Evaluating Cover Crops and Herbicides for Horseweed and Palmer Amaranth Management

by

Larry Joe Rains III

B.S., Missouri State University, 2015

A THESIS

submitted in partial fulfillment of the requirements for the degree

MASTER OF SCIENCE

Department of Agronomy
College of Agriculture

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2019

Approved by:

Major Professor
Dr. Anita Dille

Copyright

Abstract

Horseweed and Palmer amaranth are common weeds in Kansas that compete against many row crops. Horseweed can emerge in different seasons depending on the year. Palmer amaranth emerges from spring throughout the summer months and has a rapid growth rate with higher temperatures. Three separate studies were conducted near Manhattan, KS from 2016 to 2018 to determine (1) emergence timing in KS of eight horseweed populations collected from MO, IL, KS, and KY, (2) horseweed control in no-till soybean with cover crops and herbicide programs with and without residual activity, and (3) Palmer amaranth control in response to three Protoporphyrinogen Oxidase (PPO) inhibitors applied every three days once Palmer amaranth plants reached 2.5 cm tall. Cereal rye reduced weeds biomass by 78% and weed density by 75% by 8 weeks after cover crop seeding in the fall. At cover crop termination two weeks prior to soybean drilling. Cereal rye reduced horseweed biomass more than herbicide treatments, but after termination weed control was similar across treatments. Soybean yields were greater with herbicide treatments in year one, but there were no differences in soybean yields among cover crop and herbicide treatments in the second year. Emergence of all eight horseweed populations occurred at the same time. Most horseweed emergence occurred in the spring in the first year, while all horseweed populations emerged in the fall in the second year. Environmental conditions were driving factors for horseweed emergence, but horseweed seed source did not influence emergence timing. All PPO-inhibitor herbicides controlled Palmer amaranth at similar levels within an application timing. PPO-inhibitor herbicides need to be applied within three days after Palmer amaranth plants reach 2.5 cm tall to achieve greater than 90% control.

Table of Contents

List of Figures

List of Tables

Acknowledgments

I would like to express my very grateful appreciation to Dr. Anita Dille. Dr. Dille provided me with countless hours of reliable guidance, feedback, and always expressed professional behavior. I also wish to acknowledge the weed science graduate students, as they were always willing to help whenever asked upon. Assistance provided by Dr. Dallas Peterson and Dr. Kraig Roozeboom cannot go without mention, as they both were always willing to answer any questions I had, as well as assisting in the field with research projects. Garry Harter and Dustin Ridder were also individuals who helped with equipment and resources needed to conduct field projects. I enjoyed the environment within the weed science group at KSU. All people got along and worked well together; I only hope that I can find similar chemistry in future workplaces.

Chapter 1 - Literature Review

Glyphosate Resistance and Soybean

Additional tools for weed control are needed as no-tillage acres sown to soybean [*Glycine max* (L.) Merr.] and the development of glyphosate-resistant weeds increase. By decreasing tillage the number herbicide applications have increased to control weeds (Seehusen et al. 2017). For example, glyphosate was applied to more than 50 million soybean acres in the U.S. in 2006 after the release of glyphosate-resistant soybean, but decreased to 20 million acres by 2012, likely as a result of glyphosate resistant weeds (USDA 2018). From 1996 to 2012, herbicide use in the U.S increased from 62 million to 128 million pounds of active ingredients. Up to 27% of soybean yields in the U.S. were lost due to herbicide resistant weeds in 2012 (Fickett et al. 2013). Heap (2019) reported that there have been 566 unique cases of herbicide resistant weeds in the United States, 39 of which involve horseweed. No-till production systems are becoming more popular to preserve soil and in drier environments to conserve moisture, but as weeds develop resistance to herbicides new strategies for weed control are needed to control weeds.

Horseweed

Horseweed [*Conyza canadensis* (L.)] is native to North America and found infesting orchards, vineyards, corn, soybean, cotton, hay crops, pastures and rangeland (Weaver, 2001). The broad geographic distribution of horseweed, between latitudes N°55 and S°45, suggests it can establish in various climates (Weaver 2001). Horseweed is also found throughout western Europe and around the Mediterranean Basin. It was likely introduced into Europe from North America and has become one of the most abundant plant species there (Thebaud and Abbott 1995). Horseweed often establishes best in fields receiving minimum or no tillage practices.

Horseweed is a competitive plant, with reported soybean yield loss of 83% from 150 plants m^{-2} in a no-till cropping system (Bruce and Kells 1990).

In Kansas, horseweed typically emerges from late August through October and forms basal rosettes that can overwinter (McCall 2018). If environmental conditions are right, seedlings also emerge in spring, from March through early May. Plants bolt from rosettes around May and bloom in mid-July, with seed production peaking in late August and into September. Each flower head (capitulum) is composed of many outer, white pistillate ray florets, and central florets, and is about three to five mm in diameter (Yamasue et al. 1992). Approximately 60 to 70 seeds per flower head are produced (Thebaud and Abbott 1995). Total seed production is proportional to stem height. A plant 40 cm tall produces about 2000 seeds, while a plant 1.5 m tall produces about 230,000 seeds (Regehr and Bazzaz 1979).

Time of establishment

Horseweed can be difficult to control. Depending on the year and geographic location, herbicide applications may not control horseweed plants that emerge in the spring. Spring emerging horseweed accounted for 5 to 32% of total emerged plants IA (Buhler and Owen 1997). Fall-applied herbicides can decrease horseweed densities in the fall, and since competition is low horseweed emergence in the spring can increase (Davis et al. 2010).

Winter survival

Horseweed is capable of substantial carbon fixation and energy storage at low temperatures, but not all horseweed plants that emerge in the fall survive into spring. Winter survival of horseweed was 59% in one year and 91% survived the winter in the second year of a two year experiment (Buhler and Owen 1997). Rosettes larger than five cm in diameter survived into spring, but cohorts of smaller rosettes had low probabilities of winter survival (Regehr and

Bazzaz 1979). Davis and Johnson (2008) concluded that horseweed plants emerging underneath the soybean canopy prior to harvest had the best chance of surviving the winter. The results of these studies indicate that it is difficult to predict when and how many horseweed seedlings establish, increasing the difficulty for producers to make timely weed management decisions.

Germination

Horseweed germinates better under 24 and 20 C day and night temperatures under light as compared to in the dark (Nandula et al. 2006). Horseweed emergence was greatest from the soil surface and no seedlings emerged from depths greater than 0.5 cm. The base temperature for horseweed emergence is 13 C (Steinmaus et al. 2000). Horseweed emergence in the field from seeds buried one cm or less was reduced by 90% compared to seeds sown on the soil surface, and no germination occurred below six cm (Tremmel and Peterson 1983). Horseweed emerged during April and September in Tennessee with average daytime temperatures of 10 and 15.5 C and in any month when temperatures fluctuated between 10 to 25 C (Main et al. 2006).

Herbicide resistance

Horseweed control is often reliant upon herbicide applications, but with repeated herbicide applications the number of horseweed-resistant biotypes increases, otherwise known as selection. Herbicide-resistant horseweed biotypes have been found in 16 countries and the first glyphosate-resistant biotype in Kansas was reported in 2005 (Heap 2019). Within three years of using only glyphosate for weed control in continuous glyphosate-resistant soybean, glyphosate failed to control horseweed in some fields (VanGessel 2001). Now, glyphosate-resistant horseweed has been confirmed in 25 states in the U.S. (Heap 2019).

One horseweed plants was found to be resistant to both paraquat and atrazine (Pölös et al. 1988). Triazine resistance in horseweed is conferred by a mutation at the target site of the herbicide in the chloroplast and generally reduces fitness in the resistant biotype, compared to the susceptible (Gronwald 1997). Horseweed resistance to paraquat is through sequestration paraquat away from its site of action in the chloroplast and increased activity of enzymes working to detoxify herbicide molecules is thought to be the mechanism of (Powles and Holtum 2018).

Horseweed resistance to auxinic herbicides have not been reported (Heap 2019) and these herbicides are still viable options to control horseweed when applied to small weeds. Soybean cultivars with dicamba tolerance is now available to purchase, and much of the aim is to control horseweed in no-tillage soybean. Dicamba applied postemergence at 600 g a.e. ha^{-1} provided 90 to 100% control of glyphosate-resistant horseweed (Byker et al. 2013). Preemergence dicamba at 1121 g ha^{-1} provided 97% control of horseweed (Johnson et al. 2010). Dicamba provided good control of horseweed plants less than 30 cm tall, but it is important to make applications to smaller weeds to slow development of resistance (Davis et al. 2010).

Herbicide-resistant horseweed can occur in fields without the application of that herbicide, but from the spread of seeds from resistant populations. Only five years after the first glyphosate-resistant population was reported, resistant biotypes were found in more than 44,000 ha of cropland in the U.S. Horseweed offspring are easily dispersed from the plant and can transport long distances and establish. Horseweed seed can travel kilometers from source populations before settling, however, 99% of seeds fall on the soil surface within 100 m of parent plants (Dauer et al. 2007). The attached pappus, extending twice as long as the seed, and the tall stems that position seeds high above the ground, are biological traits that make seed dispersal and long distance transport possible (Weaver 2001).

Horseweed competes strongly against crops as it emerges before summer annual crops, develops resistance to herbicides, spreads seeds across areas by wind, and can establish in different seasons. Find additional tools to integrate with other weed control strategies is important for sustainable weed management.

Cover Crops

Weed suppression

As weeds become resistant and herbicides begin to lack control, the need for alternative weed management tools are needed. Crops work to suppress weeds in similar ways that weeds work to suppress crops, by limiting sunlight and nutrients from the weeds. As cover crop produce more biomass weed suppression increases by competing for water and nutrients. Cover crops can also suppress weeds through the production of allelopathic chemicals.

Cover crops shade the soil surface, decreasing the amount of sunlight available to weeds (Moore et al. 1994). Carr et al. (2013) found that early spring-emerging horseweed can be suppressed by 83 to 99% using winter wheat (*Triticum aestivum L.).* Cover crops controlled weeds similar to chemical and mechanical methods early in the season (Osipitan et al. 2018). Others found that cover crop mixtures can suppress weeds by 66% compared to fallow (Kunz et al. 2016).

Oil-seed radish [*Raphanus sativus* (L.)], canola (*Brassica napus*), and rye (*Secale cereal*) reduced weed biomass, compared to bare soil, six weeks after planting. Rye alone reduced weed density by 20% and suppressed early-season weed growth by 85% (Crawford et al. 2018). Barley (*Hordeum vulgare*), crimson clover (*Trifolium incarnatum*), or barley plus crimson clover reduced weed density by 50% and increased squash yield compared to the control (Buchanan et al. 2016). After termination cover crop residues suppressed weeds into the soybean growing season (Teasdale 1996). Italian ryegrass (*Lolium multiflorum*) residue persisted nine weeks after soybean planting and reduced density of weeds in the early soybean growing season. Late-emerged weeds were adequately controlled with oat, rye, wheat, hairy vetch, crimson clover, and subterranean clove (*Trifolium subterraneum*) with no affect to soybean yield (Reddy, 2001). Cover crops can be good alternative to herbicides in spring and fall, but for excellent weed control it is important integrate other weed control strategies during soybean growing season.

Weed seed predation

Cover crops can increase insect densities and diversity in the soil, which may increase weed seed predation. In plots with cover crop mulch, predation by beet armyworm pupae was 33% greater and significantly reduced weed seeds from the soil seedbank compared to conventional production plots (Pullar et al. 2006). Cover crops can also positively affect the diversity of arthropods and the plant community (Carpio et al. 2018).

Allelopathy

Allelopathic chemicals are defined as “any direct or indirect harmful or beneficial effect by one plant or microorganisms on another through the production of chemical compounds that escape into the environment” (Rice 1984). Radish *(Raphanus sativus)*, buckwheat (*Fagopyrum esculentum),* and black oats (*Avena strigosa*) suppressed weeds by 28% in a greenhouse study (Sturm et al. 2018). Weed suppression was 78% greater in plots that received a rye cover crop treatment, but alfalfa yield from the first cutting was reduced by 35% in rye plots, likely due to residual allopathic chemicals (Adhikari et al. 2018).

Additional benefits

Cover crops increase the health of the soil by reducing soil erosion, water runoff, and solar radiation to the soil surface. Cover crops increase organic material in the soil, help water infiltrate into the soil, and increase microbial density and diversity, and can increase transpiration of water compared to fallow (Dabney 1998). The availability of nitrogen to succeeding crops can be greater after a cover crop has been growing, as it is either prevented form leaching or nitrogen deeper in the soil profile is brought to shallower depths (Frye et al. 1988). Rose et al. (2019) examined how a pinto peanut (*Arachis pintoi*) cover crop reduced emissions of nitrogen more than poultry litter alone. Faba bean (*Vicia faba*) increased soil organic carbon sequestration compared to conventional tillage (Novara et al. 2019).

Palmer Amaranth

Palmer amaranth is a summer annual C4 plant native to northwest Mexico and has spread into the U.S. Palmer amaranth in the U.S. was first documented in Virginia in 1915, but was not a major problem until the late 1980's. In 1989 it was found in a weed survey in South Carolina and in 1995 it was the most troublesome weed in cotton in the Carolinas (Heap 2019).

Palmer amaranth has the highest photosynthetic rate among other C4 *Amaranthus* species and is three to four times the rate of row crops like corn, cotton, and soybeans (Ehleringer 1983). Palmer amaranth has the fastest growth rate and the greatest maximum growth among *Amaranthus* species (Horak and Loughin 2000). Palmer amaranth was the fastest growing species followed by common waterhemp (*Amaranthus tuberculatus*) and redroot pigweed (*Amaranthus retroflexus*) in KS (Bensch et al. 2003). Palmer amaranth can angle it's leaves towards the sun (heliotropism) to intercept more red and blue light and increase the rate of photosynthesis.

Palmer amaranth reached 10 cm tall and was at least 78% larger than six *Amaranthus* species and 65% greater than redroot pigweed alone two weeks after planting (Sellers et al. 2003). Horak and Loughin (2000) also found that Palmer amaranth produced the most biomass compared to the other *Amaranthus* species. Palmer amaranth growth increased and specifically root biomass and photosynthesis increased as air temperature increased (Guo and Al-Khatib 2003). One Palmer amaranth plant can produce 200,000 to 600,000 seeds if it emerges between March and June (Keeley 1987) and 32 Palmer amaranth plants 6 m^{-1} of row can produce 1.2 billion seeds ha^{-1} (Burke et al. 2007).

Peanut pod weight decreased by 2.9 kg ha^{-1} for every one gram of increase in Palmer amaranth biomass m^{-1} row (Burke et al. 2007). Others found that for every additional Palmer amaranth plant 15 m^{-1} row, grain sorghum yield was reduced by 2 to 3.5% and for each additional kilogram of Palmer amaranth grain sorghum yield 68 m^{-2} was reduced by 5 to 9% (Moore et al. 2004). Palmer amaranth emerging at the same time as corn emergence reduced corn yield from 11 to 91%, as Palmer amaranth density increased from 0.5 to 8 plants m^{-1} of crop row (Massinga et al. 2001). Palmer amaranth reduced soybean yield by 32, 48, 64, and 68% at densities of 1, 2, 3, and 10 plants m^{-1} of row, respectively (Klingaman and Oliver 1994). Palmer amaranth is very competitive against other plants even at low densities.

Palmer amaranth has developed resistance to five herbicide modes of action (MOA) in KS, including photosystem II (atrazine), HPPD (mesotrione, tembotrione, and topramezone), EPSPS (glyphosate), VLCFA's (pyrasulfotole) and auxins (dicamba). Additionally, Palmer amaranth has developed resistance to microtubule inhibitors in TN and NC and protoporphyrinogen inhibitors (PPO-inhibitors) in AR, TN, and IL (Heap 2019).

Protoporphyrinogen Oxidase Inhibitors (PPO-inhibitors)

Protoporphyrinogen oxidase is an enzyme in the chloroplast that oxidizes protoporphyrinogen IX to produce protoporphyrin IX, which is a precursor molecule for both chlorophyll and the electron transfer chain. This forms reactive molecules that destroy lipids and protein membranes, therefore making cells leaky and leading to lipid peroxidation (Al-Khatib 2019).

The first case of PPO resistant Palmer amaranth was documented in 2011 in AR (Heap 2019). Palmer amaranth resistant to PPO-inhibitors is now widespread in AR, especially in the northeast part of the state (Varanasi et al. 2018). PPO-inhibitors are often applied to weeds in soybean late in the growing season when weeds (pigweeds especially) are too large to control. PPO-inhibitors are effective at controlling Palmer amaranth when plants are small. This also decreases the chance of plants developing resistance. It is also important that the herbicide reaches the target weeds.

Thorough coverage is essential to achieve excellent control of Palmer amaranth when using contact herbicides applied postemergence. Palmer amaranth has many growing points, even on young plants, making them difficult to control. Many factors influence weed coverage, including total volume applied per acre, pounds of operating pressure per square inch used, wind speed, droplet size and retention, nozzle type. For example, carrier volume amount did not affect control of small weeds, but on larger plants control was reduced with reduced spray volume (Berger et al. 2014).

The objective of this research was to evaluate (1) horseweed control in no-till soybean with cereal cover crops, herbicides with and without residual activity, and a cover crop and herbicide combination treatment (2) emergence timing of eight horseweed populations collected from MO, IL, KS, and KY and sown in Kansas, and (3) Palmer amaranth control with PPO-inhibitor herbicides applied every three days starting when Palmer amaranth plants were 2.5 cm tall.

