly reduced when Palmer amaranth and waterhemp emerged 19 to 38 days after soybean emergence. Hager et al. (2002) removed waterhemp 2, 4, 6, 8, and 10 weeks after soybean emergence; soybean yield was reduced 1, 13, 19, 34, and 43%, respectively (no waterhemp density was determined). Less than a 10% soybean yield loss was recorded when waterhemp emerged at the V4 to V5 stage, suggesting that waterhemp should be controlled by V4 toV5 soybeans for optimum yields (Hartzler et al. 2004; Steckel and Sprague 2004b).

Amaranthus species are also competitive in corn production systems. Massinga et al. (2001) noted 11 to 91% reductions in grain yield when Palmer amaranth plant density increased from 0.5 to 8 plants m^{-1} of row. Palmer amaranth that emerged between the V4 and V6 growth stage decreased grain yield from 16 to 45%. Similarly, waterhemp emerging after V4 corn reduced yield by 13 to 59% (Steckel and Sprague 2004a). Although corn grows much taller than soybean, grain yield losses are greatest when plants co-emerge with *Amaranthus*.

Pigweed growth is also impacted by competition with crops. Hartzler et al. (2004) noted a decrease in waterhemp survival in soybean as the date of waterhemp emergence was delayed. Waterhemp emerging with soybean exhibited a 90% survival rate, while waterhemp emerging 50 days after planting (DAP) only had a 13% survival rate. By delaying waterhemp emergence from 14 to 20 days after soybean planting, waterhemp shoot mass was reduced by 50 to 80%. Biomass production was reduced by 90 to 99% for waterhemp emerging 50 days after soybean planting compared to those plants emerging at VE soybean. Therefore, Hartzler et al. (2004) reported that for waterhemp emerging after V4 soybean (~40 days after planting (DAP)), plants were unlikely to reduce soybean yield because of low waterhemp survivability (<50%) and poor development. However, waterhemp plants emerging late remained capable of contributing to the soil seed bank.

The adaptation of *Amaranthus* to increasing levels of light influences the impact of weed density on crop yield. Only 9,300 to 32,300 Palmer amaranth seeds m^{-2} in soybean were produced. In contrast, Massinga et al. (2001) observed up to 514,000 Palmer amaranth seeds m^{-2} while competing with corn. Massinga et al. (2001) illustrated that corn yield was more affected by Palmer amaranth emergence timing than weed density. Palmer amaranth densities of 0.5 and 8 plants m^{-1} row reduced corn yields by 11 and 91%, respectively when Palmer amaranth was allowed to emerge in VE corn; Palmer amaranth that emerged at V4 to V7 corn decreased grain yield 7 and 35% for 0.5 and 8 Palmer amaranth plants m^{-1} row. Seed production per pigweed plant decreased when density increased and as emergence dates were delayed the number of seeds m^{-2} increased when *Amaranthus* density increased. The decrease in seeds per Palmer amaranth plant was believed to result from interspecific competition between corn and weeds, while the number of seeds per plant at high Palmer amaranth densities for early emergence dates likely declined from both inter- and intraspecific competition.

***Amaranthus* Management**

With increasing prevalence of pigweeds in crop production fields, proper control is essential to protect crop yields. The first step in pigweed management is proper species identification. Control can prove difficult in mixed populations since species may differ in response to control tactics (Norsworthy et al. 2012). Today’s management systems rely heavily on non-residual, post-emergence (POST) herbicides (defined here as herbicides applied after weed emergence). The use of a residual herbicide in concert with the appropriate use of a POST herbicide improves the consistency of weed control (Nordby et al. 2007).

Effectiveness of PRE Herbicides

Preemergence (PRE) herbicides allow for extended periods of weed control, important for species with extended periods of emergence. As a result, this reduces the need for sequential herbicide applications, reducing selection potential for resistant species. Overlapping residual herbicide programs have proven helpful in controlling weeds throughout the season (Wrubel and Gressel 1994). No-till systems usually consist of a burndown with a non-selective post-emergence herbicide followed by application of residual pre-emergence herbicides (Kapusta 1979). Lack of soil moisture at planting decreases efficacy of PRE's (Guo and Al-Khatib 2003).

Across a diverse geography, different PRE herbicides effectively suppress *Amaranthus* species. At five locations, control of Palmer amaranth with residual cotton herbicides (flumioxazin and pyrithiobac) was 75 to 100% up to 20 d after application (Whitaker et al. 2011). Gossett et al. (1992) observed 93, 93, 100, 100, and 100% control of Palmer amaranth with fluometuron, alachlor, atrazine, norflurazon, and imazaquin, respectively. Niekamp et al. (1999) noted similar control of waterhemp in soybean with the use of sulfentrazone, flumioxazin and metribuzin + chlorimuron. Sulfentrazone, flumioxazin and metribuzin + chlorimuron resulted in 98, 99, and 99% control of waterhemp, respectively, in mid-Missouri. Control in northern Missouri plots was more variable; 97, 71, and 28% for sulfentrazone, flumioxazin and metribuzin + chlorimuron, respectively. Variable control may have been due to higher waterhemp populations versus other locations.

Effectiveness of POST Herbicides

Proper timing of effective POST herbicides is key to effective control of rapidly growing *Amaranthus.* POST herbicides permit wide spectrum control but may have limited residual activity.

Multiple factors including weed size, spray volume, application timing and herbicide rate must be considered before implementing a herbicide plan. Pigweeds should be sprayed before they reach 10 cm in height and with an adequate spray volume to ensure coverage (Anonymous 2010). Hager et al. (2003) monitored the influence of application timing and rate of acifluorfen, fomesafen, and lactofen (all diphenylethers) on waterhemp in soybean. Visual control was 9, 9, and 8% greater at 7, 14, and 21 days after application for 5 versus 10 cm waterhemp using comparable treatments. At medium rates, 10 cm waterhemp were controlled 62, 61, and 81% with aciflurofen, fomesafen, and lactofen, respectively, 21 days after treatment. Hager et al. (2003) concluded that diphenylethers are effective for control of waterhemp, but timing is critical with adequate coverage. Anderson et al. (1996) observed 91, 12, 88, and 91% control of 3 to 8 cm waterhemp 4 weeks after treatment for 2,4-D, atrazine, dicamba, and primisulfuron, respectively.

Similarly, Palmer amaranth shows variable responses to herbicides. Mayo et al. (1995) noted greater variability for control of Palmer amaranth compared to waterhemp, redroot pigweed and prostrate pigweed in soybean. Overall control was also lower for

Palmer amaranth. At recommended rates, acifluorfen, lactofen, chlorimuron, thifensulfuron, imazethapyr, and imazaquin all controlled waterhemp, redroot pigweed, and tumble pigweed above 90%. However, Palmer amaranth control fluctuated between locations; thifensulfuron and imazethapyr provided the most consistent control (82 to 97%).

Chemical options POST in corn and soybean are limited. Acetochlor and atrazine can be used in addition to 2,4-D or dicamba POST in corn. Lactofen and fomesafen (both non-residual) can be applied POST in soybean. Other available POST herbicides for *Amaranthus* spp. include glyphosate or glufosinate in glyphosate- or glufosinate- resistant crops, respectively. This is problematic considering the rapid increase in glyphosate-resistant *Amaranthus* species.

Herbicide Resistance

Herbicides have proven to be an effective tool for weed control, but overuse and misuse of certain modes of action (MOAs) have led to herbicide resistance. As defined by the Weed Science Society of America (Anonymous 1998), “Herbicide resistance is the inherited ability of a plant to survive and reproduce following exposure to a dose of herbicide normally lethal to the wild type. In a plant, resistance may be naturally occurring or induced by such techniques as genetic engineering or selection of variants produced by tissue culture or mutagenesis.” Herbicide-resistant weeds can increase the cost of crop production, limit the type of crop that can be grown, lower crop yields and potentially lower land values (Anonymous 2002; Green 2007). The underlying causes of herbicide resistance include repeated use of a single herbicide MOA over many years (Diggle et al. 2003). Heap (2014) reported 144 herbicide-resistant species in the U.S., far outnumbering other countries. Resistance is also common in other countries such as Australia 66 species and Canada 60 species where herbicides are used extensively.

Waterhemp is increasingly difficult to control in Midwest row crops due to herbicide resistance. Waterhemp exhibits resistance to a number of herbicides with different modes of action: triazines (Anderson et al. 1996), photosystem II inhibitors (PSII) (Anderson et al. 1996), acetolactate synthase (ALS) inhibitors (Horak and Peterson 1995), protoporphyrinogen oxidase (PPO) inhibitors (Shoup et al. 2003), glyphosate (Legleiter and Bradley 2008), and hydroxyphenyl pyruvate dioxygenase (HPPD) inhibitors (Hausman et al. 2011). Legleiter and Bradley (2008) confirmed the first biotype of waterhemp exhibiting multiple resistance; ALS inhibitors, protoporphyrinogen oxidase inhibitors (PPO) and glyphosate.

Although waterhemp has not developed resistance to dinitroanaline herbicide, resistance is common in Palmer amaranth. Dinitroanaline herbicides selectively inhibit annual grass and dicot weed growth in cotton, soybean, wheat (*Triticum aestivum* L.) and oilseed crops (Anthony and Hussey 1999). Gossett et al. (1992) identified eight trifluralin-resistant Palmer amaranth populations in South Carolina with different levels of resistance to six dinitroanaline herbicides. Palmer amaranth is also resistant to numerous other herbicide modes of action: glyphosate (Culpepper et al. 2006), ALS inhibitors (Horak and Peterson 1995; Sprague et al. 1997) and PSII inhibitors (Heap 2014). The world's first confirmed case of glyphosate resistance in *Amaranthus* spp. was reported by Culpepper et al. (2006) in Central Georgia. Nearly 83% of 5 to 13 cm tall Palmer amaranth survived a rate of glyphosate three times typically needed to control sensitive plants.

Palmer amaranth and waterhemp was selected glyphosate-resistant after 4 and 6 years of consecutive use, respectively (Culpepper et al. 2006, Legleiter and Bradley 2008). Glyphosate resistant crops have been widely used, resulting in reduced use of soil applied herbicides and overuse of the same mode of action (Culpepper and York 1999). Culpepper (2006) recommends additional herbicide MOAs in glyphosate-tolerant cropping systems, rotation to herbicides with different modes of action, and adopting use of soil applied herbicides. Legleiter and Bradley (2008) observed 19- and 9-fold levels of resistance to glyphosate in two waterhemp populations in Missouri.

Proper management of pigweeds must consider application of mixed modes of action both as residuals and POST (after crop emergence). Owen (2008) described that an increasing density of primarily one weed species in crop fields is an indication of over-reliance on a single weed control tactic. Understanding seed and seedling behavior is important in creating integrated weed management plans. According to Nordby et al. (2007), throughout the 1970s and early-1980s, producers utilized soil-applied herbicides with long residual activity. By the late 1980s through the 1990s, the use of ALS inhibitors became popular; these compounds exhibited both soil and foliar activity. As the use of ALS inhibitors increased, so did the development of resistance in Palmer amaranth and waterhemp.

In order to reduce the risk of herbicide resistance, growers should incorporate multiple practices. Norsworthy et al. (2012), recommends twelve best management practices stressing diversification of control tactics and reducing the introduction of weed seed to fields. Recommendations usually include: scouting early; proper weed identification; avoiding use of only one MOA; rotating herbicides and crops on a yearly basis; and using non-chemical control tactics such as tillage and crop rotation (Doucet et al. 1999; Frisvold et al. 2009; Pratt et al. 1999). Due to quick seed production and extended germination periods of pigweed species, management plans should be implemented early and carried through crop harvest if at all possible (Keeley et al. 1987).

Purpose of Research

The importance of common waterhemp and Palmer amaranth in row crops continues to grow. *Amaranthus* spp. emerge over an extended period of time putting pressure on crop producers to implement full-season management practices. Also, *Amaranthus* plants grow at rapid rates, making timely POST herbicide applications difficult. Few studies have examined the partitioning of plant resources into leaves and stems versus seeds in relationship to plant emergence date. This may be important to determine how long into the growing season proper control practices may be needed. Comparative studies on the growth parameters and seed productivity for plants emerging at different times is needed.

In addition to rapid growth, *Amaranthus* plants also quickly produce seed following flowering. This allows late season plants that may have escaped control to produce viable seed. Overall, this research may indicate the importance of soil seed bank contributions for late season emerging seedlings. Objectives include:

1. Assess season-long common waterhemp and Palmer amaranth emergence.
2. Determine the influence of emergence timing of common waterhemp and Palmer amaranth on the growth and reproductive potential of plants.
3. Evaluate number of days after *Amaranthus* flowering to viable seed set.

Early season emerging waterhemp and Palmer amaranth may be more competitive with annual crops than later season emerging plants, while later season plants may make significant contributions to the soil seed bank.

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Chapter II

Impact of tillage timing on common waterhemp (*Amaranthus rudis*) and Palmer amaranth (*Amaranthus palmeri*) emergence

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Abstract: Waterhemp and Palmer amaranth are troublesome annual weeds in Midwest cropping systems and emerge from mid-spring through late summer. Tillage timing strongly influences weed emergence patterns. Season-long emergence studies under different tillage regimes were conducted in 2013 and 2014 for two locations with waterhemp (Columbia [central] and Novelty [northeast]) and one location for Palmer amaranth (Portageville [southeast]). Weekly emergence was monitored for no-till as well as plots tilled in late April/early May or mid-June. Initial emergence of both species was noted with a minimum soil temperature of 13 C and emergence ceased in late October when soil temperatures dropped below 14 C; a period of up to 191 days. Cumulative emergence for waterhemp was up to 1,620 and 990 plants m^{-2} at Columbia and 1,909 and 2,895 plants m^{-2} at Novelty in 2013 and 2014, respectively. For Palmer amaranth, up to 706 plants m^{-2} emerged season-long in 2013 and 2,389 plants m^{-2} in 2014. The time period for waterhemp to reach 90% cumulative emergence ranged from 6 to 12 weeks for no-till plots over both years. In contrast, early spring tillage plants reached 90% emergence in 4 to 9 weeks. Delaying tillage until mid-June resulted in a 2 to 4 week time period to attain 90% cumulative emergence. For Palmer amaranth, the time period to reach 90% cumulative emergence in no-till plots was 9 to 13 weeks, whereas early spring tillage plants took 9 to 11 weeks. Palmer amaranth reached 90% emergence in 7 to 9 weeks in late tillage areas. Interruption by spring tillage in production systems infested

with waterhemp or Palmer amaranth may not reduce overall emergence, but may shorten the duration of control required.

Nomenclature: Common waterhemp, *Amaranthus rudis*; Palmer amaranth, *Amaranthus palmeri.*
Additional index words: Germination, no-till, pigweed.

Introduction

Infestations of Palmer amaranth (*Amaranthus palmeri* S. Wats) in the Mid-south and common waterhemp (*Amaranthus rudis* Sauer) in the Midwest continue spreading to other areas. Originating in the southwestern United States and Mexico (Sauer 1957), Palmer amaranth has spread from southern California eastward to Oklahoma, Kansas, Nebraska and Missouri (Horak 2000). Recently, Palmer amaranth was reported in Indiana and Illinois (Legleiter and Johnson 2013; Riggins et al. 2013). Waterhemp is indigenous to areas west of the Mississippi River from Nebraska to Texas, but now spans the Great Plains region and east into the Ohio River Valley (Steckel et al. 2004; 2007).

Management programs have progressed, contributing to the success of *Amaranthus* species. Widespread adoption of reduced tillage benefits small-seeded species by leaving seed near the soil surface (Nordby et al. 2007). Also, reduced use of residual herbicides may promote the prevalence of weed species with an extended emergence pattern (Young 2015). The escalation of populations resistant to one or more herbicide modes of action lead to higher in-field densities (Young 2015).

Prolonged emergence of *Amaranthus* species allows plants to develop despite periods of unfavorable environmental conditions (Hager et al. 1997; Wu and Owen 2014). Optimum emergence occurs with warm soil temperatures. Guo and Al-Khatib

(2003) observed peak germination at a day/night soil temperature of 25/20 C and 35/30 C for waterhemp and Palmer amaranth, respectively. Additionally, Jha and Norsworthy (2009) recorded mean soil temperatures of 25 C during the week of initial Palmer amaranth emergence. Jha and Norsworthy (2009) observed that rainfall near the summer solstice resulted in peak emergence. During the first year, rainfall was delayed until mid-July delaying Palmer amaranth emergence.

Seed placement of waterhemp and Palmer amaranth in the soil influences emergence. Approximately 60% of seed is located in the top 1 cm of no-tilled soil, but only 30% of the total weed seed is found at that level in chisel plowed soil (Yenish et al. 1992). Seeds in no-tillage systems are on or just beneath to the soil surface, encouraging emergence (Felix and Owen 1999; Hoffman et al. 1998; Yenish et al. 1992). Palmer amaranth emergence was reduced by 29.2% when seed burial depth was increased from 2.5 to 5.1 cm, respectively (Keeley et al. 1987). Jha and Norsworthy (2009) observed spring tillage to a depth of 10 cm initially stimulated germination, possibly due to increased aeration and soil-seed contact. In contrast, Leon and Owen (2006) reported that season-long waterhemp emergence was up to four-fold greater in no-till versus chisel (30 to 35 cm) and moldboard (20 to 25 cm) plowed plots. Duration of emergence was 4 to 6 weeks longer in no-till compared to chisel and moldboard plowed areas. Seeds subjected to moldboard and chisel plowing may have been buried too deep, limiting continued emergence. This suggested that the germinable seed in the upper level of soil may have been depleted early.

Although *Amaranthus* exhibits a prolonged emergence pattern, the majority of plants emerge early in the season. Waterhemp emergence has been recorded from early

May through early October in southern Illinois and late June through September in Wisconsin (Franca et al. 2013). In Illinois, 90% of the total waterhemp emergence occurred by the end of June, and by the beginning of August in Wisconsin. In the same study in Indiana and southern Illinois, Palmer amaranth exhibited emergence from mid-May through late October. Palmer amaranth in Tennessee initiated emergence earlier, beginning in mid-April and persisting through early September. Palmer amaranth reached 90% total emergence by the second week in July in Illinois, Indiana and Tennessee. Oryokot et al. (1997) reported that low rainfall early in the season delayed the time to 25 and 80% cumulative pigweed seedling emergence in tilled ground when compared to no-till treatments. However, under normal conditions, tillage had no significant effect on emergence.

Continual emergence and rapid growth are beneficial for survival. Overlapping emergence patterns make it hard to determine the optimum timing of post-applied herbicides (Chandi et al. 2013). A decrease in waterhemp control using protoporphyrinogen oxidase-inhibiting herbicides was reported by Falk et al. (2006). Falk et al. (2006) suggested that waterhemp's prolific growth pattern in addition to continued emergence contributed to the decline of control.

Prolonged emergence of waterhemp and Palmer amaranth allows plants a greater opportunity to survive and potentially reproduce. Continuous emergence season-long and the impact that tillage timing may have on the duration of emergence is not well documented. These data may allow managers to consider combining tillage with residual herbicides to preclude *Amaranthus* seed production. The objective of this study was to monitor how tillage timing influenced *Amaranthus* emergence patterns season-long. In addition, determining peak emergence periods and the time to 90% cumulative emergence was important.

Materials and Methods

Field plots were established in 2013 and 2014 at three locations throughout Missouri: Lee Greenley Jr. Memorial Research Center (38.88ºN, 92.19ºW) near Novelty (waterhemp); Bradford Research and Extension Center (40.03ºN, 92.19ºW) near Columbia (waterhemp); and the Fisher Delta Research Center (36.39ºN, 89.61ºW) near Portageville (Palmer amaranth). Three tillage treatments were carried out in 1.5 m by 1.5 m plots: no-tillage (NT), early spring tilled (ET), and late spring tilled (LT). Tillage was performed using an engine-powered roto-tiller, with soil disturbed to a depth of 10 cm. Depending on location, ET took place late April through mid-May while LT was carried out between late May and mid-June (Table 2.1). The soil type at Columbia was a Leonard silt loam (fine, smectitic, mesic Vertic Epiaqualfs) with pH 6.3 and 1.9% soil organic matter in 2013 and 2014. At Novelty, the soil type was a Putnam silt loam (fine, smectitic, mesic Vertic Albaqualfs) with pH 5.9 and 2.4% soil organic matter for both years. The soil type at Portageville was a Tiptonville silt loam (fine-silty, mixed, superactive, thermic Oxyaquic Argiudolls) with pH 5.4 and 1.7% soil organic matter in 2013 and a pH of 5.2 and 1.4% soil organic matter in 2014. Following initiation of treatments, plots remained undisturbed the remainder of the season.

Data Collection

From late April through late October, emergence was recorded weekly from a 1 m^2 quadrat centered in plots (Appendices A1 to A6). Emergence included plants at the cotyledon stage and larger. After recording, pigweeds were removed by hand. Every two weeks, all vegetation was removed from plots with a CO_2 pressurized backpack sprayer equipped with TeeJet® XR8002 (200 W. North Ave., Glendale Heights, IL 60139 USA) nozzle tips. Glufosinate at 0.58 kg ae ha^{-1} was broadcasted at a spray volume of 140 L ha^{-1} using a pressure of 137.8 kPa.

Soil moisture and temperature at 5 cm soil depth was recorded using HOBO data loggers (Onset Computer Corporation, 470 MacArthur Blvd. Bourne, MA 02532) in two plots of each treatment at all three locations (Appendices A7 to A12). Soil moisture was determined on a percent by volume basis. Measurements were logged every 30 minutes. A total of 672 recordings per week were averaged across two sensors per treatment at each location to calculate the mean weekly soil temperature and soil moisture. In 2013, soil moisture and soil temperature were recorded from June 26 through October 30 at Columbia, June 25 through October 14 at Novelty, and June 26 through October 30 at Portageville. In 2014, soil moisture and soil temperature were recorded from April 22 through October 30, April 24 through October 21, and April 17 through October 30 at Columbia, Novelty and Portageville, respectively. Plots were not irrigated during the time emergence was recorded.

Statistics

Plots were arranged in a randomized complete-block design with six replications and three treatments per replication. Cumulative emergence was determined by summing weekly recordings for individual plots. Weeks to 90% emergence was determined by graphing the cumulative emergence across time using a best fit line to estimate the number of weeks to reach 90% of all recorded emergence per plot. To determine 90%

cumulative emergence, the following equation was used for every treatment within location and within year: $Y = x(0.90)$. Where Y is equal to 90% cumulative emergence and x is equal to total cumulative emergence (m^{-2}). ANOVA for cumulative emergence and weeks to 90% cumulative emergence was conducted using PROC GLIMMIX in SAS (Version 9.4, SAS Institute, Inc., 100 SAS Campus Drive, Cary, NC 27513-2414 USA). Data did not follow a normal distribution according to Shapiro and Wilk (1965). Therefore, within the model statement, distribution of log-normal (Mitchell 1968) was included for cumulative emergence analysis and distribution of Poisson (Consul and Jain 1973) was included for the number of weeks to 90% cumulative emergence. Means were separated using Fisher’s Protected LSD at P=0.05.

Two equations were used to find the best fit line to estimate the number of weeks from initial emergence to 90% cumulative emergence: sigmoid 3-parameter and sigmoid 4-parameter.

Sigmoid 3-parameter (Mathews and Hopkins 1999):

$$Y = \frac{a}{1+e^{-(x-x_{o}/b)}} \qquad [1]$$

Where Y is the cumulative emergence at week x of recording, a is the maximum cumulative emergence per treatment predicted by the model, e is the base of the natural logarithm, x_0 is the time required to reach the maximum cumulative emergence, and b is the slope of the regression line.

Sigmoid 4-parameter (Mathews and Hopkins 1999):

$$Y = Y_0 + \frac{a}{1+e^{-(x-x_{o}/b)}} \qquad [2]$$

Where Y is the cumulative emergence at week x of recording, Y_0 is the cumulative emergence for infinite weeks, a is the maximum cumulative emergence per treatment predicted by the model, e is the base of the natural logarithm, x_0 is the time required to reach the maximum cumulative emergence, and b is the slope of the regression line. Sigmoid 4-parameter was used to estimate the number of weeks from initial emergence to 90% cumulative emergence for early spring tillage plots at Novelty in 2013. Sigmoid 3-parameter was used to estimate the number of weeks from initial emergence to 90% cumulative emergence for the rest of the treatments at Columbia, Novelty and Portageville in 2013 and 2014.

Results and Discussion

Waterhemp exhibited extended emergence at both locations. Emergence was initiated May 10 and 17 and ended October 3 and August 23 in 2013 at Columbia (146 d duration) and Novelty (98 d duration), respectively. For 2014, emergence began April 22 and 23 and ceased October 30 and 4 at Columbia (191 d duration) and Novelty (164 d duration), respectively. Waterhemp emergence in NT plots began when soil temperatures reached 13 C at both Columbia and Novelty in 2014 (Figure 2.1). Cessation of waterhemp emergence at Columbia does not appear to coincide with insufficient soil moisture. Emergence was initiated in 2014 and ended in 2013 at the same soil moisture, 19% by volume (Figure 2.2). Waterhemp emergence at Novelty in 2013 ended in mid-August when soil temperatures were recorded at 27 C and soil moisture was 15% by volume, suggesting soil moisture and elevated temperatures may be related to cessation of *Amaranthus* emergence. Emergence of waterhemp at Novelty in 2014 more closely followed Columbia's results than in 2013.

Similarly, Palmer amaranth exhibited prolonged emergence for all tillage treatments. Palmer amaranth emergence ranged from May 15 through October 23 (162 d duration) in 2013 and April 25 through October 17 (176 d duration) in 2014. Emergence for Palmer amaranth occurred as 5 cm soil temperatures reached 18 C in 2014 (Figure 2.1). For both years, Palmer amaranth emergence stopped when the average weekly soil temperature reached 17 C. Soil moisture was 22 and 17% by volume when emergence ceased in 2013 and 2014, respectively, suggesting that available soil moisture aided in spring germination but did not play a role as soil temperatures cooled in the fall (Figure 2.2).

Emergence of waterhemp in Columbia varied throughout the growing season depending on tillage timing (Figures 2.3, 2.4 and 2.5). Weekly emergence in NT plots in 2013 and 2014 peaked at 657 (June 13) and 113 plants m^{-2} (June 27), respectively (Figure 2.3). ET plots had in excess of 800 plants m^{-2} $week^{-1}$ (June 13) in 2013 but only 417 plants m^{-2} (June 13) in 2014 (Figure 2.4). Weekly emergence in LT plots was high immediately following tillage in the third and fourth weeks of June 2013 at 291 and 537 plants m^{-2}, respectively, but decreased quickly thereafter (Figure 2.5). Although soil moisture only decreased 1 to 2% by volume from June 27 to July 3, emergence was sharply reduced after the last week of June for the remainder of the experimental period in 2013 (Appendices A1 and A10). Similarly, peak weekly emergence occurred in mid-June 2014 at 793 plants m^{-2} in LT plots. During the first week of ET plant emergence (May 23, 2013 and May 9, 2014), NT plots had higher emergence in both years. Three weeks after ET, weekly emergence was considerably higher in the ET versus NT plots: 156 versus 133 plants m^{-2} in 2013 and 99 versus 50 plants m^{-2} in 2014. In contrast, waterhemp emergence in 2013 for LT plots was 3.5- and 6- fold higher versus NT and ET treatments, respectively. In 2014, a reduction of soil moisture (% by volume) from 19 to 14% and 19 to 18% occurred in NT and ET treatments, respectively, drastically reducing weekly emergence in early July (Appendices A2 and A10). The permanent wilting point for silty loams is approximately 12% soil moisture by volume and field capacity is 32% by volume (Zotarelli et al. 2013). Soil moisture was low (15% by volume) the first week following LT; this correlated with no waterhemp emergence in LT plots. Moisture increased to 27% two weeks after the initiation of LT and weekly emergence peaked at 764 plants m^{-2}.

For waterhemp at Novelty in 2013, 138 plants m^{-2} versus 11 plants m^{-2} emerged in NT plots and ET plots, respectively, the week following ET (May 31). In 2014, emergence during the week following initiation of ET, 137 and 5 plants m^{-2} emerged in NT and ET plots, respectively. One week after 2013 initiation of LT (June 21), emergence was 224, 47 and 254 plants m^{-2} for NT, ET and LT treatments, respectively (Figures 2.6, 2.7, and 2.8). Emergence in NT plots at Novelty in 2013 peaked during the first week in mid-May (650 plants m^{-2}). Weekly emergence in 2013 decreased as the season progressed and percent soil moisture decreased (Appendices A3 and A11). In contrast, 2014 peak emergence was not observed until mid-June at 1,183 plants m^{-2}. In 2014, from the first week in May to the second, weekly emergence increased from 30 to 137 plants m^{-2}. Soil moisture decreased over this time period from 30 to 26% by volume but, soil temperature increased from 13 to 16 C (Appendices A4, A8, and A11). Peak emergence of waterhemp in LT plots occurred by July in both years (Figure 2.8).

Although Palmer amaranth emergence extended through October, the majority of emergence occurred before August in 2013 and by mid-August in 2014. Emergence in NT plots was 11- and 5-fold higher than ET plots the week after initiation of ET (May 29, 2013 and May 8, 2014) in 2013 and 2014, respectively. Emergence in NT, ET and LT plots was similar one week after initiation of LT in 2013 (June 19). However, 2014 Palmer amaranth emergence in LT plots one week after tillage (June 5) was much higher (412 plants m^{-2}) compared to NT (241 plants m^{-2}) and ET plots (171 plants m^{-2}) during the same time period. Maximum weekly emergence in 2013 was 230, 136 and 61 plants m^{-2} in NT, ET, and LT, respectively (Figures 2.9, 2.10 and 2.11). In 2014, peak weekly emergence was higher; average peak emergence was 593, 235, and 412 plants m^{-2} for NT, ET, and LT plots (Figures 2.9, 2.10 and 2.11).

Although tillage appeared to influence weekly emergence patterns, the relationship between cumulative emergence of waterhemp and tillage was unclear. Cumulative waterhemp emergence at Columbia was numerically highest for NT treatments in 2013 (1,620 plants m^{-2}) and decreased stepwise to 1,129 and 850 plants m^{-2} for ET and LT plots, respectively (Figure 2.12). In 2014, however, this trend was reversed; NT plots exhibited the lowest emergence (394 plants m^{-2}) followed by ET (584 plants m^{-2}) and LT plots (990 plants m^{-2}).

The absence of tillage benefited waterhemp emergence at Novelty. Cumulative emergence of waterhemp was highest in both years for the NT treatment; 1,909 plants m^{-2} in 2013 and 2,895 plants m^{-2} in 2014 (Figure 2.13). NT and ET treatments in 2013 were statistically similar at 1,909 and 808 plants m^{-2}, respectively. Emergence among tillage treatments in 2014 were statistically similar, but ranged from 1,426 to 2,895 plants m^{-2}.

The cumulative emergence of Palmer amaranth among treatments followed a similar trend as waterhemp emergence did (Figure 2.14). NT plots exhibited the highest cumulative emergence across treatments in 2013 and 2014 with 706 and 2,389 plants m^{-2}, respectively. Cumulative emergence was highest in NT plots, followed by ET plots and finally LT plots. Tillage shortened the period that Palmer amaranth emerged and this appeared to reduce cumulative emergence. NT and LT plot's cumulative emergence was significantly different in 2013 and NT plots accumulated significantly more plants m^{-2} than either tillage timing in 2014.

Although emergence of waterhemp was recorded season-long, the time period to 90% emergence was relatively short. In 2013 at Columbia, NT plots reached 90% cumulative emergence during the seventh week after initial emergence (Figures 2.15 and 2.16). Weeks to 90% cumulative emergence was 5 and 2 weeks for ET and LT treatments. In 2014, the time to 90% cumulative emergence in NT plots was 12 weeks after initial emergence. ET and LT plots reached 90% emergence in 6 and 3 weeks in 2014, respectively.

Comparatively, the time to 90% cumulative waterhemp emergence at Novelty spanned a similar timeline. The weeks to 90% cumulative emergence of waterhemp at Novelty was not significantly different in 2013 across tillage treatments (4 to 6 weeks) (Figures 2.17 and 2.18). In 2014, NT plots reached 90% cumulative emergence during the twelfth week of the study and 9 and 3 weeks for ET and LT treatments, respectively.

The period for emergence of Palmer amaranth to reach 90% cumulative emergence appeared longer compared to waterhemp. This period was not significantly different between tillage treatments within year for either year (Figures 2.19 and 2.20). In

2013, plots reached 90% cumulative emergence 9, 9 and 7 weeks after initial emergence for NT, ET, and LT treatments, respectively. The time to 90% cumulative emergence was longer in 2014; 13, 11, and 9 weeks after initial emergence for NT, ET, and LT treatments, respectively.

