12-2021

Integrated Weed Management Strategies for Palmer Amaranth (Amaranthus palmeri) in Cotton and Soybean Production Systems

Rodger Bruce Farr
University of Arkansas, Fayetteville

Citation

Farr, R. B. (2021). Integrated Weed Management Strategies for Palmer Amaranth (Amaranthus palmeri) in Cotton and Soybean Production Systems. *Graduate Theses and Dissertations* Retrieved from https://scholarworks.uark.edu/etd/4260

Integrated Weed Management Strategies for Palmer Amaranth (*Amaranthus palmeri*) in Cotton and Soybean Production Systems

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Crop, Soil, and Environmental Sciences

by

Rodger Bruce Farr
University of Nebraska-Lincoln
Bachelor of Science in Agronomy, 2019

December 2021
University of Arkansas

This thesis is approved for recommendation to the Graduate Council

Jason Norsworthy, Ph.D.
Thesis Director

Tom Barber, Ph.D.
Committee Member

Thomas Butts, Ph.D.
Committee Member

Ed Gbur, Ph.D.
Committee Member

Trent Roberts, Ph.D.
Committee Member

Abstract

Management of Palmer amaranth [*Amaranthus palmeri* (S.) Wats.] in the Midsouth in soybean [*Glycine max* (L.)] and cotton (*Gossypium hirsutum* L.) production systems has become increasingly troublesome due to resistance to many of the commonly utilized herbicides in these systems. Developments have been made to utilize new chemistries as well as incorporate integrated weed management strategies to control Palmer amaranth, but questions have risen given the economic feasibility or effectiveness of these new strategies. Additionally, regulation has limited producers' abilities to utilize some herbicide chemistries. As a result, experiments were conducted to 1) understand the utility of isoxaflutole in isoxaflutole-tolerant cotton systems, 2) investigate the potential for roller wiper-based applications of dicamba in dicamba-tolerant soybean systems, and 3) optimize the use of various integrated weed management practices for dicamba-tolerant cotton production systems. The addition of isoxaflutole to cotton weed management programs garnered comparable Palmer amaranth control with minimal crop injury and no yield reductions while adding an additional site of action for weed control previously not utilized in cotton. Roller wiper applications of dicamba were generally not as efficacious for Palmer amaranth control compared to broadcast applications, limiting their potential as a substitution for over-the-top applications of dicamba. The use of integrated weed management practices showed great potential for weed population reductions, primarily with the use of one-time deep tillage and dicamba-based herbicide programs. Economically, the use of hand-weeding as part of a zero-tolerance strategy for weed management was inhibitive as the cost appeared to outweigh the benefits provided in the short term, not including the price of herbicide resistance evolving. However, weed populations were numerically reduced when hand-weed was utilized. Findings for this research will better enable producers to make informed

management decisions when looking to adopt new technologies and strategies in their production systems aimed at combating Palmer amaranth among other weeds.

Acknowledgements

I am thankful to have had so many individuals in my life who have invested in my success and growth as an individual personally and academically. First, I have to thank my dad and my brothers for my upbringing and instilling lessons of hard work, critical thinking, and perseverance. Secondly, I want to thank my mentors and advisors John Scharf, Dr. Donald Lee, Dr. Greg Kruger, Dr. Carl Coburn, Eric Gustafson, and Brad Farr for starting and leading me down a path of success in the fields of agronomy and weed science. I want to thank the Universities of Nebraska and Arkansas for providing me with all of the educations in and out of the classroom over the past six years. Thank you to Dr. Jason Norsworthy for seeing the potential in a farm boy from “Nowhere Nebraska” and taking me on to experience an entirely different world with Arkansas agriculture and weed science. The lessons that I learned while at the University of Arkansas will benefit me throughout the rest of my career as an agronomist, producer, and advisor to others aspiring to better themselves and their agricultural knowledge. I would be remiss if I didn’t thank my wife Pam for all her patience and support throughout my educational career. Finally, I want to thank God and all His blessings throughout my whole life, for which I am eternally grateful.

Table of Contents

Chapter 1

Introduction and Review of Literature

Cotton (*Gossypium hirsutum* L.) and soybean [*Glycine max* (L.) Merr.] have been historically important crops to the Midsouth. Cotton has been grown in the South since the early to mid-1600s where cotton dominated the Southern economy as the primary cash crop until the 1920s (Smith and Cothren 1992). Currently, the United States ranks 3rd in global cotton production following China and India (NCCA 2013). In 2018, national cotton production was estimated to be 18.4 million bales grown over 4.3 million hectares (USDA-NASS 2019). In Arkansas, 195,000 hectares of cotton were grown in 2018, an increase of 6900 hectares from 2017. Overall, the state of Arkansas ranks 6th nationally in total cotton production area and 4th in total production with an average yield of 5.9 bales ha^{-1} compared to the national average of 4.3 bales ha^{-1} (USDA-NASS 2019).