References

Al-Khatib K (2019) Herbicide Symptoms. http://herbicidesymptoms.ipm.ucanr.edu/MOA/PPO_inhibitors/ Accessed 5/10/2019

Adhikari L, Mohseni-Moghadam M, Missaoui A (2018) Allelopathic effects of cereal rye on weed suppression and forage yield in alfalfa. American Journal of Plant Sciences. doi.org/10.4236/ajps.2018.94054

Bensch CN, Horak MJ, Peterson D (2003) Interference of redroot pigweed (*Amaranthus retroflexus*), palmer amaranth (*A. palmeri*), and common waterhemp (*A. rudis*) in soybean. Weed Science. doi.org/10.1614/0043-1745(2003)051[0037:IORPAR]2.0.CO;2

Berger ST, Dobrow MH, Ferrell JA, Webster TM (2014) Influence of carrier volume and nozzle selection on Palmer amaranth control. Peanut Science. doi.org/10.3146/PS13-20.1

Bruce JA, Kells JJ (1990) Horseweed (*Conyza canadensis*) Control in No-Tillage Soybeans (*Glycine max*) With Preplant and Preemergence Herbicides. Weed Technology. Volume 4, pages 642-647

Buchanan AL, Kolb LN, Hooks CRR (2016) Can winter cover crops influence weed density and diversity in a reduced tillage vegetable system? Crop Protection. doi.org/10.1016/j.cropro.2016.08.006

Buhler DD, Owen MDK (1997) Emergence and survival of horseweed (*Conyza canadensis*). Weed Science. doi.org/10.2307/4045719

Burke IC, Schroeder M, Thomas WE, Wilcut JW (2007) Palmer amaranth interference and seed production in peanut. Weed Technology. doi.org/10.1614/WT-06-058.1

Byker HP, Soltani N, Robinson DE, Tardif FJ, Lawton MB, Sikkema PH (2013) Control of glyphosate-resistant horseweed (*Conyza canadensis*) with dicamba applied preplant and postemergence in dicamba-resistant soybean. Weed Technology. doi.org/10.1614/WT-D-13-00023.1

Carpio AJ, Castro J, Tortosa FS (2018). Arthropod biodiversity in olive groves under two soil management systems: presence versus absence of herbaceous cover crop. Agricultural and Forest Entomology. https://doi.org/10.1111/afe.12303

Carr PM, Horsley RD, Gunderson JJ, Winch TJ, Martin GB (2013) Weed growth and crop performance following hairy vetch, rye, and wheat cover crops in a cool semiarid region. Organic Agriculture 3:149-161

Chen Z, Wang L, Wei A, Gao J, Lu Y, Zhou J (2019) Land-use change from arable lands to orchards reduced soil erosion and increased nutrient loss in a small catchment. Science of the Total Environment. doi.org/10.1016/j.scitotenv.2018.08.141

Crawford LE, Williams MM, Wortman SE (2018) An early-killed rye (*Secale cereale*) cover crop has potential for weed management in edamame (*Glycine max*). Weed Science. doi.org/10.1017/wsc.2018.5

Dabney SM (1998) Cover crop impacts on watershed hydrology. Journal of Soil and Water Conservation. vol. 53 no. 3 207-213

Dauer JT, Mortensen DA, Vangessel MJ (2007) Temporal and spatial dynamics of long-distance *Conyza canadensis* seed dispersal. Journal of Applied Ecology. doi.org/10.1111/j.1365-2664.2006.01256.x

Davis VM, Johnson WG (2008) Glyphosate-resistant Horseweed (*Conyza Canadensis*) Emergence, Survival, and Fecundity in No-till Soybean. Weed Science. doi.org/10.1614/WS-07-093.1

Davis VM, Kruger GR, Young BG, Johnson WG (2010) Fall and spring preplant herbicide applications influence spring emergence of glyphosate-resistant horseweed (*Conyza canadensis*). Weed Technology. doi.org/10.1614/WT-09-064.1

Ehleringer J (1983). Ecophysiology of *Amaranthus palmeri*, a Sonoran Desert summer annual. Oecologia 57:107–112.

Fickett, ND, Boerboom CM, Stoltenberg DE (2013) Soybean Yield Loss Potential Associated with Early-Season Weed Competition across 64 Site-Years. Weed Science. doi.org/10.1614/WS-D-12-00164.1

Frye WW, Blevins BL, Smith MS, Corak SJ, and Varco JJ (1988). Role of annual legume cover crops in efficient use of water and nitrogen. Pages 129–153 in W. L. Hargrove, ed. Cropping Strategies for Efficient Use of Water and Nitrogen. Madison, WI: ASA Special Publication No. 51.

Gronwald JW (1997) Resistance to PS II inhibitor herbicides. In Herbicide Resistance in Plants: Biology and Biochemistry doi.org/10.1007/978-94-011-5538-0_5

Guo P, Al-Khatib K (2003) Temperature effects on germination and growth of redroot pigweed (*Amaranthus retroflexus*), Palmer amaranth (*A. palmeri*), and common waterhemp (*A. rudis*). Weed Science. doi.org/10.1614/P2002-127

Heap IM (2019) International Survey of Herbicide Resistant Weeds [On line]. Accessed 5/9/2019

Horak MJ, Loughin TM (2000) Growth analysis of four *Amaranthus* species. Weed Science. doi.org/10.2307/4046301

Johnson B, Young B, Matthews J, Marquardt P, Slack C, Bradley K, Smeda R (2010). Weed Control in Dicamba-Resistant Soybeans. Crop Management. doi.org/10.1094/CM-2010-0920-01-RS

Keeley PE, Carter CH, Thullen RJ (1987) Influence of planting date on growth of Palmer amaranth (*Amaranthus palmeri*). Weed Science. doi.org/10.2307/4044391

Klingaman T, Oliver LR (1994) Palmer Amaranth (*Amaranthus palmeri*) interference in Soybeans (Glycine max). Weed Science. doi.org/10.2307/4045448

Kunz C, Sturm DJ, Varnholt, D, Walker F, Gerhards R (2016) Allelopathic effects and weed suppressive ability of cover crops. Plant, Soil and Environment. doi.org/10.17221/612/2015-PSE

Main CL, Steckel LE, Hayes RM, Mueller TC (2006) Biotic and abiotic factors influence horseweed emergence. Weed Science. doi.org/10.1614/WS-06-026R1.1

Massinga RA, Currie RS, Horak MJ, Boyer J (2001) Interference of Palmer amaranth in corn. Source: Weed Science. doi.org/10.1614/0043-1745

McCall C (2018). Integrating cover crops and herbicides for horseweed and Palmer amaranth management in no-till soybean. Master’s thesis. Manhattan, KS: Kansas State University.

Moore JW, Murray DS, Westerman RB (2004) Palmer amaranth (*Amaranthus palmeri*) effects on the harvest and yield of grain sorghum (*Sorghum bicolor*). Weed Technology. doi.org/10.1614/WT-02-086

Moore MJ, TJ Gillespie, Swanton CJ. (1994) Effect of cover crop mulches on weed emergence, weed biomass and soybean (*Glycine max*) development. Weed Technol. 8:512-518.

Nandula VK, Eubank TW, Poston DH, Koger CH, Reddy KN (2006) Factors affecting germination of horseweed (*Conyza canadensis*). Weed Science. doi.org/10.1614/WS-06-006R2.1

Novara A, Minacapilli M, Santoro A, Rodrigo-Comino J, Carrubba A, Sarno M, Gristina L (2019) Real cover crops contribution to soil organic carbon sequestration in sloping vineyard. Science of the Total Environment. doi.org/10.1016/j.scitotenv.2018.10.247

Osipitan OA, Dille JA, Assefa Y, Knezevic SZ (2018) Cover crop for early season weed suppression in crops: Systematic review and meta-analysis. Agronomy Journal. //doi.org/10.2134/agronj2017.12.0752

Pölös E, Mikulás J, Szigeti Z, Matkovics B, Do Quy Hai, Párducz Á, Lehoczki E (1988) Paraquat and atrazine co-resistance in *Conyza canadensis* (L.) Cronq. Pesticide Biochemistry and Physiology. doi.org/10.1016/0048-3575(88)90048-X

Powles SB, Holtum, J. A. M. (2018). Herbicide resistance in plants: Biology and biochemistry. Herbicide Resistance in Plants: Biology and Biochemistry. doi.org/10.1201/9781351073189

Pullar TC, Marino PC, Jackson DM, Harrison HF, Keinath AP (2006) Effects of killed cover crop mulch on weeds, weed seeds, and herbivores. Agriculture, Ecosystems and Environment. doi.org/10.1016/j.agee.2005.12.021

Reddy KN (2001). Effects of Cereal and Legume Cover Crop Residues on Weeds, Yield, and Net Return in Soybean (*Glycine max*) 1. Weed Technology. doi.org/10.1614/0890-037X(2001)015[0660:EOCALC]2.0.CO;2

Regehr DL, Bazzaz FA (1979) The population dynamics of Erigeron canadensis, a successional winter annual. The Journal of Ecology, 923–933.

Rice EL (1984) Allelopathy. 2nd ed. Orlando, Florida, USA, Academic Press.

Rose TJ, Kearney, LJ, Morris S, Van Zwieten L, Erler DV (2019) Pinto peanut cover crop nitrogen contributions and potential to mitigate nitrous oxide emissions in subtropical coffee plantations. Science of the Total Environment, 656, 108–117.

Seehusen T, Hofgaard IS, Tørresen KS, Riley H (2017) Residue cover, soil structure, weed infestation and spring cereal yields as affected by tillage and straw management on three soils.

Sellers BA, Smeda RJ, Johnson WG, Ellersieck MR (2003) Comparative growth of six *Amaranthus* species in Missouri. Weed Science. doi.org/10.2307/4046666

Sturm DJ, Peteinatos G, Gerhards R (2018) Contribution of allelopathic effects to the overall weed suppression by different cover crops. Weed Research. doi.org/10.1111/wre.12316

Steinmaus SJ, Prather TS, Holt JS (2000) Estimation of base temperatures for nine weed species. Journal of Experimental Botany 51:275-286

Teasdale JR (1996) Contribution of cover crops to weed management in sustainable agricultural systems. FAO. doi.org/10.2134/jpa1996.0475

Thebaud C, Abbott RJ (1995) Characterization of invasive *Conyza* species (*Asteraceae*) in Europe: Quantitative trait and isozyme analysis. American Journal of Botany. doi.org/10.2307/2445581

Tremmel, DC, Peterson KM (1983) Competitive subordination of a piedmont old field successional dominant by an introduced species. American Journal of Botany. doi.org/10.2307/2443282

USDA (2018) Plants Database: Plants.usda.gov/core/profile? symbol=AMPA. Accessed: April 12, 2019

VanGessel, M. J. (2001). Glyphosate-resistant horseweed from Delaware. Weed Science. doi.org/10.1614/0043-1745(2001)049[0703:rprhfd]2.0.co;2

Varanasi VK, Brabham C, Norsworthy JK, Nie H, Young BG, Houston M, Scott RC (2018) A statewide survey of PPO-inhibitor resistance and the prevalent target-Site mechanisms in Palmer amaranth (*Amaranthus palmeri*) accessions from Arkansas. Weed Science. doi.org/10.1017/wsc.2017.68

Weaver SE (2001) The biology of Canadian weeds. 115. *Conyza canadensis*. Canadian Journal of Plant Science. doi.org/10.4141/P00-196

Yamasue Y, Kamiyama K, Hanioka Y, Kusanagi T (1992) Paraquat resistance and its inheritance in seed germination of the foliar-resistant biotypes of *Erigeron canadensis* L. and E.

sumatrensis Retz. Pesticide Biochemistry and Physiology. doi.org/10.1016/0048-3575(92)90005-K

Chapter 2 - Horseweed Emergence Patterns and Response to Herbicides from Populations Across Four States

Abstract

Predicting when horseweed will germinate and emerge is often difficult. Horseweed, in some regions, may germinate in the fall and behave as a winter annual or may germinate in the spring and behave as a summer annual. It is important to investigate the extent to which time of germination is influenced by the environment, inherited traits, or both. A common garden field study was conducted in KS, with an objective to determine the emergence timing of eight different horseweed populations. Horseweed seeds were collected from 30 plants in each of two locations across the four states, from KY, IL, and MO to KS. At least 200 viable seeds of the eight populations were sown into individual rings at the Department of Agronomy Research Field near Manhattan, KS on October 19, 2016, and on October 1, 2017. The experimental design was a randomized complete block with six replications and eight populations. There was an additional control ring to assess emergence of naturally occurring horseweed populations. Emergence counts were taken on a weekly basis during fall and spring months and on a monthly basis during winter months. Once cotyledons were visible, plants were pulled, and horseweed number was recorded. In 2016-2017, majority of horseweed emerged in spring, while in 2017-2018 the majority emerged in the fall, therefore, years were different. Across populations, all plants emerged at the same time, therefore, a single model was used to describe cumulative horseweed emergence across GDD for each year. In 2016-2017, across populations, 50 and 100% cumulative horseweed emergence occurred at 230 and 269 growing degree days (GDD). Good temperature and moisture conditions occurred during the two weeks before emergence started (March 23 to April 11, 2017) with 159 mm of precipitation and average daily maximum

and minimum air temperatures were 16 and 7 C, respectively. In 2017-2018, across populations, 50 and 100% cumulative horseweed emergence occurred at 100 and 143 GDD. In the two weeks before emergence, 53 mm of precipitation fell, and the maximum and minimum air temperatures were between 30 and 17 C.

Introduction

Horseweed (*Conyza canadensis*) is a problematic weed in soybeans, especially in minimum tillage situations (Bruce and Kells 1990). In order to manage horseweed effectively, one must understand when plants emerge, allowing the producer to implement timely weed control. In KS, horseweed typically emerges in the fall and behaves as a winter annual (McCall 2018). Fall emerging horseweed overwinters as a rosette, bolts in April or May, flowers in July, and disperses seeds in late August through September (Regehr and Bazzaz 1979; Weaver 2001).

A small percentage of plants do emerge in the spring in Kansas and the number varies by year depending on weather conditions. Horseweed seed that is dispersed and reaches the soil in late September or October may miss warm temperature and moisture and will not germinate in the fall. Horseweed seeds will lay on the soil surface through winter and germinate in the spring when favorable weather conditions return. In Indiana, Davis and Johnson (2008) found that horseweed primarily emerged in the spring with peak densities occurring in late April through mid-May. Any plants that emerged in the fall in Indiana had low winter survival. In Tennessee, Main et al. (2006) found that horseweed seeds germinated and emerged during almost any month when the maximum and minimum temperatures ranged between 25 and 10 C, respectively. Other researchers found that seeds from multiple populations across Missouri emerged in the fall for a northern Missouri location and in the spring for a southern Missouri location (Bolte 2015).

Suitable temperatures and precipitation are important for horseweed seeds to emerge from the soil. Nandula et al. (2006) found that horseweed germinates under 24/20 C day/night temperatures, which occurs in both fall and spring in KS. For a horseweed population in California the base temperature for germination was 13 C and that is what was used in this experiment as the base temperature to calculate growing degree days (GDD) (Steinmaus et al. 2000).

As one moves from north to south locations, temperatures change and may influence the time of horseweed emergence. In southern Ontario, Canada, Tozzi and Van Acker (2014) reported emergence occurred from August 27 to September 9 and spring emergence occurred from May 14 to May 27 but fall emergence was 90% greater. Horseweed at these more northern locations act more as a winter annual and in southern locations as a summer annual.

In KS, based on a 30-yr average, September is the last month that the maximum air temperature is above 25 C and is typically when horseweed seed is dispersing. The time period between seed dispersal and germination can be relatively short in KS, and late dispersed seed may miss the opportunity to establish in the fall. In this case, seeds will emerge in the spring when temperature increases, or be lost to the environment.

Horseweed germination and emergence research is sparse and variable, and that is possibly due to the delicate nature of the seed and the difficulty to work with it. However, based on previous research, horseweed emergence is environmentally driven, and populations that typically behave like summer annuals will likely behave as winter annuals if seeded in KS. This is important to know because as more farmers progress to no-tillage or minimum tillage operations, their chances for horseweed infestations will increase. Additionally, horseweed seed can travel long distances with the wind, possibly kilometers from source populations (Dauer et al., 2007), thus spreading genetically different populations across the Midwest. Producers may experience poor control of horseweed in their fields because of resistance to herbicides that have never been applied.

It is important to understand how the environment impacts horseweed germination and emergence patterns and determine if seed source influences horseweed emergence timing. The objectives of this study were to (1) determine the influence of population source on timing of horseweed emergence with eight populations sown in a common environment of KS, (2) determine temperature and moisture conditions that favor horseweed emergence over two growing seasons, and (3) determine the response of each horseweed population to six different herbicides.

Materials and Methods

Procedure for horseweed seed establishment and data collection

Horseweed seed heads from 30 plants were collected in each of two locations across four states: KY, IL, MO and KS, along a transect of eight locations at least 200 km apart (Table 2.1). Heads were placed in paper bags, dried in the greenhouse for three to five days, and then seed was shaken and collected from all heads. Seed viability for each population was assessed by identifying 50 plump, healthy seeds by using a microscope, and placing seed into plastic Petri-dishes on the surface of moist potting mix with four replications. Germinated seeds were counted every day for one week to determine the seed viability of the source to adjust seeding rates.

The experimental design was a randomized complete block with six replications of eight horseweed populations and one empty ring to document naturally-occurring seedlings, for a total of 54 rings. At least 200 viable seeds of each of the eight populations were sown into individual 20 cm diameter PVC rings, placed one meter apart, at the KSU Department of Agronomy

Ashland Bottoms Research Farm near Manhattan, KS on October 19, 2016, and at the Department of Agronomy North Farm in Manhattan, KS on October 1, 2017. Emergence counts were taken on a weekly basis during fall months and spring months and on a monthly basis during winter months. Once cotyledons were visible, plants were counted, pulled and discarded. Emergence counts ended in near the end of May for each year.

In 2016-2017 daily precipitation and max/min air temperature was collected from a weather station near Manhattan, KS (latitude/longitude: 39.126/-96.667) and 2017-2018, a different station located in Manhattan, KS (latitude/longitude: 39.209/-96.552).