Late emerging *Amaranthus* plants are much less competitive in the current season, but with the prolific nature of *Amaranthus* species, late emerging plants may add significantly to the soil seedbank. This results in management implications for future years. Regardless of tillage timing, the majority of emergence occurred by early July, before the last typical herbicide application. Although emergence may be significantly less in July and August, seedlings can escape late cultivation or herbicide applications and emerge thereafter. Waterhemp emerging in July produced 500 and 4,300 seeds plant^{-1} in narrow and wide rows, respectively (Steckel and Sprague 2004). In a similar study, waterhemp emerging from V4 to V6 soybean did not exceed the canopy but produced 3,000 to 17,000 seeds plant^{-1} versus 64,000 seeds plant^{-1} on plants that would have emerged in the typical weed management time frame (Hartzler et al. 2004).

The impact of tillage on waterhemp and Palmer amaranth emergence has been well documented. This study is being conducted at several locations in the Midwest. However, the impact of initial seed-bed preparation and timing on season-long germination has not been studied. Tillage delays establishment of *Amaranthus* species through the early stages of crop growth, but may not reduce cumulative emergence. With available soil moisture, late tillage stimulated rapid waterhemp and Palmer amaranth emergence at Columbia, Novelty, and Portageville. Early tillage did not immediately stimulate rapid emergence of either species. Typically, 2 to 3 weeks following early tillage an inflection point occurred with the exception of Palmer amaranth ET treatments in 2014. Leon and Owen (2006) reported that under no-till conditions the largest waterhemp emergence events occurred at the end of June. In chisel and moldboard plowed systems, most emergence occurred in May and the first week of June. Delaying tillage in 2013 and 2014 shortened the time to 90% emergence, therefore reducing the time of management needed. Refsell and Hartzler (2009) reported time to 90% waterhemp emergence was 40 and 26 d for NT plots and chisel-till, respectively. Weeks to 90% cumulative emergence in 2013 NT plots at both Columbia and Novelty were comparable to observations by Refsell and Hartzler (2009). *Amaranthus* typically exhibited 90% emergence by late July. Implementing late spring tillage reduced the time to reach 90% cumulative emergence of waterhemp by up to 75% compared to no-till areas and 31% for Palmer amaranth. Similar to other studies, shallow 10 cm tillage had a minimal effect on cumulative emergence compared to NT (Jha and Norsworthy 2009; Cardina et al. 2002; Oryokot et al. 1997). Shallow (10 cm) spring tillage did not influence cumulative Palmer amaranth emergence (Jha and Norsworthy 2009). Tillage timing and weather in 2013 and 2014 appears to have more influence on weekly emergence across treatments, but little effect on cumulative emergence. *Amaranthus* density greatly varied from plot to plot within tillage treatments. Oryokot et al. (1997) reported large variations in seedling densities between tillage systems, but comparable to our study, depended on the date of observation.

Integration of early-season and delayed tillage into management of *Amaranthus* may shorten the duration of control required because a majority of seedlings will have emerged within a shorter period. Late tillage systems for both Palmer amaranth and waterhemp may require fewer herbicide applications since tillage would eliminate early *Amaranthus* emergence. The majority of waterhemp and Palmer amaranth emergence occurs early but emergence can persist through October. Management of early emerging weeds is vital to protect yield. Implementing an extended management plan may help eliminate late season *Amaranthus*, thereby decreasing additions to the soil seed bank.

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Table 2.1. Specific date for initiation of tillage treatments for common waterhemp and Palmer amaranth seedling emergence plots at Columbia, Novelty, and Portageville, MO in 2013 and 2014.

	——Columbia——		——Novelty——		—Portageville—	
Treatment	2013	2014	2013	2014	2013	2014
No-Tillage	10-May	20-Apr	17-May	21-Apr	15-May	21-Apr
Early Spring Tillage	16-May	30-Apr	24-May	2-May	22-May	1-May
Late Spring Tillage	14-Jun	2-Jun	14-Jun	3-Jun	11-Jun	29-May

Table 2.2. Time required for 90% cumulative emergence of common waterhemp at Columbia and Novelty, MO and Palmer amaranth at Portageville, MO for no-tillage, early spring tillage, and late spring tillage plots in 2013 and 2014 were determined using best fit lines. The equations were derived in SigmaPlot 11.0.

Equations of Best Fit Lines to determine Weeks to 90% Cumulative Emergence							
		No-Tillage		Early Spring Tillage		Late Spring Tillage	
2013	Columbia	$Y^{a}= \frac{1,622.7}{1+e^{-(x-4.8/1.2)}}$	R^2=0.98	$Y= \frac{1, 123.7}{1+e^{-(x-5.4/0.3)}}$	R^2=0.99	$Y= \frac{844. 3}{1+e^{-(x-7.1/0.2)}}$	R^2=0.99
	Novelty	$Y= \frac{1,915.1}{1+e^{-(x-3.8/1.4)}}$	R^2=0.98	$Y^{b}= 3.7 + \frac{795.0}{1+e^{-(x-4.6/0.2)}}$	R^2=0.99	$Y= \frac{636.5}{1+e^{-(x-6.3/0.5)}}$	R^2=0.99
	Portageville	$Y= \frac{682.2}{1+e^{-(x-3.4/1.4)}}$	R^2=0.94	$Y= \frac{328.3}{1+e^{-(x-5.8/1.\ 9)}}$	R^2=0.92	$Y= \frac{169.3}{1+e^{-(x-8.1/2.3)}}$	R^2=0.91
2014	Columbia	$Y= \frac{397.9}{1+e^{-(x-7.1/2.4)}}$	R^2=0.97	$Y= \frac{581.2}{1+e^{-(x-7.3/0.3)}}$	R^2=0.97	$Y= \frac{970.5}{1+e^{-(x-7.8/0.2)}}$	R^2=0.95
	Novelty	$Y= \frac{2,899.2}{1+e^{-(x-7.6/1.7)}}$	R^2=0.99	$Y= \frac{1,418.5}{1+e^{-(x-7.5/1.5)}}$	R^2=0.99	$Y= \frac{2,003.5}{1+e^{-(x-8.5/0.2)}}$	R^2=0.99
	Portageville	$Y= \frac{2,336.4}{1+e^{-(x-6.4/2.1)}}$	R^2=0.98	$Y= \frac{1,367.3}{1+e^{-(x-8.1/2.2)}}$	R^2=0.99	$Y= \frac{1,053.8}{1+e^{-(x-9.6/2.2)}}$	R^2=0.94

[a] Sigmoid 3-parameter $Y = a/(1+e^{-(x-x_0/b)})$ Was used to estimate the time required for 90% cumulative emergence. Where Y is the cumulative emergence at week x of recording, a is the maximum cumulative emergence per treatment predicted by the model, e is the base of the natural logarithm, x_0 is the time required to reach the maximum cumulative emergence, and b is the slope of the regression line.

[b] Sigmoid 4-parameter $Y = Y_0 + [a/(1+e^{-(x-x_0/b)})]$ Was used to estimate the time required for 90% cumulative emergence. Where Y is the cumulative emergence at week x of recording, Y_0 is the cumulative emergence for infinite weeks, a is the maximum cumulative emergence per treatment predicted by the model, e is the base of the natural logarithm, x_0 is the time required to reach the maximum cumulative emergence, and b is the slope of the regression line.

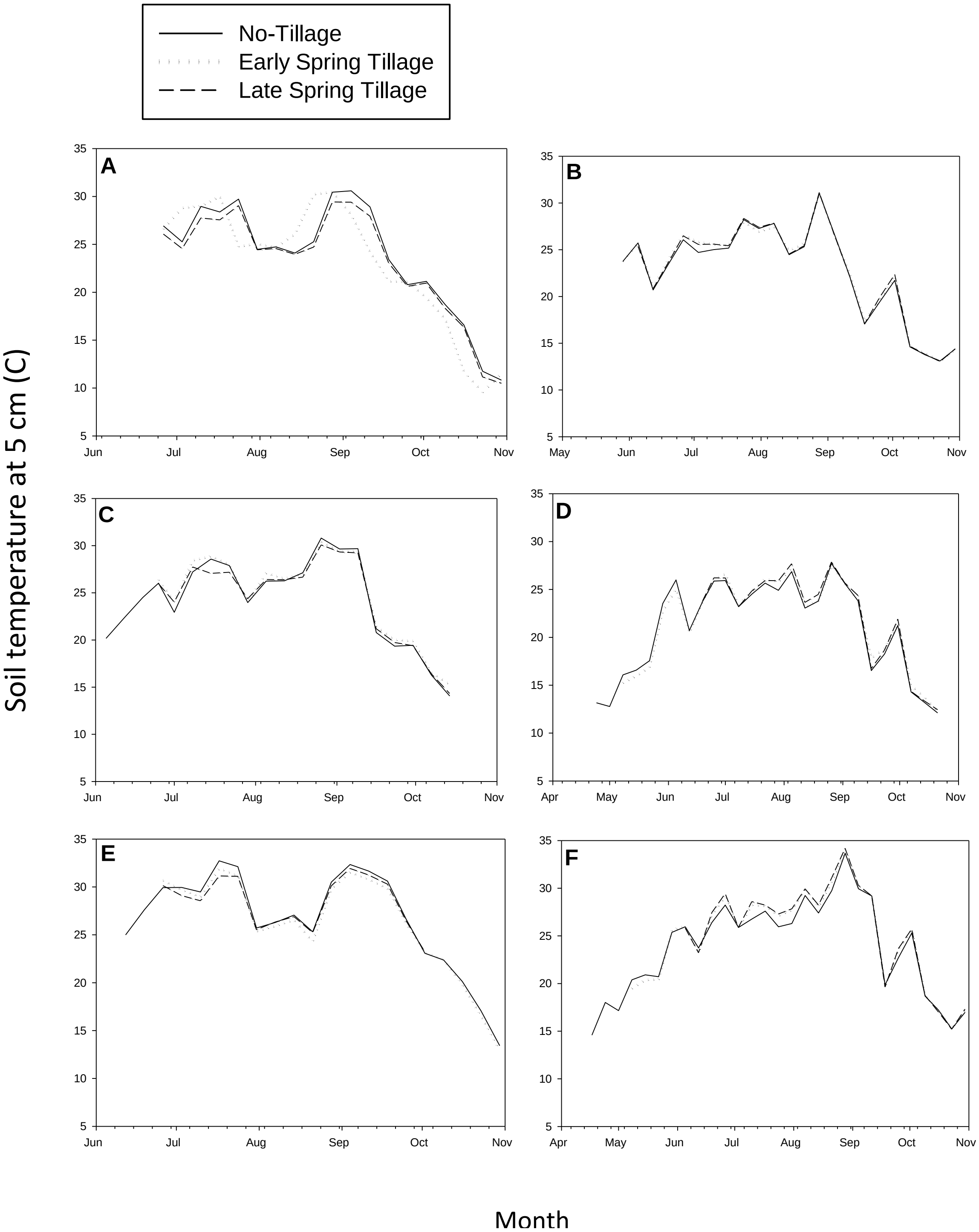

Figure 2.1. Weekly mean soil temperature (C) at 5 cm depth recorded using in-ground HOBO data logger for: Columbia 2013 (A), and 2014 (B); Novelty 2013 (C) and 2014 (D); and Portageville 2013 (E), and 2014 (F). Weekly means are based on 672 data points taken per week; data points were recorded from two sensors and estimates logged every half hour.

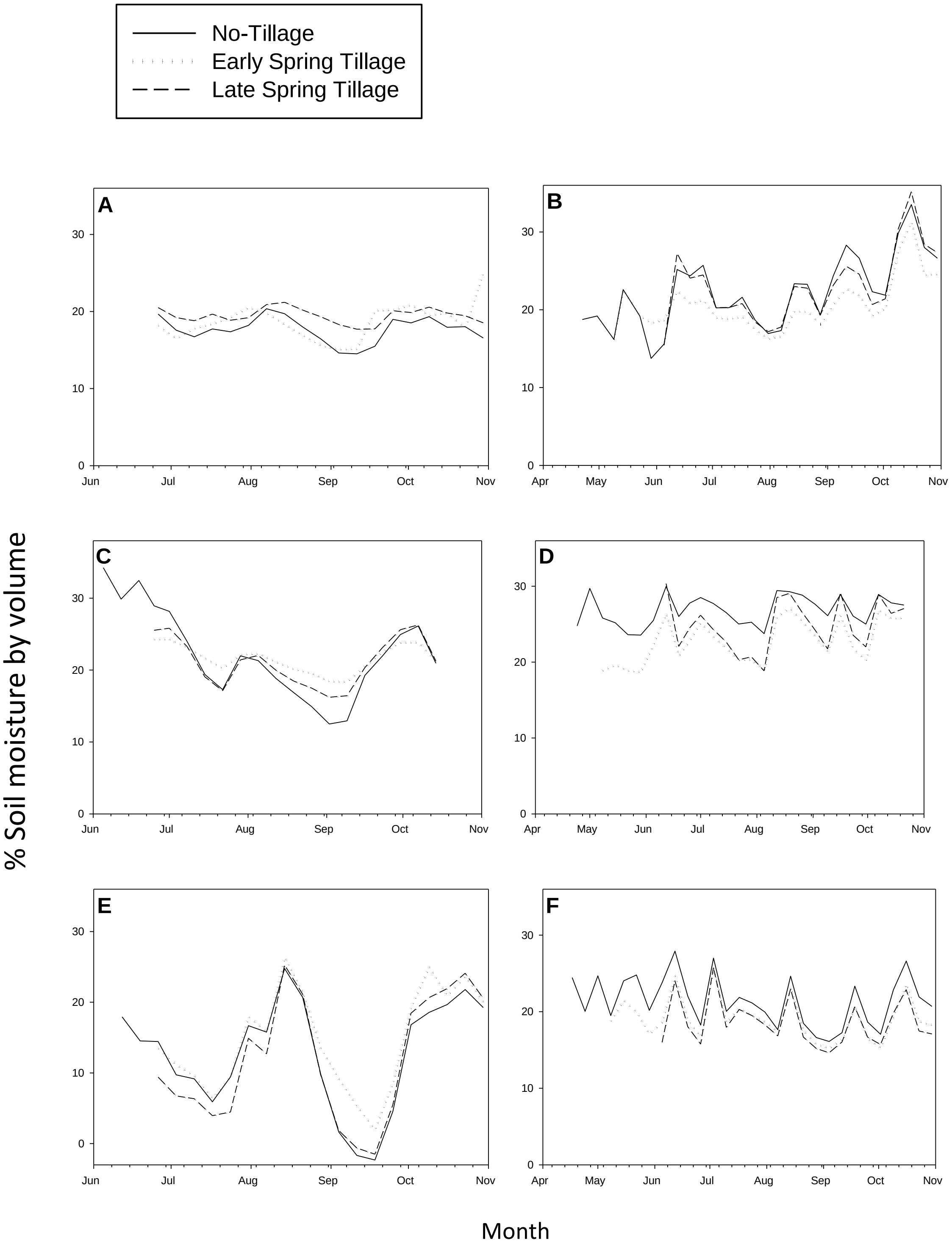

Figure 2.2. Weekly mean soil moisture (% soil moisture by volume) at 5 cm depth recorded using in-ground HOBO data logger for: Columbia 2013 (A), and 2014 (B); Novelty 2013 (C) and 2014 (D); and Portageville 2013 (E), and 2014 (F). Weekly means are based on 672 data points taken per week; data points were recorded from two sensors and estimates logged every half hour.

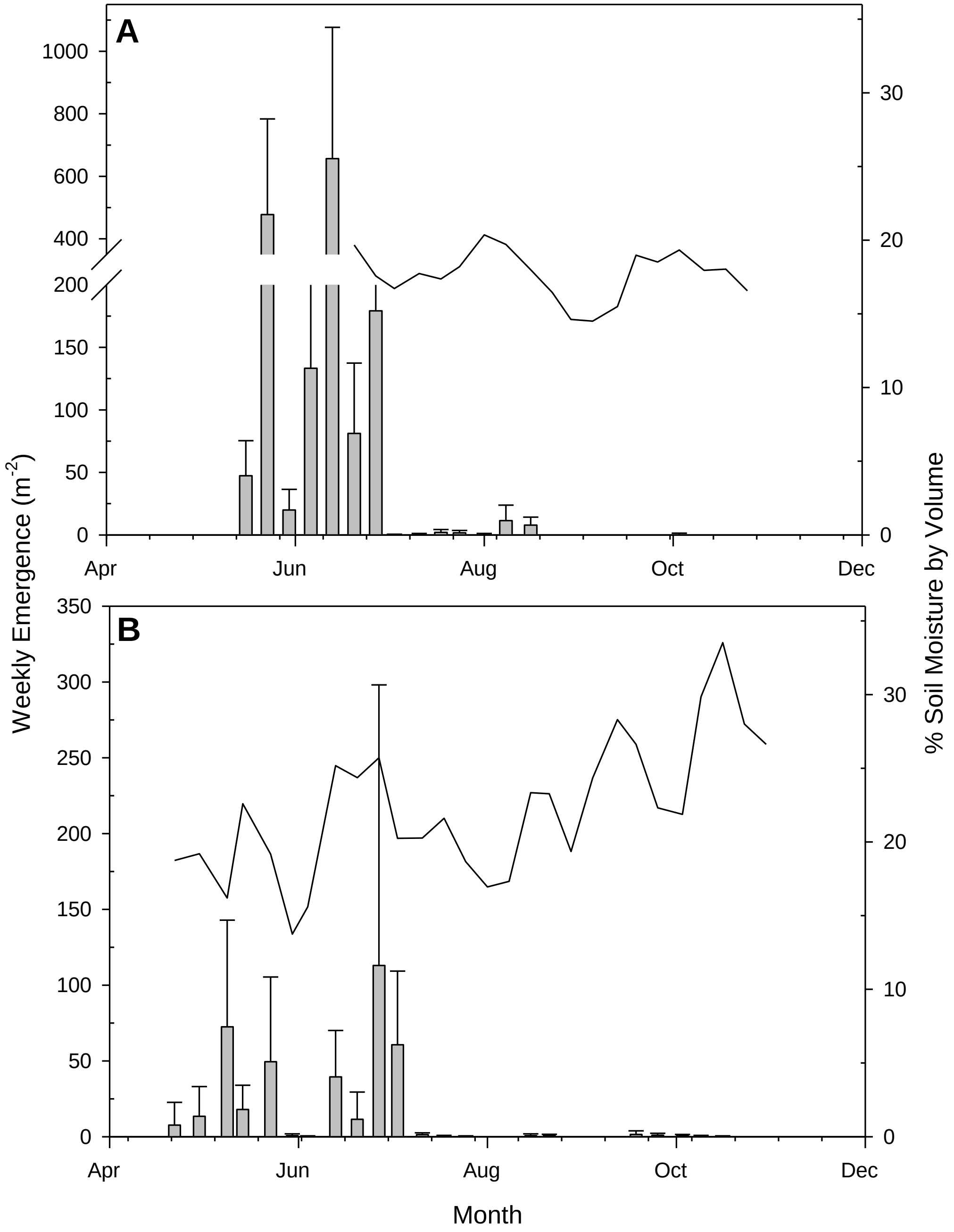

Figure 2.3. Mean weekly common waterhemp emergence per square meter in no-till plots (left axis) at Columbia, MO in 2013 (A) and 2014 (B). Soil moisture was estimated at a depth of 5 cm using HOBO data loggers. Vertical bars indicate the standard error around the mean.

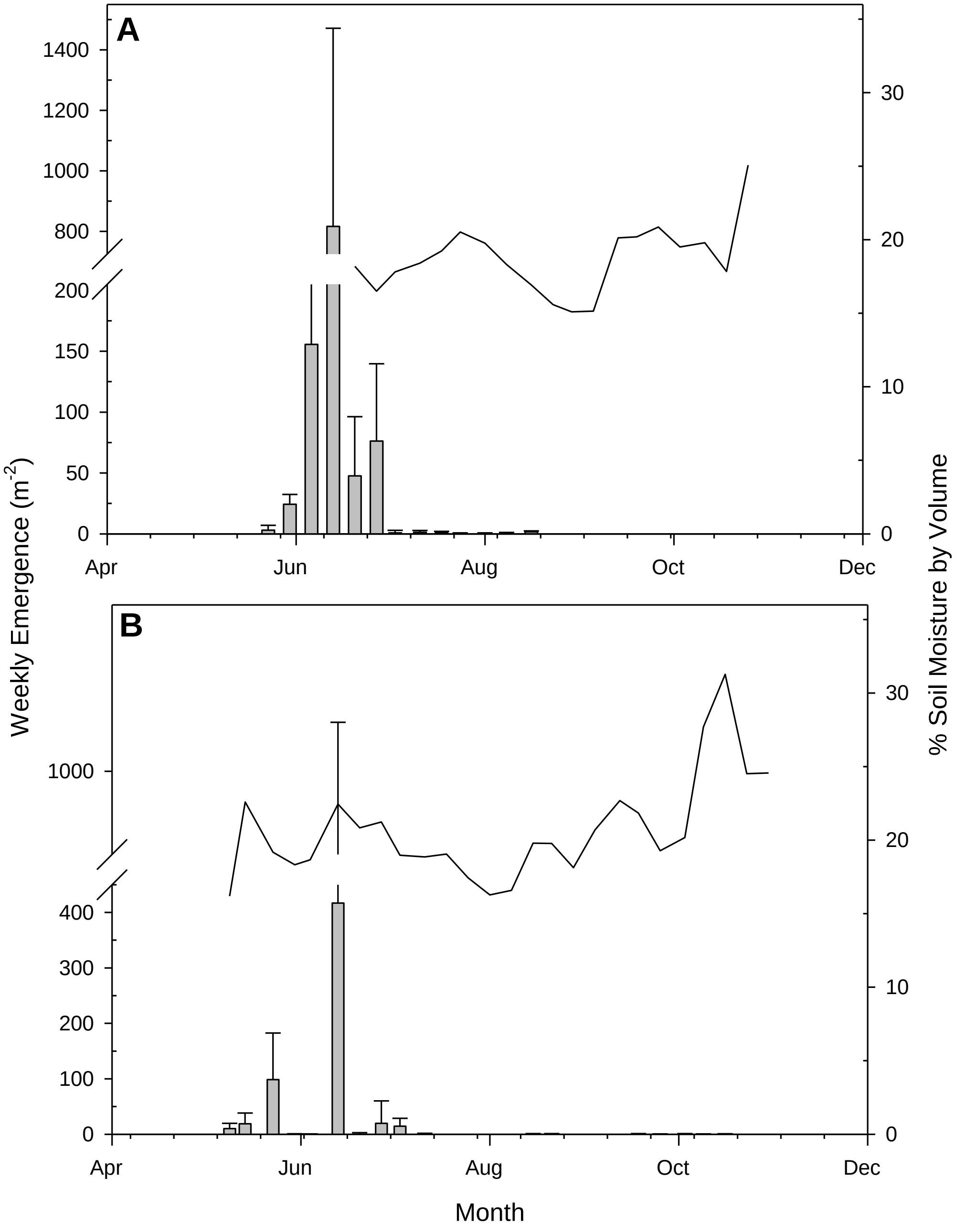

Figure 2.4. Mean weekly common waterhemp emergence per square meter in early spring tilled plots (tilled May 16, 2013 and April 30, 2014) (left axis) at Columbia, MO in 2013 (A) and 2014 (B). Soil moisture was estimated at a depth of 5 cm using HOBO data loggers. Vertical bars indicate the standard error around the mean.

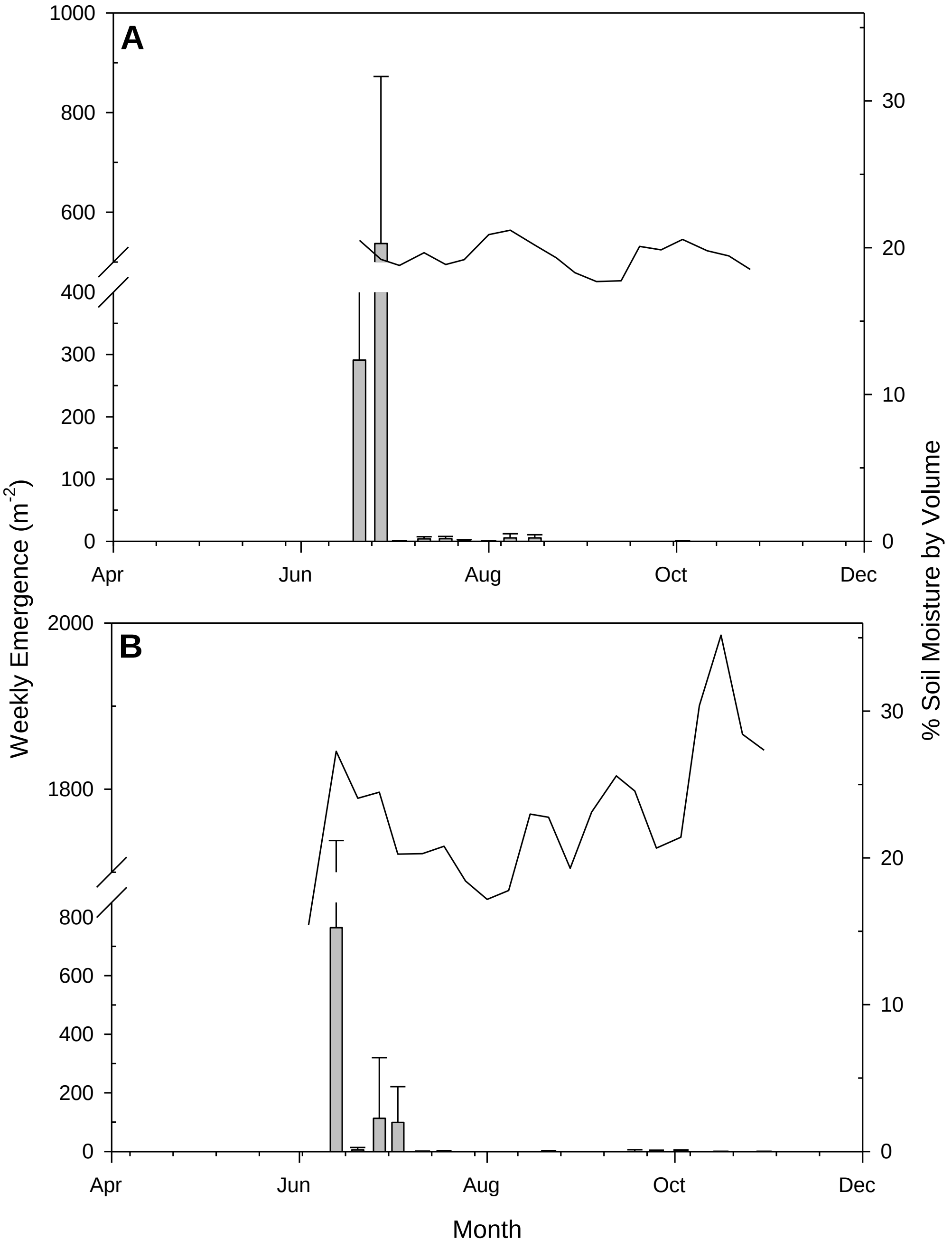

Figure 2.5. Mean weekly common waterhemp emergence per square meter in late spring tilled plots (tilled June 4, 2013 and June 2, 2014) (left axis) at Columbia, MO in 2013 (A) and 2014 (B). Soil moisture was estimated at a depth of 5 cm using HOBO data loggers. Vertical bars indicate the standard error around the mean.

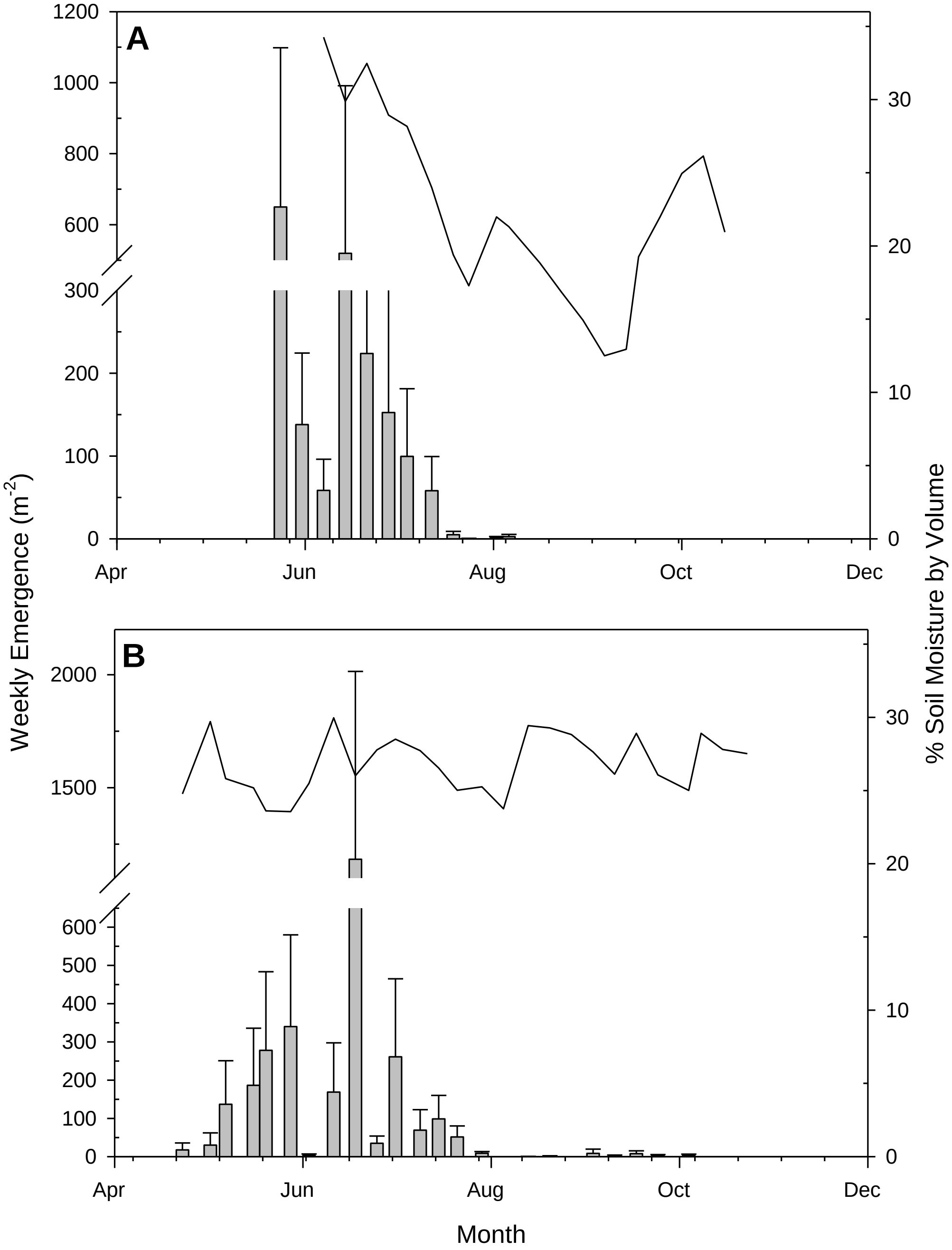

Figure 2.6. Mean weekly common waterhemp emergence per square meter in no-till plots (left axis) in Novelty, MO in 2013 (A) and 2014 (B). Soil moisture was estimated at a depth of 5 cm using HOBO data loggers. Vertical bars indicate the standard error around the mean.