Soybean also serves an important role in the agricultural economy of the United States and Arkansas. Nationally, soybean is produced on 39.3 million hectares with an average yield of 3453 kg ha^{-1}. Arkansas ranks 11th nationally in total soybean production with 3.95 billion kg produced in 2018. The state of Arkansas grew soybean on 1.3 million hectares in 2018 (USDA-NASS 2019). Soybean production in the United States began in the late 1700s when the crop was brought over from China to North America for use as a forage crop (Hymowitz and Newell 1981). Soybean continued to be used primarily as a forage crop until the 1940s when soybean production for grain surpassed soybean forage production for the first time (Hymowitz 1970). The bulk of all soybean production is concentrated in the upper Midwest with Iowa and Illinois producing one-quarter of all of the soybean produced in the United States (USDA-NASS 2019).

Over the past several decades, the production of both cotton and soybean have changed in terms of weed management. The key driver of this change has been that producers have had to adapt their practices to control herbicide-resistant weeds. With the introduction of genetically engineered (GE) herbicide-resistant crops in the mid-1990s, cotton and soybean producers have been able to utilize new in-crop herbicides in order to manage weeds that had previously become resistant to various herbicides. Over time, weeds such as Palmer amaranth [*Amaranthus palmeri* (S.) Wats.] became resistant to the herbicides that cotton and soybean had been genetically engineered to be resistant to. In response to this, the agricultural community has looked to institute an integrated pest management approach to control herbicide-resistant weeds. This has included reintroducing various forms of cultivation, cover crops, multiple herbicide applications, new herbicide tolerance traits in both cotton and soybean, and strict weed tolerance thresholds.

Herbicide-Resistant Cotton

Cotton has been historically less competitive compared to other crops such as soybean and corn (*Zea mays* L.), which leaves cotton more susceptible to yield loss as a result of weed interference (Zimdahl 1980). Cotton requires more time to reach full canopy, thus allowing more time for weeds to emerge during the season. With weeds such as Palmer amaranth, capable of emerging throughout the growing season, multiple herbicide applications are required to keep weed populations under control. An effective cotton herbicide program typically requires preplant burndown, preemergence residual, postemergence broadcast, and postemergence directed applications of herbicides to maintain weed populations. With the introduction of GE glyphosate-resistant cotton in 1997, cotton herbicide programs became simplified because glyphosate was able to control a broad spectrum of weeds (Givens et al. 2009; Kniss 2018; Sosnoskie and Culpepper 2014). The evolution of glyphosate-resistant weeds such as Palmer amaranth (Culpepper et al. 2006) led to the development of varieties of GE cotton that were resistant to herbicides other than glyphosate such as glufosinate and dicamba (Brinker et al. 2014).

XtendFlex Cotton

XtendFlex is a type of cotton that has been genetically engineered to be stacked with three separate herbicide-resistance traits, resistance to glyphosate, dicamba, and glufosinate. The glyphosate-tolerance (GT) trait was made commercially available in cotton beginning in 1997 when GT cotton was developed by the insertion of a gene from *Agrobacterium* that encodes for a gene that allows for the production of an herbicide insensitive 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS) that confers resistance to the herbicide glyphosate (Shah et al. 1990). The glufosinate-resistance trait that has been inserted into cotton encodes for a gene that prevents the inhibition of glutamine synthase by glutamine synthase inhibitors such as glufosinate by coding for an enzyme that allows for the cotton plant to metabolize glutamine synthase inhibitors (Brinker et al. 2014). Dicamba-resistant cotton was first commercially available as BollGard II XtendFlex cotton in 2015 (Norsworthy, personal communication). Dicamba resistance in cotton is conferred through the insertion of a gene isolated from *Stenotrophomonas maltophilia* that encodes for dicamba monooxygenase (Brinker et al. 2014). This enzyme allows for the cotton plant to effectively degrade dicamba molecules and metabolize the molecule through the use of dicamba monooxygenase, rendering the molecule ineffective (Clemente et al. 2007).