Cumulative emergence of horseweed seedlings was determined using the maximum number observed for a given ring. Cumulative emergence was plotted against accumulated growing degree days (GDD), where GDD accumulation started on October 1, for both years, and ended past emergence counts on July 4, 2017 and June 13, 2018. GDD was calculated as follows:

$$GDD = \{[(T_{max} + T_{min}) \div 2] - T_{base}\} \qquad \text{Equation 2.1}$$

where T_{max} was the maximum temperature (C) for each day, T_{min} was the minimum temperature for each day, and T_{base} was the base air temperature (13 C) for horseweed emergence (Steinmaus et al. 2000). A non-linear 3-parameter sigmoidal regression curve was fit to cumulative horseweed emergence data across GDD in SigmaPlot v. 12.3 (Systat Software Inc., San Jose, CA):

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

where y was the cumulative percentage of total emerged horseweed plants, x was the cumulative GDD, x_o was the cumulative GDD for 50% horseweed emergence (inflection point), a was the maximum percentage of total emerged horseweed plants (100), and b is the slope of the line at the inflection point. To determine if the populations had different emergence patterns, the regression lines were compared using a pairwise F-test:

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

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

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

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

Herbicide screening

The eight horseweed populations collected in 2017-2018 were screened for response to six different herbicides. The experimental design was randomized complete block with eight populations, six herbicides and non-treated control, and replicated five times (one plant per replication). Seed from each horseweed population were sown into flats (30 cm wide by 40 cm long by 10 cm deep) filled with Pro-mix in the greenhouse on May 23, 2018. Individual seedlings were transplanted on June 6, 2018 into 10 by 10 cm wide pots and randomized. Rosette diameters were measured prior to herbicide applications made on July 18, 2018. The six herbicides, rates, and appropriate adjuvants were glufosinate at 738 g ha^{-1} plus 1% v/v AMS, paraquat at 841 g ha^{-1} plus 1% v/v NIS, dicamba at 560 g ha^{-1}, glyphosate at 1260 g ha^{-1} plus 2% v/v AMS, chlorimuron at 13.1 g ha^{-1} plus 1% AMS and 2% v/v COC, and atrazine at 560 g ha^{-1} plus 1% v/v COC.

Herbicide applications were made using XR Teejet 8003 nozzles (TeeJet Technologies, Wheaton, IL) calibrated to deliver 187 L ha^{-1} at 207 kPa, producing medium sized droplets in a bench-type chamber sprayer (DeVries Manufacturing, Inc.).

Percent control of each horseweed plant was recorded at 1, 2, and 4 WAT on a visual scale from 0 (no injury) to 100% (dead plants) relative to a non-treated control. Influence of horseweed population source on rosette size and response to herbicides were tested using PROC GLM in SAS 9.4 (SAS Institute Inc., Cary, NC) and differences were detected at alpha =0.05.

Results and Discussion

Horseweed emergence patterns in Kansas environments

In a common garden in Kansas all horseweed populations emerged at the same time but in different seasons; in year one all emerged in the spring and in year two all emerged in the fall; therefore, years were different and will be presented separately. There were no differences in emergence timing among populations within a given year, therefore, a single model was used to describe cumulative horseweed emergence across GDD across populations for each year.

Across populations, 33% of approximately 200 viable seed that were seeded emerged (Tables 2.2 and 2.3). The slopes of the lines at the inflection points (parameter b) were 4.8 in year one and 6.2, and cumulative GDD for 50% horseweed emergence was 224 GDD in year one and 89 GDD in year two (Table 2.4).

In the first year, horseweed emergence occurred in the spring, indicated by the greater GDD needed for 50% emergence (Figure 2.1). No emergence occurred in fall because sowing occurred in mid-October (too late), and weather conditions had become cool and dry for the remainder of the fall (Figure 2.1). Steinmaus et al. (2000) found that the base temperature for horseweed emergence was 13 C. Also, only 7 mm of precipitation occurred in the two weeks after sowing, with only 7 mm falling. Then fall temperatures began to cool and were below threshold temperatures for horseweed germination. The 8 days from October 19 to 27, 2016 had an average maximum air temperature of 23 C and a minimum temperature of 5 C (Figure 2.2). Nandula et al. (2006) discovered that horseweed seeds did not germinate when maximum and minimum temperatures were 12 and 6 C, but germination increased with temperature, peaking at 24 and 20 C maximum and minimum air temperatures.

Cumulative 50 and 100% horseweed emergence occurred at 230 and 269 GDD, respectively, across populations in 2016-2017 (Figure 2.1). This corresponded to April 14 and April 21, 2017. In the week prior (April 7 to April 14, 2017), 159 mm of precipitation was received, and average maximum and minimum air temperatures were 24 and 10 C, respectively (Figure 2.2). These conditions were conducive to horseweed emergence in the spring in Kansas. Other researchers in Tennessee observed greatest horseweed emergence, when the average daytime temperature fluctuated between 15.5 and 10 C, which occurred in the spring in April and in the fall in September, and some plants emerged in any month when temperatures ranged from 10 to 25 C (Main et al. 2006).

In the second year of the study (2017-2018) horseweed mostly emerged in the fall of 2017 (Figure 2.3). Based on the model, 50% horseweed emergence occurred by 88 GDD. During that time, 53 mm of precipitation fell, and the maximum and minimum air temperatures were between 30 and 17 C, respectively (Figure 2.4). After this first emergence flush, the average maximum and minimum air temperatures were 18 and 3 C, respectively between October 15 and November 11, 2017, which was becoming cool for horseweed to emerge and it was also too dry as only 1 mm of rain fell (Figure 2.4). McCall (2018) observed that naturally-occurring horseweed plants mostly emerged in fall in KS.

By the spring of the second year (2018) there was no new emergence. There was much less spring moisture in 2018 than 2017. There was only 55 mm of precipitation between March 1 to April 30, 2018, compared to 230 mm of precipitation in the same period in 2017.

Herbicide screening of eight horseweed populations from 2017-2018.

At transplanting horseweed rosettes were 2 to 4 cm in diameter and 42 days later when herbicides were applied, plants ranged from 8.5 cm (± 0.23) to 12 cm (± 0.26) (Table 2.5). At the time of herbicide application, horseweed plants were healthy, with approximately 30 leaves and no visual nutrient deficiency.

Glufosinate controlled all horseweed plants across all populations (Table 2.6). Glufosinate works well when applied POST to small actively growing weeds. There are no cases of glufosinate-resistant horseweed in the U.S. (Heap 2019).

Paraquat provided greater than 95% control of horseweed across all populations, at one and two WAT, but randomly sized individual plants that were not completely controlled began to regrow and produce new leaves by four WAT (Table 2.6). Horseweed resistance to paraquat in the U.S. has been documented in MS, DE, and CA (Heap 2019).

Dicamba provided good control of horseweed, with greater than 95% observed weed control for all populations besides Garnett, KS (Table 2.6). In a greenhouse study, diglycolamine rate salt of dicamba provided 97% control of horseweed plants 30 cm tall or less (Kruger et al.

2010). Currently, no horseweed populations have been identified as resistant to group 4 herbicides in the U.S (Heap 2019). Dicamba remains a good option for POST horseweed control and is now available to apply in soybeans when a dicamba tolerant variety is used, but the size of horseweed plants at this time may be too large for good control.

Glyphosate did not control the two populations from KY and IL, or the one from Columbia, MO, with 53% or less control observed (Table 2.6). Both populations from Kansas and the one from Louisville, MO were controlled by at least 92%. There were no differences in plant sizes across all eight populations. The populations with low levels of control are likely resistant to glyphosate, and occurrence of glyphosate-resistant populations have been confirmed in MO, KS, IL, and KY (Heap 2019).

Chlorimuron, an ALS-inhibitor, did not control any population well with less than 42% control observed (Table 2.6). In this study, the rate for chlorimuron was lower than the maximum rate a producer can apply, which may explain the reduction in horseweed control with chlorimuron. Chlorimuron is labeled for small actively growing broadleaf weeds and to be applied at 30 to 50 g ha^{-1} (Anonymous 2019). Horseweed resistance to chlorimuron itself has been confirmed in OH, MI, and IN, but not MO, KS, IL, and KY; horseweed resistant to other ALS-inhibitors has been confirmed in KS and IL, specifically, chlorsulfuron, iodosulfuron-methyl-sodium, metsulfuron-methyl, rimsulfuron, thiencarbazone-methyl, thifensulfuron-methyl, and tribenuron-methyl (Heap 2019). Chlorimuron should not be applied alone to control horseweed, as it is not permitted on the label (Anonymous 2019) but, there are already horseweed-resistant populations to similar ALS-inhibitors (Heap 2019). Further evaluations are needed to confirm if plants were resistant to chlorimuron or if POST chlorimuron alone is poor at controlling horseweed of that size.

Atrazine applied as a POST herbicide was not effective at controlling any horseweed population with less than 60% control observed (Table 2.6). One would need to increase the rate or consider it as a PRE to effectively control horseweed. The only cases of atrazine-resistant horseweed have been from MI (Heap 2019). Further evaluations of horseweed response to PSII-inhibitors are needed to confirm resistance.

Conclusions

Common Garden

The environment and year have a significant role in timing of horseweed emergence. In Kansas, September is the last month that maximum air temperatures are above 25 C, based on a 30-yr climate record of Manhattan, KS (NOAA, 2019), and is often the month when horseweed seed are dispersing. Horseweed typically sheds seed between late July and October (Shields et al. 2006). The time period between seed dispersal and germination can be relatively short in Kansas, and late dispersed seed may miss the opportunity to establish in the fall. Compared to fall, the probability of horseweed seeds that germinate in the spring is low, because many seeds do not last long on the soil surface during winter months or may be lost to predation. Horseweed seed that has been buried is more likely to remain viable longer, compared to seeds sitting on the soil surface (Vargas et al. 2018). Additionally, seeds that survive to spring still may not germinate and emerge until conditions become favorable.

In Kansas, horseweed can behave like a winter annual by germinating in the fall, surviving the winter as rosettes, bolting in the spring, and producing seed in late summer. Horseweed can also germinate in the spring and behave like an early-established summer annual weed, especially if conditions were unfavorable for germination in the fall, but favorable in the spring. As weather conditions shift from cool to warm temperatures, so may horseweed emergence. Producers will need to watch for horseweed emergence in the fall and spring to conduct management accordingly for effective control. More work is needed to quantify the most favorable weather conditions for horseweed emergence in Kansas environments, specifically related to soil temperature and moisture.

Herbicide screening

Horseweed resistance may quickly spread throughout a field; therefore, it is important that suspected resistant plants be controlled before seeds are shed. Only five years after the first glyphosate-resistant population was reported, resistant biotypes were found in more than 44,000 ha of cropland in the U.S. (VanGessel 2001). Herbicides remain effective at controlling horseweed, but when rosettes are too large, herbicides rates are too low, or there are no effective modes of action in the herbicide mixture, horseweed control may be reduced. By integrating more weed management strategies, the pressure of any one control method is reduced.

References

Bolte JD (2015). Emergence and control of horseweed (*Conyza canadensis*). University of Missouri--Columbia.

Bruce JA, Kells JJ (1990). Horseweed (*Conyza canadensis*) control in no-tillage soybeans (Glycine max) with preplant and preemergence herbicides. Weed Technology 4:642-647

Davis VM, Johnson WG (2008) Glyphosate-resistant horseweed (*Conyza Canadensis*) emergence, survival, and fecundity in no-till soybean. Weed Science. doi.org/10.1614/WS-07-093.1

Dauer JT, Mortensen DA, VanGessel MJ (2007). temporal and spatial dynamics of long-distance *Conyza canadensis* seed dispersal. Journal of Applied Ecology. https://doi.org/10.1111/j.1365-2664.2006.01256.x

Heap IM (2019) International survey of herbicide resistant weeds [On line]. Assessed 5/9/2019

Kruger GR, Davis VM, Weller SC, Johnson WG (2010). Control of horseweed (*Conyza canadensis*) with growth regulator herbicides. Weed Technology. https://doi.org/10.1614/WT-D-10-00022.1

Main CL, Steckel LE, Hayes RM, Mueller TC (2006). Biotic and abiotic factors influence horseweed emergence. Weed Science. https://doi.org/10.1614/WS-06-026R1.1

McCall C (2018) Integrating cover crops and herbicides for horseweed and Palmer amaranth management in no-till soybean. Master’s thesis. Manhattan, KS: Kansas State University.

Nandula VK, Eubank TW, Poston DH, Koger CH, Reddy KN (2006). Factors affecting germination of horseweed (*Conyza canadensis*). Weed Science. https://doi.org/10.1614/WS-06-006R2.1

[NOAA] National Oceanic and Atmospheric Administration (2019)

Regehr D, Bazzaz FA (1979). The population dynamics of Erigeron canadensis, a successional winter annual. Journal of Ecology, vol: 923–933.

Shields EJ, Dauer JT, VanGessel MJ, Neumann G (2006) Horseweed (*Conyza canadensis*) seed collected in the planetary boundary layer. Weed Sci. 54:1063–1067.

Steinmaus SJ, Prather TS, Holt JS (2000) Estimation of base temperatures for nine weed species. Journal of Experimental Botany 51:275-286

Vargas AAM, Agostinetto D, Zandoná RR, Fraga DS, Avila (2018). Longevity of horseweed seed bank depending on the burial depth. Planta daninha vol.36

Weaver SE (2001) The biology of Canadian weeds. 115. *Conyza canadensis*. Canadian Journal of Plant Science. doi.org/10.4141/P00-196

Table 2.1 Locations of horseweed patches where seed was collected and corresponding abbreviations, for both years.

Years	Locations/Seed Source	Abbrev.
2016-2017	Ashland Bottoms, KS	ASHKS
	Garnett, KS	GARKS
	Blackwater, MO	BLAMO
	Louisville, MO	LOUMO
	Desoto, IL	DESIL
	Belleville, IL	BELIL
	Lexington, KY	LEXKY
	Princeton, KY	PRIKY
2017-2018	Ashland Bottoms, KS	ASHKS
	Garnett, KS	GARKS
	Columbia, MO	COLMO
	Louisville, MO	LOUMO
	Desoto, IL	DESIL
	Belleville, IL	BELIL
	Lexington, KY	LEXKY
	Princeton, KY	PRIKY

Ashland Bottoms is an incorporated town near Manhattan, KS.

Table 2.2 Horseweed emergence (mean + SE) for each population across sampling dates in 2016-2017 for Ashland Bottoms, KS.

Date	Population								
	ASHKS	GARKS	BLAMO	LOUMO	DESIL	BELIL	PRIKY	LEXKY	Non-seeded
	---Plants ring^{-1}---								
1-Nov	0	0	0	0	0	0	0	0	0
16-Nov	0	0	0	0	0	0	0	0	0
12-Dec	0	0	0	0	0	0	0	0	0
27-Mar	0	0	0	0	0	0	0	0	0
6-Apr	0	0.3 (0.2)	0.2 (0.2)	0.3 (0.2)	1.7 (1.1)	0.8 (0.8)	0.5 (0.5)	0.3 (0.2)	0
14-Apr	17.3 (2)	47.8 (3.7)	30.5 (3.7)	83.7 (7.4)	223.5 (4.6)	23.3 (2.4)	43.5 (2)	35.3 (6.4)	1.2 (0.2)
21-Apr	1.2 (0.7)	2.8 (0.8)	1.7 (0.5)	8.8 (2)	13.2 (4.3)	2 (1.2)	4 (1.9)	3.2 (0.6)	0.5 (0.3)
1-May	0	0	0.2 (0.2)	0.7 (0.7)	1.5 (1)	0	0.5 (0.5)	0.8 (0.5)	0
Total	18.5	50.9	32.6	93.5	239.9	26.1	48.5	39.6	1.7

Table 2.3 Horseweed emergence (mean + SE) for each population across sampling dates in 2017-2018 for Manhattan, KS.

Date	Population								
	ASHKS	GARKS	COLMO	LOUMO	DESIL	BELIL	PRIKY	LEXKY	Non-seed
	------------------------Plants ring^{-1}------------------------								
10-Oct	0	0	0	0	0	0	0	0	0
16-Oct	20.5 (2)	31.8 (3)	14.7 (2)	9.5 (1)	13.7 (3)	13.3 (2)	42.8 (6)	21.3 (3.5)	0
24-Oct	7.5 (3)	5.7 (3)	2.5 (2)	1.5 (1)	0.7 (0.1)	0.2 (0.2)	3.8 (1.5)	3.2 (2)	0.5 (1)
1-Nov	0	0.3 (0.2)	0	0.84 (1)	0.7 (0)	0.2 (0)	1 (1)	0	1.3 (0)
17-Nov	0	0.2	0	0.17 (0)	0	0	0	1 (1)	0
Total	28.0	38.0	17.2	12.1	15.1	13.7	47.6	25.5	1.8

Table 2.4 Parameter estimates describing the relationship between cumulative horseweed emergence and cumulative GDD using Equation 2.2 and the predicted date of 50% emergence.

Year	Location of Study	Parameter Estimates			R^2	Date of 50% Emergence
		a (SE)	b (SE)	x_0 (SE)		
		%		GDD		
2016-2017	Ashland Bottoms Farm	99.5 (0.18)	4.8 (0.25)	224 (0.65)	0.99	April 14, 2017
2017-2018	North Farm	99.8 (0.6)	6.2 (3.5)	89 (6.5)	0.99	October 16, 2017

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

Table 2.5 Average diameter (cm) of horseweed rosettes and SE for each population prior to herbicide applications. Horseweed size was not different among populations prior to the herbicide applications.