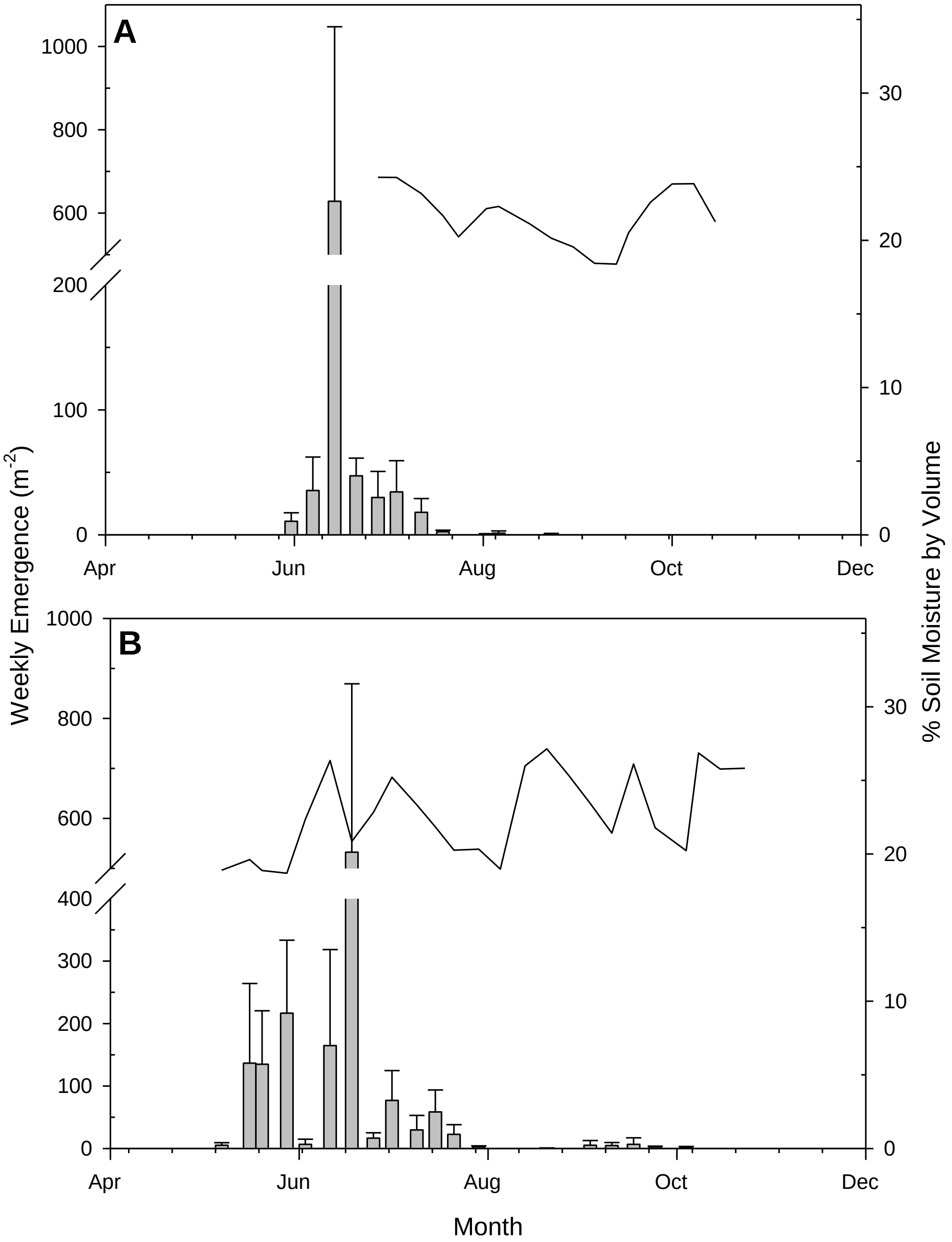

Figure 2.7. Mean weekly common waterhemp emergence per square meter in early spring tilled plots (tilled May 24, 2013 and May 2, 2014) (left axis) in Novelty, MO in 2013 (A) and 2014 (B). Soil moisture was estimated at a depth of 5 cm using HOBO data loggers. Vertical bars indicate the standard error around the mean.

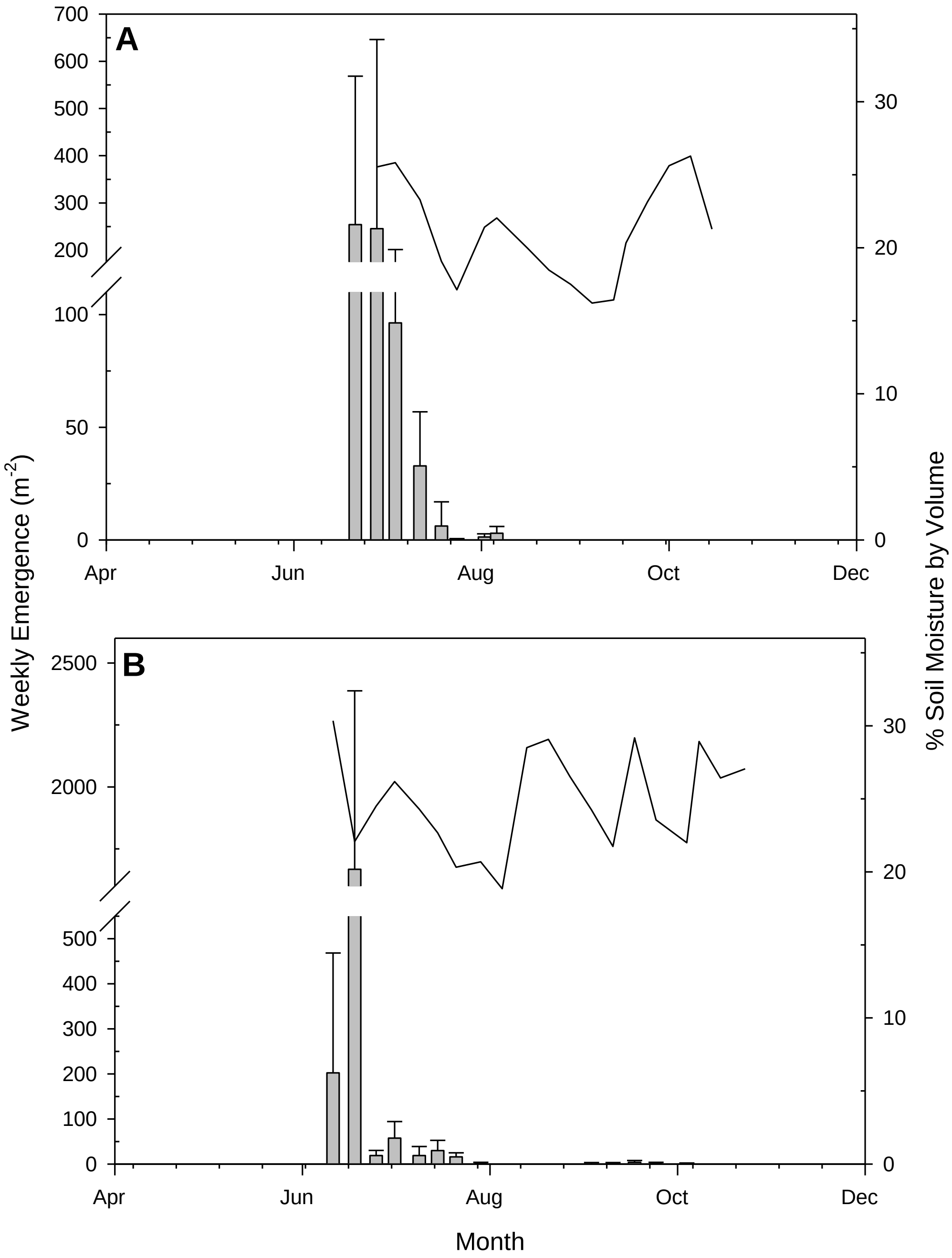

Figure 2.8. Mean weekly common waterhemp emergence per square meter in late spring tilled plots (tilled June 14, 2013 and June 3, 2014) (left axis) in Novelty, MO in 2013 (A) and 2014 (B). Soil moisture was estimated at a depth of 5 cm using HOBO data loggers. Vertical bars indicate the standard error around the mean.

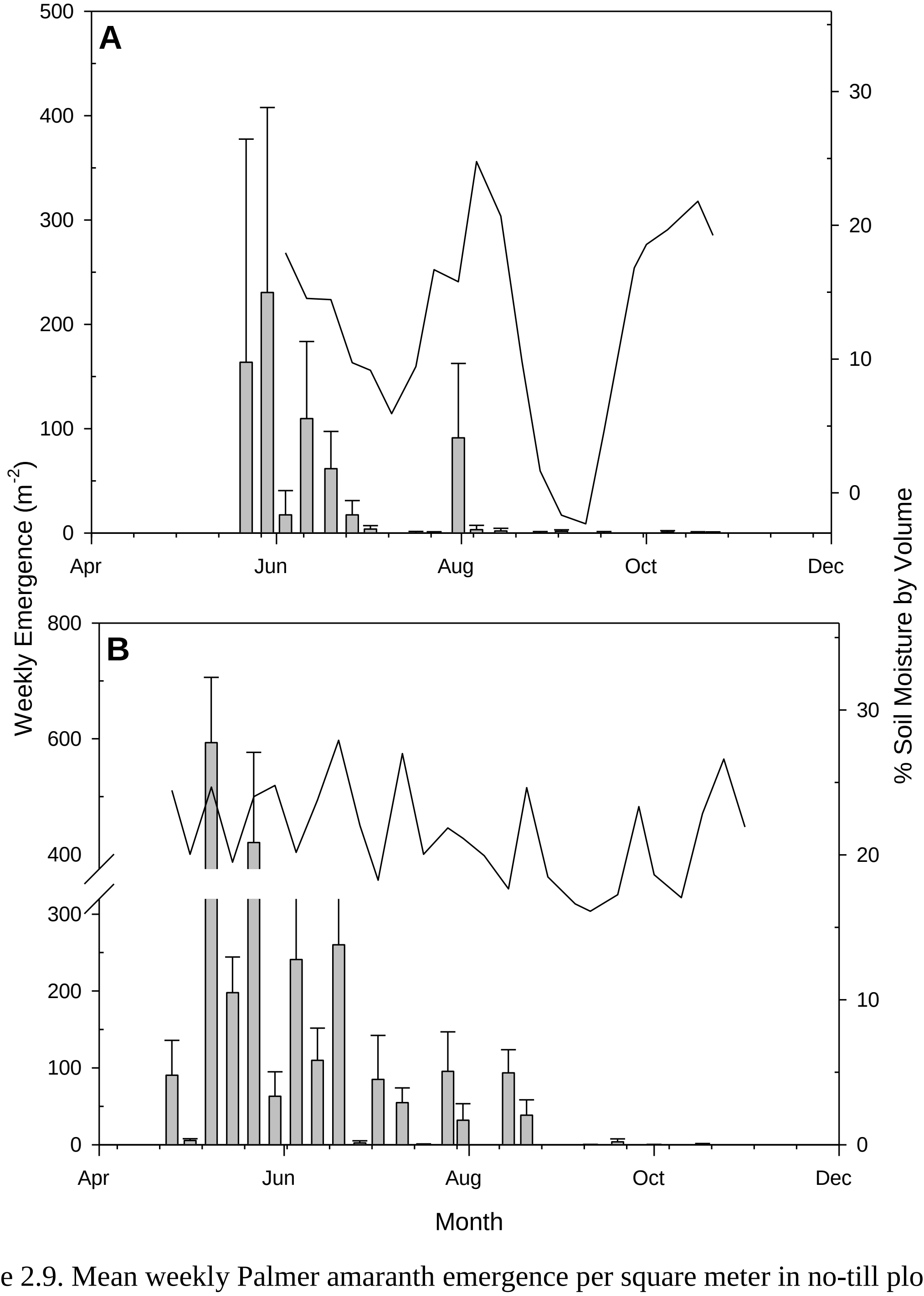

Figure 2.9. Mean weekly Palmer amaranth emergence per square meter in no-till plots (left axis) in Portageville, MO in 2013 (A) and 2014 (B). Soil moisture was estimated at a depth of 5 cm using HOBO data loggers. Vertical bars indicate the standard error around the mean.

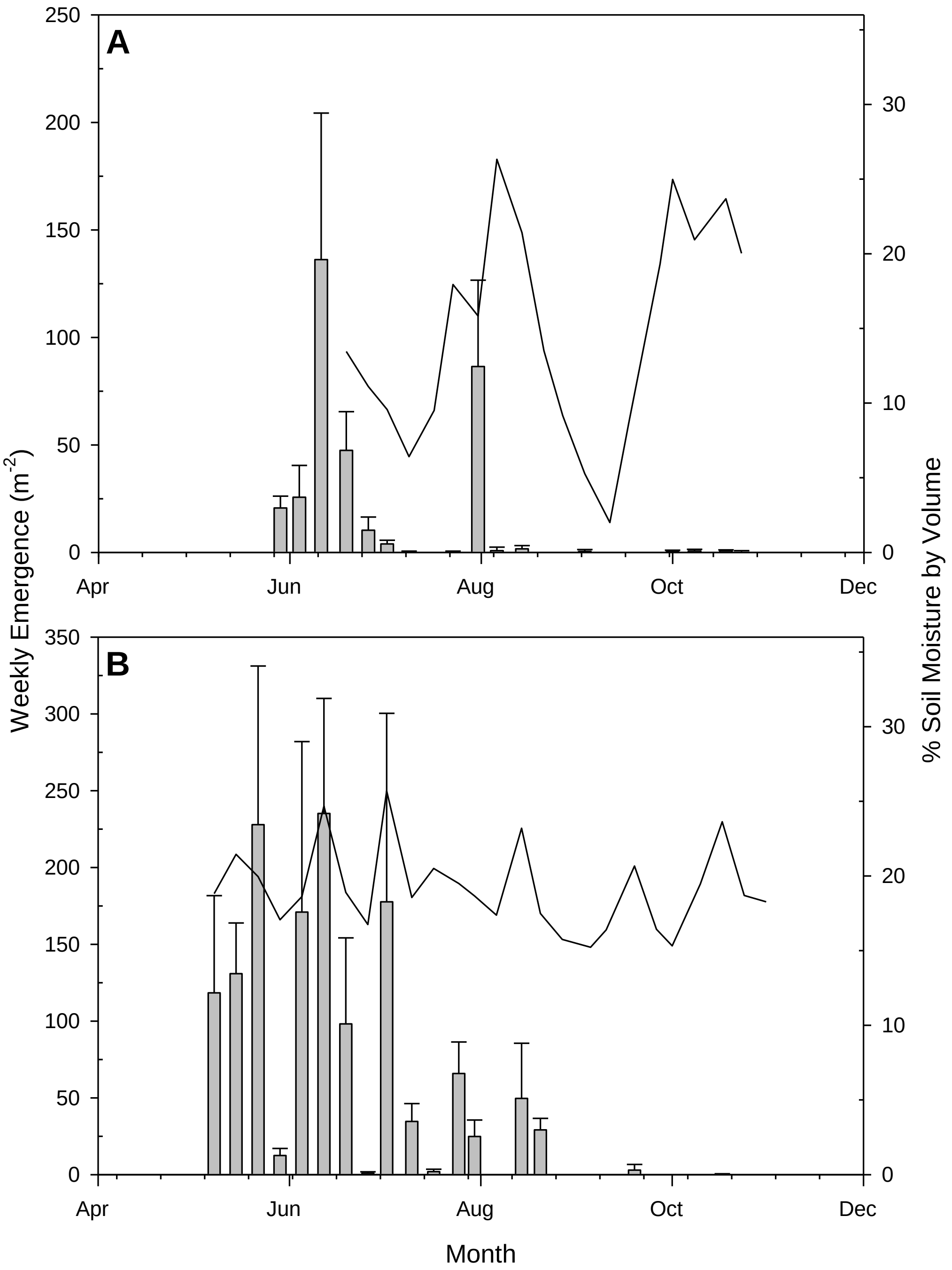

Figure 2.10. Mean weekly Palmer amaranth emergence per square meter in early spring tilled plots (tilled May 22, 2013 and May 1, 2014) (left axis) in Portageville, MO in 2013 (A) and 2014 (B). Soil moisture was estimated at a depth of 5 cm using HOBO data loggers. Vertical bars indicate the standard error around the mean.

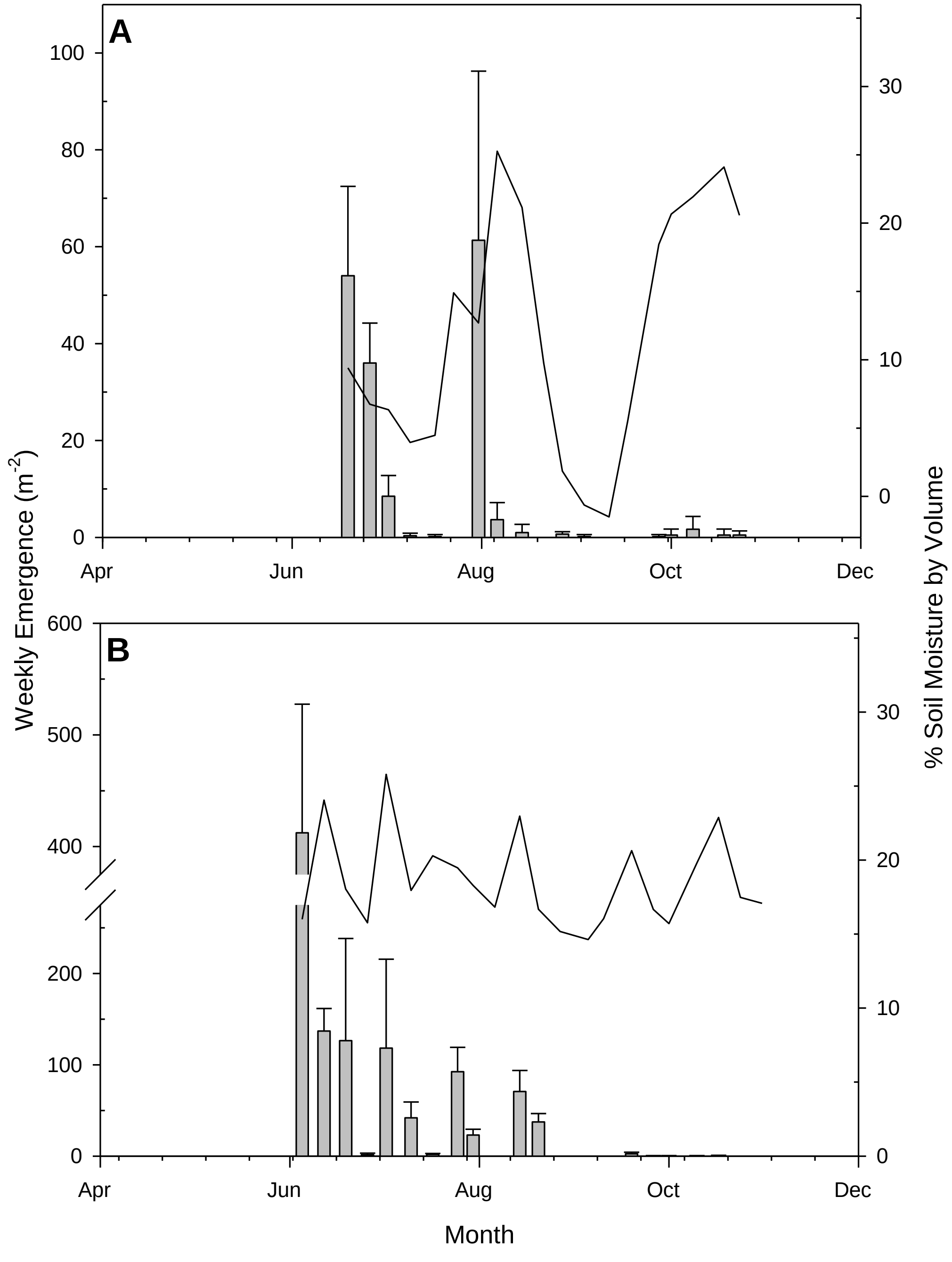

Figure 2.11. Mean weekly Palmer amaranth emergence per square meter in late spring tilled plots (tilled June 11, 2013 and May 29, 2014) (left axis) in Portageville, MO in 2013 (A) and 2014 (B). Soil moisture was estimated at a depth of 5 cm using HOBO data loggers. Vertical bars indicate the standard error around the mean.

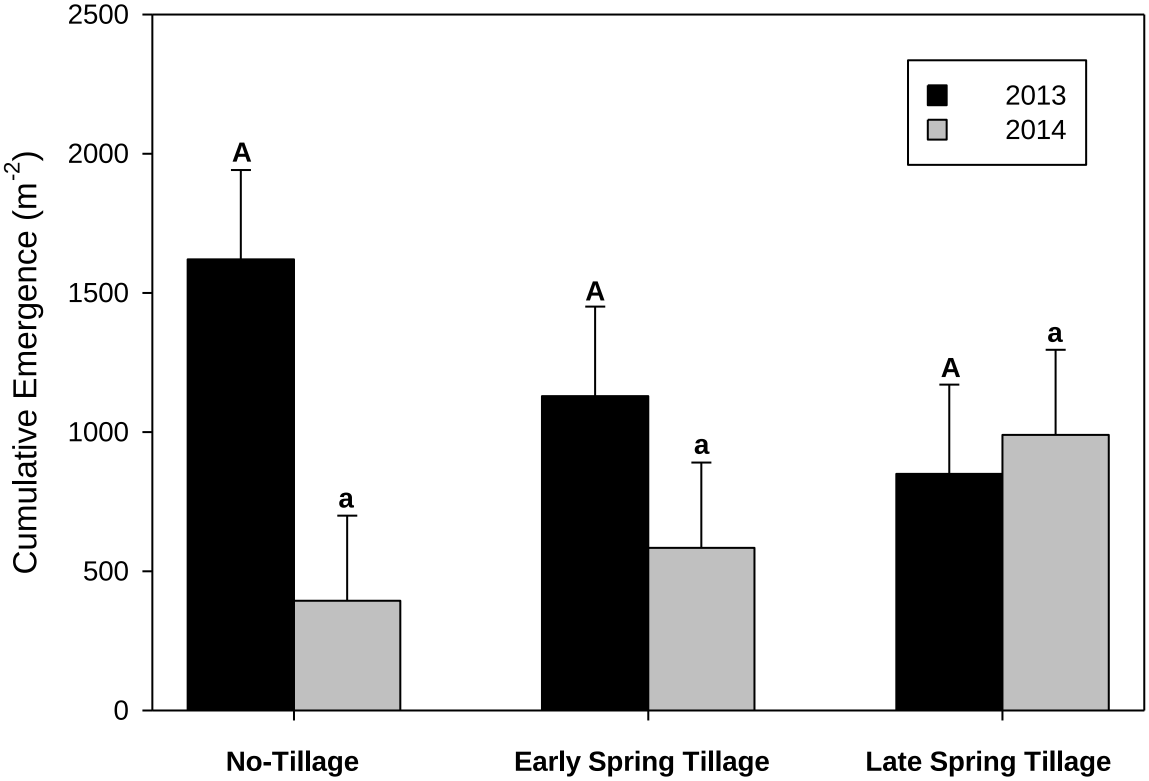

Figure 2.12. Season-long cumulative emergence per square meter of common waterhemp in no-tillage, early spring tillage, and late spring tillage areas at Columbia, MO in 2013 and 2014. Means with the same letter within year are not significantly different following separation with Fisher's Protected LSD at p=0.05. Vertical bars indicate the standard error around the mean.

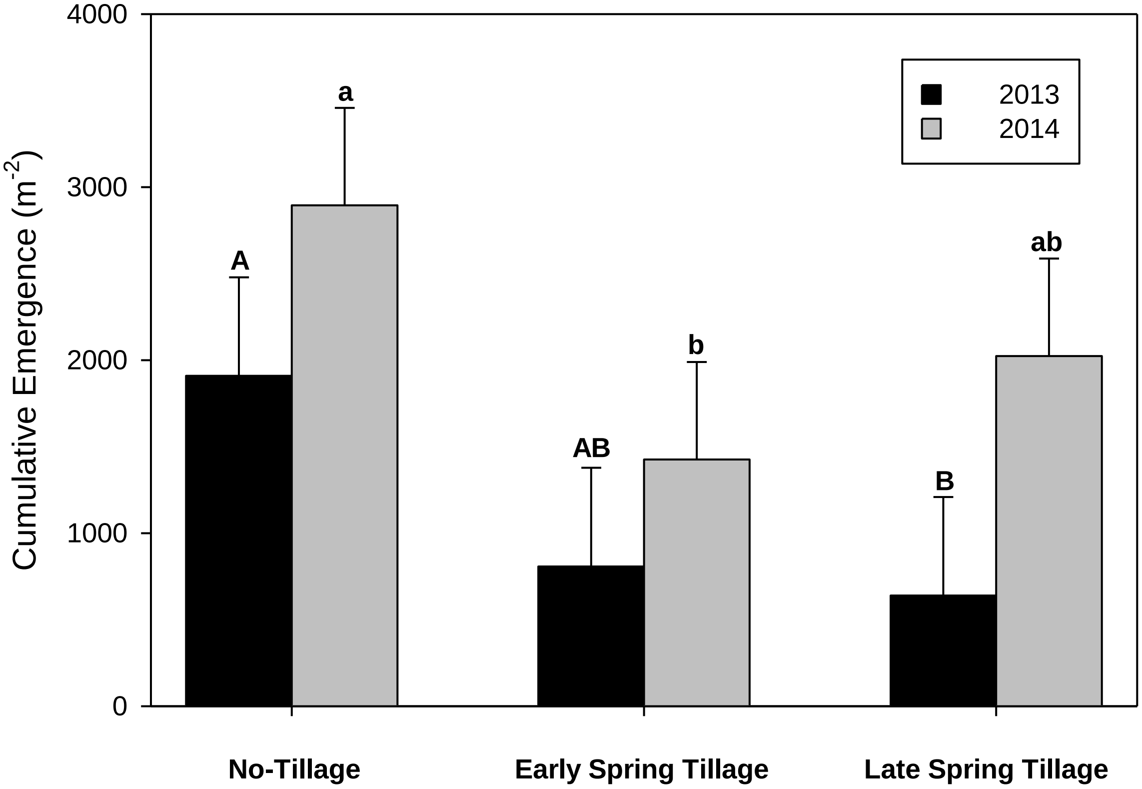

Figure 2.13. Season-long cumulative emergence per square meter of common waterhemp in no-tillage, early spring tillage, and late spring tillage plots at Novelty, MO in 2013 and 2014. Means with the same letter within year are not significantly different following separation with Fisher’s Protected LSD at p=0.05. Vertical bars indicate the standard error around the mean.

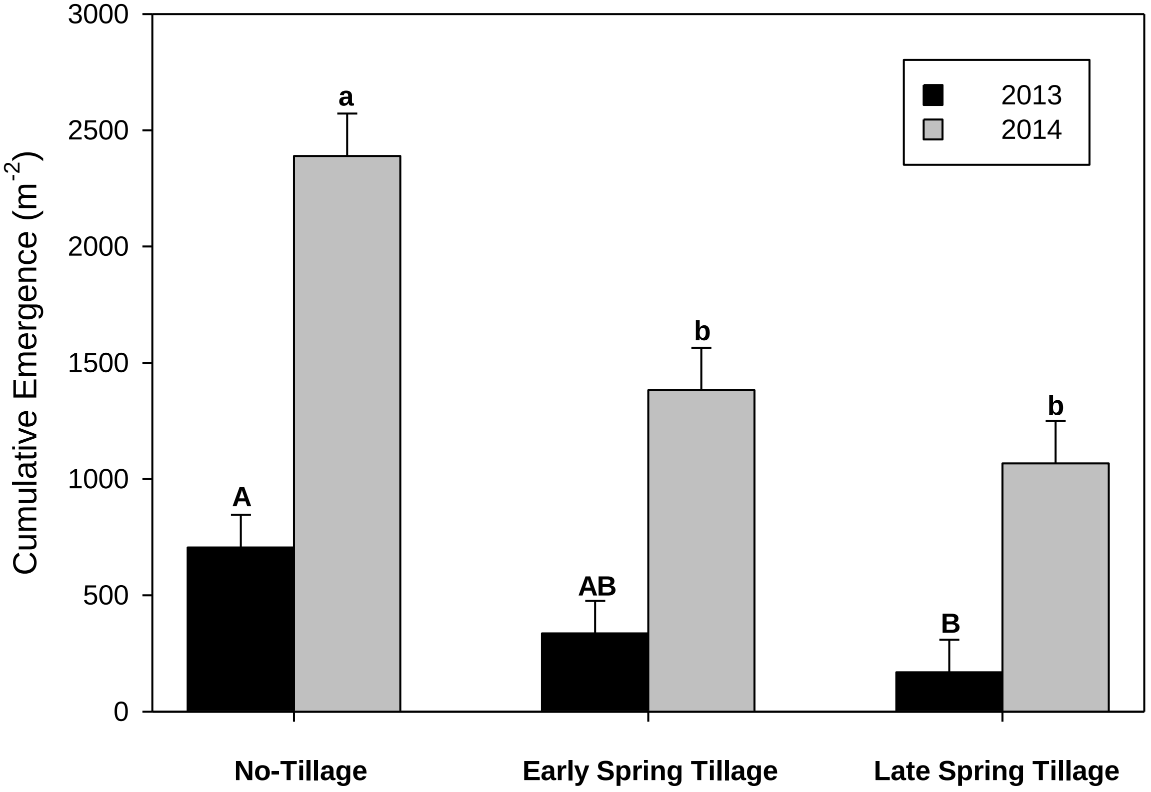

Figure 2.14. Season-long cumulative emergence per square meter of Palmer amaranth in no-tillage, early spring tillage, and late spring tillage plots at Portageville, MO in 2013 and 2014. Means with the same letter within year are not significantly different following separation with Fisher's Protected LSD at $p=0.05$. Vertical bars indicate the standard error around the mean.

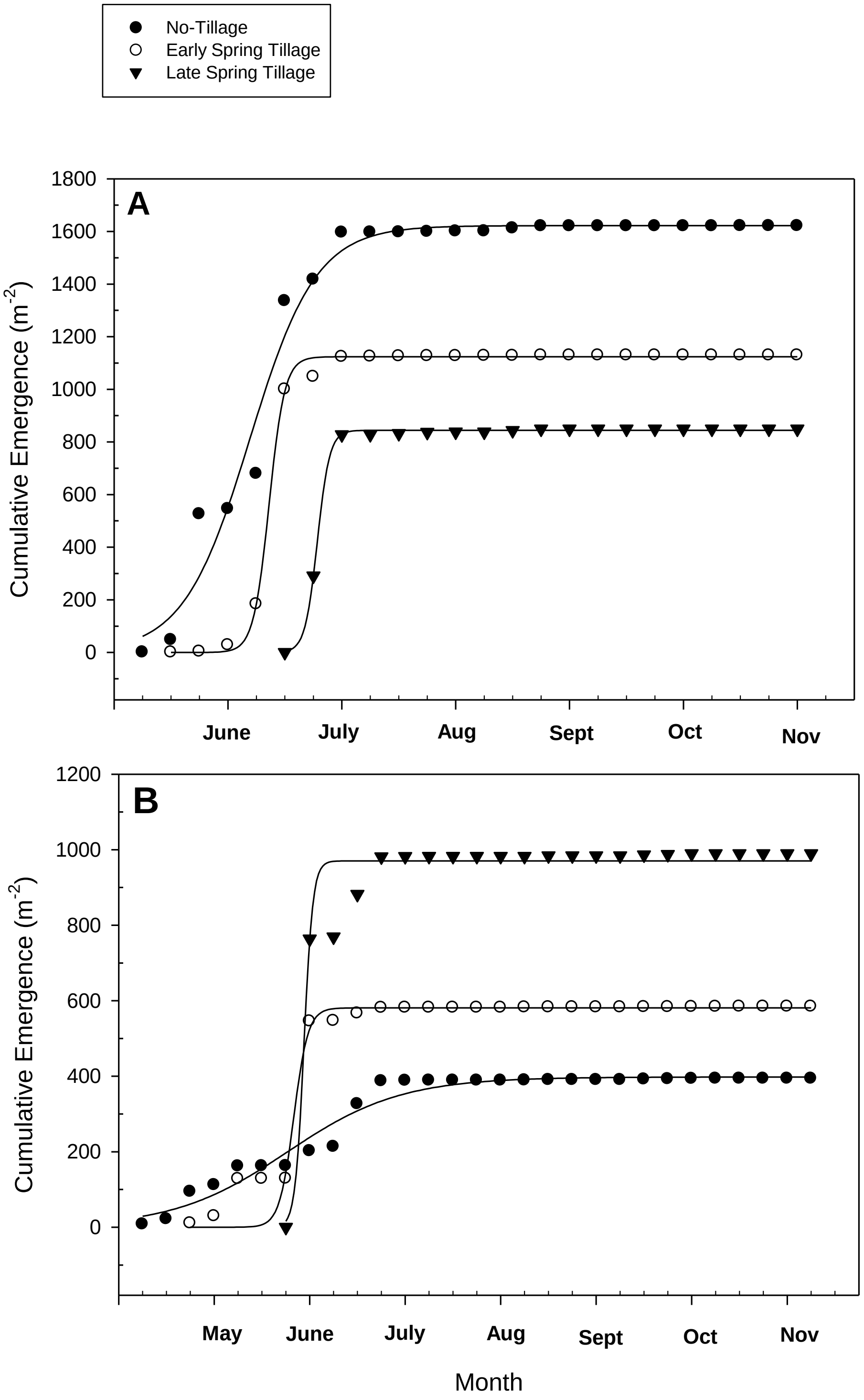

Figure 2.15. Cumulative common waterhemp emergence per square meter in Columbia, MO in 2013 (A) and 2014 (B). The time required for 90% cumulative emergence for treatments was determined using best fit lines; equations were derived using SigmaPlot (Table 2.2).