Isoxaflutole-Tolerant Cotton

Isoxaflutole (IFT) is a Group 27, 4-hydroxyphenylpyruvate dioxygenase (HPPD) inhibiting herbicide that has traditionally been used in crops such as corn for broadleaf and grass weed control (Pallett et al. 1998). Isoxaflutole has been shown to be effective as a tank-mixture partner with photosystem II inhibiting herbicides such as atrazine for glyphosate-resistant Palmer amaranth control, especially when used in a glufosinate-based herbicide system (Jhala et al. 2014; Stephenson and Bond 2012). Currently, while there are other pigment inhibitors such as fluridone (WSSA Group 12), there are no HPPD-inhibiting herbicides that are labeled in cotton production in the Midsouth (Barber et al. 2021). BASF is currently developing cotton that is tolerant to IFT, with the intention of labeling IFT for cotton production as a preemergence (PRE) or early postemergence (EPOST) option in cotton in order to add another effective site of action in cotton production acres.

Palmer amaranth

Palmer amaranth is an invasive weed species that is native to the Southwestern United States and Northwestern Mexico. Known for its adaptive growth pattern, Palmer amaranth can reach heights of over 2 m while simultaneously producing many lateral branches. The leaves of Palmer amaranth are lanceolate in shape and are suspended by characteristically long petioles (Sauer 1957). The plant exhibits a warm-season, annual growth pattern and is one of ten dioecious *Amaranthus* species globally (Steckel 2007).

The spread of Palmer amaranth out of the American Southwest began in the early 1900s. In 1915, Palmer amaranth was discovered in Virginia followed by its discovery in Oklahoma in 1926 and then South Carolina in 1957 (Culpepper et al. 2010). Since then, Palmer amaranth has spread throughout the Southeastern United States and into Midwestern states, posing as a significant threat to producers in field crop situations.

As of 2016, Palmer amaranth was listed as the number one most troublesome weed in all broadleaf crops in the United States and Canada. In Arkansas, Palmer amaranth was ranked as the most troublesome and common weed in both cotton and soybean (Van Wychen 2019). One reason this weed has become so troublesome is its ability to quickly spread into a new area with its small seed size and large seed production volume. Female Palmer amaranth can produce upwards of 600,000 seeds per single, mature plant (Keeley et al. 1987) and the small (1 to 2 mm) seeds (Sauer 1957) can be easily dispersed by wind, irrigation, floodwaters, compost, manure, transport of farm equipment, plowing, and crop residues (Costea et al. 2004; Norsworthy et al. 2009). As a dioecious plant, Palmer amaranth tends to cross with other Palmer amaranth plants as an obligate outcrosser (Franssen et al. 2001). As an obligate outcrosser, Palmer amaranth has a high genetic diversity within a given population. Coupling this characteristic with the high volume of seed production by each female plant, Palmer amaranth can produce a large number of offspring with relatively high genetic variability that can spread throughout a field in a relatively short time (Keeley et al. 1987; Norsworthy et al. 2014). These diverse individuals can result in new genetic combinations that may result in individuals that are resistant to herbicide modes-of-action to which they were previously susceptible to.

Another factor contributing to the invasiveness of Palmer amaranth lies within the ability of the plant to aggressively compete with other crops within a cropping system. Palmer amaranth has the ability to emerge throughout much of the growing season for soybean and cotton and can rapidly accumulate biomass during this time. This allows Palmer amaranth to compete directly with crops such as soybean and cotton and interfere with the yield and productivity of these crops (Jha and Norsworthy 2009).

Seedbank Biology

In order to effectively determine the impact of weed management programs, especially in long term, it is important to investigate how the seedbank of a particular weed changes over time (Norsworthy et al. 2018). This is especially important for weeds that have a high fecundity such as Palmer amaranth. One of the keys to creating an effective weed management program for Palmer amaranth is understanding how Palmer amaranth seeds behave in the seedbank and how different factors influence the emergence of Palmer amaranth.