Herbicide	Population							
	ASHKS	GARKS	LOUMO	COLMO	DESIL	BELIL	PRIKY	LEXKY
	----------cm----------							
dicamba	9 (0.5)	8.6 (0.2)	12.1 (1.1)	9.8 (0.6)	9.8 (0.4)	7 (0.3)	9.8 (0.4)	12.4 (0.8)
paraquat	8.2 (0.2)	10.2 (0.5)	11.2 (0.5)	9.4 (0.5)	8.8 (0.4)	7.2 (0.6)	10.4 (0.5)	9.2 (0.4)
atrazine	9.2 (0.4)	9.8 (0.2)	11.6 (0.5)	9.6 (0.5)	11 (0.4)	9.8 (0.5)	10 (0.3)	11 (0.3)
glyphosate	8.8 (0.2)	11 (0.5)	11.8 (0.9)	11.6 (0.4)	8.6 (0.2)	9 (0.3)	11 (0.5)	12.8 (0.2)
chlorimuron	8.6 (0.2)	10.2 (0.6)	12.8 (0.2)	11.6 (0.5)	9.8 (0.4)	8.6 (0.4)	12.2 (0.4)	13.2 (0.2)
glufosinate	10.2 (0.2)	10.8 (0.4)	11.2 (0.5)	12.2 (0.5)	9.8 (0.4)	8.8 (0.2)	10.8 (0.7)	11.6 (0.4)

Table 2.6 Visual control rating (0 to 100%) and SE at 4 WAT with six herbicides applied to each of eight populations.

Herbicide	Population							
	ASHKS	GARKS	LOUMO	COLMO	DESIL	BELIL	PRIKY	LEXKY
	---% (SE)---							
dicamba	96.4 (1.2)	84 (4.1)	99.8 (0.2)	87 (9.7)	100	100	100	96.8 (3.0)
paraquat	100	100	82 (18.0)	100	100	84 (16.0)	83 (17.0)	100
atrazine	42 (16.2)	53 (19.2)	35 (16.4)	55 (19.6)	37 (4.6)	10 (1.6)	60 (19.9)	28 (10.1)
glyphosate	92 (8.0)	100 (0)	97 (3.0)	53 (19.5)	10 (0)	5 (0)	14 (2.9)	15.4 (8.1)
chlorimuron	7 (1.2)	7 (2.0)	42.4 (21.1)	15 (3.2)	11 (3.7)	7.4 (3.2)	23 (11.0)	15 (8.8)
glufosinate	100	100	100	100	100	100	100	100

Figure 2.1 Cumulative percent of total horseweed emergence in 2016-2017. See Table 2.4 for parameter estimates for the regression.

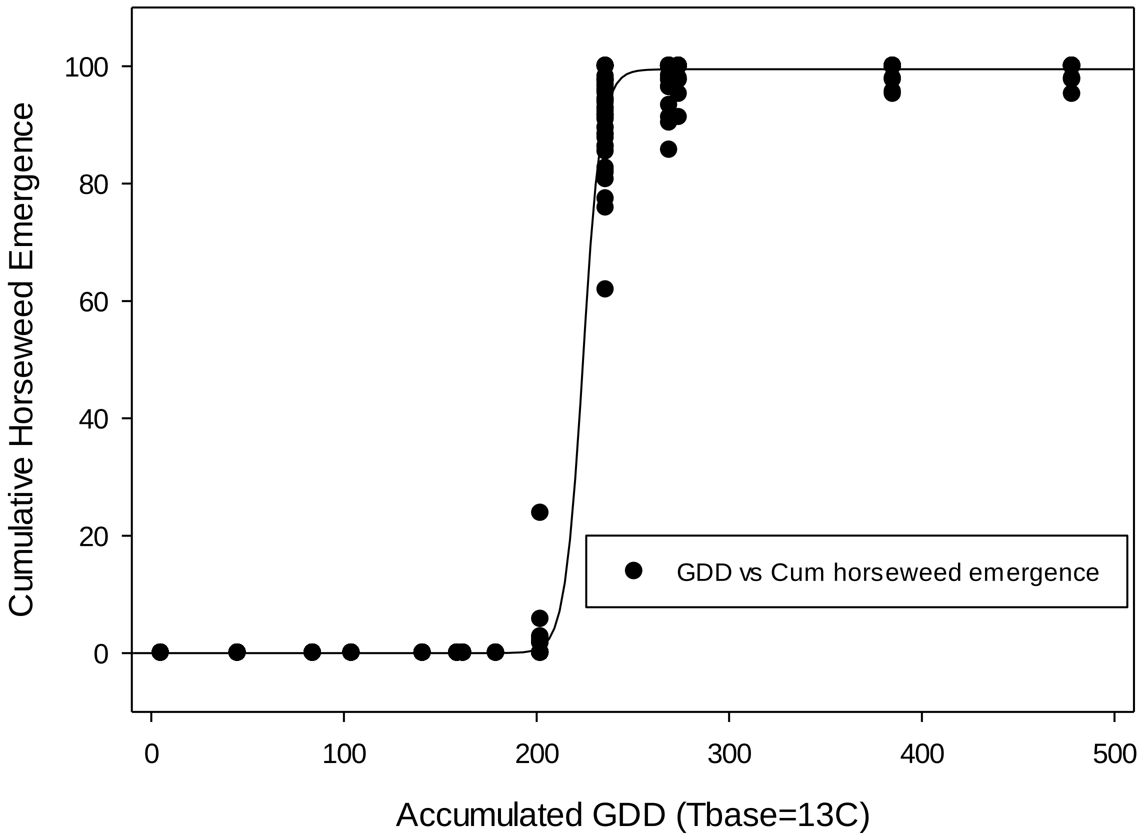


Figure 2.2 Maximum and minimum air temperature (C) and total precipitation (mm) for 2016-2017. Horseweed seed was sown on October 19, 2016.

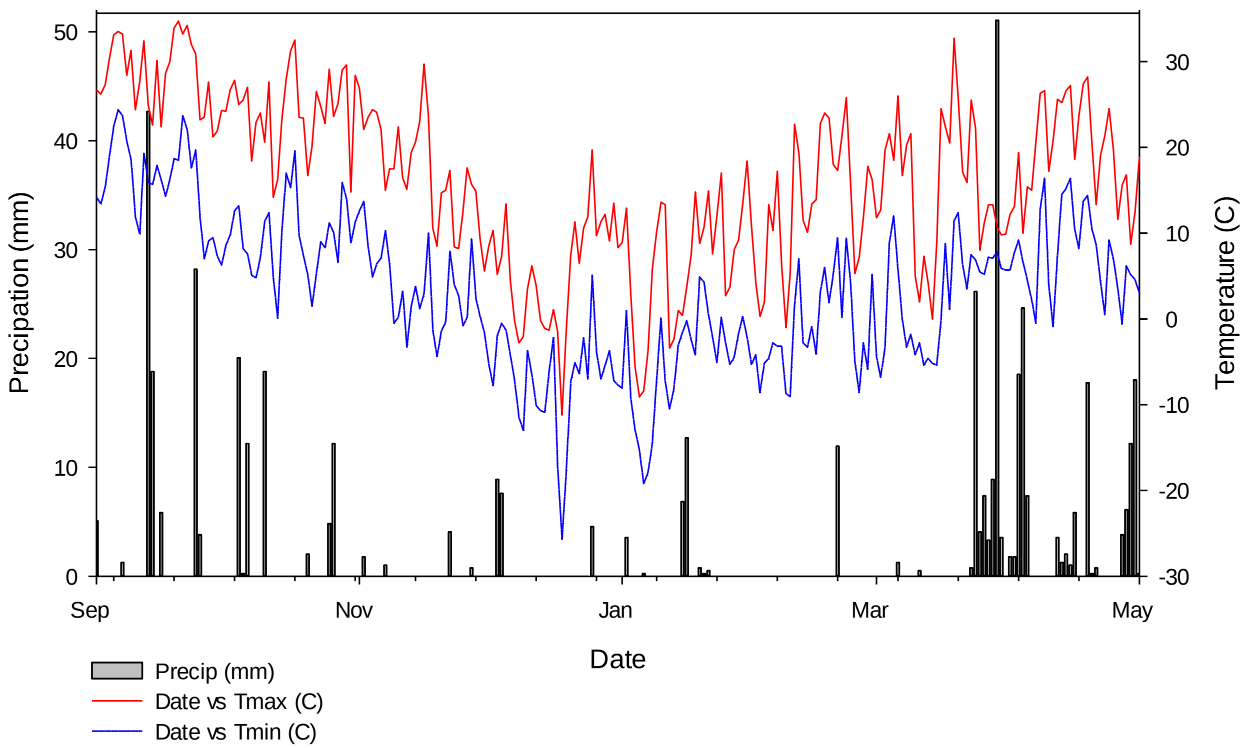


Figure 2.3 Cumulative percent of total horseweed emergence in 2017-2018. Table 2.4 for parameter estimates for the regression.

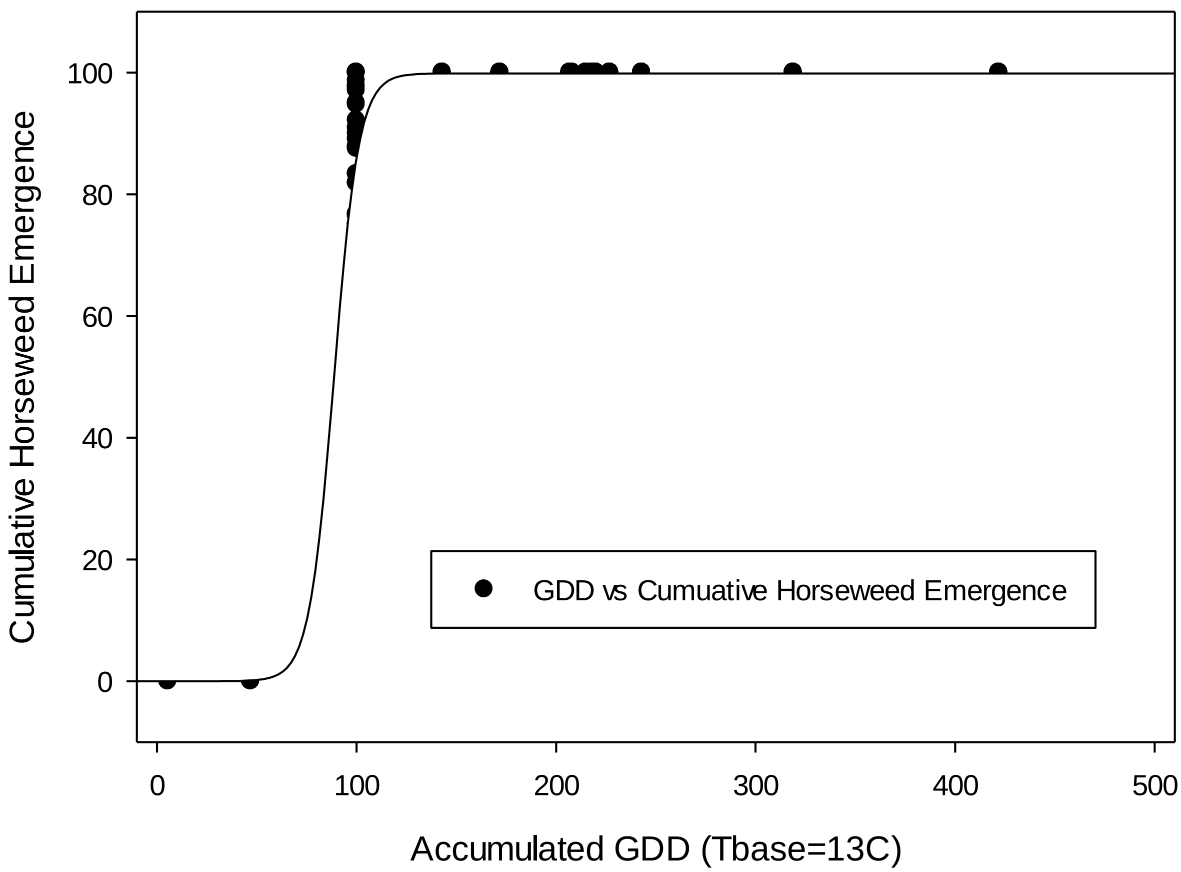
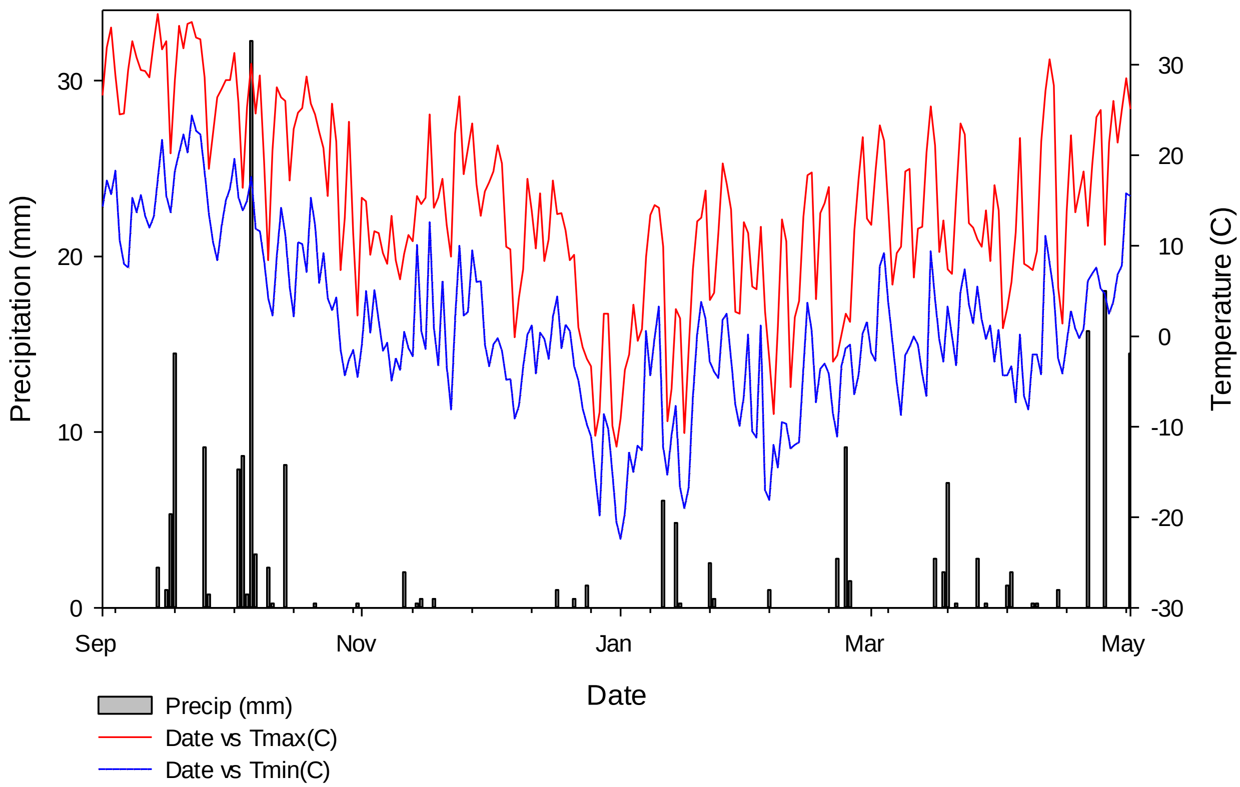


Figure 2.4 Maximum and minimum air temperature (C) and total precipitation (mm) for 2017-2018. Horseweed seed sowing on October 1, 2017.



Chapter 3 - Evaluating Cover Crops and Herbicides for Horseweed Management in No-till Soybean

Abstract

Horseweed establishes well in no-till environments and in many fields, plants are resistant to several key herbicides used in no-till soybean, including glyphosate, chlorimuron, and atrazine. A field experiment was conducted in 2016-2017 and 2017-2018 near Manhattan, KS to evaluate cover crops and herbicides for horseweed management in no-till soybean. In year one, fall-seeded cover crops were winter triticale and spring oat and spring-seeded cover crops were spring triticale and spring oat. In year two, only fall-seeded cover crops of winter rye and spring oat were studied. In each year, residual herbicides were applied in the fall and non-residual herbicides were applied in fall and spring. Horseweed and all other weeds biomass were reduced the most with winter triticale, cereal rye, and cereal rye plus a herbicide at the time of terminating cover crops, in both years. Fall-and spring-seeded oat were least effective at suppressing horseweed during the growing season. Herbicides applied in the spring with no residual controlled horseweed better than fall-applied herbicides with or without residual, across years. In year one, soybean yields were greater with herbicide treatments compared to cover crops treatments, because a) soybeans did not establish well in winter triticale plots (residue too thick and wet), b) fall-seeded oat did not provide weed suppression into the spring, and c) spring-seeded cover crops did not establish well due to cool and wet conditions. In year two, there were no differences in soybean yield across cover crop and herbicide treatments because a) soybeans established well in all cereal rye plots, and b) there was no difference in weed control after cover crop termination. Cover crops are an effective integrated weed management tool that producers can use to manage horseweed.

Introduction

It is common for horseweed to establish in no-till soybean fields in the U.S. In KS, horseweed typically emerges in the fall, soon after seeds have shed (McCall 2018). Fall-emerged plants overwinter as rosettes, bolt in April or May, flower in July, and disperse seed in late August through September (Regehr and Bazzaz 1979; Weaver 2001). Some horseweed emergence does occur in the spring in KS (McCall 2018). In that case, producers would need to plan horseweed management activities in the fall and spring to adequately manage horseweed in no-till soybean in KS.

The availability of herbicides with effective sites of action to control horseweed is lessening as herbicide-resistant biotypes evolve and spread. The first case of glyphosate-resistant horseweed occurred in one producer's field within three years after using glyphosate exclusively (VanGessel 2001). Horseweed is resistant to glyphosate in more than 25 states in the U.S. (Heap 2019). The mechanism of horseweed resistance to glyphosate is altered translocation and sequestration of glyphosate. Susceptible plants move glyphosate from source to sink tissue, but in resistant horseweed plants much less glyphosate is translocated and instead resistant horseweed sink-leaf vacuoles accumulate the majority of glyphosate (Ge et al. 2010).