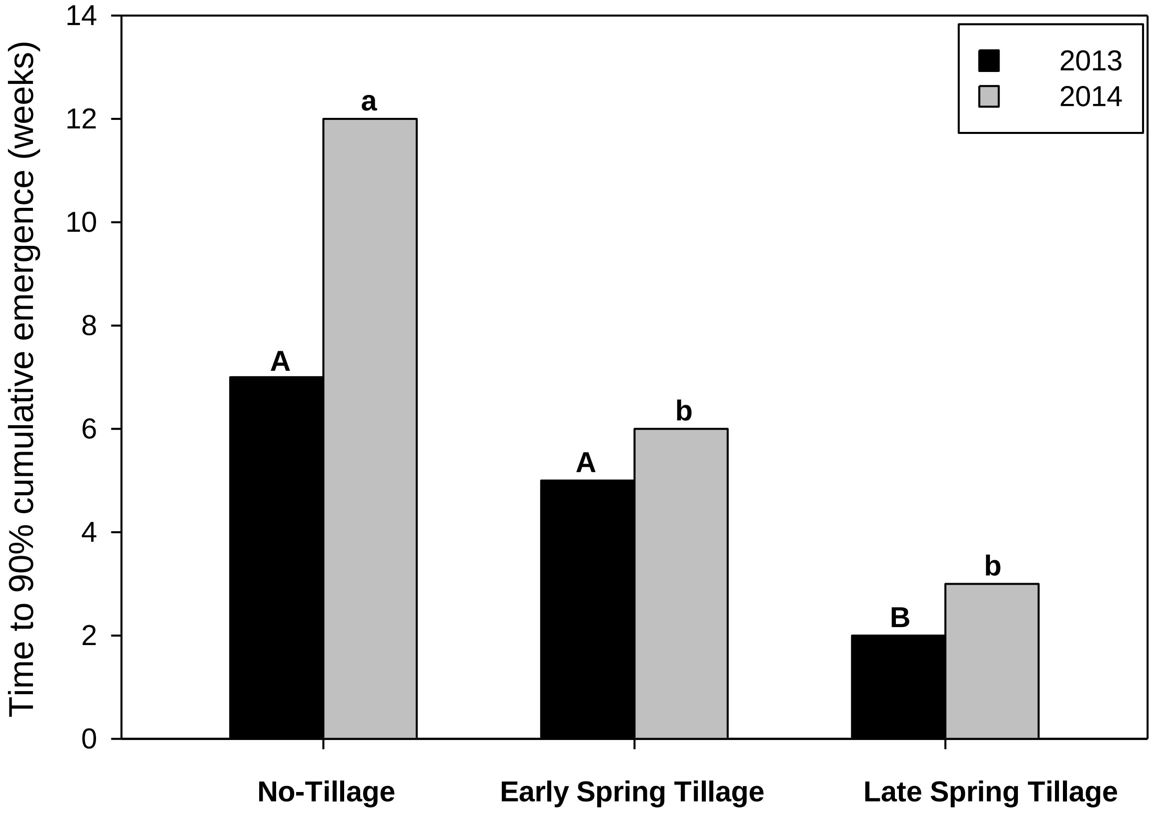

Figure 2.16. Number of weeks for common waterhemp to reach 90% cumulative emergence in Columbia, MO for 2013 and 2014. Means within year with the same letter are not significantly different following separation with Fisher's Protected LSD at p=0.05.

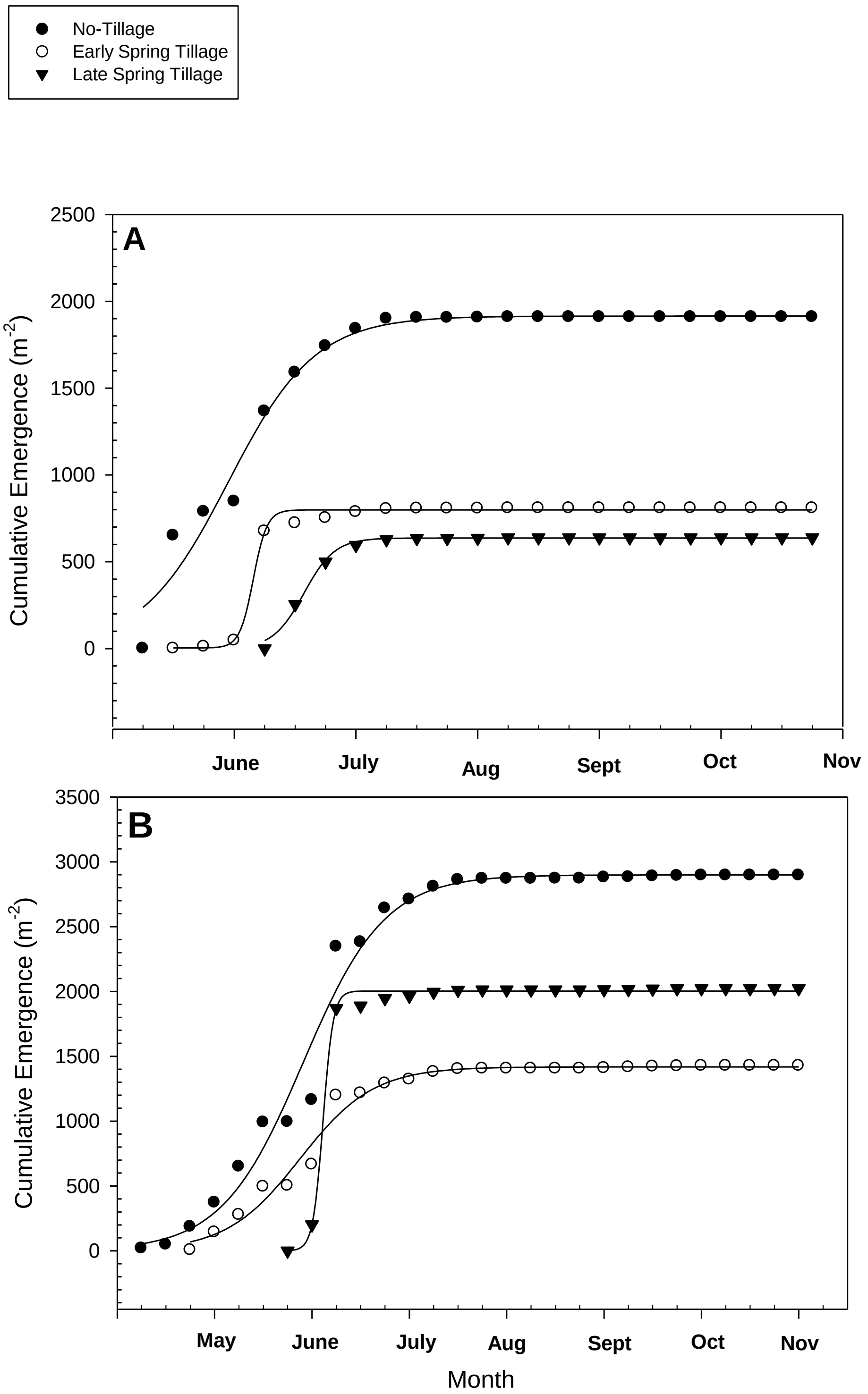

Figure 2.17. Cumulative common waterhemp emergence per square meter in Novelty, MO in 2013 (A) and 2014 (B). The time required for 90% cumulative emergence for treatments was determined using best fit lines; equations were derived using SigmaPlot (Table 2.2).

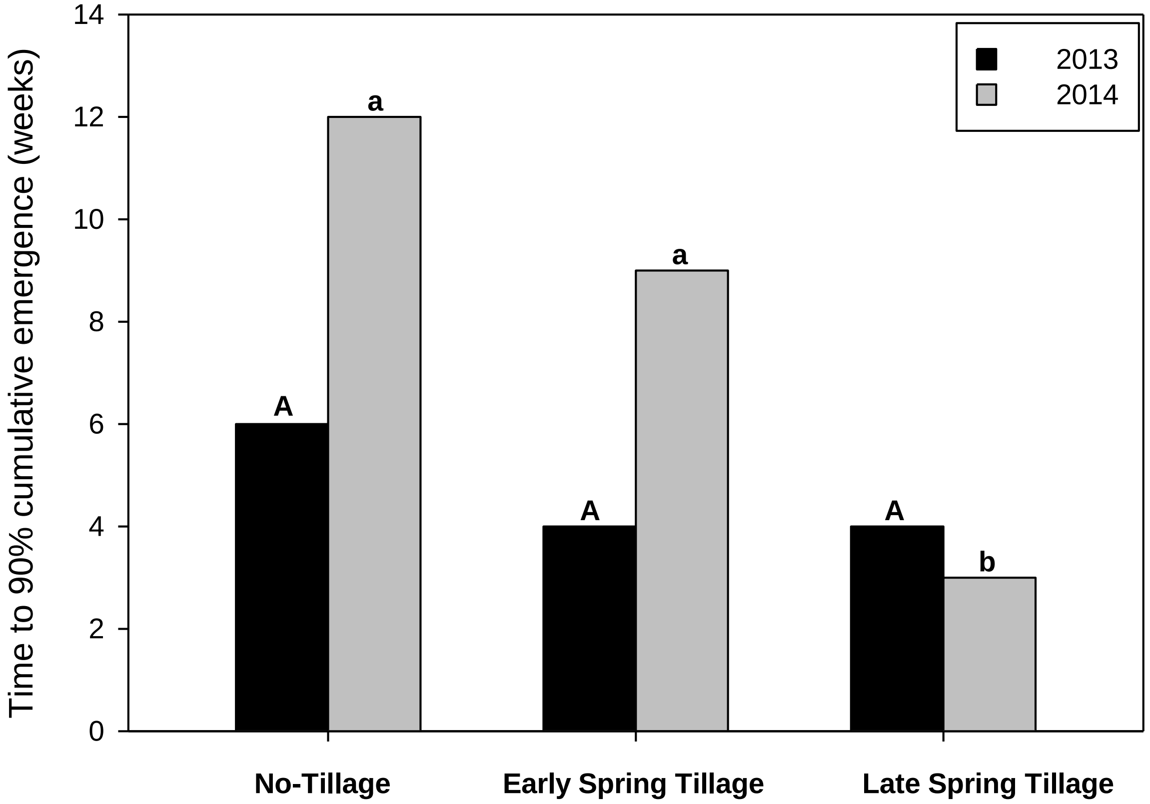

Figure 2.18. Number of weeks for common waterhemp to reach 90% cumulative emergence in Novelty, MO for 2013 and 2014. Means within year with the same letter are not significantly different following separation with Fisher's Protected LSD at p=0.05.

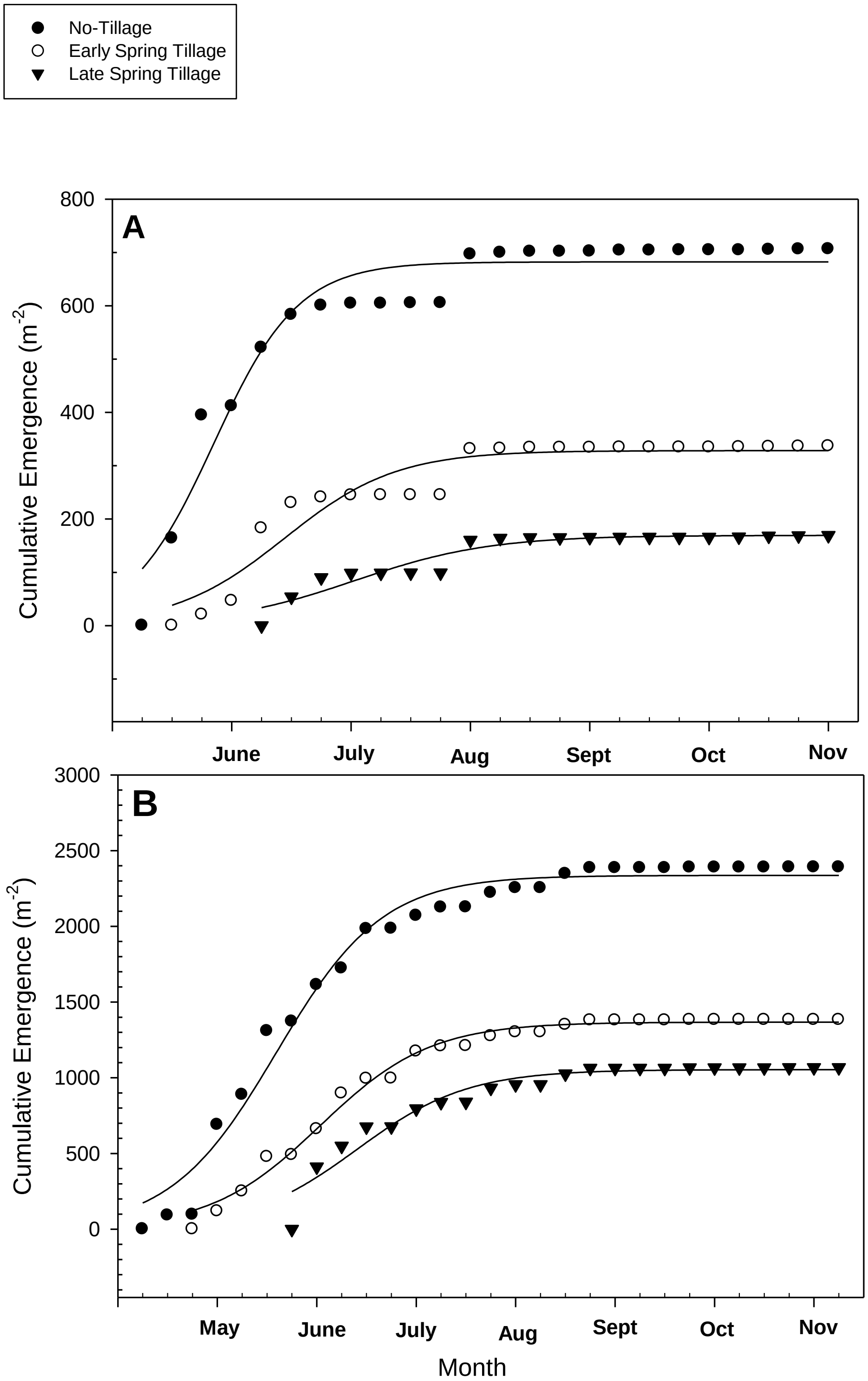

Figure 2.19. Cumulative Palmer amaranth emergence per square meter in Portageville, MO in 2013 (A) and 2014 (B). The time required for 90% cumulative emergence for treatments was determined using best fit lines; equations were derived using SigmaPlot (Table 2.2).

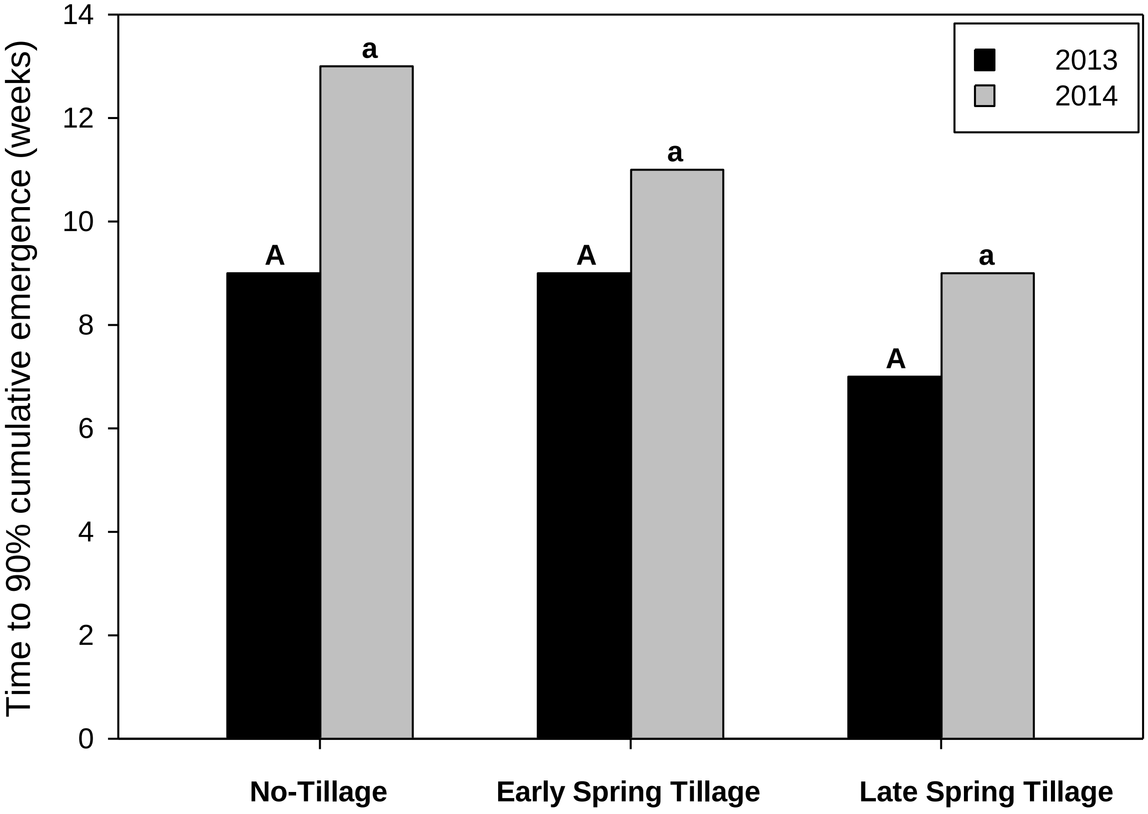

Figure 2.20. Number of weeks for Palmer amaranth to reach 90% cumulative emergence in Portageville, MO for 2013 and 2014. Means within year with the same letter are not significantly different following separation with Fisher's Protected LSD at p=0.05.

Chapter III

Impact of emergence date on vegetative and reproductive potential of *Amaranthus*

HEIDI R. DAVIS and REID J. SMEDA

Abstract: *Amaranthus* species such as common waterhemp (*Amaranthus rudis*) and Palmer amaranth (*Amaranthus palmeri*) are troublesome annual weeds that emerge throughout the growing season. Understanding the relationship of emergence date to plant growth and seed production is necessary to optimize management and reduce additions to the soil seedbank. In Missouri, waterhemp (central) and Palmer amaranth (southeast) seedlings were established at five emergence timings from late April through mid-September in 2013 and 2014. Weekly through plant senescence, plant height and the number of nodes were recorded. At maturity, plant biomass and seed production were estimated for female plants. Following emergence, waterhemp and Palmer amaranth reached 15.2 cm in height, which is the maximum labeled height for a number of POST herbicides, in as few as 20 days. Across both years, plant heights reached up to 220.8 cm for waterhemp and 209.4 cm for Palmer amaranth. Upon flowering, the percentage of female plants for both species varied from 43 to 62% over both years, but did not follow a pattern based on time of seedling emergence. Waterhemp seedlings emerging in early spring produced up to 803,400 seeds, whereas plants emerging in late July produced as few as 46,560 seeds. For Palmer amaranth, up to 179,640 and 51,960 seeds plant^{-1} were produced for mid-May and late July emerging plants, respectively. Seed production for plants emerging in mid-September averaged 11 and 33 seeds plant^{-1} for waterhemp and Palmer amaranth, respectively. Tetrazolium assays revealed seed viability ranged from 26 to 52% and 16 to 81% for waterhemp and

Palmer amaranth plants, respectively. Waterhemp partitioned up to 17% more plant biomass into seed production for plants emerging in July versus May for both years; partitioning of Palmer amaranth biomass into seed production was not strongly related to emergence date. Under current management practices, lack of controlling late-season emerging *Amaranthus* may allow significant seed production to re-charge the soil seed bank.

Nomenclature: Common waterhemp, *Amaranthus rudis*; Palmer amaranth, *Amaranthus palmeri,* tetrazolium, 2,3,5-triphenyl-2H-tetrazolium chloride.

Additional index words: Common waterhemp, Palmer amaranth, seed production.

Introduction

Waterhemp and Palmer amaranth are small seeded summer annuals that require placement at or near the soil surface for proficient emergence (Felix and Owen 1999; Hoffman et al. 1998; Yenish et al. 1992). Pigweed germination begins at approximately 350 growing degree days (10 C base temperature) (Horak and Loughin 2000). Guo and Al-Khatib (2003) reported peak emergence of common waterhemp (*Amaranthus rudis* Sauer) and Palmer amaranth (*Amaranthus palmeri* S. Wats) was observed when the day/night temperature fluctuated between 25/20 and 35/30 C, respectively.

Once established, *Amaranthus* seedlings develop rapidly. At maturity, both waterhemp and Palmer amaranth averaged 2 m in height (Keeley et al. 1987; Steckel et al. 2007). Horak and Loughin (2000) reported maximum growth rates for Palmer amaranth and waterhemp emerging in June in monoculture systems. Palmer amaranth grew up to 0.21 cm growing degree day^{-1} (GDD^{-1}), whereas waterhemp grew up to 0.16

cm GDD^{-1}. Rapid growth resulted in tall plants at maturity. Mid-June emerging Palmer amaranth reached a final height of 231 cm and produced 69 lateral branches, while waterhemp reached an average of 221 cm and generated 47 lateral branches.

In addition to plant height, plants accumulate biomass quickly. In greenhouse conditions at a 15/10 C day/night temperature, Guo and Al-Khatib (2003) reported waterhemp seedlings five weeks after emergence weighed 15 g while Palmer amaranth only attained 5 g. Palmer amaranth flourished at higher temperatures (25/20 and 35/30 C) and consistently weighed 3 to 20 g more than waterhemp from 1 to 4 weeks after emergence. Sellers et al. (2003) observed minimal biomass differences in the field between 1 and 4 weeks after emergence, but the biomass of Palmer amaranth was nearly 37% greater than waterhemp 14 weeks after seedling emergence.

Initial emergence timing of *Amaranthus* may impact plant growth and total seed production. Cooper (2003) suggests that initiation of flowering near the summer solstice encourages longer reproductive and seed maturity periods, ultimately resulting in higher seed production. Keeley et al. (1987) reported Palmer amaranth emerging during March through June produced 200,000 to 600,000 seeds plant $^{-1}$, while those emerging in July through September produced 115 to 80,000 seeds plant $^{-1}$. Sellers et al. (2003) observed that Palmer amaranth and waterhemp plants produced in excess of 250,000 seeds plant^{-1}. On a plant dry weight basis, waterhemp produced 535 seeds per g plant tissue, while Palmer amaranth only produced 261 seeds g^{-1} plant dry weight.

Amaranthus species are highly competitive in row crops such as soybean and corn throughout the mid-west and mid-south. Maximum soybean yield losses reached 79 and

56% when a density of eight Palmer amaranth or waterhemp plants m^{-1} row emerged with soybean, respectively (Bensch et al. 2003). Soybean yield was not impacted when waterhemp and Palmer amaranth emerged in mid-July and competed through soybean harvest. Season-long competition of waterhemp with soybean resulted in 44 and 37% yield reductions in wide (76 cm) and narrow (19 cm) row spacings, respectively (Steckel and Sprague 2004b). Delaying waterhemp emergence until V2 and V3 soybean resulted in yield reductions of 27 and 15% in wide and narrow rows, respectively. Lower than 10% yield losses were observed when waterhemp emerged in V4 to V5 stage soybean. In corn, Palmer amaranth and waterhemp emerging after V4 stage plants reduced maize yield from 16 to 45% and 13 to 59%, respectively (Massinga et al. 2001; Steckel and Sprague 2004a).

Emergence timing of *Amaranthus* determines the extent of competition with crops, but also impacts plant size before shorter days convert plants from vegetative to reproductive growth (Goyne and Schneiter 1988). Older (6 to 8 weeks old) accessions of Palmer amaranth allocated more resources toward reproductive structures when compared to younger accessions (2 to 4 weeks old) (Bond and Oliver 2006). Similarly, in the absence of competition, redroot pigweed (*Amaranthus retroflexus* L.) in Kansas partitioned 8, 30 and 62% of plant resources as dry matter into leaves, stems and reproductive structures, respectively, during reproductive stages (Knezevic et al. 2001). During vegetative stages in June and July, 66% of plant dry matter was allocated to leaves and 34% to stems. Redroot pigweed emerging in one-leaf sorghum (*Sorghum bicolor* L. Moench) partitioned 64% dry matter to reproductive structures compared to 16% for plants emerging at the 8.6-leaf stage of sorghum.

Although management practices for *Amaranthus* target early season emerging seedlings to preclude competition, the relationship between waterhemp and Palmer amaranth emergence and seed production is incomplete. It has been hypothesized that plants emerging after late herbicide applications (after V5 soybean) are not significant competitors with crops but may contribute significantly to the soil seed bank (Hartzler et al. 2004; Steckel and Sprague 2004b). Little information is known about the partitioning of plant resources into leaves and stems versus seeds in relationship to emergence date. These data would identify the importance of management to preclude both competition with crops and seed production. The objective of this research was to identify the relationship between emergence date and the vegetative and reproductive potential of both waterhemp and Palmer amaranth.

Materials and Methods

Field trials with waterhemp were conducted at the Bradford Research and Extension Center near Columbia, MO (38.89ºN, 92.19ºW) and with Palmer amaranth at the Fisher Delta Research Center near Portageville, MO (36.39ºN, 92.19ºW) in 2013 and 2014. The soil type at Columbia was a Mexico silt loam (fine, smectitic, mesic, Vertic Epiaqualfs) with pH 6.3 and 1.9% soil organic matter in 2013. In 2014, the soil type was a Leonard silt loam (fine, smectitic, mesic Vertic Epiaqualfs) with pH 6.3 and 1.9% soil organic matter. At Portageville, the soil type was a Tiptonville silt loam (fine-silty, mixed, superactive, thermic Oxyaquic Argiudolls) with pH 5.2 and 1.4% soil organic matter in both 2013 and 2014.

Amaranthus emergence timing was targeted for five periods: two timings prior to the summer solstice; at summer solstice; and two periods after summer solstice. The first emergence date represented natural emergence and the final timing was approximately six weeks before the expected frost date based on the Farmer's Almanac (Anonymous 2013d; Anonymous 2014b). Emergence timings were designated as E1, E2, E3, E4 and E5, representative of emergence from late April through mid-September in 2013 and 2014 (Table 3.1). Plants emerged naturally and were kept free of interspecific competition. Plant density was controlled initially by placing plastic cups over desirable plants and applying 0.58 kg ae ha^{-1} glufosinate at 140.3 L ha^{-1} and 137.8 kPa using a CO_2 backpack sprayer (speed of 4.8 km h^{-1}). Approximately 60 plants were selected per plot. Cups were placed over plants spaced 30.5 cm apart to form three rows 76 cm apart. For late time points, unwanted vegetation was removed by hand or hoed. An electric fence was placed around the experimental area to preclude feeding damage from deer (*Odocoileus virginianus*). Waterhemp was subjected to feeding from blister beetles (*Epicauta* vittata); plants were sprayed with 0.028 kg ai ha^{-1} of Mustang® Maxx (S-Cyano (3-phenoxyphenyl) methyl (+) cis/trans 3-(2,2 dichloroethenyl)-2,2 dimethylcyclopropane carboxylate). In 2013, plots at both Columbia and Portageville were irrigated with 3.75 cm water on July 15 and July 17, respectively, due to extreme dry conditions. Plots were three by nine meters.

Precipitation from April through October was higher in 2014 compared to 2013 at Columbia (waterhemp) (Table 3.2). Waterhemp plants accumulated more biomass and produced more seed in 2014. Plants in 2013 were stressed and apportioned a higher percentage of plant dry weight as seed weight. Although precipitation was higher in 2013 at Portageville (Palmer amaranth), there was more available moisture through flowering in 2014. Weekly soil temperatures at a depth of 5 cm were up to 6 C higher in 2013 at

Columbia, whereas 2013 soil temperatures at Portageville were up to 10 C in 2013 (Table 3.3). From the end of July 2014 through the middle of August at Columbia, soil temperatures were slightly higher compared to 2013. The entire month of August was warmer in 2014 at Portageville. Overall, soil temperature was typically higher in 2013. Plants in 2014 accumulated more biomass, but plants in 2013 partitioned a higher percentage of dry weight toward seed weight compared to 2014.

Data Collection

Plant height (from ground level to the apical meristem) and the number of nodes (of fully expanded leaves) were recorded for six random plants per plot on a weekly basis (6 different plants each week). As dioecious species, the proportion of female plants for waterhemp and Palmer amaranth was recorded observing 10 to 55 waterhemp and 14 to 72 Palmer amaranth plants when flowers were open. Once female plants reached approximately 80% seed maturity, six plants were harvested per plot at ground level. Harvested plants were air dried at 27 C. Bagavathiannan et al. (2013) reported that a large percentage of Palmer amaranth seed does not shatter from the plant prior to crop harvest. For this reason, seed was thrashed with a hand operated plant thrasher and seed cleaned using sieve pans and a desk fan to remove excess chaff. Clean seed was stored at room temperature.

Estimates of total seed production were based on separating two random, 200 seed subsamples per plant across emergence timings.

$$T = [W(S/C)]/(S/200) \quad [1]$$

Where T equals the total number of seeds per plant, W is the collective weight of seeds and chaff of one plant, S is the pure seed weight per 200 seeds, and C is the weight of 200 seeds including chaff. The weight of one seed is estimated by $S/200$.

Number of seeds per one kg of seed weight was determined by the formula:

$$K=T\,[1000/\,(W(S/C))] \tag{2}$$

Where K is equal to number of seeds per one kg of seed weight, T is the total number of seeds per plant, W is the collective weight of seeds and chaff of one plant, S is the pure seed weight per 200 seeds and C is the weight of 200 seeds including chaff.

Percent seed weight versus overall plant dry weight was determined by the formula:

$$P= [W(S/C)]/D \tag{3}$$

Where P is equal to the percent pure seed weight versus overall plant dry weight, W is the collective weight of seeds and chaff of one plant, S is the pure seed weight per 200 seeds, C is the weight of 200 seeds including chaff, and D is the total plant dry weight, including seeds.

The number of days to 15.2 cm was estimated using quadratic, cubic and sigmoid 3-parameter models in SigmaPlot (Version 11.2 Systat Software, Inc., 2107 North First Street, Suite 360, San Jose, CA 95131 USA). The height of Palmer amaranth in 2013 and waterhemp in 2013 and 2014 for the final emergence date (E5) failed to reach 15.2 cm. The cubic model equation is as follows (Dos Santos et al. 2014):

$$Y=y_0+ax+bx^2+cx^3 \tag{4}$$

Where Y is plant height, y_0 is the intercept, x is the days after plant emergence, a is the slope, b is the quadratic term for week and c is the cubic term for week. The quadratic model is as follows (Daroub et al. 2000):

$$Y=y_0+ax+bx^2 \qquad [5]$$

Where Y is plant height, y_0 is the intercept, x is the days after plant emergence, a is the slope, and b is the quadratic term for week. The sigmoid 3-parameter model is as follows (Mathews and Hopkins 1999):

$$Y = \frac{a}{1+e^{-(x-x_0/b)}} \qquad [6]$$

Where Y is plant height, a is the maximum plant height predicted by the model, e is the base of natural logarithms, x is the days after plant emergence, x_0 is the time required to reach 50% of the maximum height predicted by the model, and b is the slope of the regression line.

Data recorded for each plant included: final plant height; number of nodes; seed quantity; percentage of plant dry weight allocated to seed; and seed viability. Final plant height and number of nodes were recorded for plants from ground level before harvest. Percent viable seed was determined using a tetrazolium (2,3,5-Triphenyl-2H-tetrazolium chloride, 98% $C_{19}H_{15}ClN_4$) analysis. Waterhemp seeds had low germination so they were put into mesh bags in wet sand prior to tetrazolium testing. Samples were first incubated at 33 C for three days and then alternated every three days between 4 and 33 C to break dormancy over a nine day period. Methods to increase initial germination were adapted from Guo and Al-Khatib (2003) and Leon and Owen (2006) who observed fluctuating temperatures and stratification at 4 C under wet conditions maximizes germination. The stratification period allowed for imbibition of ungerminated seeds. Palmer amaranth seeds in 2013 and 2014 had high germination without alternating temperatures so seeds were only submerged into water to allow for initial seed germination.

Amaranthus plants undergo several flowering pulses during the course of reproduction, which results in alternating ages of developing seed (Wu and Owen 2014). Therefore, it was important to estimate overall seed viability. The tetrazolium technique used was adapted from the AOSA/SCST Tetrazolium Testing Handbook (Miller and Peters 2010). For each harvested plant, two sub-samples of 25 seeds were selected randomly and placed in water for 48 h to soften the seed coat. Number of germinated seeds were recorded for both species at the end of the imbibition period and removed. Ungerminated seeds were subjected to tetrazolium analysis. With the ungerminated seed on edge (Figure 3.1), seeds were cut longitudinally. Each seed half was placed embryo down on P8 grade, coarse filter paper in a petri dish containing 2 mL of a 1% tetrazolium solution. Petri dishes were wrapped in foil to preclude light and stored at room temperature (22 C) for 24 h. Under a dissecting scope, visible pink/red staining of the embryo (Figure 3.2) revealed viable seeds.