Palmer amaranth seeds can germinate in as little as one day once the soil presents seeds with favorable conditions, much more rapidly than other *Amaranthus* species (Steckel et al. 2004). As a small-seeded weed, Palmer amaranth requires shallow seed placement in order to germinate successfully. At depths of less than 1.3 cm, successful germination and establishment of Palmer amaranth seedlings is around 40%, while at depths greater than 5.1 cm, the establishment is reduced to 7% (Keeley et al. 1987). In seed burial studies, Palmer amaranth that had been buried to a depth of 10 cm had lost more than 50% of its viability after a year, and after three years the viability of the Palmer amaranth seed had been reduced to less than 15% compared to initial seed viability. Meanwhile, at great burial depths of 40 cm, the seed viability was reduced to only 22% after three years (Sosnoskie et al. 2013). In a study investigating changes in Palmer amaranth viability over time, buried Palmer amaranth seed viability was reduced by 80% over three years compared to properly stored seeds which retained 92% viability after the same duration of time (Korres et al. 2018). The reduction in successful germination as a result of seed depth may be in part due to the lack of natural light that penetrates through the soil as well as a decrease in fluctuations of temperature deeper in the soil profile (Jha et al. 2010). Another important parameter for successful Palmer amaranth emergence and establishment is temperature. In terms of growing degree days, the base temperature for Palmer amaranth has been determined to be 16.6 C (Steinmaus et al. 2000). There is a positive correlation between Palmer amaranth emergence and temperature until temperatures exceed 35 C and emergence begins to decline (Steckel et al. 2004).

Economic Impact

Palmer amaranth is the most economically detrimental weed in the United States. This is a result of the disruptive and competitive nature of Palmer amaranth. A study investigating how Palmer amaranth infestations affect cotton yield concluded that Palmer amaranth at a density of 1.1 plants m^{-2} can reduce cotton yield by as much as 59% compared to a weed free check (Morgan et al. 2001). Another study in cotton determined that cotton lint production decreased linearly as the Palmer amaranth population increased at rates between 5.9 and 11 plants m row^{-1}. (Rowland et al. 1999). Infestations of Palmer amaranth are not only detrimental to cotton yield. Palmer amaranth may also reduce the harvest efficiency and increase downtime during cotton harvest. One study concluded that infestations of Palmer amaranth at a density of 3260 weeds ha^{-1} significantly decreased harvest efficiency from 92.3% down to 89.9% and increased the time to harvest a hectare by 200 minutes (Smith et al. 2000). Even though soybean is more aggressive than cotton in terms of growth, Palmer amaranth also reduces soybean yield. Studies in Arkansas have shown that soybean yield can be reduced by 68% from a density of 10 Palmer amaranth m row^{-1} when compared to a weed free check (Klingaman and Oliver 1994). In Kansas, Palmer amaranth densities of eight plants m row^{-1} reduced soybean yield by 79% compared to a weed free check (Bensch et al. 2003).

The cost of Palmer amaranth has not been constrained to harvest losses. The spread of Palmer amaranth has affected the way producers have had to manage their crops in terms of cultural practices. To lessen the spread of seed, producers, ag product distributors, and ag product processors have had to take extra precautions by thoroughly cleaning their equipment to prevent spreading seed from one area to the other. With the rise of herbicide-resistant crops, producers were able to switch to conservation tillage practices. Without frequent cultivation, producers have had to adapt their herbicide programs for the wide emergence window and the evolving herbicide resistance of Palmer amaranth. Many have looked to going back to occasional deep tillage with moldboard plows to try to bury the seed (DeVore et al. 2012; DeVore et al. 2013), but doing so would require the purchase of tillage equipment that many producers no longer have.

Herbicide Resistance

The invasive nature of Palmer amaranth has hinged on its extraordinarily high plasticity in relation to competing with crops for resources, as well as the wide genetic diversity of Palmer amaranth. Given the tendency for Palmer amaranth to outcross with other individuals within a population, each Palmer amaranth within a population has the opportunity to cross with essentially any other individual that is within a distance that pollen can travel. It has been reported that viable Palmer amaranth grains can travel up to 300 meters to pollinate another individual (Sosnoskie et al. 2007). Based on the potential for individual plants to be exposed to a diverse array of genotypes from a diverse population, the potential for herbicide resistance development by Palmer amaranth is high.

One of the primary components of the development of herbicide resistance in a population is selection pressure, whereby a plant population shift primarily exhibits only the herbicide resistance phenotype (Beckie and Reboud 2009). The use of herbicides such as glyphosate, dicamba, and glufosinate has increased since the adoption of crops that are tolerant to these herbicides (Kniss 2018; USDA-NASS 2017). As a result of increased glyphosate use, herbicide site-of-action (SOA) diversity decreased. Soybean SOA diversity decreased from nearly 8 different SOAs applied per unit of area in 1994 to nearly 2 in 2006 with glyphosate accounting for nearly 76% of all herbicide used on soybean that year. For cotton, the herbicide diversity decreased from 7.6 in 1999 to 5 in 2006, with glyphosate accounting for 54% of all herbicide used in cotton (Kniss 2018).