It is important to use a wide variety of weed management strategies to control weeds to slow the development of resistant weeds. Cover crops have been proven to provide many benefits to the soil, along with their use as weed suppressants. Cover crops can shade the soil surface and decrease the amount of solar radiation available to weeds, thus affecting germination, emergence, and growth of weeds (Moore et al. 1994). A meta-analysis revealed that cover crops can suppress weeds comparable to chemical and mechanical control in the early-season (Osipitan et al. 2018).

Winter hardy cereals are commonly used as cover crops in KS, like cereal rye and winter triticale, to suppress weeds in no-till environments. Italian ryegrass and rye biomass residue persisted up to nine weeks after soybean planting and reduced the density of weeds emerging in the early-season (Reddy 2001).

Although many herbicides, such as glyphosate, provide little control of horseweed if resistant, herbicides such as dicamba and 2,4-D remain good options for horseweed control with no known resistance. Little resistance has been developed to auxinic herbicides, and if used correctly and in combination with other weed management strategies, dicamba and 2,4-D may continue to control horseweed. Cover crops have shown that they can be good suppressors of weeds and relieve the efforts of effective herbicides, such as dicamba and 2,4-D, so they can be used longer and when needed. The objective of this study was to determine the effectiveness of fall and spring-planted cover crops and fall and spring-applied herbicides, both with and without soil residual, on horseweed management in a no-till soybean crop.

Materials and Methods

Field experiments were conducted through two growing seasons in 2016-2017 and 2017-2018 at Kansas State Department of Agronomy North Farm, located in Manhattan, KS (Table 3.1). In year one, field plots were established in no-till stubble immediately after grain sorghum harvest. Grain sorghum was planted 76 cm wide row spacing at 170,000 seeds ha^{-1}. Soil type in the study area was a Wymore silty clay loam (Fine, smectitic, mesic Aquertic Argiudolls). In year two, field plots were established in a no-till fallow field. After grain sorghum harvest in 2016 the field remained fallow until establishment of cover crops in fall 2017. Weeds were not controlled during the fallow season; the field was mowed prior to establishing the experiment. The soil type was a Kahola silt loam (Fine, alluvium parent material, well drained, loamy lowland). Soil samples were collected, and nutrient levels were analyzed. Filed sites were selected because of naturally occurring horseweed populations.

The experiment was arranged in a randomized complete block design, plots were 3 m wide by 7 m long, and four replications. Nine weed management treatments were evaluated in the first year. There were four cover crop and three herbicide treatments, as well as weed-free and non-treated checks (Table 3.3). Ten treatments were evaluated in the second year. There were two cover crop, three herbicide, two cover crop and herbicide combinations, and cover crop plus tillage, as well as weed-free and non-treated checks.

In 2016-2017, the four cover crop treatments included fall-seeded winter triticale and fall-seeded spring oat, which were seeded on October 25, 2016, and spring-seeded spring triticale and spring-seeded spring oat, which were seeded on March 11, 2017. Cover crops were seeded in 19 cm row spacings using a no-till drill (Model 3P605NT, Great Plains Manufacturing, Inc., Salina, KS) with double-disc openers at a depth of approximately 3 cm. The fall-applied residual herbicide treatment was a tank mix of dicamba plus chlorimuron and flumioxazin applied on October 27, 2016 and fall and spring-applied non-residual herbicide treatments were a tank mix of dicamba plus 2, 4-D applied on October 27, 2016 and March 20, 2017, respectively (Table 3.3 and 3.3).

In 2017-2018, fall-seeded cover crop treatments were cereal rye and spring oat drilled in 19 cm wide row spacing on September 28, 2017 (Table 3.3). Fall treatments included cereal rye alone, cereal rye plus saflufenacil (no residual), cereal rye plus tillage, cereal rye plus spring-applied dicamba plus 2,4-D (no residual). Tillage was conducted using a three meter wide disc set to a shallow depth with two passes per plot on September 27, 2017. A fall residual herbicide treatment was a tank mix of dicamba plus chlorimuron plus flumioxazin applied on September

29, 2017. Fall and spring-applied non-residual herbicide treatments were a tank mix of dicamba plus 2, 4-D was applied September 29, 2017 and May 3, 2018, respectively for the second year.

Herbicides were applied using a backpack sprayer at 140 L ha^{-1} and 276 kPa, using TT110015 Turbo TeeJet wide angle flat fan nozzles. In 2016-2017, all plots were terminated on May 24, 2017 with glyphosate plus 2,4-D and saflufenacil with 2% AMS v/v (Table 3.4). In 2017-2018, plots with cover crops were terminated using glyphosate on May 10, 2018 and plots without cover crops were terminated using paraquat on May 23, 2018. Plots with spring-applied no residual herbicide were sprayed on May 3, 2018 and did not receive a termination application. Timing of termination was before cover crop heading and when weeds were present, actively growing, and small.

Liberty Link P37T09L soybeans were seeded perpendicular to the cover rows on June 7, 2017 and parallel to the cover crop rows on May 26, 2018, at a rate of 346,000 seeds ha^{-1} in 38 cm wide row spacings, using a Great Plains no-till drill spanning 4.6 m. Each year a POST application of glufosinate with 2% v/v AMS at a volume of 140 L ha^{-1} at 276 kPa was applied using a tractor-mounted sprayer on June 15, 2017 and on July 1, 2018 (Table 3.5). Clethodim was applied in the second year, on June 16, 2018 to control a flush of summer annual grass species (Table 3.5).

Visual weed control was evaluated on a scale of 0 (no effect) to 100% (all plants dead) in the fall at 2, 4, 8, and 16 weeks after establishing fall treatments (WAFT) and in the spring before and after cover crops were terminated for both years. Horseweed height, density, and biomass and cover crop biomass were collected prior to cover crop termination from two random 0.25 m^2 quadrats in every plot in the first year. Horseweed and other weeds density and biomass and cover crop biomass were collected prior to termination from two random 0.25 m^2 quadrats in every plot in the second year. Additionally, cover crop biomass and all weeds biomass were collected on December 12, 2017 in the second year. All biomass samples were oven dried at 70 C for 72 hours and then dry biomass was recorded. Cereal rye height was measured on several key dates during the growing season.

Soybean plant density was determined at V2 (early vegetative) growth stage in each year. Additionally, soybean plants were collected on September 13, 2018 from 0.5 m of 2 rows (0.38-m^2) and leaf area, number of nodes, number of pods, and stem height were measured for each soybean plant. All weeds biomass was also collected. Soybean pods were pulled and placed into separate bags and remaining plant parts were bulk stored. All plant samples were oven dried at 70 C for 72 hours and then dry biomass was recorded.

Soybeans were harvested from each plot on November 1, 2017 in the first year to determine seed yield. Soybeans plants were clipped from 1.14 m^2 quadrats and threshed using a stationary thresher and soybean seed weight was recorded. In year two, soybeans were harvested from each plot on October 23, 2018 to determine seed yield. Soybeans were collected from 6.1 m^2 quadrats and threshed using a stationary thresher and soybean seed weight was recorded.

Data for visual weed control, horseweed density and biomass, other weeds density and biomass, cover crop biomass and height, and soybean health parameters were analyzed using PROC GLM procedure in SAS 9.4 (SAS Institute Inc., Cary, NC) and least significant differences (LSD) at an alpha of 0.05 was used to test for differences among treatments. Each year had different treatments and therefore, the years will be analyzed separately.

Results and Discussion

Weather and fall cover crop establishment

The weather was different between year one and year two from the time of seeding cover crops in the fall to soybean harvest the following year. More specifically, fall weather was compared to spring weather to better understand effects of treatments. Cover crops can accumulate more biomass with warmer fall temperatures. Maximum and minimum yearly temperatures were higher than 30-yr averages in year one, and lower in year two (Table 3.6). From August to July 850 and 552 mm of precipitation was received in year one and two, respectively. Both years received less precipitation than the 30-yr average of 904 mm. Average maximum and minimum temperatures and precipitation were greater in the fall (measured August to October) and spring (measured February to April) of year one, compared to year two (Table 3.6)

One week after seeding cover crops in the fall 15 and 53 mm of precipitation were received in year one and two, respectfully. Overall, the fall in year one was warmer than fall in year two. October maximum and minimum temperatures were 24.0 and 9.7 C, respectively, for year one and 14.4 and 1.6 C, respectively, for year two. From the time of seeding fall cover crops to the last day of December 56 and 140 GDD were accumulated in year one and two, respectively. Warm weather extending longer into fall may increase cover crop biomass in the fall. Between time of fall cover crop seeding to cover crop termination 284 and 276 GDD were accumulated in year one and two, respectively. The number of GDD were similar because cover crop termination timing was when cereal rye and winter triticale were in boot stage.

Weed diversity for both years

The main weed of interest for this study was horseweed and it occurred with an average density of 24 plants m^{-2} in non-treated plots, but other weed species included Palmer amaranth *(Amaranthus palmeri),* henbit *(Lamium amplexicaule),* foxtail species *(Setaria spp.),* volunteer wheat, common chickweed *(Stellaria media),* prickly lettuce *(Lactuca serriola),* and dandelion *(Taraxacum officinale)* (Table 3.2). There were fewer summer annual and more winter annual species in year one compared to year two, and in year one there was a high presence of Palmer amaranth in certain areas of the field.

Fall weed control

Visual weed control was evaluated for both herbicide and cover crops treatments. Year one and two were different and therefore will be reported separately. In year one, weed control was greatest with fall residual treatment at 92% (±1.8) and then fall no residual treatment with 72% (±2.5) observed weed control, measured 8 weeks after fall treatment (WAFT) (Table 3.7). In a similar study it was observed that the emergence of winter annual weed species were reduced when a residual herbicide was added to the tank mixture, such as chlorimuron plus sulfentrazone plus 2,4-D, or chlorimuron plus tribenuron plus 2,4-D, compared to no residual in the mixture, such as glyphosate plus 2,4-D (Monnig and Bradley 2008).

Weed control was greater than 95% with fall residual and fall no residual treatments 16 WAFT, but it is important to note that some plants may have died from continuous freeze and thaw cycles and not from the herbicides (personal observation). Weed control was lowest with fall-seeded cover crops by 8 WAFT (<10%), as cover crops were small (Table 3.7). Earlier cover crop seeding can increase cover crop biomass in the fall. It is recommended to seed cover crops as soon as temperatures are warm, moisture is adequate, and the ground is available.

Weed control was 94% by 8 WAFT with all fall-applied herbicide treatments and treatments with a mixture of cover crop and herbicide. Weed control with winter rye plus tillage controlled weeds the least compared to the other cover crop treatments. Tillage may have increased the germination of weeds by decreasing field residue.

By December 2017, fall rye biomass was 73% greater than fall-seeded spring oat, however, many oat plants froze out by that point (Table 3.8). Winter rye reduced weed biomass by 78% and density by 75%, while the oat cover crop reduced weed biomass by 69% and density by 35%. By this point in the season most oat plants had died from cold temperatures. Lawley et al. (2011) found that rye and forage radish provided complete suppression of winter annual weeds such as horseweed and henbit during the fall cover crop growing season.

Spring cover crop establishment and weed control

Spring triticale and spring oat cover crop stands were poor in the first year because weather conditions became cool and wet after seeding cover crops on March 11, 2017. From the time of seeding to the March 20, 2017 the average maximum and minimum temperatures were 13.7 and 3.2 C, with 100 mm of precipitation occurring (Table 3.6). For maximum competition against weeds it is important to seed cover crops earlier and achieve a high level of plant establishment.

Weeds did not grow as fast in the spring in the second year compared to the first year, therefore, the spring no residual treatment was applied later in the spring of the second year (March 20, 2017 vs May 3, 2018). Weed control during spring was different between years and will be reported separately by year. Weed control evaluation timing was relative to spring treatments but weed control across all treatments was evaluated.

Spring no residual and fall residual weed control levels were greater than 94% and fall no residual and fall triticale were greater than 88% on May 20, 2017 8 weeks after spring treatments (WAST), in year one (Table 3.9). Fall triticale plants were >80 cm tall at this point in the growing season (Table 3.10). Fall-seeded spring oat only controlled weeds by 8% at 8 WAST.

In the second year, by April 2018 weed control evaluated in the fall reduced to 75% with fall residual and 52% with fall no residual herbicides evaluated in the spring (Figure 2.4). Weed control further reduced to 70% with fall residual and 20% with fall no residual by May 10, 2018, the day of cover crop termination. McCall (2018) found that fall herbicides suppressed biomass by 93% and density by 86%, compared to no fall application, but effectiveness of herbicides may depend on field and growing conditions of each year. Weed control was lower in the spring with fall-applied herbicide treatments as compared to the first year because weeds were small and dense and underlying a thick layer of residue, thus resulting in poor coverage and escaped weeds.

Weed control in plots that include cereal rye (23 cm tall) increased from 30% to greater than 90% between the time of seeding cover crops in the fall to April 20, 2018 (Tables 3.9 and 2.9). On April 20, 2018 winter rye was similar in size across treatments that included cereal rye (Table 3.10). Weed control in the same cereal rye plots was >94% and plants were approximately 78 cm tall by May 10, 2018. Other research indicated that cereal rye suppressed weed shoot biomass from 60 to 90% across years compared to a non-treated control in Wisconsin (Ateh and Doll 2018).

Weed control immediately prior to termination

No horseweed plants remained with spring no residual in year one, but that was not the case in year two (Tables 3.11 and 3.12). Horseweed density was not reduced with spring treatments at the time cover crops were terminated, but horseweed biomass was reduced by 74%.

Weed control increased over the next two weeks as the herbicide treatment was still affecting the weeds.

Horseweed density was reduced by 92% and horseweed biomass reduced by 86% with fall residual treatment compared to the non-treated check, which was greater than the fall-applied no residual treatment in year one (Table 3.11). Wilson and Worsham (1988) found that horseweed control was better, no matter the size of plants, when adding residual herbicides to the fall-applied mixture.

Horseweed density was reduced by 83% and horseweed biomass by 30% with fall residual treatment compared to the non-treated check in the second year (Table 3.12). Horseweed density and biomass were greater with fall no residual compared to with residual. Fall no residual reduced horseweed density and biomass by 50 and 65%, respectively, and all other weeds density and biomass were reduced by 47 and 20%, respectively, compared to the non-treated control, in the second year (Table 3.12).

Fall triticale reduced horseweed density and biomass by 78 and 84%, respectively, compared to the non-treated control in the first year. Fall-seeded spring oat reduced horseweed density and biomass by 45 and 31%, respectively, compared to the non-treated control. Other researchers found that winter hardy cover crops can significantly reduce weed biomass. For example, winter wheat reduced Palmer amaranth biomass by 97% (McCall 2018).

Neither spring triticale or spring oat reduced horseweed density and biomass compared to the non-treated control by cover crop termination in the first year (Table 3.11). Establishment of spring cover crops were low due to cool and wet conditions after seeding. However, other researchers demonstrated that when spring-seeded cover crops, like spring oat, get established they significantly reduce Palmer amaranth biomass into early summer (McCall 2018).

Horseweed density was reduced by 80% and horseweed biomass was reduced by 94% with cereal rye treatment in the second year (Table 3.12). All other weeds densities and biomass were reduced more when a herbicide or tillage program was combined with cereal rye compared to cereal rye treatment alone, however, there was no difference in all other weeds biomass between the two treatments. Other researchers in Kansas found that weed density was not reduced much by cover crops, but weed biomass was reduced (Christenson 2015). Fall-seeded spring oat was not able to reduced horseweed density, but biomass was reduced by 45%.

Weed control after terminating plots

Glyphosate was applied to terminate all plots prior to soybean seeding in year one (Table 3.5). In year two, cover crops were terminated two weeks before soybean seeding with glyphosate and one week before soybean seeding non-cover crop plots were terminated with paraquat.

Weed control increased in all plots after termination occurred, but the amount varied by treatment in the first year (Table 3.11 and 3.12). Winter triticale provided the greatest weed control after termination with 95% (±1.9) control observed. Weed control after termination was greater than 89% with fall residual, fall no residual, and spring no residual in year one. Spring-seeded oat and triticale provided the lowest weed control after termination in year one (<31%) (Table 3.11).

Weed control was similar across treatments two weeks after termination in the second year. The greatest weed control was with cereal rye plus a herbicide, providing greater than 97% observed weed control. Rye alone controlled weeds by 94% (±1.3) (Table 3.12). Fall residual provided the greatest weed control among treatments with herbicides only, with 94% (±1.8) observed weed control. Fall-seeded spring oat and fall no residual weed control was similar and the lowest among treatments, with 77% and 84% observed weed control, respectively, in the second year (Table 3.12).

After seeding soybeans

Soybean stands were more variable in the first year than the second year (Table 3.14). Plots with winter triticale had poor soybean stands; there were high levels of triticale biomass and when drilling soybean triticale plants were flattened, creating a thick layer of residue on the soil surface. This was followed by cool and wet conditions that suppressed soybean emergence (Table 3.14). This was less of an issue with cereal rye in the second year, as cereal rye biomass was considerably less compared to winter triticale.

Mid-to-late season soybean and weed assessment in year two

Soybean densities ranged from 24 plants m^{-2} with cereal rye plus fall tillage to 37 plants m^{-2} with winter rye plus fall no residual, but there was no difference in soybean stands among treatments (Table 3.15). Overall, soybean leaf area was greater with fall treatments compared to spring treatments. The greatest number of pods per plant was with fall residual, compared to all other treatments. Cereal rye alone and the non-treated control had the fewest nodes, but there were no differences across the other treatments. Soybean height was lowest in the non-treated. Soybean biomass was lower with spring applied treatments. Overall, soybeans were just as healthy with cereal rye as with herbicide treatments.