Weather was a limiting factor for late emerging plant seed maturity. Waterhemp emerging in September 2013 flowered but did not successfully pollinate and produce seed prior to frost. For 2013 Palmer amaranth, inflorescences formed on plants emerging in September, but no seed formed by harvest (prior to frost).

Statistics

Experiments were designed as a randomized complete block with five replications. Plants within a plot that were measured weekly and harvested were considered pseudoreplications. Data for percent plant dry weight as seed was transformed using the model statement link=logit and distribution=beta (Kieschnick and McCullough 2003). Seed viability and the proportion of females in relation to the overall plot population were transformed using the model statement link=logit and distribution=bin (Nelder and Wedderburn 1972). Homogenous variance could not be met, PROC Rank (Conover and Iman 1981) was performed on all parameters except for the female proportion, percent plant dry weight as seed, and percent viable seed. Data were not pooled across years for each species due to differing environmental conditions. All variables were assumed to be fixed except for replication and the replication by treatment interaction, which were considered random. ANOVA was conducted using PROC GLIMMIX in SAS (Version 9.4, SAS Institute, Inc., 100 SAS Campus Drive, Cary, NC 27513-2414 USA). Means were separated using Fisher's Protected LSD at P=0.05.

Results and Discussion

Vegetative Production

By the end of the growing season, waterhemp height exceeded 2 m (Figure 3.3). In both 2013 and 2014, plants emerging in May reached heights exceeding all other emergence timings, with a step-wise reduction in plant height for later emerging plants. E4 plants ranged in height from 79 to 89 cm, approximately 60% shorter than E1 plants. For E5 plants, the maximum height was 6 cm. Differences in plant growth between years may be attributable to environmental variation. Precipitation was higher through the summer solstice for 2013 versus 2014, but precipitation decreased and plants became stressed, allocating more resources toward reproduction (Table 3.2). Therefore, E1 and E2 plants were taller in 2013 but abundant precipitation later in 2014 enabled E3 and E4 plants to grow taller in 2014 than 2013.

Palmer amaranth plants also grew rapidly, with many plants exceeding 2 m in height (Figure 3.4). Plants from E1 through E3 were similar in height, surpassing E4 plants that reached 102 and 189 cm in 2013 and 2014, respectively. E5 plant height was drastically reduced and only reached 10 cm. Vegetative growth was greatest in 2014, although season-long precipitation was higher for 2013, rainfall was greater through flowering in 2014, promoting vegetative growth (Table 3.2).

After an initial lag in growth following emergence, waterhemp and Palmer amaranth seedlings at all emergence dates grew rapidly. In both 2013 and 2014, waterhemp seedlings emerging in late July (E4) grew more rapidly in height than E3 and E2 seedlings, with height accumulation of E1 plants growing the slowest (Figure 3.5). Because many POST herbicides labelled for *Amaranthus* control recommend a maximum height of 15.2 cm, the time for waterhemp to reach this height was predicted (Figure 3.6). In 2013, the range in time for waterhemp to reach 15.2 cm was 20 to 39 d for E1 to E4 plants. For both years, plants emerging in mid-September did not reach a height of 15.2 cm, therefore time could not be estimated. Palmer amaranth plants reached 15.2 cm at similar rates between years (Figure 3.7). Days to 15.2 cm decreased from 34 d to as few as 17 d as emergence timing was delayed from E1 to E4 for both years (Figure 3.8). In 2014, E5 plants took 21 d to reach 15.2 cm. Plants emerging in mid-September in 2013 did not reach 15.2 cm, consequently, no estimation of time could be made.

Although *Amaranthus* exhibits rapid vertical growth, extensive branching was noted for plants (Table 3.4). For both 2013 and 2014, E1 waterhemp plants produced the greatest number of nodes (62.1 to 64.3), with progressively fewer nodes for later emerging plants. Both E4 and E5 plants generated up to 86% fewer lateral branches compared to E1 plants.

Palmer amaranth also generated fewer nodes for early versus later emerging plants (Table 3.4). Plants accumulated 8 to 59 nodes across emergence timings over two years. E4 and E5 plants produced up to 54 and 85% fewer lateral branches compared to late April emerging plants, respectively.

Dry weight of waterhemp decreased with later emergence dates (Figure 3.9). Plants emerging in May accumulated up to 747 g biomass in both 2013 and 2014, and decreased significantly thereafter. E2 plants were up to 43% smaller than E1 plants. Dry weight decreased from 178 to 32 g and 312 to 146 g for E3 compared to E4 plants in 2013 and 2014, respectively. At the last emergence timing (E5), biomass only reached up to 5 g per plant.

Similar to waterhemp, biomass of Palmer amaranth was greatest for May emerging plants (E1) and decreased for emergence timings thereafter (Figure 3.10). For E1 plants in 2013, dry biomass was 321 g and decreased to 55 g for late July emerging plants (E4). E1 and E2 plants averaged greater than 400 g whereas E3 and E4 plants accumulated 336 and 136 g, respectively. E5 plants only accumulated up to 1 g biomass.

Flowering

The frequency of female *Amaranthus* plants was determined to identify if the percent of females per population is impacted by emergence date (Table 3.5). The percent of female waterhemp plants per emergence timing ranged from 43 to 51% for both years. For Palmer amaranth, the female proportion fluctuated from 43 to 62% in 2013 and 2014. In 2013 and 2014, the female percentage was not significantly different from 50% for either species except for Palmer amaranth E4 plants in 2014.

An important factor contributing to reproductive potential of *Amaranthus* is the duration from emergence to initial flowering. Days to initial flowering after emergence decreased as emergence timing was delayed. From emergence to initial flowering, waterhemp required 33 to 69 d and 43 to 89 d in 2013 and 2014, respectively (Table 3.1). Emergence timing influenced initial flowering timing as day length shortened. E1 plants required up to 52% more days to flower than plants emerging in mid-September.

Palmer amaranth followed a similar trend as waterhemp for days from emergence to initial flowering (Table 3.1). In 2013, days to initial flowering following emergence decreased from 54 d for E1 to 47 d for E4. E5 plants did not flower in 2013. Days from emergence to initial flowering for E1 to E5 in 2014 decreased from 66 to 26 d. E5 plants initiated flowering 61% more quickly than E1 plants.

Reproduction

Seed weight as a percentage of total dry biomass was estimated for both waterhemp and Palmer amaranth. Waterhemp plant dry weight partitioned to seed weight increased for plants with later emergence timings with the exception of E5 plants (Table

3.6). In 2013, percent seed weight increased from 25 to 30% for E1 to E4 plants, respectively. For 2014, percent seed weight for plants increased more dramatically; 12% for E1 to 29% for E4 plants. Up to 18% more of waterhemp biomass was apportioned in seed weight in 2013 versus 2014 for E1 through E4. E5 plants in 2014 allocated 1.5% dry weight toward seed production. Water stressed plants in 2013 distributed higher percentages of plant dry matter into seed than 2014 plants.

Palmer amaranth apportioned less plant dry weight toward seed than waterhemp (Table 3.6). In 2013, Palmer amaranth plants partitioned 16 to 18% plant dry weight into seed for E1 to E4 plants. In 2014 however, only 0.6 to 12% of plant biomass was measured as seed. Similar to waterhemp, little biomass was accumulated as seed in 2014 for E5 plants. In contrast to waterhemp, there was no relationship between emergence date for Palmer amaranth and amount of plant biomass contributed as seed. Plants in 2013 versus 2014 contributed more resources to seed.

Emergence timing of *Amaranthus* had a strong influence on total seed production. In 2013 for waterhemp, E1 plants produced an average of 803,400 seeds, with step-wise reductions to 432,140, 275,250, and 46,560 seeds plant^{-1} for E2, E3, and E4 plants, respectively (Figure 3.11). E5 plants did not produce seeds in 2013. E1 plants in 2014 produced fewer seeds versus E1 plants in 2013, an average of 634,200 seeds plant^{-1}. Seed production declined from 468,900 to 11 seeds plant^{-1} for E2 to E5 emergence timings in 2014. Seed production was higher in 2014 except for 2013 E1. Precipitation was higher prior to the summer solstice in 2013 versus 2014 (Table 3.2). E1 plants in 2013 began to flower after the summer solstice and may contribute to higher seed production versus E1 plants in 2014.

Palmer amaranth was less prolific compared to waterhemp in both 2013 and 2014. Similar to waterhemp, total seed production decreased for plants emerging later in the growing season. In 2013, E1 through E4 plants produced an average of 115,300, 141,420, 84,320, and 28,940 seeds (Figure 3.12). Maximum seed production occurred in 2014 for E1 plants with 179,640 seeds. For plants emerging in late July (E4), plants produced up to 51,960 seeds. Although no seed were collected from E5 plants in 2013, 33 seeds plant^{-1} were collected in 2014.

Another measure of reproductive capacity of *Amaranthus* is seed quality. This can be assessed by determining the number of seeds kg^{-1} seed weight. E1 through E3 waterhemp plants in 2013 produced in excess of 4,500,000 seeds kg^{-1}, whereas E4 plants generated 3,817,700 seeds (Figure 3.13). Plant dry weight was higher in 2014 as well as seed production, with the exception of E1 plants. Consequently, the number of seeds kg^{-1} seed weight increased to an excess of 8,000,000 seeds for E1 and E2 plants. Seeds per kg^{-1} decreased from 7,857,500 to 3,793,100 for E3 to E4 plants. E5 plants only generated 2,659,200 seeds kg^{-1} in 2014.

Palmer amaranth seed were visibly larger compared to waterhemp, which was reflected in the number of seeds per seed weight. In 2013, seeds kg^{-1} fluctuated for E1 to E4 plants, ranging from 2,164,500 to 2,625,700 seeds (Figure 3.14). For E1 through E4 plants in 2014, the number of seeds kg^{-1} also fluctuated varying between 2,629,700 and 3,409,000 seeds. The number of seeds kg^{-1} greatly increased for E5 plants, up to 6,218,500 seeds kg^{-1}.

Despite prolific seed production for both species, seed viability varied. Waterhemp seed viability was up to 21% higher in 2013 than 2014 (Table 3.7). In 2013, waterhemp seed viability decreased from E1 to E4 plants, 52 to 26%. Percent viability fluctuated across emergence timings in 2014. Viability of seed from E1 through E5 plants ranged from 29 to 31%.

Palmer amaranth seed viability remained similar over both years and was considerably higher compared to waterhemp. In both years, there was no evident relationship between emergence date and percent viability (Table 3.7). In 2013, viability ranged from 51 to 63% for E1, E2, E3, and E4 plants. Viability of seed from E1 plants in 2014 was considerably higher at 81%. In 2014, E2 through E4 seed viability was 11 to 14% lower than E1 plants. Approximately 85% of seeds produced on plants emerging six weeks before the expected frost date (E5) were not viable, suggesting that the majority of seeds were unable to mature before plant senescence.

Rapid growth of *Amaranthus* species following emergence limits the effective duration for application of POST herbicides. POST applications of atrazine (2-chlor-4-ethylamino-6-isoproplyamino-s-triazine), lactofen (2-ethoxy-1-methyl-2-oxyethyl-5-[2-chloro-4-(trifluoromethyl)-phenoxy]-2-nitorbenzoate), fomesafen (5-[2-chloro-4-(trifluoromethyl)phenoxy]-N-(methylsulfonyl)-2-nitrobenzamide), and glufosinate ammonium (2-amino-4-(hydroxymethylphosphinyl)butyric acid-monoammonium salt) on *Amaranthus* species are recommended for plants less than 15.2 cm (Anonymous 2013a; Anonymous 2013b; Anonymous 2013c; Anonymous 2014a). For soybean, in-crop applications of lactofen and fomesafen are recommended for *Amaranthus* species up to 5 to 7.6 cm (Anonymous 2013b; Anonymous 2013c). Rapid growth is a contributing characteristic that makes timely weed control difficult, resulting in producers missing target applications (Baker 1975). Large farm size and undesirable weather patterns can limit control and plants may rapidly exceed labelled sizes, leading to plant escapes after application (Norsworthy et al. 2012). Later emerging *Amaranthus* grew more rapidly than early season plants. Time until plants reach 15.2 cm is influenced by photoperiod interval but may also be effected by air temperature during early growth. Plants from E2 and E4 typically had similar photoperiod duration, yet days to 15.2 cm greatly differed. One suggestion to explain the opposing growth rate is the differing soil temperature over the period to 15.2 cm. Waterhemp and Palmer amaranth emerging at E2 were exposed to an average of 24 and 26 C at a 5 cm soil temperature, respectively (Table 3.3). Soil temperatures for E4 plants were 27 C for both species. Optimum day temperatures for growth of waterhemp and Palmer amaranth are reported to be 25 and 35 C, respectively (Guo and Al-Khatib 2003). E1 plants reached 15.2 cm at a slower rate than later emerging seedlings, suggesting that early plant growth is slowed by low temperatures.

Emergence timing of *Amaranthus* is an important factor that influences the amount of seed contributed to the soil seed bank. Nordby et al. (2007) and Hartzler et al. (2004) reported later emerging *Amaranthus* had a reduced effect on crop yield. Bensch et al. (2003) also noted insignificant soybean yield losses when waterhemp and Palmer amaranth emerged in mid-July compared to plants emerging earlier in the season. Bensch et al. (2003), Hartzler et al. (2004), and Nordby et al. (2007) suggest that although late emerging plants may not be competitive, they possibly contribute significantly to the soil seed bank. Waterhemp and Palmer amaranth plants accumulated up to 95% less biomass as emergence timing was delayed from May to late July. Late emerging waterhemp compensated for lower biomass production by partitioning a higher percent of plant weight into seed production. Although later emerging waterhemp plants produced fewer seeds per plant, there were fewer seeds kg^{-1} suggesting that seeds were larger, possibly increasing seed quality. However, late emerging Palmer amaranth plants typically partitioned more energy into seed production but seed size did not considerably increase as emergence timing was delayed. Viability was higher for seeds from late emerging Palmer amaranth in 2013 and it was similar across emergence timings in 2014. These data suggest that late emerging plants would be less competitive and productive. Instead of vegetative production, plants emerging after the summer solstice partitioned energy into seed weight. Bond and Oliver (2006) reported more resources were partitioned into Palmer amaranth stems and reproductive structures as plants matured. Redroot pigweed allocated 62% biomass toward reproductive structures versus 8 and 30% into leaves and stems, respectively (Knezevic et al. 2001).

Delayed emergence of *Amaranthus* did not affect the plants ability to initiate reproduction, as initiation of flowering was significantly shortened. Vegetative periods lasted up to 89 d for May emerging waterhemp and decreased to 33 to 43 d for late July emerging seedlings. Palmer amaranth emerging in May did not initiate flowering until at least 54 d after emergence. Mid-September emerging plants had a 26 d vegetative period. Wu and Owen (2014) reported similar vegetative periods; up to 54 and 28 d for mid-May and early July emerging plants, respectively. Early emerging waterhemp initiated flowering in late July and mid-September emerging plants produced viable seeds by the end of October. Palmer amaranth emerging in early May initiated flowering as early as July 2 and late emerging plants produced seed through the end of October, similar to waterhemp. Although other studies have not compared seedling emergence timings to seed production, there have been reports of rapid seed maturation after anthesis. Prickly sida (*Sida spinosa* L.) (Egley 1976) and purple moonflower (*Ipomoea turbinata* Lag.) (Chandler et al. 1977) produced germinable seed in as few as 12 and 20 days, respectively, suggesting that late emerging plants may be similarly efficient seed producers compared to plants emerging earlier. Emergence timing did not influence the percentage of females; female percentage did not deviate from 50% except for Palmer amaranth E4 plants in 2014. Across emergence timings, 43 to 62% of waterhemp and Palmer amaranth populations were females and actively produced seed for up to 97 and 121 d, for respective species.

This data is representative of the first reports of *Amaranthus* viability of seed produced by plants with varying emergence dates. Waterhemp seed viability increased as emergence date was delayed, whereas there was no relationship between emergence timing and percent viable seed production for Palmer amaranth. Number of waterhemp seeds kg^{-1} was near 2-fold for E1 through E3 in 2014 compared to 2013. Viability was also lower in 2014, suggesting that E1 through E3 plants in 2014 may have a higher number of immature seeds plant^{-1}. Wu and Owen (2014) reported 7 to 8 flowering peaks over a 40 to 60 day period, suggesting that stigmas are not pollinated collectively and fertilization may be delayed. Delayed fertilization of a portion of the stigmas on a female plant may contribute to lower overall seed viability per plant due to varying levels of maturity. Although fewer waterhemp seeds comprised one kg of seed for late emerging plants compared to early season plants, this did not correlate to higher seed quality and viability. Palmer amaranth seed weight varied within year and between years, suggesting there is no relationship between emergence timing and seed quality, just as with seed viability patterns.

Many studies have enumerated seeds produced by *Amaranthus* plants emerging in May through early July, but few have considered seed prolificness of late-season emerging plants. Sellers et al. (2003) reported that late May/early June emerging waterhemp and Palmer amaranth in Missouri produced in excess of 250,000 seeds plant^{-1}. Waterhemp plants emerging in early July in Iowa produced nearly 200,000 seeds plant^{-1} (Wu and Owen 2014). However, as a portion of total seed production, our research suggests that waterhemp and Palmer amaranth seedlings emerging in late July are capable of generating up to 55,957 and 36,408 viable seeds plant^{-1}, respectively. Plants emerging in mid-September produced viable seeds, but viability was low at only 16 and 29% for Palmer amaranth and waterhemp, respectively.

Waterhemp and Palmer amaranth management must encompass a large portion of the growing season. Early emerging plants generate large, competitive plants that are prolific seed producers. Later season emerging plants rapidly eclipse the target height for many contact herbicides applied POST. Although seed production is reduced, a greater portion of plant biomass may be allocated to seed. Reductions of *Amaranthus* in the soil seed bank are limited unless later season emerging seedlings are controlled.

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Table 3.1. Date of establishment, flowering and harvest for common waterhemp and Palmer amaranth in 2013 and 2014 field trials. Common waterhemp was grown at the Bradford Research and Extension Center (Columbia, MO) and Palmer amaranth was grown at the Delta Research Center (Portageville, MO).

Year	Species	———Emergence———		Initial Flowering Date	Days to Initial Flowering	Harvest Date[a]
2013	common waterhemp	1	17-May	24-Jul	69	20-Sep
		2	31-May	1-Aug	63	26-Sep
		3	21-Jun	8-Aug	49	7-Oct
		4	26-Jul	29-Aug	35	11-Oct
		5	18-Sep	19-Oct	33	21-Oct
	Palmer amaranth	1	17-May	9-Jul	54	11-Sep
		2	31-May	9-Jul	41	27-Sep
		3	21-Jun	31-Jul	41	1-Oct
		4	19-Jul	3-Sep	47	8-Oct
		5	18-Sep	—[b]	—	23-Oct
2014	common waterhemp	1	28-Apr	25-Jul	89	4-Sep
		2	7-Jun	1-Aug	56	12-Sep
		3	23-Jun	8-Aug	47	6-Oct
		4	15-Jul	25-Aug	42	6-Oct
		5	8-Sep	20-Oct	43	30-Oct
	Palmer amaranth	1	28-Apr	2-Jul	66	5-Sep
		2	2-Jun	25-Jul	54	10-Sep
		3	16-Jun	30-Jul	45	10-Sep
		4	14-Jul	14-Aug	32	26-Sep
		5	15-Sep	10-Oct	26	31-Oct

[a] Harvest date determined when seed was visibly 80% mature.

[b] Plants did not flower.

Table 3.2. Cumulative weekly precipitation (cm) was recorded by weather stations at the Bradford Research and Extension Center near Columbia, MO and the Fisher Delta Research Center near Portageville, MO in 2013 and 2014 from April 1 through October 31.

	Precipitation (cm)			
	Columbia		Portageville	
Week	2013	2014	2013	2014
7-Apr	0.3	12.3	0.1	3.6
14-Apr	7.3	1.5	4.5	6.6
21-Apr	9.6	0.1	5.1	0.0
28-Apr	2.3	2.8	6.5	10.9
5-May	3.2	0.2	5.0	0.1
12-May	0.7	5.6	0.5	1.9
18-May	0.2	0.3	0.5	3.8
25-May	4.2	0.1	4.8	0.1
1-Jun	18.1	0.9	6.6	2.3
7-Jun	0.2	4.7	2.1	3.4
14-Jun	0.4	3.6	2.3	3.4
21-Jun	2.9	5.0	2.1	0.4
28-Jun	0.6	2.9	0.5	8.8
5-Jul	0.6	0.4	0.9	2.8
12-Jul	1.4	2.6	0.1	0.2
19-Jul	3.8[a]	1.1	3.8[a]	3.9
26-Jul	1.2	0.1	7.2	2.5
2-Aug	2.8	0.1	1.1	0.0
9-Aug	1.3	4.2	4.6	5.2
16-Aug	1.8	1.3	9.3	0.0
23-Aug	0.0	0.1	0.7	0.0
30-Aug	0.0	0.0	0.0	0.2
6-Sep	0.0	16.4	0.0	0.2
13-Sep	0.5	2.1	0.0	4.7
20-Sep	2.9	0.1	1.4	0.0
27-Sep	0.0	0.0	3.0	0.1
4-Oct	1.2	12.7	3.1	2.2
11-Oct	1.5	5.6	5.4	3.1
18-Oct	1.5	4.8	2.0	2.8
25-Oct	0.0	0.0	0.6	0.0
31-Oct	3.7	1.4	1.4	1.6
Total	**74.3**	**93.0**	**85.5**	**74.9**

[a] Plots were irrigated with 3.8 cm water.

Table 3.3. Mean weekly soil temperature (C) at Columbia and Portageville, MO from late April through October in 2013 and 2014. Measurements were recorded at 5 cm by HOBO data loggers at 30 min intervals.

Columbia Soil Temperature			Portageville Soil Temperature		
	—Temperature (C)—			—Temperature (C)—	
Week	2013	2014	Week	2013	2014
22-Apr	—[a]	13.3	17-Apr	—	14.6
30-Apr	—	14.1	24-Apr	—	18.0
9-May	—	18.1	1-May	—	17.2
14-May	—	18.9	8-May	—	20.4
23-May	—	18.6	15-May	—	20.9
29-May	—	23.8	22-May	—	20.7
5-Jun	—	25.7	29-May	—	25.4
12-Jun	—	20.7	5-Jun	—	26.0
19-Jun	—	23.4	12-Jun	25.0	23.7
26-Jun	26.9	26.1	19-Jun	27.6	26.4
3-Jul	25.3	24.7	26-Jun	29.9	28.2
10-Jul	28.9	25.0	3-Jul	30.0	25.9
17-Jul	28.4	25.2	10-Jul	29.5	26.8
24-Jul	29.7	28.2	17-Jul	32.7	27.6
31-Jul	24.5	27.3	24-Jul	32.1	26.0
7-Aug	24.7	27.8	31-Jul	25.7	26.3
14-Aug	24.1	24.5	7-Aug	26.3	29.2
21-Aug	25.3	25.3	14-Aug	27.1	27.4
28-Aug	30.5	31.0	21-Aug	25.3	29.8
4-Sep	30.6	26.7	28-Aug	30.5	33.7
11-Sep	28.9	22.2	4-Sep	32.3	30.0
18-Sep	23.4	17.1	11-Sep	31.7	29.2
25-Sep	20.8	19.4	18-Sep	30.6	19.9
2-Oct	21.1	21.7	25-Sep	26.6	22.7
9-Oct	18.7	14.6	2-Oct	23.1	25.3
16-Oct	16.6	13.8	9-Oct	22.4	18.7
23-Oct	11.8	13.1	16-Oct	20.1	17.2
30-Oct	10.8	14.4	23-Oct	17.1	15.2
			30-Oct	13.4	17.0

[a] Missing values indicate data were not collected.

Table 3.4. Mean number of nodes (counted as lateral branches at harvest) per common waterhemp and Palmer amaranth plant emerging at numerous times throughout the season were recorded at harvest. Common waterhemp was located at Columbia, MO and Palmer amaranth located at Portageville, MO in 2013 and 2014.

Year	Species	Emergence Timing	Final Number of Nodes[a]
2013	common waterhemp	1	64.3 A
		2	54.7 B
		3	35.6 C
		4	27.8 D
		5	10.6 D
	Palmer amaranth	1	58.5 A
		2	55.9 A
		3	57.2 B
		4	26.7 C
		5	8.5 C
2014	common waterhemp	1	62.1 A
		2	53.6 B
		3	48.9 B
		4	36.7 C
		5	29.3 C
	Palmer amaranth	1	59.1 A
		2	59.2 A
		3	57.0 B
		4	48.7 C
		5	9.6 D

[a] Means within species and within year followed by the same letter are not significantly different following Fisher's Protected LSD P=0.05.

Table 3.5. Representative mean percent for common waterhemp at Columbia, MO and Palmer amaranth at Portageville, MO in 2013 and 2014. Plant gender was determined once flowering structures fully opened. Means were calculated across five replications per emergence timing.

Year	Species	Emergence Timing	Females (%)		
2013	common waterhemp	1	51.4	(3.41, 3.42)	0.697
		2	47.9	(3.39, 3.41)	0.558
		3	50.8	(3.14, 3.15)	0.804
		4	50.2	(2.92, 2.92)	0.954
		5	50.6	(5.21, 5.24)	0.917
	Palmer amaranth	1	54.6	(3.17, 3.21)	0.18
		2	42.8	(3.24, 3.30)	0.052
		3	49.7	(3.08, 3.08)	0.919
		4	55.3	(3.97, 4.04)	0.218
		5			
2014	common waterhemp	1	45.5	(3.66, 3.72)	0.244
		2	46.3	(3.76, 3.79)	0.338
		3	51.3	(4.39, 4.41)	0.774
		4	43.1	(6.16, 6.39)	0.299
		5	43.1	(6.16, 6.39)	0.299
	Palmer amaranth	1	48.5	(3.33, 3.33)	0.647
		2	48.3	(3.27, 3.28)	0.607
		3	51.3	(3.96, 3.98)	0.755
		4	61.5	(3.45, 3.57)	0.006*
		5	46.9	(4.65, 4.71)	0.5198

[a] Values represent percent females.

[b] Number in parenthesis indicates the lower and upper standard error of the mean after being transformed from a logit.

[c] Values represent the p-value resulting after the mean was compared to 50%. P-values followed by an asterisk are considered significantly different from 50% at p=0.05.

[d] Plants did not produce adequate reproductive structures for identification.

Table 3.6. Percent plant dry weight partitioned into seed for common waterhemp at Columbia, Mo and Palmer amaranth at Portageville, MO were estimated for five emergence timings (E1 to E5) in 2013 and 2014. E1 to E5 represent dates from May through mid-September.

Year	Species	Emergence Timing	Plant Dry Weight Partitioned Into Seed (%)		
2013	common waterhemp	1	25.1	(1.04, 1.16)	B
		2	23.4	(1.01, 1.12)	B
		3	30.9	(1.25, 1.27)	A
		4	30.4	(1.11, 1.17)	A
		5		——	
	Palmer amaranth	1	15.7	(1.98, 2.22)	A
		2	16.7	(2.05, 2.35)	A
		3	16.7	(2.05, 2.27)	A
		4	17.9	(2.13, 2.41)	A
		5		——	
2014	common waterhemp	1	11.8	(2.19, 2.24)	B
		2	13.1	(2.31, 2.71)	B
		3	18.4	(2.74, 3.10)	B
		4	28.8	(3.35, 3.59)	A
		5	1.5	(0.70, 1.20)	C
	Palmer amaranth	1	12.3	(1.09, 1.16)	A
		2	9.1	(0.92, 1.01)	BC
		3	7.3	(0.84, 0.91)	C
		4	10.5	(0.99, 1.09)	AB
		5	0.6	(0.21, 0.30)	D

[a] Values represent percent plant dry weight partitioned into seed.

[b] Number in parenthesis indicates the lower and upper standard error of the mean after being transformed from a logit.

[c] Means within species and within year followed by the same letter are not significantly different following Fisher's Protected LSD P=0.05.

[d] Plants did not produce seed.

Table 3.7. Viability of common waterhemp seeds at Columbia, MO and Palmer amaranth seeds at Portageville, MO produced was assessed for five emergence timings (E1 to E5) in 2013 and 2014. E1 to E5 represent dates from May through mid-September.

Year	Species	Emergence Timing	Viable Seed (%)		
2013	common waterhemp	1	51.8	(3.81, 3.82)	A
		2	34.3	(3.42, 3.58)	B
		3	34.3	(3.42, 3.58)	B
		4	25.8	(2.90, 3.12)	B
		5		——	
	Palmer amaranth	1	55.5	(2.20, 2.21)	BC
		2	51.4	(2.22, 2.23)	C
		3	61.7	(2.11, 2.14)	AB
		4	62.7	(2.08, 2.13)	A
		5		——	
2014	common waterhemp	1	30.3	(3.63, 3.90)	A
		2	28.6	(3.49, 3.76)	A
		3	29.9	(3.63, 3.91)	A
		4	31.2	(3.75, 4.02)	A
		5	29.4	(5.65, 6.37)	A
	Palmer amaranth	1	81.1	(4.19, 5.05)	A
		2	70.1	(5.85, 6.59)	A
		3	67.8	(6.14, 6.82)	A
		4	70.1	(5.85, 6.59)	A
		5	15.5	(3.64, 4.49)	B

[a] Values represent the percent viability of the overall seed produced.

[b] Number in parenthesis indicates the lower and upper standard error of the mean after being transformed from a logit.

[c] Means within species and within year followed by the same letter are not significantly different following Fisher’s Protected LSD P=0.05.

[d] Plants did not produce seed.

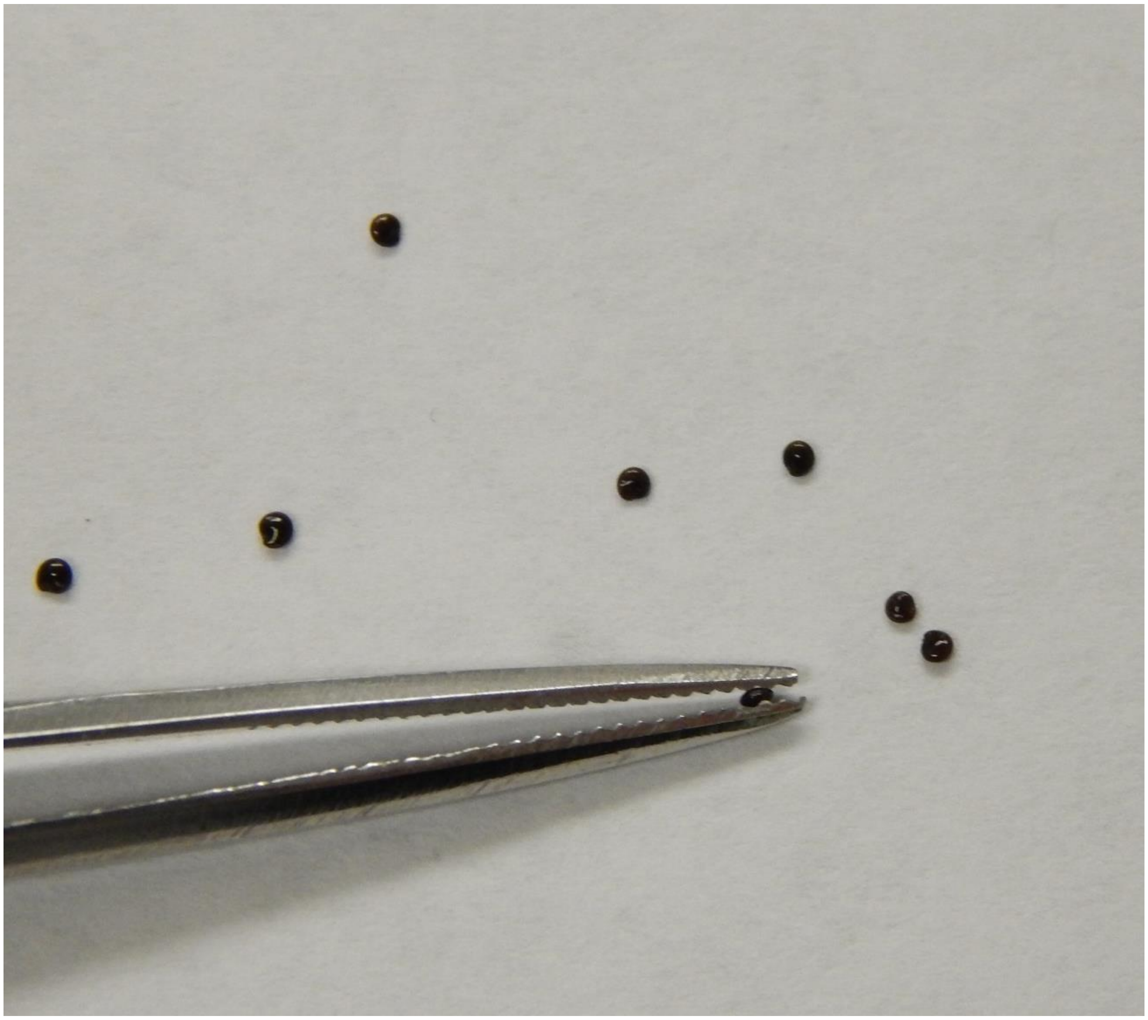

Figure 3.1. Common waterhemp seeds were held with forceps in order to slice seeds from five emergence timings longitudinally with a scalpel for preperation of tetrazolium assays in 2013 and 2014.