Horseweed density and biomass were greatest with fall-seeded spring oat and the fall residual herbicide treatment (Table 3.16). All other treatments had similar levels of weed control. All other weeds biomass was lowest with cereal rye, cereal rye plus fall or spring no residual, and spring no residual treatments. There were in horseweed biomass and density when comparing cover crops to herbicides.

Soybean yield

Soybean yield was greatest with spring no residual treatment with 2,633 kg ha^{-1} (±214) in year one (Table 3.17). Yield was the lowest with winter triticale and spring oat and spring triticale, compared to yields with herbicide treatments. Weed control in the spring was poor with spring cover crops, subsequently effecting yield. Among cover crop treatments fall-seeded spring oat yielded most with 1478 kg ha^{-1}. Winter triticale controlled weeds similar to herbicide treatments up to soybean planting, but yield was low with winter triticale because soybeans were poorly established. There were no differences of soybean yield among all treatments (excluding weed-free and non-treated checks) in the second year.

Conclusions

Winter triticale controlled horseweed and all other weeds from fall to soybean seeding similarly as the herbicide treatments in year one and treatments with cereal rye controlled weeds from fall to soybean seeding in year two. Burndown and cover crop termination applications controlled weeds better among treatments in the second year compared to the first year. There was a high density of winter annual weeds in the second year that competed against each other and were not able to grow as tall as weeds in the first year by time of termination. Fall treatments with residual herbicides were more effective at controlling horseweed and other weeds than without residual herbicides in the mix, but overall, spring residual controlled weeds the best going into soybean seeding, in both years. In Kansas, sometimes horseweed can behave as a summer annual and germinate in the spring. In this case, fall-applied herbicides would need last long in the soil, or an additional application would need to be made in the spring. Based on this research, a producer could wait until spring to make herbicide applications, with effective modes of action, to control winter annual weeds in similar environments. However, if winter annual weeds are big or resistant to the herbicides in the system, herbicide applications may be less effective. Winter hardy cover crops are a good alternative to herbicides for horseweed management, as they provide similar weed control to fall-applied herbicides both with and without residual and to spring applied herbicides, but keep in mind that weed density was not reduced nearly as much as biomass with cover crops in this study, however, weed control will likely be excellent when weeds are small. Burndown/termination would likely need to include glyphosate plus another herbicide with a different site of action, in case of resistance, to kill any small weeds and the grass cover crop. Good soybean establishment and control of weeds after soybean seeding is essential to maintain high soybean yield potential. Soybean establishment in the second year was better in cover crop plots compared to year one because cover crops were terminated at boot stage in year two and at heading in year one. It is important to terminate cover crops before heading because cereals will lay over quickly and create thick residues that can lock in moisture and cooler air in the furrow, making it difficult for soybeans to emerge. With good establishment of winter hardy cover crops in the fall and good soybean establishment in the early summer, winter annuals weeds, such as horseweed, can be controlled in similar levels with winter hardy cereal cover crops as the best herbicide treatments used in this study.

References

Ateh CM, Doll JD (2018) Spring-planted winter rye (*Secale cereale*) as a living mulch to control weeds in soybean (*Glycine max*). Weed Technology. doi.org/10.1017/s0890037x00040070

Christenson A (2015). Cover crops for horseweed [*Conyza canadensis* (L.)] control before and during a soybean crop. Master's thesis. Manhattan, KS: Kansas State University.

Ge, X., André d'Avignon, D., Ackerman, J. J. H., & Douglas Sammons, R. (2010). Rapid vacuolar sequestration: The horseweed glyphosate resistance mechanism. Pest Management Science. https://doi.org/10.1002/ps.1911

Heap IM (2019) International Survey of Herbicide Resistant Weeds [Online] Accessed 5/9/2019

Lawley YE, Weil RR, Teasdale JR (2011) Forage radish cover crop suppresses winter annual weeds in fall and before corn planting. Agronomy Journal. doi.org/10.2134/agronj2010.0187

McCall C (2018) Integrating cover crops and herbicides for horseweed and Palmer amaranth management in no-till soybean. Master's thesis. Manhattan, KS: Kansas State University.

Monnig N, Bradley KW (2008) Influence of fall and early spring herbicide applications on winter and summer annual weed populations in no-till corn. Weed Technology. doi.org/10.1614/wt-06-196.1

Moore MJ, Gillespie TJ, Swanton CJ (1994) Effect of cover crop mulches on weed emergence, weed biomass and soybean (*Glycine max*) development. Weed Technol. 8:512-518.

Reddy KN (2001) Effects of cereal and legume cover crop residues on weeds, yields, and net return in soybean (*Glycine max*). Weed Technol. 15:660-668.

Regehr DL, Bazzaz FA (1979) The population dynamics of *Erigeron canadensis*, a successional winter annual. The Journal of Ecology volume 67: 923–933

VanGessel MJ (2001) Glyphosate-resistant horseweed from Delaware. Weed Science. doi.org/10.1614/0043-1745

Weaver SE (2001) The biology of Canadian weeds. 115. *Conyza canadensis*. Canadian Journal of Plant Science. doi.org/10.4141/P00-196

Wilson JS, Worsham DA (1988) combinations of nonselective herbicides for difficult to control weeds in no-till corn (*Zea mays)*, and soybeans (*Glycine max*). Weed Science.

Table 3.1 Study locations and soil types for each year.

Year	Location Name	Coordinates	Soil Type	Landform	Parent Material	Water Storage Capacity
2016-2017	Manhattan, KS	39.215394° W 96.598889° N	Smolan silt loam	Paleoterraces	Loess	Moderately low to moderately high
2017-2018	Manhattan, KS	39.220357° N 96.580446° W	Kahola silt loam	Flood plains	Alluvium	Moderately high to high

Table 3.2 Initial horseweed density (mean and SE) for both years.

Years	Treatments	Horseweed density
		plants 0.25 m^{-2} (SE)
2016-2017	Fall-seeded spring oat	2.3 (4.3)
	Winter triticale	3.5 (6.7)
	Fall no residual	5.3 (5.4)
	Fall residual	5.5 (10.7)
	Spring oat	10.3 (11.3)
	Spring triticale	10.3 (6.7)
	Spring no residual	6.2 (4.5)
	Non-treated check	11.5 (12.3)
	Weed-free check	7.8 (7.1)
2017-2018	Fall-seeded spring oat	8.2 (2.5)
	Fall rye	12.8 (4.4)
	Fall no residual	7.8 (4.6)
	Fall residual	16.5 (13.6)
	Fall rye + fall no residual	19.5 (8.7)
	Fall rye + fall tillage	6.9 (4.6)
	Fall rye + spring no residual	9.3 (3.7)
	Spring no residual	4.8 (2.1)
	Non-treated check	9.3 (3.5)
	Weed-free check	16.8 (3.5)

Table 3.3 Common name, trade name, and manufacture.

Common Name	Trade Name	Manufacturer
dicamba	Clarity	BASF, Ludwigshafen, Germany
2,4-D	2,4-D LV4	Albaugh, Inc., Ankeny, IA
flumioxazin	Valor	Valent U.S.A. Corporation, Walnut Creek, CA
chlorimuron	Classic	Corteva (Dupont) Indianapolis, IN
glyphosate	Roundup PowerMax	Bayer (Monsanto), Leverkusen, Germany
saflufenacil	Sharpen	BASF, Ludwigshafen, Germany
glufosinate	Liberty	Bayer CS, Leverkusen, Germany
paraquat	Gramaxone SL	Syngenta, Basel, Switzerland
clethodim	Select Max	Valent U.S.A. Corporation, Walnut Creek, CA

Table 3.4 List of establishment season, treatments, herbicides, and rates for each year.

Year	Timing	Treatments	Herbicides	Herbicide rate (g ai/ae ha^{-1})
2016-2017	Fall	Spring oat		
		Winter triticale		
		No residual	dicamba + 2,4-D	71+1135
		Residual	dicamba + flumioxazin + chlorimuron	285+85+29
	Spring	Spring oat		
		Spring triticale		
		No residual	dicamba + 2,4-D	71+1135
2017-2018	Fall	Spring oat		
		Cereal rye		
		Cereal rye + no residual	saflufenacil	98
		Cereal rye + tillage		
		Cereal rye + spring no residual	dicamba + 2,4-D	71+1135
		No residual	dicamba + 2,4-D	71+1135
		Residual	dicamba + flumioxazin + chlorimuron	285+85+29
	Spring	No residual	dicamba + 2,4-D	71+1135

All cover crops were seeded at 112 kg ha^{-1}, except fall-seeded spring oat in 2017-2018, which was seeded at 90 kg ha^{-1}.

Table 3.5 Additional herbicide application made each year.

Year	Applications	Herbicides	Rate	Adjuvants
			g ai/ae ha^{-1}	v/v
2016-2017	cover crop termination	glyphosate + 2,4-D + saflufenacil	1270 + 544 + 25	2% AMS
	maintenance	glufosinate	740	2% AMS
2017-2018	cover crop termination	glyphosate	1125	2% AMS
	cover crop termination	paraquat	1686	
	maintenance	clethodim	281	NIS 0.25% + AMS 2%
	maintenance	glufosinate	740	2% AMS

Table 3.6 Monthly maximum and minimum and 30-yr average temperature (C) and precipitation for each study year for Manhattan, KS.

	Temperature						Precipitation		
	2016-2017		2017-2018		30-yr Average		2016-2017	2017-2018	30-yr Average
Month	Max	Min	Max	Min	Max	Min			
	C						mm		
August	30.4	19.8	29.1	16.8	32.3	18.8	149.6	144.0	104.6
September	28.6	16.5	29.5	15.7	27.7	13.2	156.9	33.0	87.1
October	24.1	9.7	14.4	1.6	20.9	6.2	55.1	3.3	68.3
November	17.4	4.0	14.4	1.6	13.0	-0.7	10.9	3.3	43.9
December	5.6	-6.5	6.9	-5.2	5.8	-6.7	19.1	2.8	27.2
January	6.3	-4.6	5.7	-7.4	4.8	-8.1	34.3	14.2	16.0
February	13.5	-0.7	7.2	-6.7	8.1	-5.9	11.7	14.5	27.4
March	15.2	2.9	14.3	0.7	13.9	-0.9	100.6	15.2	63.2
April	19.5	7.9	16.2	1.6	19.6	5.4	114.8	38.6	80.5
May	24.7	11.6	30.2	15.8	24.8	12.0	80.0	96.0	129.3
June	31.2	17.9	33.1	20.4	30.1	17.2	74.4	65.3	144.8
July	33.7	21.1	33.6	20.1	33.1	20.2	38.9	61.5	112.3
Total precip.							850	552	904

Table 3.7 Weed control (% and SE) observed 2, 4, 8, and 16 weeks after fall treatments (WAFT) for each year. Means followed by the same letter in a column were not different at α=0.05.

Year	Treatments	2 WAFT	4 WAFT	8 WAFT	16 WAFT
		------------------------------% (SE)-----------------------			
2016-2017	Fall-seeded spring oat	0 d	6 (6.3) d	9 (4.8) d	33 (24) c
	Winter triticale	5 (3.5) c	8 (2.5) c	11 (1.3) c	80 (3.3) b
	Fall no residual	16 (2.4) b	51 (1.3) b	71 (2.4) b	96 (0.3) a
	Fall residual	63 (4.3) a	79 (3.1) a	91 (1.3) a	97 (0.5) a
2017-2018	Fall-seeded spring oat	4 (0.9) d	6 (1.3) c	18 (1.4) cd	22 (1.8) c
	Cereal rye	4 (0.8) d	13 (5.9) c	31 (3.4) b	33 (1.4) b
	Fall no residual	65 (3.5) c	82 (2.7) ab	93 (1.2) a	96 (0.8) a
	Fall residual	74 (1.8) b	81 (3.1) b	94 (2.1) a	96 (1.0) a
	Cereal rye + fall no residual	84 (2.2) a	91 (0.6) a	95 (2.5) a	97 (0.7) a
	Cereal rye + fall tillage	9 (2.2) d	11 (4.7) c	24 (3.1) cd	29 (2.4) bc
	Cereal rye + spring no residual	6 (0.9) d	13 (3.9) c	27 (3.1) bc	34 (1.5) b

Table 3.8 Cover crop biomass and weed biomass and density sampled in December of year two. Means followed by the same letter in a column were not different at α=0.05.

Treatment	Cover crop biomass	Weeds biomass	Weeds density
	g m^{-2} (SE)	g m^{-2} (SE)	plants m^{-2} (SE)
Non-treated control	0	17.3 (2.7) c	146 (34) c
Fall-seeded spring oat	12.5 (2.5) b	9.4 (0.9) b	95 (16.1) b
Cereal rye	45.4 (11.2) a	4 (1.3) a	40 (12.2) a

Table 3.9 Weed control (% and SE) at 2, 4 and 8 weeks after spring treatments (WAST) for each year. Means followed by the same letter in a column for each year were not different at α=0.05.

Year	Treatment		2 WAST	4 WAST	8 WAST
2016-2017			------------------------- % (SE)-------------		
	Fall-seeded spring oat		19 (2.5) d	26 (21.4) c	9 (4.8) c
	Winter triticale		64 (5.0) b	81 (3.1) b	88 (1.4) b
	Fall no residual		95 (0.3) a	95 (0.5) a	91 (0.8) ab
	Fall residual		95 (1.8) a	94 (1.2) a	95 (2.9) a
	Spring-seeded spring oat		5 (1.3) e	3 (1.2) d	6 (1.3) c
	Spring-seeded spring triticale		2.5 (1.4) e	5 (0.0) d	5 (0.0) c
	Spring no residual		56 (3.1) c	80 (4.6) b	94 (0.8) a
2017-2018		Before Spring App.	1 WAST	2 WAST	3 WAST
		----------------------------- % (SE) -----------------------------			
	Fall-seeded spring oat	10 (2.0) d	14 (2.4) d	81 (2.4) bc	77 (3.6) b
	Cereal rye	95 (1.0) a	95 (0.3) a	95 (0.3) a	94 (1.3) a
	Fall no residual	53 (6.0) c	33 (3.2) d	30 (2.5) d	38 (8.3) d
	Fall residual	78 (3.2) b	70 (7.4) b	64 (8.0) c	58 (3.2) c
	Cereal rye + fall no residual	94 (0.8) a	95 (0.5) a	96 (1.0) a	95 (0.9) a
	Cereal rye + fall tillage	94 (0.8) a	93 (1.4) a	97 (0.9) a	95 (0.3) a
	Cereal rye + spring no residual	93 (1.2) a	94 (1.3) a	96 (1.2) a	97 (0.8) a
	Spring no residual	0	31 (7.5) c	82 (1.3) bc	86 (2.5) ab

In year one, all treatments were assessed later into the growing season, as spring treatments were established earlier than year two. In year two, 2 and 3 WAST include terminating herbicide for cover crop plots but not for herbicide plots.

Table 3.10 Winter rye height and SE for year two. Means followed by the same letter in a row were not different at α=0.05.

Sampling Dates	Cereal rye	Cereal rye + fall no residual	Cereal rye + fall tillage	Cereal rye + spring no residual
	------------------------------------	----------cm (SE)----------	------------------------------------	
12/12/2017	9.5 (0.6) b	9.2 (0.6) b	10.5 (1.1) a	8.9 (0.5) b
2/18/2018	12.0 (1.1) a	12.5 (0.8) a	11.4 (1.3) a	11.0 (1.2) a
4/20/2018	22.5 (0.3) b	21.0 (1.6) b	24.0 (1) a	23.2 (1.7) a
5/8/2018	78.7 (2.3) a	73.7 (2.1) b	80.0 (3.3) a	79.0 (1.6) a

Table 3.11 Horseweed height, density, and biomass prior to cover crop termination, and weed control by 4 weeks after termination (WAT) in year one. Means followed by the same letter in a column were not different at α=0.05.

	Horseweed			Weed control
Treatments	height	density	biomass	4 WAT
	cm (SE)	plants m^{-2} (SE)	g m^{-2} (SE)	% (SE)
Fall-seeded spring oat	24 (7.0) c	24 (18.2) c	195 (112.6) c	45 (10.8) c
Winter triticale	24 (2.2) c	11 (8.1) b	45 (37.6) b	95 (1.9) a
Fall no residual	8 (7.1) b	20 (40.4) c	130 (120.6) c	89 (2.5) b
Fall residual	8 (6.3) b	4 (8.3) a	40 (38.4) b	91 (2.2) ab
Spring-seeded spring oat	21 (1.7) c	45 (23.1) cd	255 (101.5) d	25 (4.0) d
Spring-seeded spring triticale	28 (5.1) d	64 (21.7) cd	340 (96.6) e	31 (4.7) d
Spring no residual	0 a	0 a	0 a	90 (1.0) b
Non-treated check	27 (1.5) d	49 (19.5) cd	280 (108.2) d	0 e
Weed-free check	12 (4.5) b	4 (4.4) a	36 (19.3) b	98 (1.8) a

Table 3.12 Density and biomass of horseweed and other weeds prior to cover crop termination and efficacy of weed control at 1 and 2 weeks after termination (WAT), in year two. Means followed by the same letter in a column were not different at α=0.05.