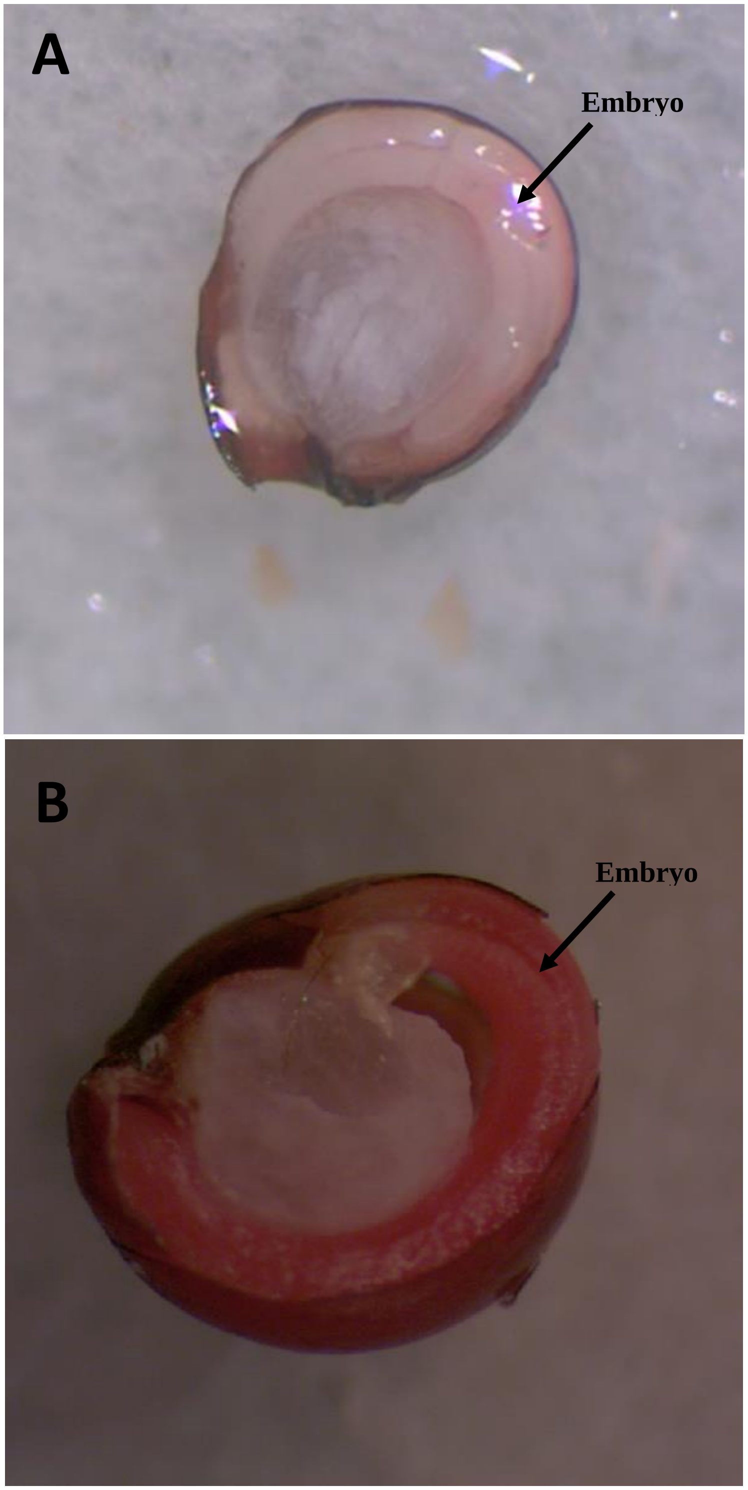

Figure 3.2. Representative staining of common waterhemp seed by tetrazolium (50X magnification). Non-viable embryos (A) were poorly stained while viable (B) embryos were stained pink/red.

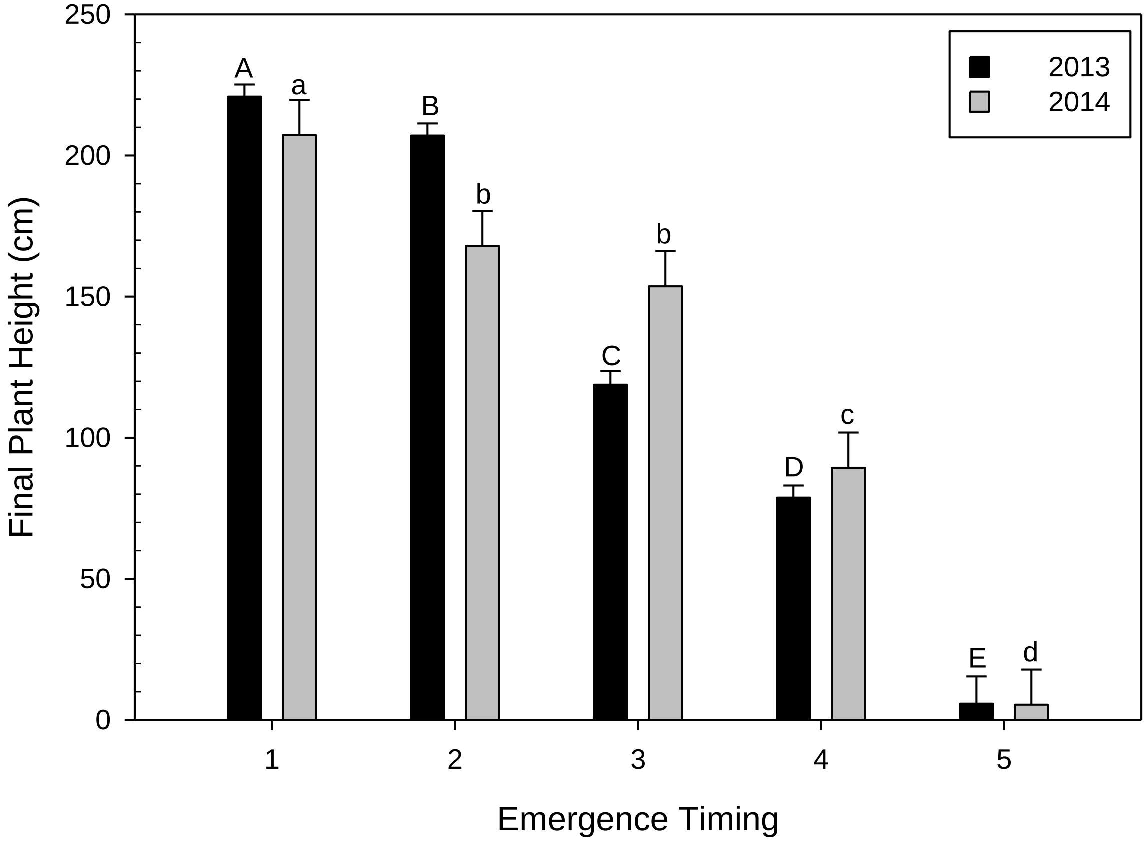

Figure 3.3. Mean final common waterhemp plant heights (cm) are represented for 2013 and 2014 at Columbia, MO. Emergence timing ranged from May (E1) to mid-September (E5). Means within year with the same letter are not significantly different following separation with Fisher's Protected LSD at $p=0.05$. Vertical bars indicate the standard error around the mean.

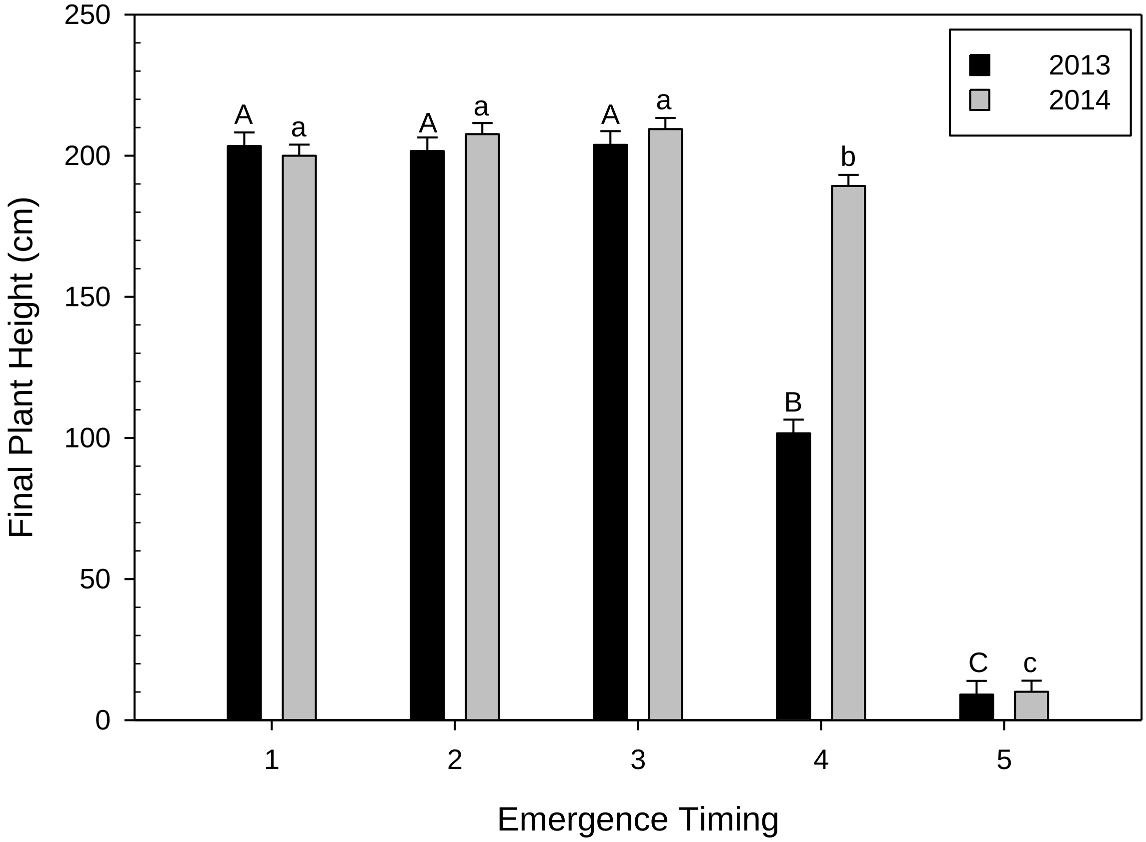

Figure 3.4. Mean final Palmer amaranth plant heights (cm) are represented for 2013 and 2014 at Portageville, MO. Emergence timing ranged from May (E1) to mid-September (E5). Means within year with the same letter are not significantly different following separation with Fisher's Protected LSD at $p=0.05$. Vertical bars indicate the standard error around the mean.

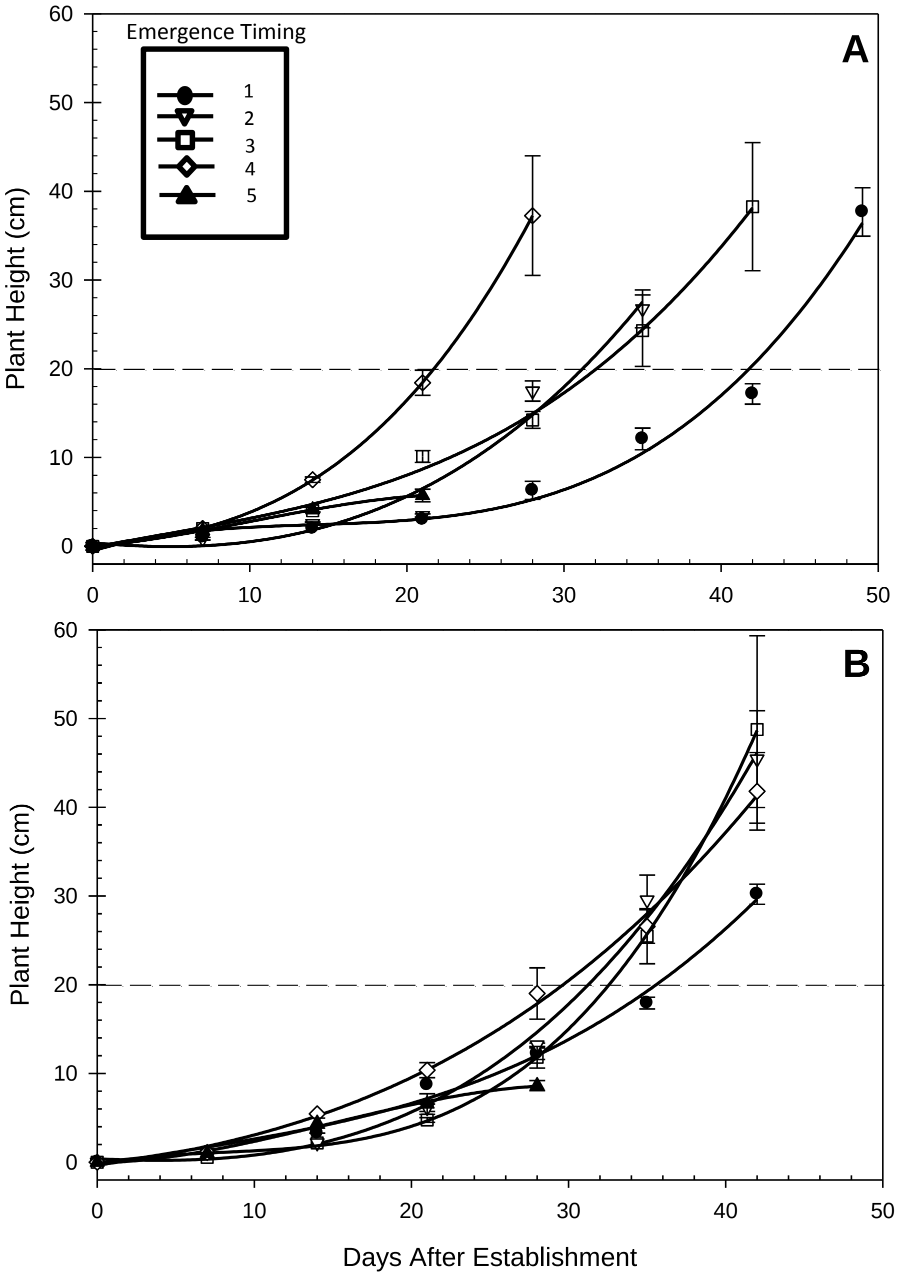

Figure 3.5. Early season growth of common waterhemp for five emergence timings (E1 to E5) at Columbia, MO, in 2013 (A) and 2014 (B). Five emergence times (E1 to E5) represent May to mid-September. Estimated time in days after emergence to reach 15.2 cm. The dashed line represents 15.2 cm, which is the maximum target size as described for many POST herbicides on *Amaranthus*. The predicted line: $Y = y_0+ax+bx^2+cx^3$. Vertical bars indicate the standard error around the mean.

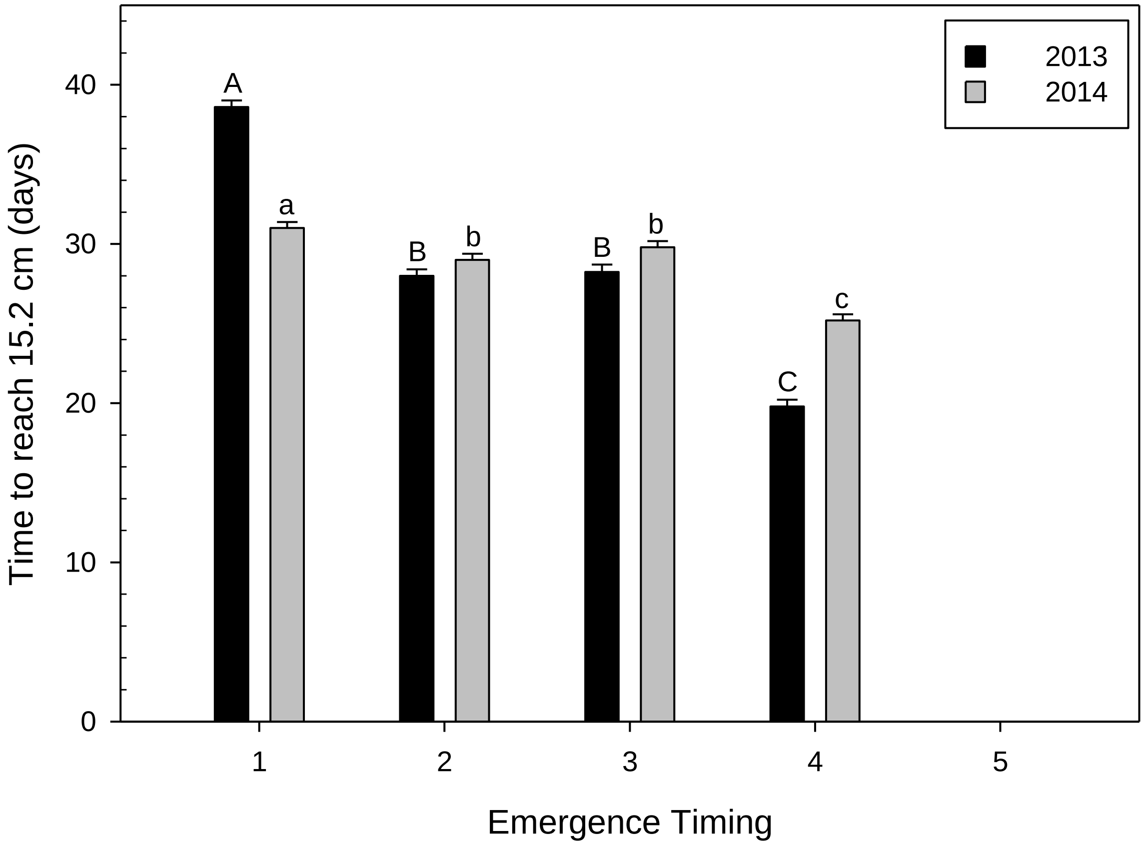

Figure 3.6. Time following emergence for common waterhemp to reach 15.2 cm at Columbia, MO in 2013 and 2014. Emergence dates (E1 to E5) ranged from May to mid-September. Data from Figure 3.5 were fitted to a curve using SigmaPlot 11.2. Means within year with the same letter are not significantly different following separation with Fisher's Protected LSD at p=0.05. Vertical bars indicate the standard error around the mean.

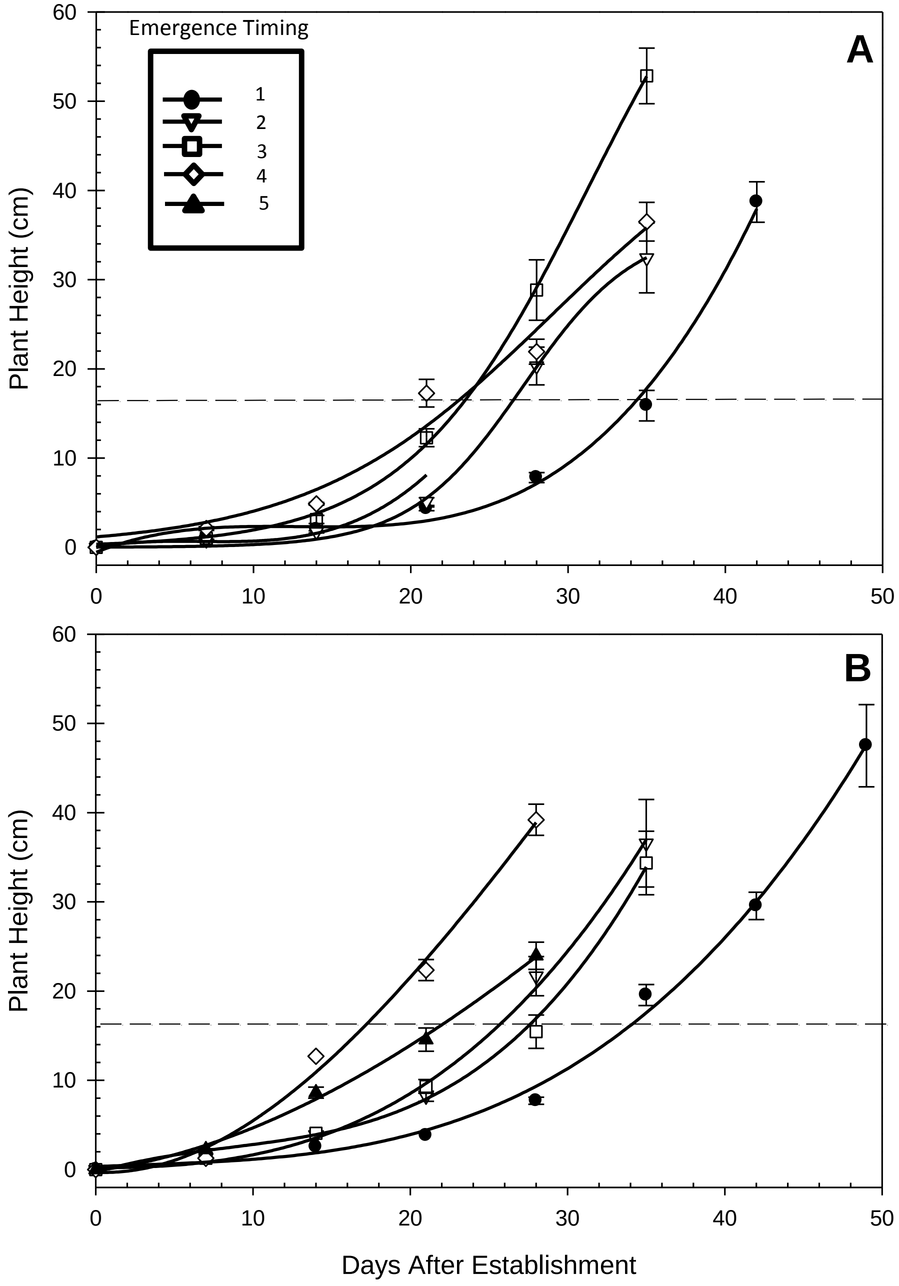

Figure 3.7. Early season growth of Palmer amaranth for five emergence timings (E1 to E5) at Portageville, MO, in 2013 (A) and 2014 (B). Five emergence times (E1 to E5) represent May through mid-September. Estimated time in days after emergence to reach 15.2 cm. The dashed line represents 15.2 cm which is the maximum target size as described for many POST herbicides on *Amaranthus*. The predicted line in 2014 was estimated using $Y = y_0+ax+bx^2+cx^3$. The first, third and fifth emergence timings in 2013 were described using the cubic model; the fourth timing by $Y= y_0+ax+bx^2$; and the second timing with $Y = \frac{a}{1+e^{-(x-x_o/b)}}$. Vertical bars indicate the standard error around the mean.

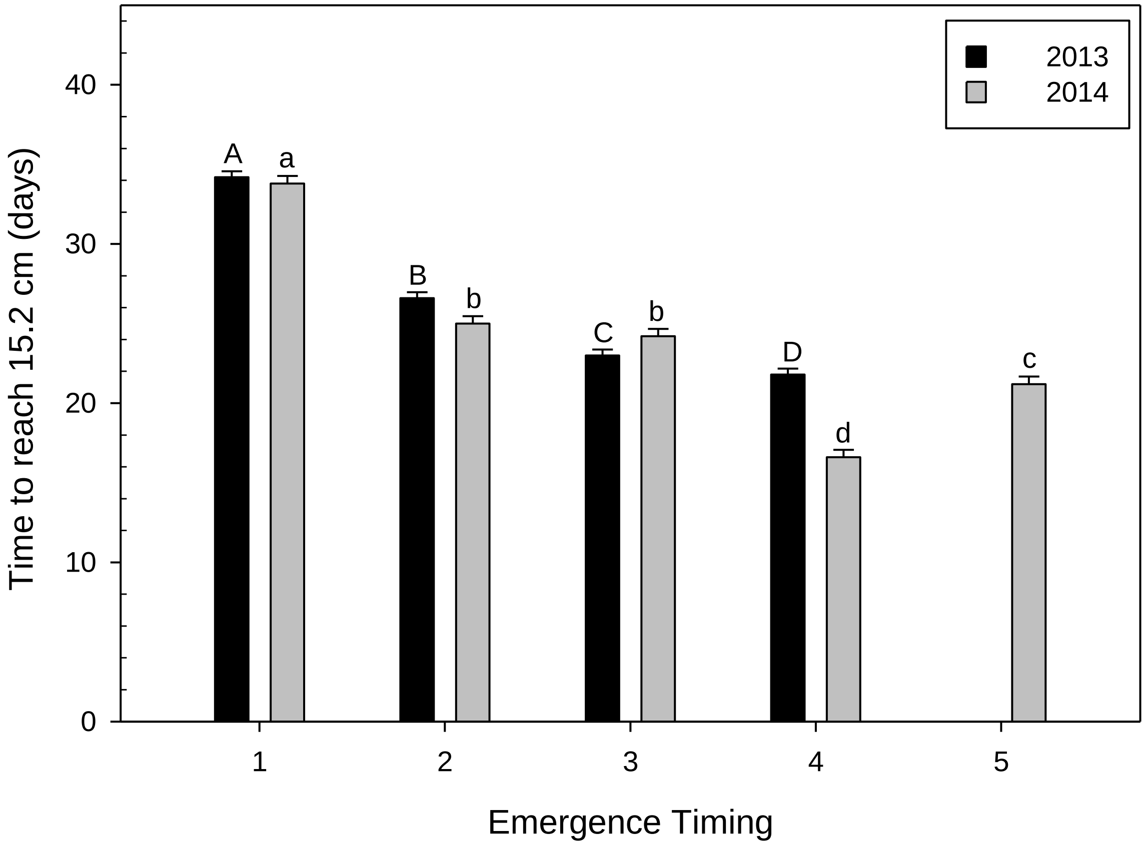

Figure 3.8. Time following emergence for Palmer amaranth to reach 15.2 cm at Portageville, MO in 2013 and 2014. Emergence dates (E1 to E5) ranged from May to mid-September. Data from Figure 3.7 were fitted to a curve using SigmaPlot 11.2. Means within year with the same letter are not significantly different following separation with Fisher’s Protected LSD at p=0.05. Vertical bars indicate the standard error around the mean.

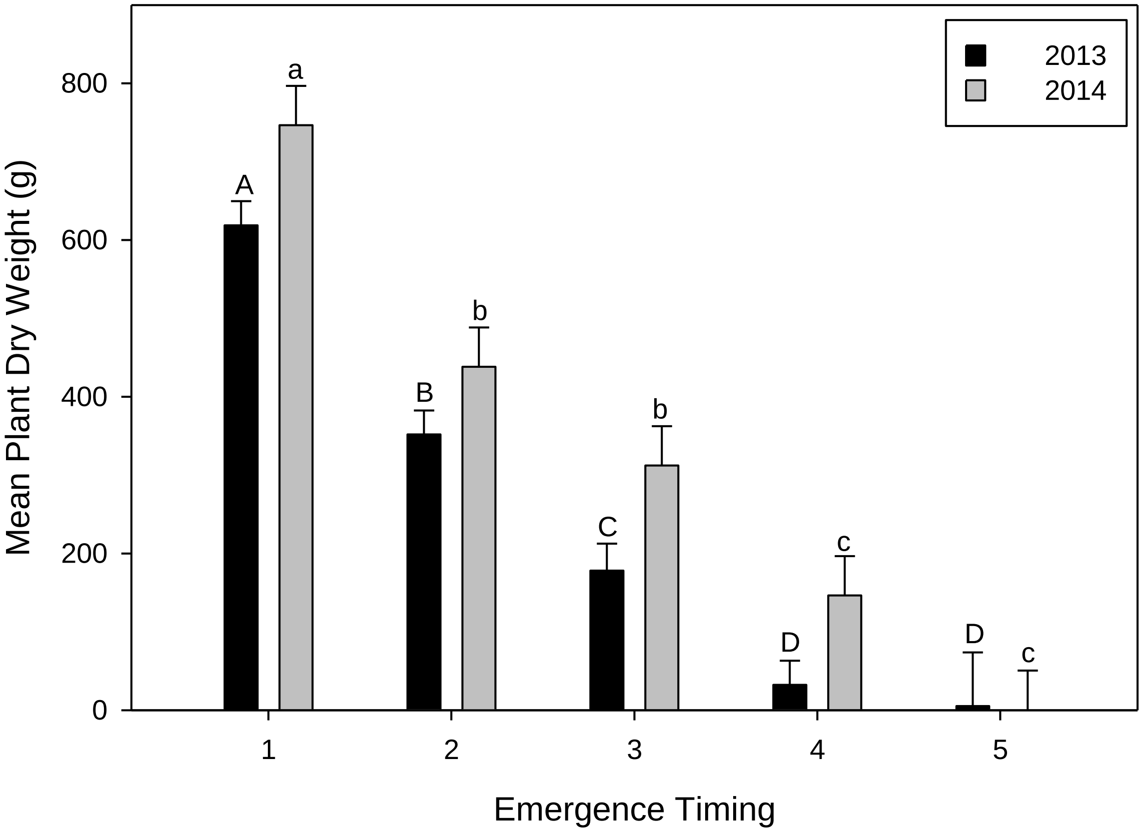

Figure 3.9. Accumulation of common waterhemp dry weight for female plants emerging throughout the growing season (E1 to E5) in 2013 and 2014 at Columbia, MO. Plants were harvested in early fall when seed was assessed to be 80% mature. Means within year with the same letter are not significantly different following separation with Fisher's Protected LSD at p=0.05. Vertical bars indicate the standard error around the mean.

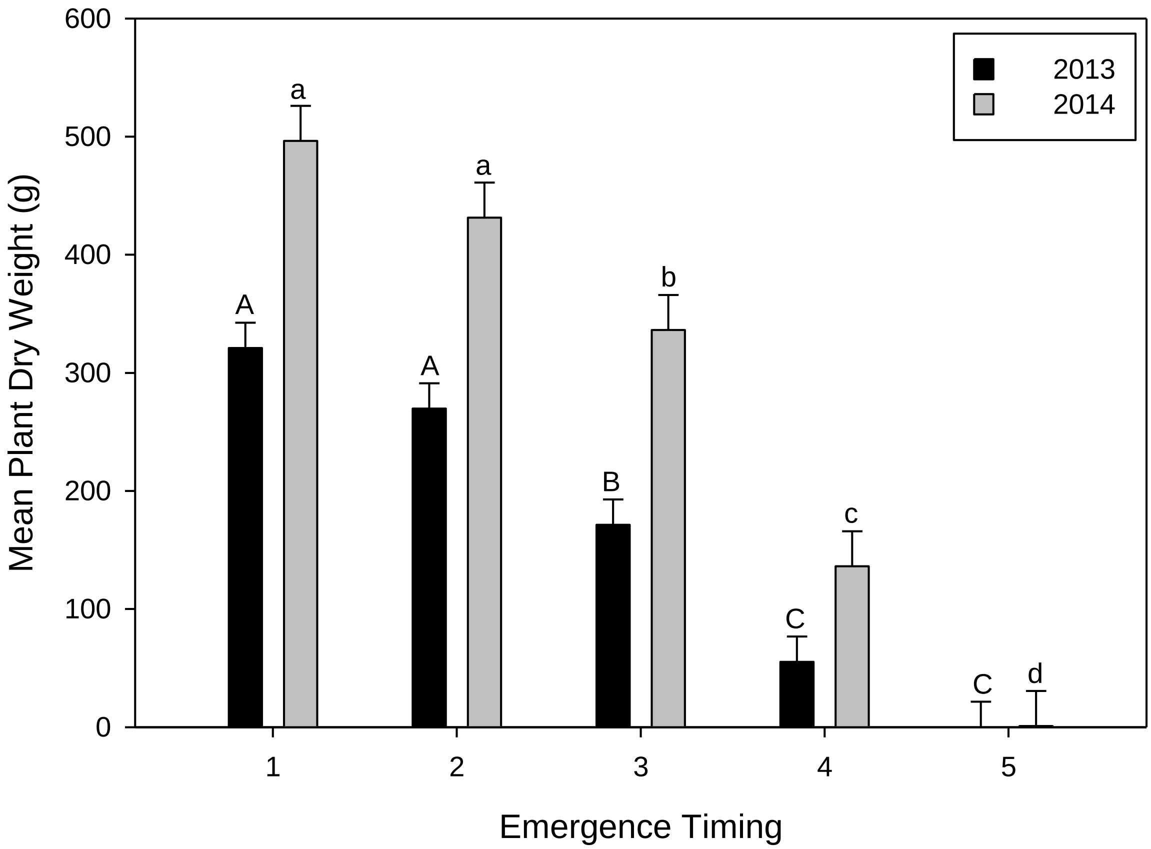

Figure 3.10. Accumulation of Palmer amaranth dry weight for female plants emerging throughout the growing season (E1 to E5) in 2013 and 2014 at Portageville, MO. Plants were harvested in early fall when seed was assessed to be 80% mature. Means within year with the same letter are not significantly different following separation with Fisher's Protected LSD at p=0.05. Vertical bars indicate the standard error around the mean.