	Horseweed		Other weeds		Weed control	
Treatments	density	biomass	density	biomass	1 WAT	2 WAT
	plants m^{-2} (SE)	g m^{-2} (SE)	plants m^{-2} (SE)	g m^{-2} (SE)	----------% (SE)----------	
Fall-seeded spring oat	78 (18.6) d	7.1 (2.9) cd	121 12.3) de	60.8 (9.8) c	81 (2.4) c	77 (3.6) c
Cereal rye	13 (5.3) a	1.1 (0.4) ab	63 (16.5) abc	6.3 (1.5) a	95 (0.3) a	94 (1.3) ab
Fall no residual	31 (10.9) c	5.3 (1.7) bc	70 (13.2) cd	57.8 (14.6) c	88 (0.5) b	84 (1.4) b
Fall residual	11 (4.1) a	10.6 (3.4) d	61 (19.2) abc	34.5 (7.8) b	95 (1.2) ab	94 (1.8) ab
Cereal rye + fall no residual	8 (3.7) a	0.8 (0.4) ab	24 (5.2) abc	8.2 (3.2) a	95 (1.0) ab	97 (0.9) a
Cereal rye + fall tillage	11 (5.3) ab	1.9 (1) ab	19 (2.5) abc	3.9 (0.9) a	95 (0.9) ab	97 (0.5) a
Cereal rye + spring no residual	16 (13.5) ab	0.4 (0.3) ab	14 (5.3) ab	3.2 (0.3) a	98 (1.2) a	97 (1.1) a
Spring no residual	24 (4.9) b	2.6 (1.7) abc	57 (18.2) abc	34.1 (7.7) b	*	89 (9.7) b
Non-treated control	62 (23.9) cd	15.3 (1.6) d	130 (43.7) e	71.6 (10.6) c	0 d	0 d
Weed-free control	2.5 (1) a	1.2 (0.4) a	9 (1) a	3.3 (1) a	99 a	99 (0.6) a

**Spring no residual did not receive a terminating herbicide.

Table 3.13 Cover crop biomass and SE prior to termination for both years. Means followed by the same letter in a column were not different at α=0.05.

Years	Treatments	Biomass
		g m^{-2} (SE)
2016-2017	Fall-seeded spring oat	325 (60) b
	Winter triticale	1210 (109) a
	Spring-seeded spring oat	30 (24) c
	Spring-seeded spring triticale	33 (9) c
2017-2018	Fall-seeded spring oat	31 (4.3) c
	Cereal rye	689 (12.3) a
	Cereal rye + fall no residual	557 (18.8) b
	Cereal rye + fall tillage	676 (15.6) a
	Cereal rye + spring no residual	598 (25.4) b

Table 3.14 Soybean stands 4 weeks after seeding for each year. Means followed by the same letter in a column were not different at α=0.05.

Year	Treatments	Soybean stand
		Plants m^{-2} (SE)
2016-2017	Fall-seeded spring oat	30.5 (2.6) a
	Winter triticale	15.3 (2.1) c
	Fall no residual	29.3 (3.1) a
	Fall residual	27.3 (4.5) a
	Spring-seeded spring oat	24.5 (2.9) b
	Spring-seeded spring triticale	25.5 (3.4) a
	Spring no residual	31.5 (2.3) a
	Non-treated control	28.5 (2.8) a
	Weed-free control	30.8 (2.6) a
2017-2018	Fall-seeded spring oat	33.5 (2.1) a
	Cereal rye	33.1 (1.1) a
	Fall residual	28.8 (1.7) b
	Fall no residual	27.3 (2.1) bc
	Cereal rye + fall no residual	34.3 (1.8) a
	Cereal rye + fall tillage	23.5 (2.2) c
	Cereal rye + spring no residual	34.5 (2.1) a
	Spring no residual	27.3 (1.7) bc
	Non-treated check	30.5 (0.8) b
	Weed-free check	30.1 (2.3) b

Table 3.15 Mid-season soybean health assessment for year two. Means followed by the same letter in a column were not different at α=0.05.

Treatments	Soybean							
	Stand	LA	Pods	Nodes	Height	Stems	Pods	Leaves
	plants m^{-2}	cm^2 $plant^{-1}$	---------No. $plant^{-1}$--------		cm $plant^{-1}$	---------------------g m^{-2}-----------------------		
Fall-seeded spring oat	36 (4) a	1604 (253) a	88 (4) b	17 (0.4) a	155 (25) a	239 (34) a	587 (73) a	135 (38) ab
Winter rye	33 (4) a	1258 (55) b	84 (6) bc	16.5 (0.4) b	162 (27) a	281 (69) a	662 (52) a	154 (59) a
Fall residual	28 (4) bc	1346 (407) b	93 (19) b	17.5 (0.7) a	161 (25) a	214 (62) a	461 (63) b	198 (56) a
Fall no residual	28 (5) bc	1901 (401) a	107 (11) a	17 (0.8) a	162 (29) a	253 (82) a	604 (203) a	143 (38) a
Winter rye + fall no residual	37 (4) a	1666 (228) a	89 (9) b	17 (0.5) a	168 (16) a	213 (25) a	617 (30) a	150 (8) a
Winter rye + fall tillage	24 (2) c	1801 (304) a	94 (5) b	17.5 (0.6) a	167 (30) a	223 (65) a	528 (42) b	131 (53) ab
Winter rye + spring no residual	37 (3) a	1309 (200) b	94 (8) b	17 (0.3) a	164 (24) a	271 (116) a	533 (117) b	148 (76) a
Spring no residual	28 (5) bc	1109 (163) b	94 (8) b	17 (0.7) a	153 (23) a	257 (47) a	570 (68) b	138 (54) ab
Non-treated control	31 (2) b	991 (102) c	95 (9) b	15.5 (0.1) b	136 (22) b	171 (56) b	503 (43) b	113 (48) b
Weed-free control	30 (3) b	1885 (197) a	87 (5) b	17 (0.5) a	168 (19) a	267 (68) a	638 (91) a	150 (53) a

Table 3.16 Mid-to-late season horseweed biomass and density and other weeds biomass for year two. Means followed by the same letter in a column were not different at α=0.05.

Treatments	Horseweed density	Horseweed biomass	Other weeds biomass
	plants m^{-2} (SE)	-------------g m^{-2} (SE)----------	
Fall-seeded spring oat	35 (5.5) c	14 (3.1) c	19 (2.2) c
Cereal rye	8 (2.0) a	5 (6.6) b	5 (2.9) a
Fall residual	23 (12.3) bc	2 (2.0) ab	17 (13.6) c
Fall no residual	4 (3.9) a	1 (0.7) a	18 (17.5) c
Cereal rye + fall no residual	1 (0.7) a	1 (0.7) a	6 (3.5) a
Cereal rye + fall tillage	1 (0.8) a	2 (2.9) a	4 (2.1) a
Cereal rye + spring no residual	1 (0.7) a	1 (0.7) a	12 (10.1) b
Spring no residual	0 a	0 a	7 (4.7) a
Non-treated check	10 (7.4) b	12 (1.5) c	21 (3.9) c
Weed-free check	3 (3.3) a	1 (0.8) a	4 (3.1) a

Table 3.17 Soybean yield and SE for each year. Means followed by the same letter in a column were not different at α=0.05.

Years	Treatments	Yield
		kg ha^{-1} (SE)
2016-2017	Fall-seeded spring oat	1478 (229) c
	Winter triticale	1283 (198) c
	Fall no residual	2229 (180) b
	Fall residual	2548 (166) a
	Spring oat	1427 (153) c
	Spring triticale	1279 (101) c
	Spring no residual	2633 (214) a
	Non-treated control	1238 (96) c
	Weed-free control	2762 (131) a
2017-2018	Fall-seeded spring oat	2913 (184) a
	Cereal rye	3098 (203) a
	Fall no residual	2974 (54) a
	Fall residual	3377 (109) a
	Cereal rye + fall no residual	2948 (230) a
	Cereal rye + fall tillage	2820 (308) a
	Cereal rye + spring no residual	3121 (171) a
	Spring no residual	3033 (183) a
	Non-treated control	2605 (177) b
	Weed-free control	3266 (89) a

Chapter 4 - Application Timing of PPO-inhibitor Herbicides Influences Level of Palmer Amaranth Control

Abstract

Application timing is critical for postemergence PPO-inhibitor herbicides to control Palmer amaranth because of rapid weed growth. The best herbicide option needs to be selected based on weed height and growth stage. A field experiment was conducted in 2016 and repeated in 2017, near Manhattan, KS to evaluate application timing of three PPO-inhibitor herbicides for Palmer amaranth control. Seven application timings were evaluated for each of three herbicides. Herbicides were applied every three days for 18 days, starting when the average height of Palmer amaranth in the field was 2.5 cm. Acifluorfen, fomesafen, and lactofen were applied at 426 g ha^{-1}, 280 g ha^{-1}, and 224 g ha^{-1}, respectively, in 140 L ha^{-1} spray solution in combination with methylated seed oil at 1.2 L ha^{-1} and ammonium sulfate at 2.3 L ha^{-1}. Palmer amaranth height was documented prior to each herbicide application timing. Visual control was evaluated at one and two week intervals after each herbicide application timing. Palmer amaranth control was below an acceptable level (70%) when lactofen was applied six days after initial application, while acifluorfen and fomesafen still provided acceptable control (>95%). All herbicides applied 12 days after the initial application resulted in 65% Palmer amaranth control or less, with Palmer amaranth 30 cm tall and corresponded to a growth rate of 2.5 cm per day. Due to the fast growth rates of Palmer amaranth, PPO-inhibitor herbicides must be applied within 3 days after plants reach 2.5 cm to achieve greater than 90% control of Palmer amaranth.

Introduction

Palmer amaranth is currently ranked by as the most problematic weed in the U.S. (WSSA 2019). Among *Amaranthus* species, Palmer amaranth has the fastest growth rate and the greatest maximum growth compared to waterhemp and redroot pigweed (Horak and Loughin 2000). Palmer amaranth reached 10 cm tall two weeks after seeding and was at least 78% larger than all other five *Amaranthus* species that were studied when not competing with a crop (Sellers et al. 2003).

A single Palmer amaranth plant can be extremely competitive against crops. Densities of 1, 2, 3 and 10 plants m-1 of soybean row reduced yield by 32, 48, 64, and 68%, respectively (Klingaman & Oliver, 1994). One plant can produce between 200,000 to 600,000 seeds if it emerges between March and June (Keeley et al. 1987) and 32 plants 6 m^{-1} of row can produce 1.2 billion seeds ha^{-1} (Burke et al. 2007).

Palmer amaranth can emerge many times during summer months in KS, once the right temperature is reached and soil moisture is adequate. All Palmer amaranth and smooth pigweed seed germinated on the first day at a temperature of 30 C, while seven other *Amaranthus* species required three to eight days to achieve 50% emergence. Germination increased with increased temperatures, with < 8% emergence at 5 C and > 71% at 35 C (Steckel et al. 2006). Palmer amaranth growth rate was greatest at higher temperatures and likely due to its extensive growth and high photosynthetic rates. The largest root volume among three *Amaranthus* species was in Palmer amaranth grown at 35/30 C (Guo and Al-Khatib 2003).

Palmer amaranth populations were identified to be resistant to six herbicide modes of action (MOA) in KS (Heap 2019). These MOA include PSII, HPPD, ALS, EPSPS, PPO and synthetic auxin inhibitors. The specific herbicides are atrazine, mesotrione, tembotrione, topramezone, pyrasulfotole, thifensulfuron-methyl, imazethapyr, glyphosate, and 2,4-D. Additionally, Palmer amaranth has developed resistance to microtubule inhibitors in TN and NC and protoporphyrinogen oxidase (PPO) inhibitors in AR, TN, and IL (Heap 2019).

PPO-inhibitor herbicides applied POST have been very effective at controlling Palmer amaranth, but they do not provide good control when used as “rescue” applications for escaped weeds late in the soybean growing season because weeds are too tall (Johnson and Legleiter, 2013). Grichar (1997) evaluated the control of Palmer amaranth in peanuts and found that acifluorfen at 560 g ha^{-1}, when applied early POST controlled 94% of Palmer amaranth plants and lactofen at a rate of 280 g ha-1 provided 99%. For each herbicide used in this study, the labels sate that if Palmer amaranth plants are taller than approximately 14 cm or have more than six true leaves applications will not be effective (Anonymous 2019). Fomesafen and lactofen must be applied before Palmer amaranth is 8 cm tall to be effective (Prostko 2011; Steckel et al. 2012) and if that window is missed, it is recommended that soybean crops in the southern U.S. be plowed under and replanted because of impending competition (Norsworthy et al. 2012; Steckel et al. 2012).

To effectively control Palmer amaranth with PPO-inhibitor herbicides, applications must be made when weeds are small. However, because of Palmer amaranth’s fast growth rate, it can be difficult to determine when to apply these herbicides. The objective of this study was to determine the impact of time of application of three different PPO-inhibitor herbicides on Palmer amaranth control in a no-crop situation.

Materials and Methods

Field experiments were conducted in 2016 and in 2017 at the Department of Agronomy Ashland Bottoms Research Farm near Manhattan, KS. The experimental design was a split plot with four replications in a no-crop situation. Main plots were seven application timings and subplots were three PPO-inhibitor herbicides. One non-treated control treatment was included. Each herbicide was applied on three-day intervals for 18 days starting when average height of Palmer amaranth was 2.5 cm tall. The first herbicide application was July 10 in 2016 and May 25 in 2017. Acifluorfen, fomesafen, and lactofen were applied separately and at labeled rates for Palmer amaranth control in soybeans (Table 4.1). Rates for acifluorfen were 426 g ha^{-1}, fomesafen at 280 g ha^{-1}, and lactofen at 224 g ha^{-1}. Each herbicide treatment was made in combination with methylated seed oil at 1.2 L ha^{-1} and urea ammonium sulfate at 2.3 L ha^{-1}. All herbicide treatments were applied using a CO2 backpack sprayer with four Turbo Teejet 11002 nozzles (TeeJet Technologies, Wheaton, IL) spaced 48 cm apart and calibrated to deliver 140 L ha^{-1} spray solution at an operating pressure of 276 kPa.

Average height of Palmer amaranth plants in 0.25 m^{-2} per subplot were measured immediately prior to each herbicide application. Palmer amaranth height data were modeled over time and a 3-parameter sigmoid model was fit in SigmaPlot 12.3 (Systat Software, Inc):

$$y = \frac{a}{1+e^{\left(\frac{x-x_O}{b}\right)}} \qquad \text{Equation 4.1}$$

Visual injury of Palmer amaranth was evaluated at one and two weeks after treatment (WAT) on a scale of 0 (no injury) to 100% (all plants died). Visual control ratings were analyzed in SAS using PROC GLM procedure to determine which herbicides worked best and when.

Results and Discussion

The average density of Palmer amaranth in the experiment was 37 plants m^{-2}. The rate of Palmer amaranth growth was approximately 3 cm (± 1.3) per day between July 10 and 28, 2016. It grew from 2.5 to 38 cm tall in that period of 18 days. In the second year, the rate of growth was 3.8 (± 2.9) cm per day between May 25 and June 10. It grew from 2.5 to 72 cm over this period of 18 days (Figure 4.1).

A 3-parameter, sigmoidal model was used to describe parameters of Palmer amaranth growth in height. The maximum estimated height of Palmer amaranth was greater in 2017, and specifically was estimated to be 43 cm (±3) in 2016 and 122 cm (±27) in 2017 (Table 4.2). Growth of Palmer amaranth was faster in 2016 than in 2017; in 2016 the steepness of the curve was 4.5 (±0.6) and 3.8 (±0.6) in 2018. Critical height for control is 10 cm and it took only six days for Palmer amaranth to grow from 2.5 to 10 cm in both years.

Differences in Palmer amaranth percent control were observed in 2016 and 2017. There was no interaction between main effects of application timing and herbicides; therefore, data for each effect will be reported separately for each year.

Across all application timings, herbicides controlled Palmer amaranth differently in 2016, but no differences in percent control were observed in 2017 (Figures 4.2 and 4.3). In 2016, acifluorfen was the best herbicide, providing 83 and 80% control at 1 and 2 WAT, respectively; fomesafen provided 79 and 72% control at 1 and 2 WAT, respectively, while lactofen provided 69 and 62% control at 1 and 2 WAT, respectively. Although herbicide rates were slightly greater, Grichar (1997) evaluated the control of Palmer amaranth in peanuts and found that acifluorfen at 560 g ha^{-1}, when applied early POST controlled 94% of Palmer amaranth plants in 2 of 3 years of the study. Lactofen at a rate of 280 g ha-1 provided better control at 99% compared to acifluorfen in the same 2 of 3 years.

In 2017, each herbicide controlled Palmer amaranth by at least 66 and 59% at 1 and 2 WAT, respectively, across all application timings. The timing of application was more important than the specific PPO-inhibitor herbicide.

There were differences in Palmer amaranth percent control in both 2016 and 2017 among the different application timings. Overall, as the time of application was delayed, percent control of Palmer amaranth control decreased (Figures 4.3 and 4.4). When herbicides were applied by the first two timings (0 and 3 days), Palmer amaranth control was at least 95% in 2016 and near 100% in 2017; 12 days later Palmer amaranth control was reduced to 40 and 30%, in 2016 and 2017, respectively.

In 2017, applications made three days later (18 days) resulted in only 15% control of Palmer amaranth. Bell et al. (2015) found that Palmer amaranth control with glufosinate at 595 g ha^{-1} plus S-metolachlor at 1,217 g ha^{-1} plus fomesafen at 266 g ha^{-1} applied 21 days after planting (DAP) followed by glufosinate at 738 g ha^{-1} plus acetochlor at 1,260 g ha^{-1} applied 42 DAP, was 26, 50, and 18% in 19, 45, and 90 cm soybean row spacings, respectively. Control was low because Palmer amaranth was at least 10 cm tall at the time of application.

Once Palmer amaranth plants are noticed in the field, they are likely already 2.5 cm tall and these results suggest that applications must be made within 6 days from observing 2.5 cm tall Palmer amaranth plants or by the time plants are 8 cm tall to achieve greater than 95% control. Given Palmer amaranth's competitiveness, even 95% control may not be good enough in the long-term. Massinga et al. (2001) reported that 0.5 Palmer amaranth plants m^{-1} row can decrease corn yield by 11%. Bensch et al. (2003) found that 8 Palmer amaranth plants m^{-1} row can reduced soybean yield by 78.7, 56.2, and 38.0% for Palmer amaranth, common waterhemp, and redroot pigweed, respectively. Furthermore, one female Palmer amaranth plant can produce 200,000 to 600,000 seeds (Keeley et al. 1987).