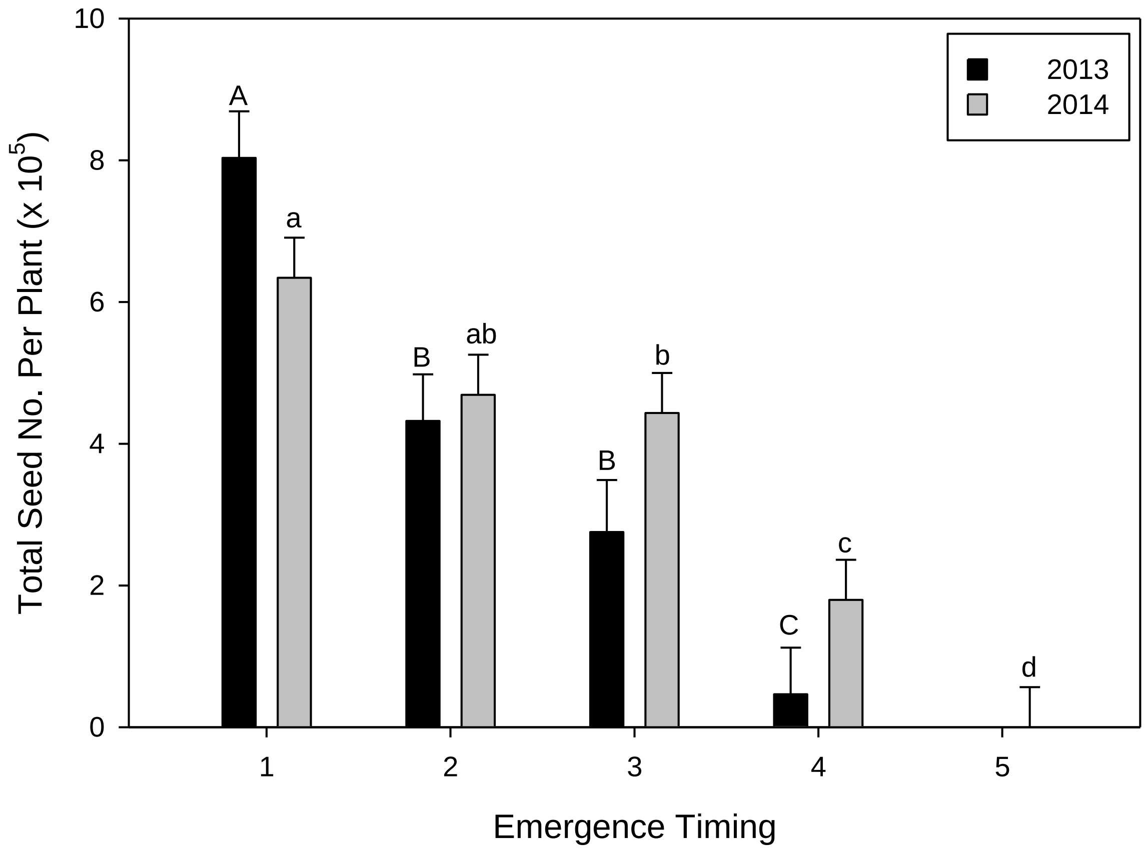

Figure 3.11. Mean common waterhemp seed production (x10^5) per plant was determined for five emergence times (E1 to E5) at Columbia, MO in 2013 and 2014. E1 to E5 represent emergence dates from May through mid-September. Means within year with the same letter are not significantly different following separation with Fisher's Protected LSD at p=0.05. Vertical bars indicate the standard error around the mean.

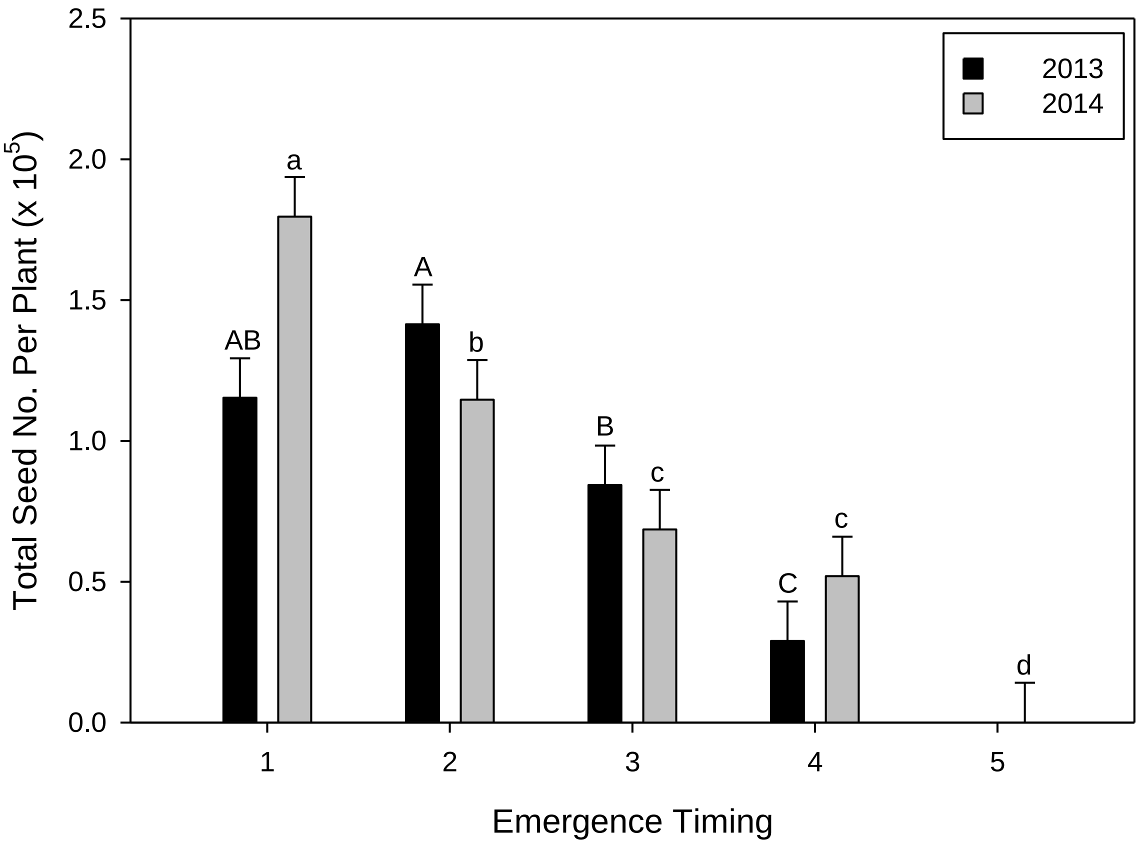

Figure 3.12. Mean Palmer amaranth seed production (x10^5) per plant was determined for five emergence times (E1 to E5) at Portageville, MO in 2013 and 2014. E1 to E5 represent emergence dates from May through mid-September. Means within year with the same letter are not significantly different following separation with Fisher's Protected LSD at p=0.05. Vertical bars indicate the standard error around the mean.

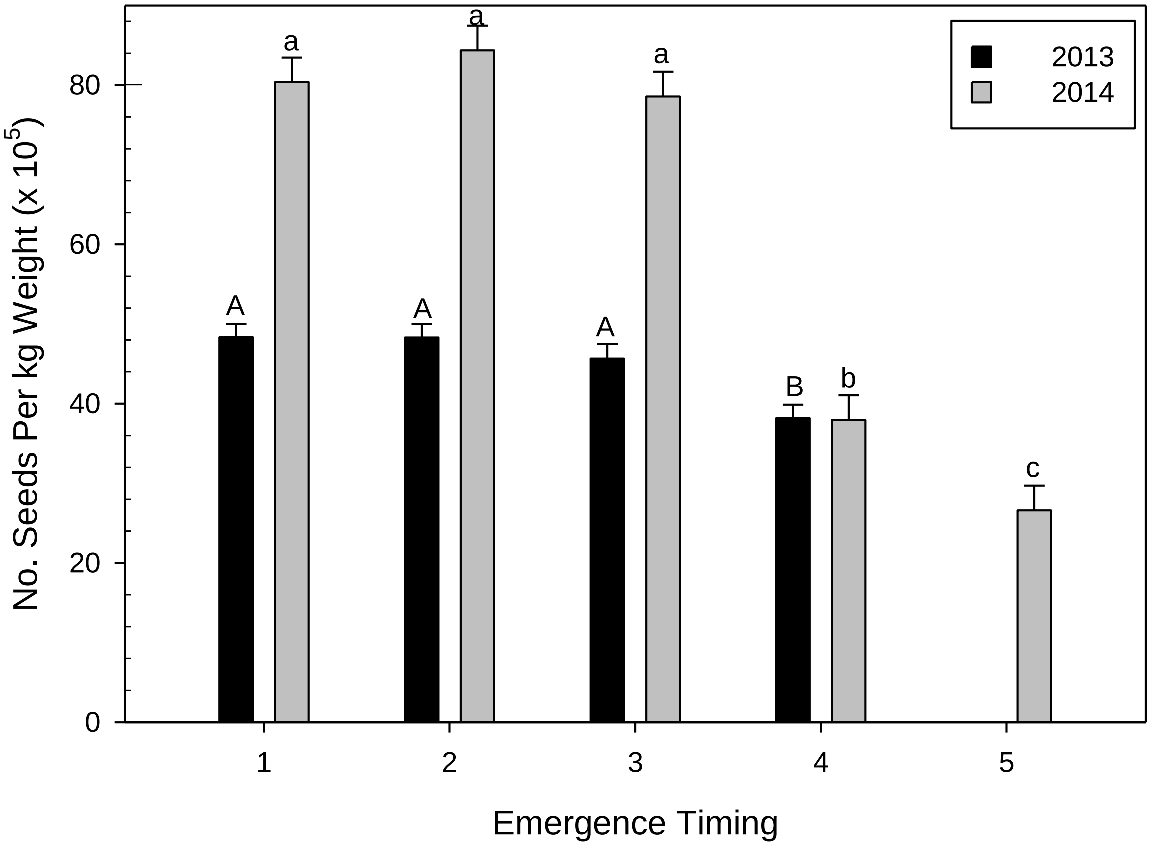

Figure 3.13. Common waterhemp seeds kg^{-1} seed weight were determined for five emergence timings (E1 to E5) at Columbia, MO in 2013 and 2014. E1 to E5 represent dates from May through mid-September. Means within year with the same letter are not significantly different following separation with Fisher's Protected LSD at p=0.05. Vertical bars indicate the standard error around the mean.

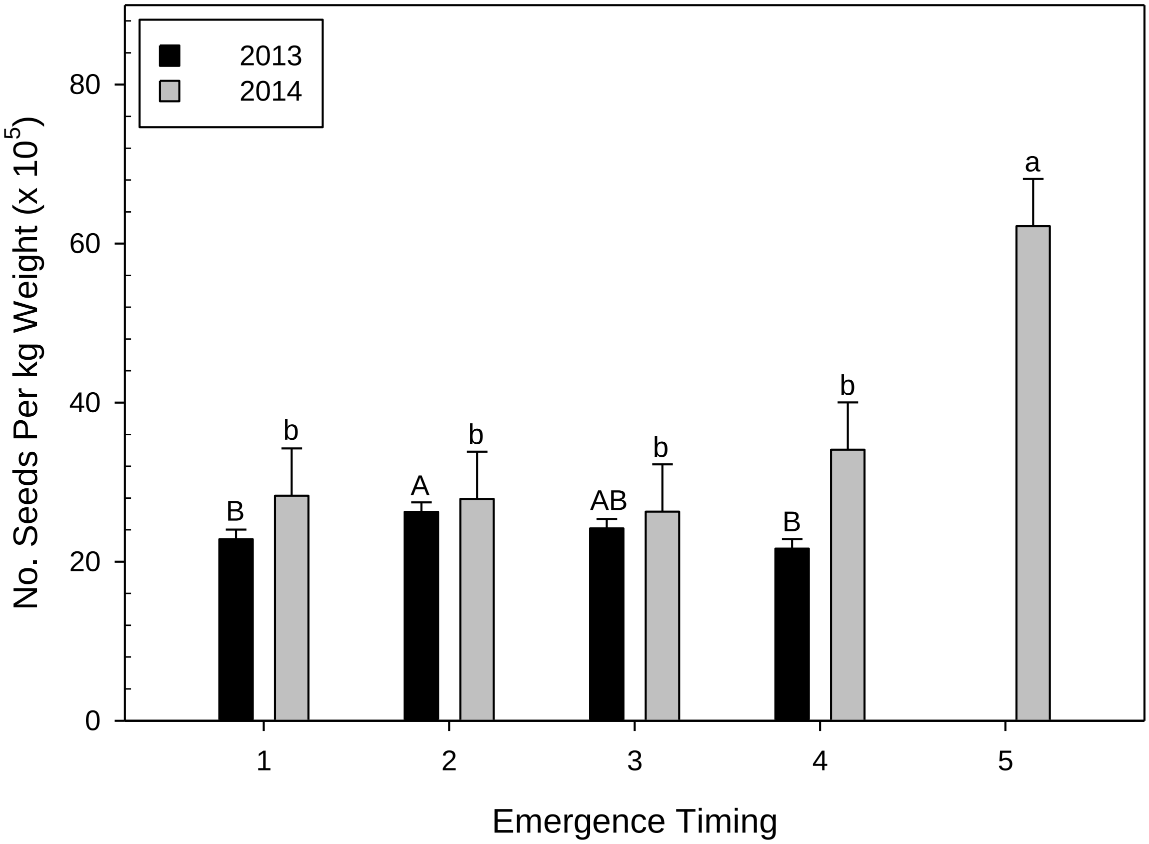

Figure 3.14. Palmer amaranth seeds kg^{-1} seed weight were determined for five emergence timings (E1 to E5) at Portageville, MO in 2013 and 2014. E1 to E5 represent dates from May through mid-September. Means within year with the same letter are not significantly different following separation with Fisher's Protected LSD at p=0.05. Vertical bars indicate the standard error around the mean.

Chapter IV

Initiation of viable *Amaranthus* seed following flowering

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Abstract: Rapid seed maturation after floral initiation is a common characteristic that contributes to weed fecundity. *Amaranthus* species produce prolific amounts of seed, but viability of seed produced by late season emerging plants under field conditions has not been reported. Waterhemp and Palmer amaranth seedlings were allowed to germinate in June in central Missouri and seed was harvested from 0 to 42 days following stigma opening on female plants. Tetrazolium testing was used to assess seed viability. Viable waterhemp seeds were produced in as few as 6 days after floral initiation in 2013 and 2014. Waterhemp seed viability in 2013 ranged from 1.3 to 50.0%. In 2014, viability ranged from 5.3 to 74.0%. For both years, waterhemp viability increased significantly between 9 and 12 days after floral initiation; from 5.3 to 20.0% in 2013 and from 8.0 to 47.3% in 2014. Palmer amaranth seed were viable in as few as 9 days after floral initiation in 2013 and 6 days in 2014.Viability ranged from 2.7 to 45.3% for both years. In 2013, rapid changes in viability occurred between 12 and 15 days after floral initiation (8.7 to 42.7%); in 2014, viability increased from 5.3 to 26.0% between 9 and 12 days after floral initiation. A short duration from flowering to viable seed production necessitates rapid control of flowering plants to preclude addition of viable seed to the soil seed bank.

Nomenclature: Common waterhemp, *Amaranthus rudis*; Palmer amaranth, *Amaranthus palmeri.*

Additional index words: Pigweed, seed production, tetrazolium.

Introduction

Amaranthus species such as common waterhemp (*Amaranthus rudis* Sauer) and Palmer amaranth (*Amaranthus palmeri* S. Wats) are dioecious annuals that continue to spread across corn and soybean production areas. There are approximately 75 species in the *Amaranthus* genus (Sauer 1955; Steckel 2007), with waterhemp and Palmer amaranth most often reported for their negative impact on crop production (Horak and Loughin 2000; Massinga et al. 2001; Steckel and Sprague 2004a). Both species exhibit prolonged emergence from spring through late summer (Hartzler et al. 1999; Jha and Norsworthy 2009).

Seeds of *Amaranthus* are small and elliptical (Bell and Tranel 2010) and plants produce copious amounts of seed. Under Missouri conditions without crop competition, waterhemp and Palmer amaranth emerging in May produced in excess of 250,000 seeds per plant (Sellers et al. 2003). However, waterhemp has been reported to produce up to 1,000,000 seeds per plant (Steckel et al. 2003). Waterhemp plants emerging in early July produced over 200,000 seeds per plant under Iowa conditions (Wu and Owen 2014). In competition with soybean season-long, Steckel and Sprague (2004b) reported up to 26,000 waterhemp seeds per plant. Palmer amaranth emerging with corn at a density of 8 plants per meter of row produced 514,000 seeds per square meter (Massinga et al. 2001).

Three primary factors contribute to successful seed production: flowering patterns/flowering peaks; flowering duration; and flowering synchrony between individual plants within a population (especially dioecious species) (Ollerton and Lack 1998). Wu and Owen (2014) observed 7 and 8 periods of flowering for waterhemp within 40 and 60 day intervals for 2009 and 2010, respectively, with each period lasting 1 to 3 d.

Michalski and Durka (2007) suggest that a pulsed flowering pattern (many flowering periods over the course of a season) improves the success of wind pollinated species under conditions of periodic rainfall, extreme heat, and low humidity, permitting at least a segment of a population to be productive. Wu and Owen (2014) reported flowering synchronization between male and female waterhemp plants changed as emergence timing was delayed. Male plants often initiated pollen production prior to females flowering in the population. Wu and Owen (2014) suggested that for wind pollinated plants the release of pollen prior to female flowering may optimize fertilization.

Amaranthus plants produce long-lived pollen capable of extended travel, increasing the likelihood of fertilizing a female plant. Waterhemp pollen can remain viable up to 5 days following anthesis of male plants and can fertilize females up to 800 m from the original source (Liu et al. 2012). Sosnoskie et al. (2012) reported the highest percentage of fertilization of Palmer amaranth females occurred 1 to 5 m from the pollen source; some females were pollinated up to 250 m from the pollen source. Complex biochemical signaling between the stigma and pollen grain initiates an increase in water, nutrients, and other small molecules in the pollen grain. This influx activates metabolism, stored RNA, proteins, and bioactive small molecules to establish a pollen tube on a receptive stigma (Becker and Feijo 2007; Taylor and Helper 1997). As a result, the pollen tube grows through the transmitting tract of the pistil and the pollen tube delivers two gamete cells within the embryo sac for fertilization. The process is very specialized to ensure the embryo is fertilized by gametes of the proper species. Shauck (2014) found that pollen grows several millimeters within 30 minutes of reaching a stimulating environment *in vitro*.

In addition to an extended flowering period, *Amaranthus* species produce seed rapidly after fertilization, contributing to fecundity. Viable seed as determined by tetrazolium was confirmed 11 d after stigma opening when seed was stored for 48 h at -20 C and 7 to 9 d for seed stored at 30 C, respectively (Bell and Tranel 2010). Germination began 12 d after pollination for seeds treated at -20 C whereas seeds stored at 30 C germinated as soon as 9 days after pollination. For both storage temperatures, germination increased rapidly between 9 and 12 days after pollination. Maximum germination (near 80%) was observed 12 and 24 days after pollination for seed stored at 30 and -20 C, respectively.

Rapid development of viable seed following fertilization allows seedlings emerging later in the growing season to contribute to the soil seed bank. Waterhemp and Palmer amaranth exhibit emergence season-long (Hager et al. 1997; Hartzler et al. 1999; Jha and Norsworthy 2009; Wu and Owen 2014), complicating management plans focused on preventing competition with crops and precluding seed production. Time to viable seed production following flowering has been documented in waterhemp under controlled conditions, but not for plants maintained under field conditions. Days to viable seed set after floral initiation in Palmer amaranth has not been studied. In California, Keeley et al. (1987) hypothesized that Palmer amaranth emerging between April and June could be expected to generate viable seed as early as 3 to 6 weeks after initial flowering and 2 to 3 weeks for plants emerging after June. The objective of this research was to identify the time required for viable seeds following stigma initiation for waterhemp and Palmer amaranth under field conditions.

Materials and Methods

Waterhemp and Palmer amaranth plants were both prevalent in a field site at the Bradford Research and Extension Center near Columbia, MO (38.89ºN, 92.20ºW). The area was field cultivated and seedlings were allowed to emerge in June of 2013 and 2014. The soil type was a Mexico silt loam (fine, smectitic, mesic, Vertic Epiaqualfs) with pH 6.3 and 1.9% organic matter. Target plants were within a 13 by 30 meter area. Common cocklebur (*Xanthium strumarium* L.) and ivyleaf morningglory (*Ipomoea hederacea* L.) were frequent in plots. To reduce competition, common cocklebur and ivyleaf morningglory near *Amaranthus* plants were removed by hand. Female plants of both species were identified and monitored regularly for open stigmas using a hand lens. Upon floral initiation, approximately 50 female plants per species were marked randomly and considered day zero for flowering. Shoots of three plants of each *Amaranthus* species were harvested 0, 3, 6, 9, 12, 15, 18, 21, 24, 27, 30, 34, 38, and 42 days after floral initiation, (hereafter referred to as DAFI). Following harvest, plants were air dried. Seed was then thrashed and cleaned with screens to isolate seed for viability tests. Seed was stored at 4 C in dry conditions until seed viability was assessed (up to 18 months for seed from 2013 and 6 months for 2014 seed in order to break dormancy). Bell and Tranel (2010) procedure was followed to test viability with the following modifications: tetrazolium assays were performed for every harvest timing and ungerminated seeds were not pooled after the germination period. In 2013, plant harvests began August 21 for both species and ended October 3. In 2014, the majority of target Palmer amaranth plants began to initiate stigmas near July 30 and plants were harvested through September 11. Waterhemp plants began floral initiation around August 19 and harvests extended through October 2 in 2014.

Air temperature (Figure 4.1) and cumulative precipitation (Figure 4.2) was recorded from July 25 to October 3 in 2013 and 2014. Temperature was higher and rainfall was lower in 2013 than in 2014 (Figure 4.1 and 4.2). Consequently, waterhemp plants in 2014 were considerably larger than the previous year (~175 cm in 2014 versus ~100 cm in 2013). Palmer amaranth plant size was comparable across years (~100 cm).

Seed Viability

Assessment of seed viability for stored seeds occurred using a tetrazolium (2,3,5-triphenyl-2H-tetrazolium chloride; Alfa Aesar, A Johnson Matthey Company, 26 Parkridge Rd., Ward Hill, MA 01835) analysis. The tetrazolium protocol was adapted from the AOSA/SCST Tetrazolium Testing Handbook (Miller and Peters 2010). Two, twenty-five seed subsamples from each of the three plants per harvest date were soaked in 8 ml of deionized water in petri dishes. Samples were left at room temperature for 48 h to soften seed coats. Germinated seedlings (radicals emerging from seed) were removed from the petri dishes and considered viable. Waterhemp seeds germinated for most harvest dates that viable seed was present; in 2013, 0 to 26.7% of seed germinated, whereas in 2014 only 0 to 1.3% of seed germinated. There were germinable Palmer amaranth seeds present for most sample dates that viable seeds were recorded; from 5.3 to 42.7% and 1.3 to 18.7% Palmer amaranth seeds germinated in 2013 and 2014, respectively.

Ungerminated seeds were placed on edge (Figure 4.3) and bisected longitudinally to expose the embryo. Sliced seeds were placed on P8 grade, coarse filter paper in 2 mL of a 1% tetrazolium solution. Both halves of the seed were placed embryo side down. Petri dishes were wrapped in aluminum foil and allowed to incubate for 24 h at room temperature. Each seed half was then examined (embryo side up) using a 10x dissecting scope. Seeds were determined viable if 90% or more of an embryo was stained pink/red (Figure 4.4). Total viability was determined by summing the percent of germinable seeds and percent seeds considered viable using the tetrazolium assay.

Statistics

The study was arranged as a completely randomized design with each of the three plants considered a replication. Data for the proportion of viable seeds per treatment was transformed using the model statement link=logit and dist=bin (Nelder and Wedderburn 1972). An ANOVA was conducted using PROC GLIMMIX in SAS (Version 9.4, SAS Institute, Inc., 100 SAS Campus Drive, Cary, NC 27513-2414 USA). Means were compared to 0.01% at a 95% confidence interval to calculate t-values. Replication was random and the remaining variables were defined fixed. Data were not pooled across years for both species due to variable environmental conditions.

Results and Discussion

Initial viability of waterhemp seed was rapid in both 2013 and 2014. Viability was detected in as little as 6 DAFI for both years, although only between 1.3 and 5.3% (Table 4.1). The majority of seeds from plants harvested 6 DAFI appeared light tan and were shriveled, with the exception of a few light brown, smooth seeds.

In contrast to waterhemp, days after floral initiation to viable Palmer amaranth seed set varied from 2013 to 2014. In 2013, Palmer amaranth plants exhibited 10% viable seed by 9 DAFI in 2013, but 2.7% by 6 DAFI for 2014 (Table 4.2). Seeds produced prior to 9 DAFI appeared light tan and shriveled.

The total viability of waterhemp fluctuated across harvest dates following floral initiation. The time to reach peak viability was similar in 2013 and 2014. In 2013, maximum viability reached 50% by 38 DAFI while 2014 plants achieved maximum viability (74%) by 42 DAFI (Table 4.1).

Optimization of Palmer amaranth seed viability was similar compared to waterhemp although total viability was lower, especially for 2014. Maximum viability reached 42.7 and 45.3% in 2013 and 2014, respectively (Table 4.2). The time for peak emergence occurred 15 and 24 DAFI for 2013 and 2014, respectively.

Although initial viability was low for waterhemp, a large increase in viability occurred over a relatively short period and was similar between years. In 2013, waterhemp exhibited a drastic increase in viability between 9 and 12 DAFI, from 5.3 to 20.0% (Table 4.1). At the same timing, an increase of viability from 8.0 to 47.3% occurred in 2014. Visibly, seeds appeared dark brown after 9 DAFI.

A rapid increase in Palmer amaranth seed viability also occurred over a short duration, but differed between years. In 2013, the rapid change in viability occurred between 12 and 15 DAFI with viability increasing from 8.7 to 42.7%. In 2014, viability increased markedly from 5.3 to 26.0% between 9 and 12 DAFI.

Limited seed viability for both waterhemp and Palmer amaranth may be related to the method of pollination and plant harvest. The flower head at the top of the main shoot was monitored for initial flowering. Subsequently, flowers at the end of lateral branches developed. Wu and Owen (2014) reported that waterhemp plants exhibited flowering events over a 60 day period. Therefore, because entire plants were harvested to determine seed viability, some seeds were younger than others, thus limiting overall viability and contributing to fluctuations in viability between harvest dates. Nevertheless, because plants were monitored for initial flowers opening, estimations of initial viability are accurate. Bell and Tranel (2010) reported viability of waterhemp seed reached in excess of 80%. In their study, the apical meristem was removed to promote lateral branching. Also, male plants were not introduced to pollinate female plants until a significant number of stigmas were visible on female plants. In addition, male plants were held above female plants and shaken to release pollen. Males only remained in contact with female plants for 24 h to limit pollination of later developing female flowers.

Prolific seed production is a technique that waterhemp and Palmer amaranth may exhibit to increase species frequency in infested fields; overall viability of seeds may be less important. Excessive seed production may also compensate for low viability. Sellers et al. (2003) reported that waterhemp and Palmer amaranth plants produced in excess of 250,000 seeds plant^{-1}. Despite differences between years in air temperature and precipitation, 6 to 9 DAFI was sufficient for both species to generate viable seed. Bell and Tranel (2010) reported that waterhemp seed reached 12% germinability in a 7 to 9 day period in a greenhouse setting. This characteristic has also been observed with other weed species, albeit not as rapidly as *Amaranthus*. Prickly sida (*Sida spinosa* L.) and purple moon flower (*Ipomoea turbinata* Lag.) produced viable seed in as little as 12 and 20 d after anthesis, respectively (Chandler et al. 1977; Egley 1976).

These data represent the first report for rapid maturation of waterhemp and Palmer amaranth under field conditions. An abbreviated period between flowering and viable seed production increases the importance of managing late season waterhemp and Palmer amaranth.

Management of waterhemp and Palmer amaranth is often practiced through mid-July in Missouri to preclude crop competition. However, later season emerging plants may have sufficient time to generate viable seeds. Wu and Owen (2014) reported a decrease in flowering duration for mid-May emerging plants versus early July emerging plants. Although the interval for fertilization of female flowers may shorten later in the growing season, rapidly maturing seed may permit significant additions to the soil seed bank. Davis (2015) found waterhemp and Palmer amaranth seedlings emerging in July can generate up to 179,580 and 51,960 seeds plant^{-1}, respectively. Up to 32.7% of seed produced by waterhemp emerging in July was viable, whereas Palmer amaranth emerging in July produced seed that was up to 71.2% viable. Even plants emerging in mid-September in mid-Missouri produced viable seed. Management of waterhemp and Palmer amaranth should be extended throughout the growing season in order to reduce viable seed production.

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Table 4.1. Mean viability of common waterhemp seed following days after floral initiation (DAFI). Plants were grown at the Bradford Research and Extension Center near Columbia, MO in 2013 and 2014. Viability was averaged over three plants per time increment with two sub-samples of 25 seeds.

	Viability (%)					
DAFI[a]	2013			2014		
0	0.0[b]	(0.00, 0.00)[c]	0.28[d]	0.0	(0.00, 0.00)	0.28
3	0.0	(0.00, 0.00)	0.28	0.0	(0.00, 0.00)	0.28
6	1.3	(0.67, 1.35)	3.66*	5.3	(1.56, 2.17)	11.09*
9	5.3	(1.56, 2.16)	11.04*	8.0	(1.96, 2.51)	14.84*
12	20.0	(3.07, 3.47)	27.05*	47.3	(4.05, 4.09)	41.60*
15	14.0	(2.59, 3.09)	21.64*	38.0	(3.87, 4.04)	38.16*
18	28.7	(3.54, 3.83)	33.20*	56.0	(3.99, 4.10)	43.46*
21	35.3	(3.79, 3.94)	36.91*	67.3	(3.71, 3.93)	43.83*
24	31.3	(3.65, 3.91)	34.79*	72.7	(3.48, 3.79)	43.04*
27	42.7	(3.99, 4.07)	40.05*	62.7	(3.86, 4.03)	43.99*
30	38.7	(3.90, 4.04)	38.44*	66.7	(3.71, 3.98)	43.89*
34	32.0	(3.67, 3.93)	35.17*	70.0	(3.60, 3.88)	43.52*
38	50.0	(4.07, 4.07)	42.30*	59.3	(3.94, 4.06)	43.84*
42	48.7	(4.07, 4.08)	41.95*	74.0	(3.42, 3.74)	42.74*

[a] DAFI= Days after floral initiation.

[b] Values represent percent viability.

[c] Number in parenthesis indicates the lower and upper standard error of the mean after being transformed from a logit.

[d] Values represent the t-value resulting after the mean was compared to 0.01%. T-values followed by an asterisk are considered significantly different from 0.01% at a 95% confidence interval.

Table 4.2. Mean viability of Palmer amaranth seed following days after floral initiation (DAFI). Plants were grown at the Bradford Research and Extension Center near Columbia, MO in 2013 and 2014. Viability was averaged over three plants per time increment with two sub-samples of 25 seeds.