Growers need to control all plants in their fields to ensure greater yields and decrease the chance of developing herbicide resistant biotypes. In a field study, less than two years after introducing 20,000 glyphosate resistant seeds into a 1 m^{-2} area, seeds were found in 1,000 m^{-2} (Norsworthy et al. 2014).

For each PPO-inhibitor herbicide studied, the label indicated that applications are not permitted when Palmer amaranth plants no taller than 7.5 cm or have more than six true leaves (Anonymous 2019). This research coincides with what is already mentioned in each herbicide label, however, keeping in mind that 10 cm tall plants is the absolute maximum height that one should apply PPO-inhibitor herbicides to effectively control Palmer amaranth; and to achieve this it must be done within six days after Palmer amaranth has reached 2.5 cm tall.

References

Anonymous (2019) Cobra® product label. Valent. Walnut Creek, CA

Anonymous (2019) Ultra Blazer® herbicide product label. No. 70506-60 UPI. King of Prussia, PA

Anonymous (2019) Flexstar® herbicide product label. Syngenta. Basel, Switzerland

Bell HD, Norsworthy JK, Scott RC, Popp M (2015). Effect of row spacing, seeding rate, and herbicide program in glufosinate-resistant soybean on Palmer amaranth management. Weed Technology. https://doi.org/10.1614/WT-D-14-00156.1

Bensch, CN, Horak, MJ, Peterson D (2003). Interference of redroot pigweed (*Amaranthus retroflexus*), palmer amaranth (*A. palmeri*), and common waterhemp (*A. rudis*) in soybean. Weed Science. https://doi.org/10.1614/0043-1745(2003)

Burke IC, Schroeder M, Thomas WE, Wilcut JW (2007) Palmer amaranth interference and seed production in peanut. Weed Technology. https://doi.org/10.1614/WT-06-058.1

Grichar WJ (1997). Influence of herbicides and timing of application on broadleaf weed control in peanut (*Arachis hypogaea*). Weed Technology. Volume 15 pages 26-29.

Guo P, Al-Khatib K (2003). Temperature effects on germination and growth of redroot pigweed (*Amaranthus retroflexus*), Palmer amaranth (*A. palmeri*), and common waterhemp (*A. rudis*). Weed Science. https://doi.org/10.1614/P2002-127

Heap IM (2018). International survey of herbicide resistant weeds [Online]. Assessed 5/9/2019

Horak MJ, Loughin TM (2000). Growth analysis of four *Amaranthus* species. Weed Science. https://doi.org/10.2307/4046301

Johnson and Legleiter (2013) Palmer amaranth biology, identification, and management. [Online]. Assessed 5/9/2019

Keeley PE, Carter CH, Thullen RJ (1987). Influence of planting date on growth of Palmer amaranth (*Amaranthus palmeri*). Weed Science. https://doi.org/10.2307/4044391

Klingaman T, Oliver LR (1994) Palmer Amaranth (*Amaranthus palmeri*) interference in Soybeans (*Glycine max*). Weed Science. https://doi.org/10.2307/4045448

Massinga RA, Currie RS, Horak MJ and Boyer J (2001) Interference of Palmer amaranth in corn. Weed Science. https://doi.org/10.1614/0043-1745(2001)

Norsworthy JK, KL Smith RC, Scott LE, Steckel JA, Bond TW, Eubank, D. Stephenson (2012) Midsouth weed management survey with emphasis on Palmer amaranth. Page 1544 in Proceedings of the 2012 Beltwide Cotton Conference. Cordova, TN: National Cotton Council of America

Norsworthy JK, Griffith G, Griffin T, Bagavathiannan M, Gbur EE (2014). In-field movement of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) and its impact on cotton lint yield: evidence supporting a zero-threshold strategy. Weed Science. https://doi.org/10.1614/WS-D-13-00145.1

Prostko EP (2011). Developing a herbicide resistant weed management plan. Page 1538 in Proceedings of the 2011 Beltwide Cotton Conference. Cordova, TN: National Cotton Council of America.

Sellers, BA, Smeda RJ, Johnson WG, Ellersieck MR (2003) Comparative growth of six *Amaranthus* species in Missouri. Weed Science. https://doi.org/10.2307/4046666

Steckel LE, Sprague CL, Stoller EW, Wax LM (2006) Temperature effects on germination of nine *Amaranthus* species. Weed Science. https://doi.org/10.1614/ws-03-012r

Steckel LE, TW Eubank, J Weirich, B Scott, and R Montgomery (2012) Glyphosate-resistant Palmer amaranth control in dicamba tolerant soybean system in the midsouth. Page 65 in

2012 Proceedings of the Southern Weed Science Society. Las Cruces, NM: Southern Weed Science.

Table 4.1 Herbicide common name, trade name, application rate, product concentration, and manufacturer for the herbicides used in this study.

Herbicide	Trade name	Rate (g ai ha^{-1})	Manufacturer	Location
acifluorfen	Ultra Blazer ®	426	United Phosphorus.	King of Prussia, PA
fomesafen	Flexstar ®	280	Syngenta	Basel, Switzerland
lactofen	Cobra ®	224	Valent	Walnut Creek, CA

Table 4.2 Parameter estimates describing Palmer amaranth growth over time in 2016 and 2017, using Equation 4.1.

Year	Parameter Estimates			R^2
	a (SE)	b (SE)	x_0 (SE)	
	cm		days	
2016	43 (3)	4.5 (0.5)	10 (0.8)	0.92
2017	122 (27)	3.8 (0.6)	16 (1.8)	0.90

Figure 4.1 Height of Palmer amaranth measured every three days, prior to each herbicide application, starting on day 0, for 2016 and 2017.

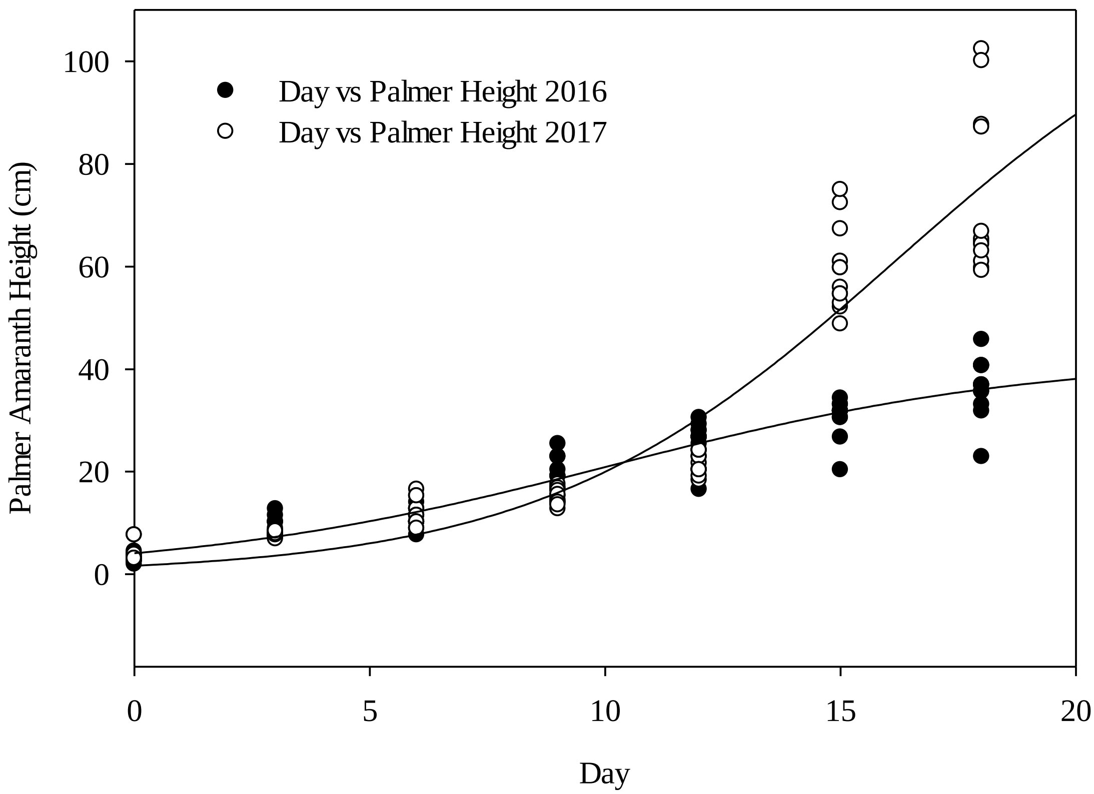


Figure 4.2 Palmer amaranth control with three PPO herbicides, averaged across application timings in 2016.

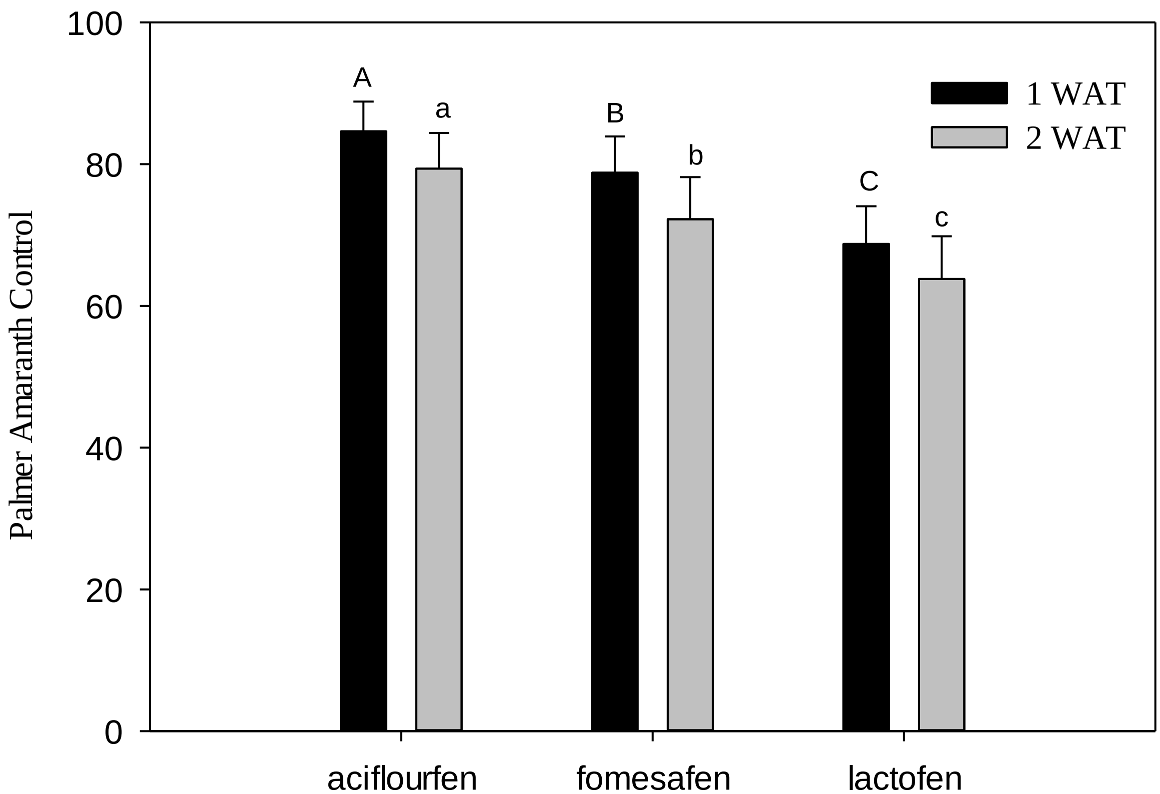


Figure 4.3 Palmer amaranth control with three PPO herbicides, averaged across application timings in 2017.

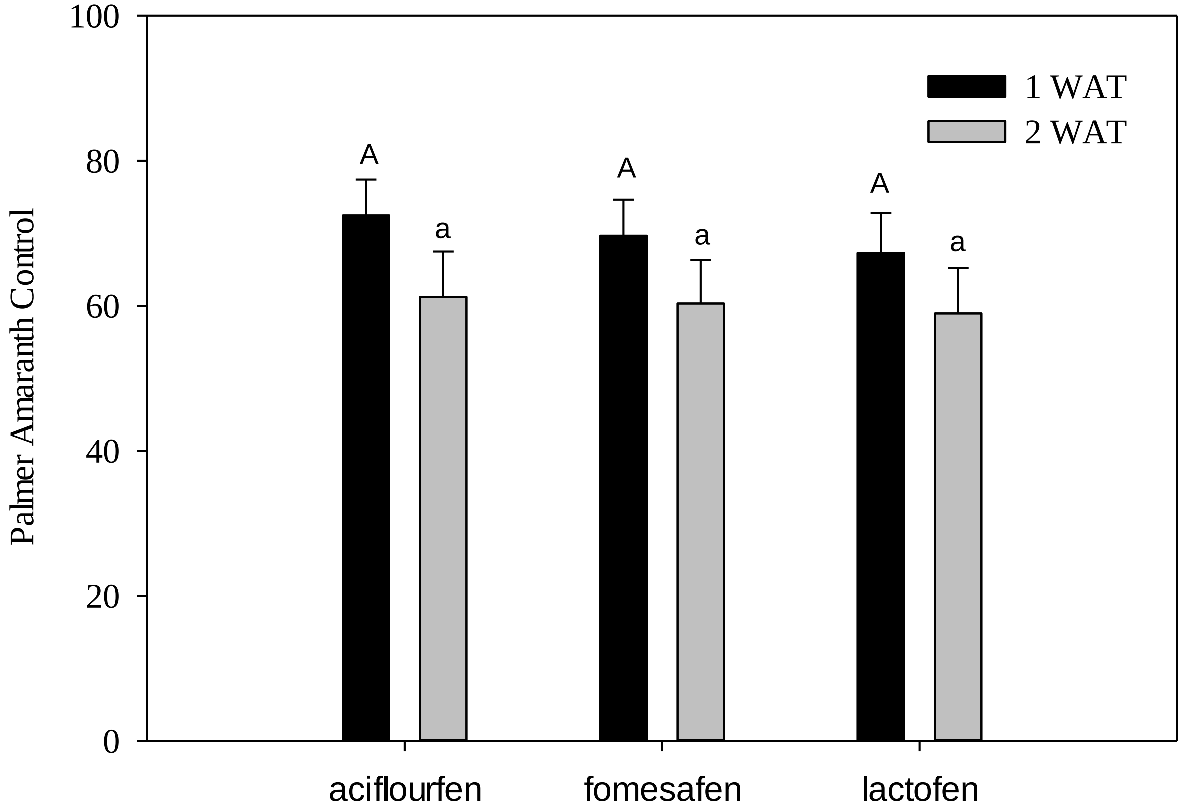


Figure 4.4 Palmer amaranth control within an application timing, averaged across herbicides in 2016.

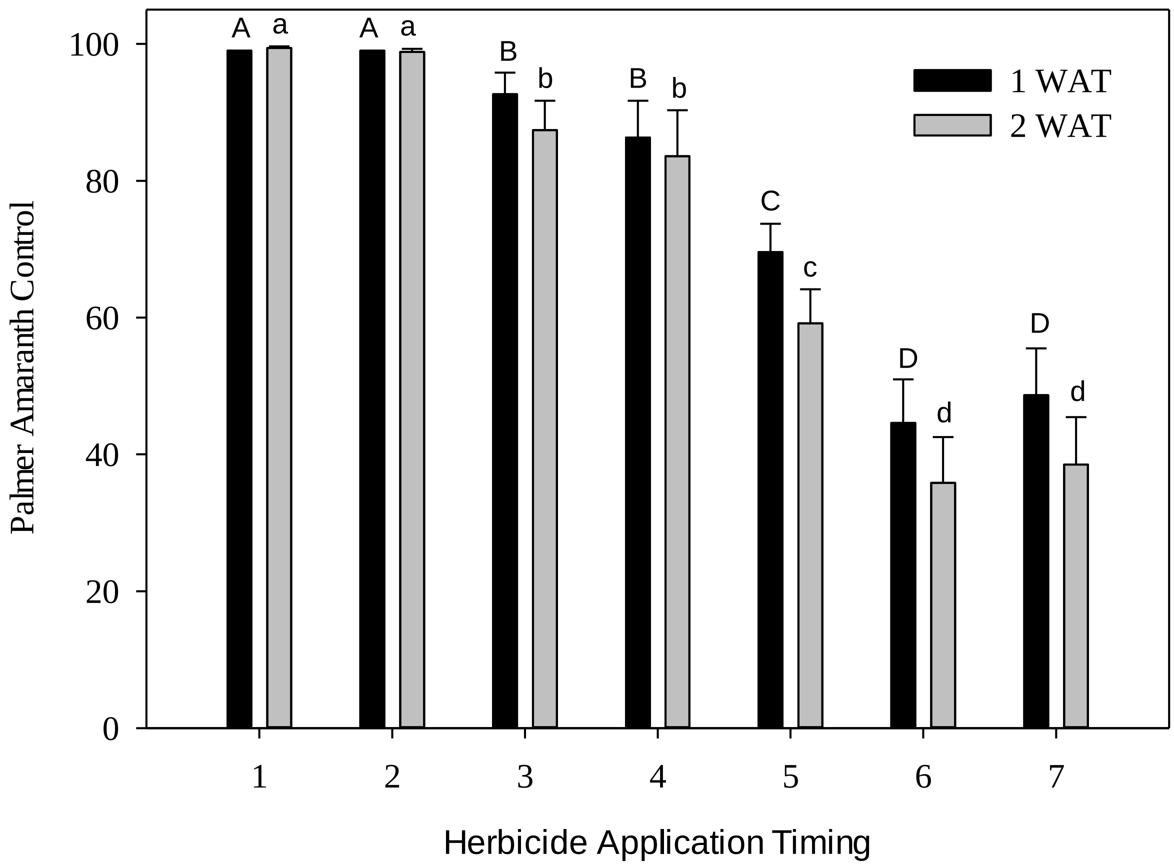


Figure 4.5 Palmer amaranth control within an application timing, averaged across herbicides in 2017.