	Viability (%)					
DAFI*	2013			2014		
0	0.0	(0.0, 0.0)*	0.28*	0.0	(0.0, 0.0)	0.28
3	0.0	(0.0, 0.0)	0.28	0.0	(0.0, 0.0)	0.28
6	0.0	(0.0, 0.0)	0.28	2.7	(1.05, 1.68)	6.53
9	10.0	(2.2, 2.73)	17.31	5.3	(1.56, 2.17)	11.09
12	8.7	(2.04, 2.59)	15.69	26.0	(3.41, 3.75)	31.5
15	42.7	(3.99, 4.08)	40.05	19.3	(3.02, 3.43)	26.5
18	28.7	(3.55, 3.83)	33.2	16.7	(2.83, 3.27)	24.18
21	36.0	(3.81, 4.01)	37.23	19.3	(3.02, 3.43)	26.5
24	40.0	(3.93, 4.05)	39.01	45.3	(4.02, 4.09)	40.98
27	28.0	(3.52, 3.81)	32.8	43.3	(3.99, 4.08)	40.29
30	40.0	(3.93, 4.05)	39.01	26.7	(3.45, 3.76)	31.94
34	37.3	(3.85, 4.03)	37.85	22.7	(3.24, 3.60)	29.13
38	40.0	(3.93, 4.05)	39.01	33.3	(3.73, 3.96)	35.88
42	30.7	(3.63, 3.89)	34.4	17.3	(2.87, 3.31)	24.78

[a] DAFI= Days after floral initiation.

[b] Values represent percent viability.

[c] Number in parenthesis indicates the lower and upper standard error of the mean after being transformed from a logit.

[d] Values represent the t-value resulting after the mean was compared to 0.01%. T-values followed by an asterisk are considered significantly different from 0.01% at a 95% confidence interval.

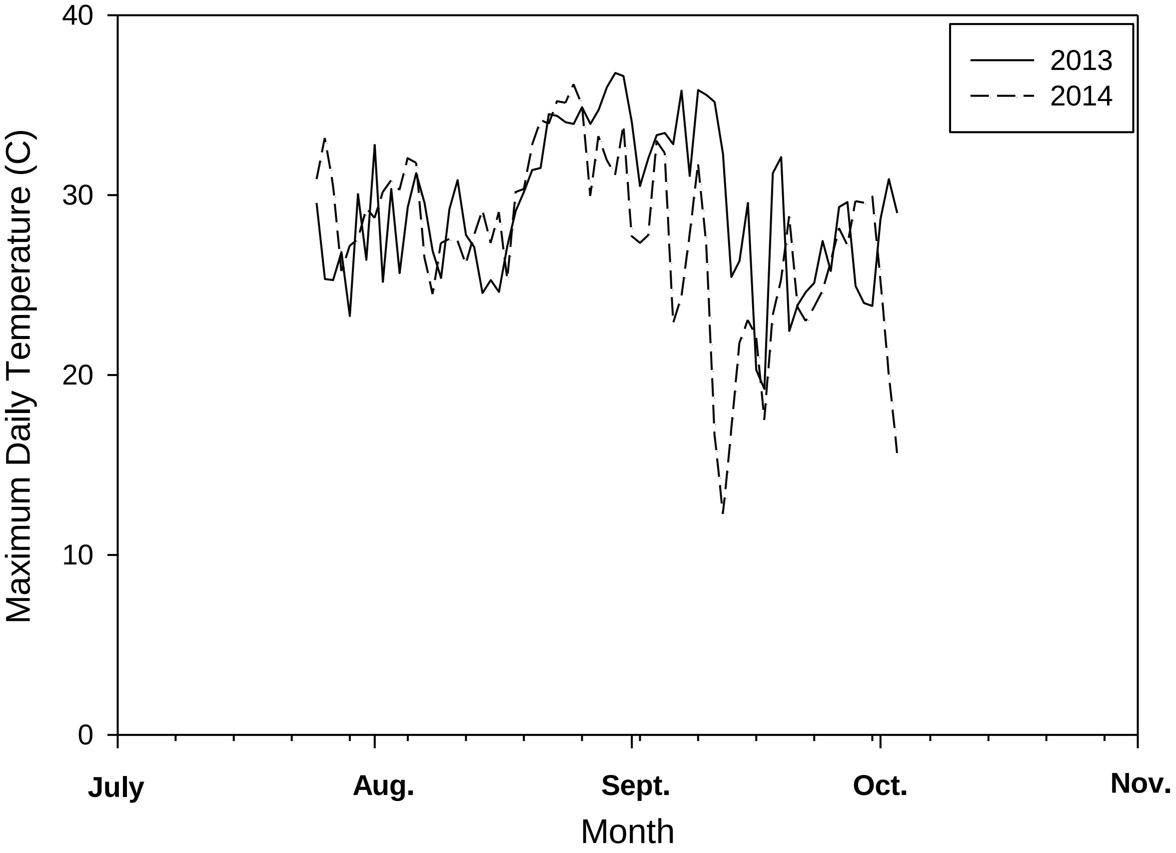

Figure 4.1. Maximum daily air temperature (C) was recorded by a weather station located at the Bradford Research and Extension Center near Columbia, MO in 2013 and 2014. Maximum daily temperatures were recorded from first observation of stigmas for common waterhemp and Palmer amaranth in late July through the last sampling date (42 days after floral initiation) in early October.

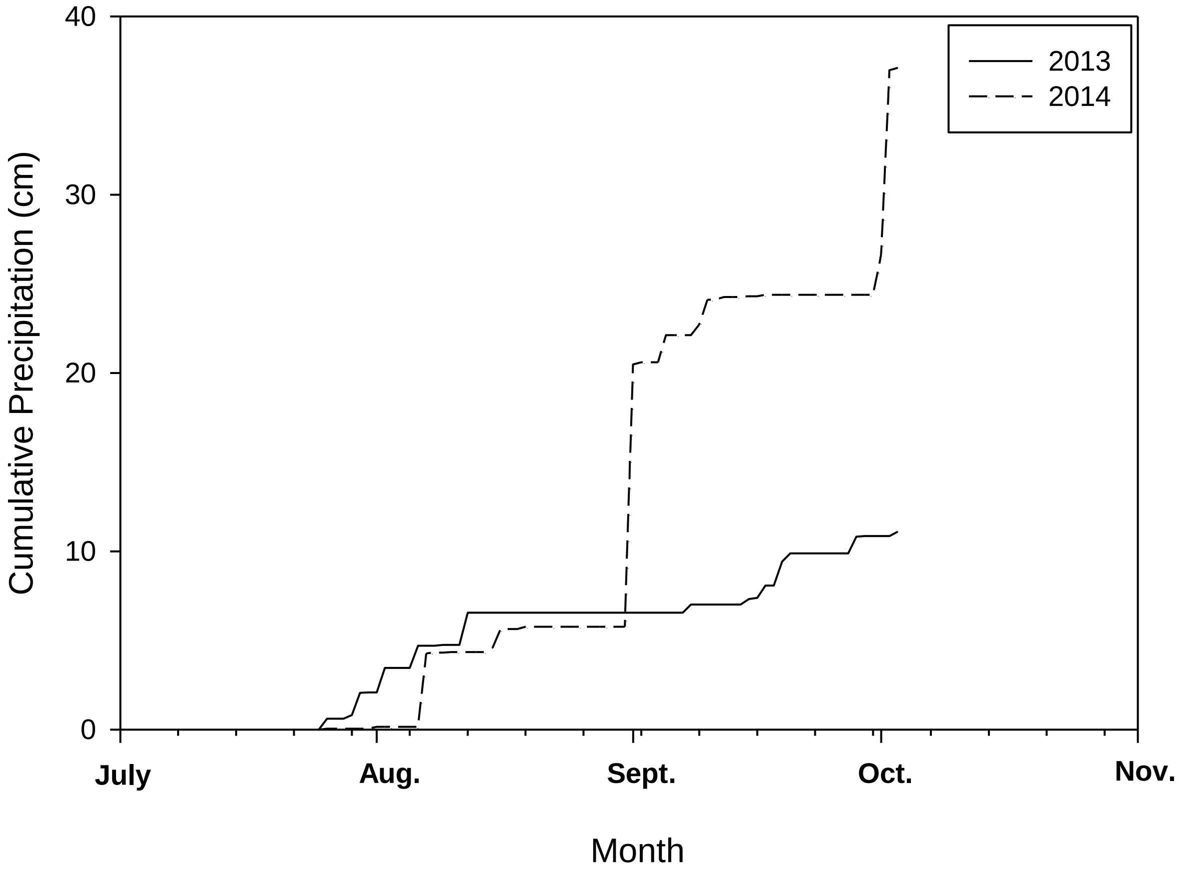

Figure 4.2. Cumulative precipitation (cm) was determined by summing daily rainfall recorded by a weather station located at the Bradford Research and Extension Center near Columbia, MO in 2013 and 2014. Precipitation was recorded from first observation of stigmas for common waterhemp and Palmer amaranth in late July through the last sampling date (42 days after floral initiation) in early October.

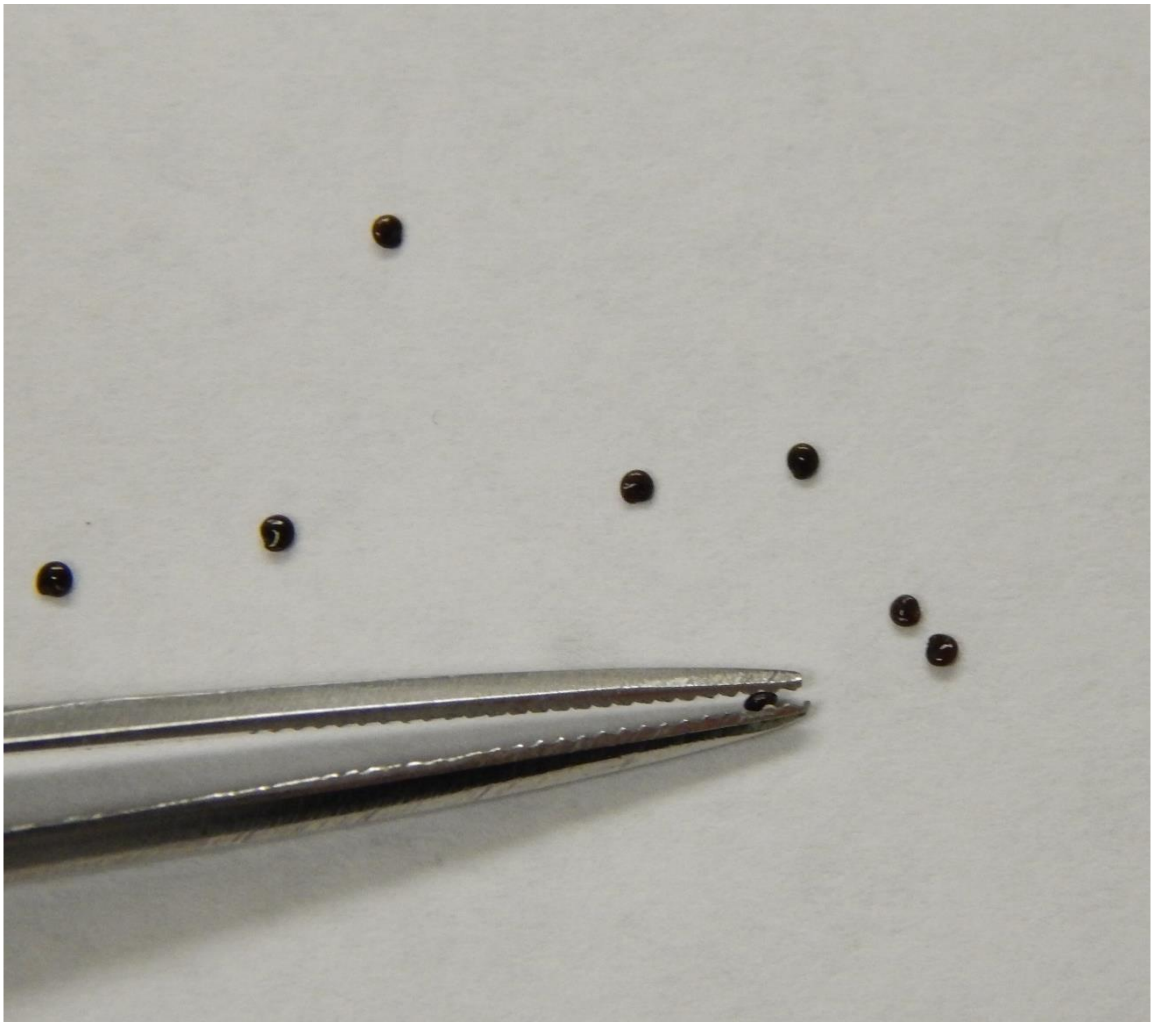

Figure 4.3. Common waterhemp seeds were held with forceps to facilitate slicing seeds longitudinally with a scalpel prior to initiation of staining with tetrazolium.

Figure 4.4. Representative embryo of common waterhemp seeds following 24 h staining with tetrazolium. Embryos of viable seeds exposed to tetrazolium solution stain red, indicating respiration. Magnification of photograph is 50X.

Appendix A1. Weekly common waterhemp emergence (m^{-2}) in no-till (May10), early (May 16) and late (June 14) spring tilled plots in Columbia, MO in 2013.

	Emergence (m^{-2})		
Week	No-Tillage	Early Spring Tillage[a]	Late Spring Tillage
16-May	47.3	—	—
23-May	477.8	3.0	—
30-May	20.0	24.3	—
6-Jun	133.3	155.7	—
13-Jun	656.8	816.5	—
20-Jun	81.2	47.7	291.0
27-Jun	179.2	76.2	537.0
3-Jul	0.2	0.8	0.5
11-Jul	0.7	1.3	4.0
18-Jul	2.0	0.8	4.2
24-Jul	1.7	0.3	1.3
1-Aug	0.3	0.3	0.2
8-Aug	11.5	0.3	5.5
16-Aug	7.8	1.7	5.5
23-Aug	0.0	0.0	0.0
29-Aug	0.0	0.0	0.0
5-Sep	0.0	0.0	0.0
13-Sep	0.0	0.0	0.0
19-Sep	0.0	0.0	0.0
26-Sep	0.0	0.0	0.0
3-Oct	0.5	0.0	0.2
11-Oct	0.0	0.0	0.0
18-Oct	0.0	0.0	0.0
25-Oct	0.0	0.0	0.0

[a] Dashed lines represent no recorded emergence due to delayed tillage timings.

Appendix A2. Weekly mean common waterhemp emergence (m^{-2}) in no-till (April 20), early (April 30) and late (June 2) spring tilled plots in Columbia, MO in 2014.

	Emergence (m^{-2})		
Week	No-Tillage	Early Spring Tillage[a]	Late Spring Tillage
22-Apr	7.7	—	—
30-Apr	13.5	—	—
9-May	72.5	10.2	—
14-May	18.0	19.0	—
23-May	49.5	98.7	—
30-May	0.7	0.3	—
4-Jun	0.2	0.2	0.0
13-Jun	39.5	416.8	763.8
20-Jun	11.5	1.3	5.5
27-Jun	113.0	19.8	112.8
3-Jul	60.7	14.7	99.2
11-Jul	1.3	0.7	0.7
18-Jul	0.3	0.0	0.7
25-Jul	0.2	0.0	0.0
1-Aug	0.0	0.0	0.0
8-Aug	0.0	0.0	0.0
15-Aug	0.7	0.5	0.0
21-Aug	0.8	0.7	1.3
28-Aug	0.0	0.0	0.0
4-Sep	0.0	0.0	0.0
12-Sep	0.0	0.0	0.0
18-Sep	1.5	0.3	2.3
25-Sep	1.0	0.2	1.5
3-Oct	0.7	0.3	1.7
9-Oct	0.3	0.2	0.0
16-Oct	0.2	0.3	0.2
23-Oct	0.0	0.0	0.0
30-Oct	0.0	0.0	0.2
6-Nov	0.0	0.0	0.0

[a] Dashed lines represent no recorded emergence due to delayed tillage timings.

Appendix A3. Weekly common waterhemp emergence (m^{-2}) in no-till (May 17), early (May 24) and late (June 14) spring tilled plots in Novelty, MO in 2013.

	Emergence (m^{-2})		
Week	No-Tillage	Early Spring Tillage[a]	Late Spring Tillage
24-May	650.2	—	—
31-May	137.8	10.8	—
7-Jun	58.5	35.5	—
14-Jun	519.2	628.2	—
21-Jun	223.7	47.2	254.0
28-Jun	152.5	29.8	245.5
4-Jul	99.5	34.3	96.3
12-Jul	58.2	18.0	32.8
19-Jul	5.0	2.5	6.2
24-Jul	0.2	0.0	0.2
2-Aug	1.5	0.3	1.3
6-Aug	2.7	1.3	3.0
16-Aug	0.0	0.0	0.0
23-Aug	0.0	0.3	0.0
30-Aug	0.0	0.0	0.0
6-Sep	0.0	0.0	0.0
13-Sep	0.0	0.0	0.0
17-Sep	0.0	0.0	0.0
24-Sep	0.0	0.0	0.0
1-Oct	0.0	0.0	0.0
8-Oct	0.0	0.0	0.0
15-Oct	0.0	0.0	0.0

[a]Dashed lines represent no recorded emergence due to delayed tillage timings.

Appendix A4. Weekly common waterhemp emergence (m^{-2}) in no-till (April 21), early (May 2) and late (June 3) spring tilled plots in Novelty, MO in 2014.

	Emergence (m^{-2})		
Week	No-Tillage	Early Spring Tillage[a]	Late Spring Tillage
23-Apr	17.5	—	—
2-May	30.0	—	—
7-May	137.0	5.3	—
16-May	186.7	136.7	—
20-May	278.0	135.0	—
28-May	340.3	216.7	—
3-Jun	3.5	6.7	—
11-Jun	169.0	164.7	202.2
18-Jun	1182.7	532.3	1667.3
25-Jun	35.0	16.5	19.0
1-Jul	260.8	77.0	57.7
9-Jul	69.0	29.7	18.8
15-Jul	98.5	58.5	30.0
21-Jul	51.5	22.7	16.0
29-Jul	9.0	2.7	2.2
5-Aug	0.0	0.0	0.0
13-Aug	0.2	0.0	0.0
20-Aug	0.8	0.3	0.0
27-Aug	0.0	0.0	0.0
3-Sep	8.7	5.2	1.5
10-Sep	2.3	4.7	1.8
17-Sep	7.5	6.7	3.8
24-Sep	3.7	2.7	2.3
4-Oct	3.0	2.2	0.8
8-Oct	0.0	0.0	0.0
15-Oct	0.0	0.0	0.0
23-Oct	0.0	0.0	0.0
3-Nov	0.0	0.0	0.0

[a] Dashed lines represent no recorded emergence due to delayed tillage timings.

Appendix A5. Weekly Palmer amaranth emergence (m^{-2}) in no-till (May 15), early (May 22) and late (June 11) spring tilled plots in Portageville, MO in 2013.

	Emergence (m^{-2})		
Week	No-Tillage	Early Spring Tillage[a]	Late Spring Tillage
22-May	163.7	—	—
29-May	230.5	20.7	—
4-Jun	17.3	25.7	—
11-Jun	109.7	136.2	—
19-Jun	61.7	47.5	54.0
26-Jun	17.3	10.3	36.0
2-Jul	3.8	4.0	8.5
9-Jul	0.0	0.2	0.3
17-Jul	0.7	0.0	0.2
23-Jul	0.3	0.2	0.0
31-Jul	91.2	86.5	61.3
6-Aug	3.2	0.8	3.7
14-Aug	2.0	1.7	1.0
21-Aug	0.0	0.0	0.0
27-Aug	0.5	0.0	0.7
3-Sep	1.7	0.5	0.2
11-Sep	0.0	0.0	0.0
17-Sep	0.5	0.0	0.0
27-Sep	0.0	0.0	0.2
1-Oct	0.0	0.5	0.5
8-Oct	1.0	0.7	1.7
18-Oct	0.7	0.7	0.5
23-Oct	0.5	0.3	0.5

[a] Dashed lines represent no recorded emergence due to delayed tillage timings.

Appendix A6. Weekly Palmer amaranth emergence (m^{-2}) in no-till (April 21), early (May 1) and late (May 29) spring tilled plots in Portageville, MO in 2014.

	Emergence (m^{-2})		
Week	No-Tillage	Early Spring Tillage[a]	Late Spring Tillage
25-Apr	90.5	—	—
1-May	5.5	—	—
8-May	593.3	118.3	—
15-May	197.8	130.8	—
22-May	420.8	227.8	—
29-May	63.2	12.5	—
5-Jun	241.0	171.0	412.3
12-Jun	109.8	235.2	137.0
19-Jun	260.2	98.2	126.5
26-Jun	2.3	1.0	1.7
2-Jul	85.0	177.7	118.2
10-Jul	54.8	34.7	42.0
17-Jul	0.5	2.0	2.0
25-Jul	95.5	65.8	92.5
30-Jul	32.0	24.8	23.2
6-Aug	0.0	0.0	0.0
14-Aug	93.7	49.7	70.8
20-Aug	38.5	29.2	37.5
27-Aug	0.0	0.0	0.0
5-Sep	0.0	0.0	0.0
10-Sep	0.2	0.0	0.0
19-Sep	3.8	3.0	2.7
26-Sep	0.0	0.0	0.2
1-Oct	0.2	0.0	0.2
10-Oct	0.0	0.0	0.2
17-Oct	0.7	0.2	0.3
24-Oct	0.0	0.0	0.0
31-Oct	0.0	0.0	0.0

[a] Dashed lines represent no recorded emergence due to delayed tillage timings.

Appendix A7. Bare soil temperature (C) at 5 cm was recorded by HOBO data loggers at Columbia, MO in 2013 and 2014. Temperature was recorded in 30 minute increments and means were determined by 672 values logged per week from two plots of the same treatment.

	Soil Temperature (C)					
	No-Tillage		Early Spring Tillage		Late Spring Tillage	
Week	2013[a]	2014	2013	2014	2013	2014
22-Apr	—	13.33	—	—	—	—
30-Apr	—	14.10	—	—	—	—
9-May	—	18.13	—	18.13	—	—
14-May	—	18.93	—	18.93	—	—
23-May	—	18.58	—	18.58	—	—
29-May	—	23.75	—	23.76	—	—
5-Jun	—	25.73	—	25.77	—	25.36
12-Jun	—	20.70	—	20.93	—	20.83
19-Jun	—	23.41	—	23.98	—	23.61
26-Jun	26.93	26.07	26.62	26.57	26.07	26.48
3-Jul	25.27	24.71	28.81	25.82	24.56	25.56
10-Jul	28.96	25.01	28.99	25.57	27.75	25.60
17-Jul	28.38	25.17	30.00	25.46	27.54	25.42
24-Jul	29.72	28.22	24.78	27.98	29.05	28.36
31-Jul	24.48	27.27	25.04	26.92	24.44	27.39
7-Aug	24.74	27.81	24.69	27.43	24.55	27.84
14-Aug	24.09	24.47	26.08	24.90	23.96	24.54
21-Aug	25.28	25.32	30.22	25.70	24.72	25.43
28-Aug	30.45	31.04	30.47	30.98	29.42	31.12
4-Sept	30.59	26.67	28.09	26.52	29.40	26.59
11-Sept	28.91	22.22	24.21	22.52	27.93	22.22
18-Sept	23.40	17.05	21.13	17.35	23.04	17.06
25-Sept	20.79	19.42	21.10	19.72	20.61	19.91
2-Oct	21.14	21.73	19.42	22.01	20.95	22.36
9-Oct	18.72	14.61	17.22	14.66	18.33	14.68
16-Oct	16.58	13.76	11.70	13.95	16.35	13.81
23-Oct	11.75	13.11	9.57	13.10	11.16	13.03
30-Oct	10.82	14.39	11.52	14.34	10.49	14.41

[a] Dashed lines represent missing records, loggers were not in the field at these times.

Appendix A8. Bare soil temperature (C) at 5 cm was recorded by HOBO data loggers at Novelty, MO in 2013 and 2014. Temperature was recorded in 30 minute increments and means were determined by 672 values logged per week from two plots of the same treatment.

	Soil Temperature (C)					
	No-Tillage		Early Spring Tillage		Late Spring Tillage	
Week	2013[a]	2014	2013	2014	2013	2014
24-Apr	—	13.17	—	—	—	—
1-May	—	12.77	—	—	—	—
8-May	—	16.08	—	15.25	—	—
15-May	—	16.58	—	15.97	—	—
22-May	—	17.55	—	16.89	—	—
29-May	—	23.54	—	22.76	—	—
5-Jun	20.17	25.99	—	25.03	—	—
12-Jun	22.37	20.71	—	20.47	—	—
19-Jun	24.51	23.73	—	23.76	—	23.80
25-Jun	26.02	25.88	26.37	25.98	25.96	26.21
1-Jul	22.93	25.93	24.07	26.65	24.02	26.19
8-Jul	27.21	23.20	28.43	23.35	27.74	23.18
15-Jul	28.57	24.52	28.88	24.84	27.06	24.84
22-Jul	27.89	25.66	27.98	26.10	27.18	25.93
29-Jul	23.96	24.91	24.04	25.80	24.38	25.91
5-Aug	26.24	26.87	27.09	27.24	26.41	27.69
12-Aug	26.27	23.05	26.51	23.14	26.38	23.64
19-Aug	27.13	23.79	27.00	23.84	26.67	24.48
26-Aug	30.81	27.71	30.41	27.52	30.08	27.86
2-Sept	29.65	25.63	29.36	25.59	29.32	25.69
9-Sept	29.68	23.82	29.45	23.86	29.23	24.36
16-Sept	20.78	16.53	21.39	17.83	21.20	16.75
23-Sept	19.34	18.26	20.02	18.87	19.73	18.66
30-Sept	19.44	21.24	19.88	21.49	19.39	21.91
7-Oct	16.27	14.29	16.53	14.93	16.41	14.35
14-Oct	14.07	13.21	15.25	13.76	14.33	13.35
21-Oct	—	12.11	—	12.24	—	12.44

[a] Dashed lines represent missing records, loggers were not in the field at these times.

Appendix A9. Bare soil temperature (C) at 5 cm was recorded by HOBO data loggers at Portageville, MO in 2013 and 2014. Temperature was recorded in 30 minute increments and means are determined by 672 values logged per week from two plots of the same treatment.

	Soil Temperature (C)					
	No-Tillage		Early Spring Tillage		Late Spring Tillage	
Week	2013[a]	2014	2013	2014	2013	2014
17-Apr	—	14.59	—	—	—	—
24-Apr	—	18.02	—	—	—	—
1-May	—	17.16	—	—	—	—
8-May	—	20.39	—	19.49	—	—
15-May	—	20.91	—	20.37	—	—
22-May	—	20.72	—	20.43	—	—
29-May	—	25.37	—	25.65	—	—
5-Jun	—	25.95	—	25.99	—	25.82
12-Jun	24.99	23.73	—	23.29	—	23.23
19-Jun	27.61	26.39	—	27.24	—	27.43
26-Jun	29.93	28.24	30.67	29.14	30.14	29.43
3-Jul	29.95	25.88	29.70	25.83	29.09	25.88
10-Jul	29.48	26.77	28.96	28.25	28.55	28.59
17-Jul	32.72	27.60	31.94	28.12	31.15	28.22
24-Jul	32.11	25.95	31.14	27.11	31.11	27.29
31-Jul	25.71	26.30	25.36	27.72	25.53	27.84
7-Aug	26.29	29.23	25.92	29.92	26.34	29.94
14-Aug	27.06	27.40	26.56	28.07	26.89	28.23
21-Aug	25.31	29.75	24.30	30.71	25.22	31.10
28-Aug	30.50	33.67	29.83	34.05	30.11	34.19
4-Sept	32.34	29.95	31.53	30.23	31.93	30.29
11-Sept	31.65	29.19	30.79	29.19	31.23	29.19
18-Sept	30.60	19.86	29.82	19.76	30.28	19.63
25-Sept	26.63	22.71	26.17	23.62	26.46	23.67
2-Oct	23.07	25.30	23.14	25.67	23.21	25.73
9-Oct	22.37	18.68	22.39	18.76	7.96	18.76
16-Oct	20.13	17.22	19.78	17.15	19.92	17.02
23-Oct	17.06	15.24	16.52	15.31	16.58	15.21
30-Oct	13.42	16.99	12.91	17.31	12.86	17.31

[a] Dashed lines represent missing records, loggers were not in the field at these times.

Appendix A10. Bare soil moisture (% by volume) at 5 cm depth was recorded by HOBO data loggers at Columbia, MO in 2013 and 2014. Soil moisture was recorded in 30 minute increments and means were determined by 672 values logged per week from two plots of the same treatment.

	Soil Moisture (%)					
	No-Tillage		Early Spring Tillage		Late Spring Tillage	
Week	2013[a]	2014	2013	2014	2013	2014
22-Apr	—	19	—	—	—	—
30-Apr	—	19	—	—	—	—
9-May	—	16	—	16	—	—
14-May	—	23	—	23	—	—
23-May	—	19	—	19	—	—
29-May	—	14	—	18	—	—
5-Jun	—	16	—	19	—	15
12-Jun	—	25	—	22	—	27
19-Jun	—	24	—	21	—	24
26-Jun	20	26	18	21	21	24
3-Jul	18	20	17	19	19	20
10-Jul	17	20	18	19	19	20
17-Jul	18	21	18	19	20	21
24-Jul	17	19	19	17	19	18
31-Jul	18	17	21	16	19	17
7-Aug	20	17	20	17	21	18
14-Aug	20	23	18	20	21	23
21-Aug	18	23	17	20	20	23
28-Aug	16	19	16	18	19	19
4-Sept	15	24	15	21	18	23
11-Sept	15	28	15	23	18	26
18-Sept	16	27	20	22	18	25
25-Sept	19	22	20	19	20	21
2-Oct	19	22	21	20	20	21
9-Oct	19	30	20	28	21	30
16-Oct	18	34	20	31	20	35
23-Oct	18	28	18	25	19	28
30-Oct	17	27	25	25	19	27

[a] Dashed lines represent missing records, loggers were not in the field at these times.

Appendix A11. Soil moisture (% by volume) at 5 cm depth was recorded by HOBO data loggers at Novelty, MO in 2013 and 2014. Soil moisture was recorded in 30 minute increments and means were determined by 672 values logged per week in two plots of the same treatment.

	Soil Moisture (%)					
	No-Tillage		Early Spring Tillage		Late Spring Tillage	
Week	2013[a]	2014	2013	2014	2013	2014
24-Apr	—	25	—	—	—	—
1-May	—	30	—	—	—	—
8-May	—	26	—	19	—	—
15-May	—	25	—	20	—	—
22-May	—	24	—	19	—	—
29-May	—	24	—	19	—	—
5-Jun	34	26	—	22	—	—
12-Jun	30	30	—	26	—	—
19-Jun	32	26	—	21	—	22
25-Jun	29	28	24	23	26	25
1-Jul	28	29	24	25	26	26
8-Jul	24	28	23	23	23	24
15-Jul	19	27	22	22	19	23
22-Jul	17	25	20	20	17	20
29-Jul	22	25	22	20	21	21
5-Aug	21	24	22	19	22	19
12-Aug	19	29	21	26	20	29
19-Aug	17	29	20	27	18	29
26-Aug	15	29	20	25	18	27
2-Sept	13	28	18	23	16	24
9-Sept	13	26	18	21	16	22
16-Sept	19	29	21	26	20	29
23-Sept	22	26	23	22	23	24
30-Sept	25	25	24	20	26	22
7-Oct	26	29	24	27	26	29
14-Oct	21	28	21	26	21	26
21-Oct	—	28	—	26	—	27

[a] Dashed lines represent missing records, loggers were not in the field at these times.

Appendix A12. Soil moisture (% by volume) at 5 cm depth was recorded by HOBO data loggers at Portageville, MO in 2013 and 2014. Soil moisture was recorded in 30 minute increments and means were determined by 672 values logged per week from two plots of the same treatment.

	Soil Moisture (%)					
	No-Tillage		Early Spring Tillage		Late Spring Tillage	
Week	2013[a]	2014	2013	2014	2013	2014
17-Apr	—	24	—	—	—	—
24-Apr	—	20	—	—	—	—
1-May	—	25	—	—	—	—
8-May	—	20	—	19	—	—
15-May	—	24	—	21	—	—
22-May	—	25	—	20	—	—
29-May	—	20	—	17	—	—
5-Jun	—	24	—	19	—	16
12-Jun	18	28	—	25	—	24
19-Jun	15	22	—	19	—	18
26-Jun	14	18	13	17	9	16
3-Jul	10	27	11	26	7	26
10-Jul	9	20	10	19	6	18
17-Jul	6	22	6	21	4	20
24-Jul	9	21	10	20	4	19
31-Jul	17	20	18	19	15	18
7-Aug	16	18	16	17	13	17
14-Aug	25	25	26	23	25	23
21-Aug	21	18	21	17	21	17
28-Aug	10	17	14	16	10	15
4-Sept	2	16	10	15	2	15
11-Sept	0	17	5	16	0	16
18-Sept	0	23	2	21	0	21
25-Sept	5	19	9	16	6	17
2-Oct	17	17	19	15	18	16
9-Oct	19	23	25	19	21	20
16-Oct	20	27	21	24	22	23
23-Oct	22	22	24	19	24	17
30-Oct	19	21	20	18	21	17

[a] Dashed lines represent missing records, loggers were not in the field at these times.