The ability of Palmer amaranth to evolve herbicide resistance in a rapid manner is one of the reasons that it has become the most troublesome weed in the United States (Van Wychen 2019). Currently, Palmer amaranth populations have been documented to be resistant to eight different herbicide SOAs. These nine different herbicide groups are microtubule inhibitors, photosystem II inhibitors, acetolactate synthase (ALS) inhibitors, 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS) inhibitors, very-long-chain fatty acid (VLCFA) inhibitors, protoporphyrinogen oxidase (PPO) inhibitors, synthetic auxins, glutamine synthetase inhibitors, and HPPD inhibitors. In Arkansas alone, Palmer amaranth has become resistant to eight different SOAs (ALS, EPSPS, HPPD, microtubule assembly inhibitors, VLCFA, synthetic auxins, glutamine synthetase inhibitors, and PPO), and cross-resistant populations to several different SOAs have also been reported (Heap 202). Resistance to glutamine synthetase and synthetic auxins by Palmer amaranth were only recently confirmed in Arkansas and Tennessee, with the mechanisms of resistance not confirmed at this time (Heap 2021)

Acetolactate Synthase Inhibitor (WSSA Group 2)-Resistant Palmer Amaranth

Acetolactate synthase-inhibiting herbicides (ALS inhibitors) are a group of amino acid synthesis inhibiting herbicides that inhibit the production of valine, leucine, and isoleucine, three different branched amino acids that are essential for plant growth, by inhibiting the production of the acetolactate synthase enzyme (Saari et al. 1994; Shaner et al. 1984). These amino acids are essential for photosynthate translocation to meristems, which in turn leads to cessation of cell division and plant death. Resistance to ALS-inhibiting herbicides is typically the result of a base change in the gene that encodes for the ALS enzyme. This base change alters the shape of the ALS enzyme, creating an enzyme that is less sensitive to the binding of an ALS-inhibiting herbicide. This resistance is caused by a single mutation in an allele and is passed on as a dominant trait (Tranel and Wright 2002) and is typically how Palmer amaranth develops resistance to ALS inhibitor herbicides (Burgos et al. 2001; Franssen et al. 2001; Sprague et al. 1997). One alternative mechanism of resistance to ALS-inhibiting herbicides in Palmer amaranth is that the herbicide is metabolized through metabolic degradation within the plant (Burgos et al. 2001).

Microtubule Inhibitor (WSSA Group 3)- Resistant Palmer Amaranth

Microtubule inhibitor herbicides are a seedling root growth-inhibiting herbicide that work by binding to the tubule enzyme and inhibiting the separation of chromosomes during mitosis (WSSA 2019). Resistance to dinitroaniline herbicides was reported in South Carolina in 1989 and was one of the first cases of herbicide resistance by Palmer amaranth (Gossett et al. 1992). Populations, in this case, were found to be cross-resistant to several microtubule inhibiting herbicides such as pendimethalin, trifluralin, benefin, isopropalin, and ethalfluralin.

Dinitroaniline resistance was confirmed in Arkansas Palmer amaranth populations in 2017 (Schwartz-Lazaro et al. 2017a).

Photosystem II Inhibitor (WSSA Group 5)-Resistant Palmer Amaranth

Photosystem II inhibitors affect weeds by inhibiting the transport of electrons from Q_a to Q_b prior to Photosystem II in the thylakoid membrane in the chloroplast of plants, disrupting the electron transport chain of photosynthesis (Taiz et al. 2014; WSSA 2019). The first instances of reported Palmer amaranth resistance to PSII inhibitors were discovered in Texas in 1993 and in Kansas in 1995 with atrazine, a herbicide in the triazine family, (Heap 2020). Palmer amaranth resistance to atrazine was confirmed in Nebraska in 2013, and multiple resistance involving three HPPD herbicides, tembotrione, topramezone, and mesotrione, and atrazine was confirmed in 2014 (Jhala et al. 2014). Although the mechanism of resistance to triazines and inheritance of resistance are not known, it has been deduced that resistance is caused by a mutation of the psbA gene (Heap 2020; Ward et al. 2013).

EPSP Synthase Inhibitor (WSSA Group 9)-Resistant Palmer Amaranth

Glyphosate is the only herbicide in the EPSPS classification of herbicides. The herbicide inhibits the production of 5-enolpyruvylshikimate-3-phosphate (EPSP) by inhibiting the EPSPS enzyme. The act of inhibiting the EPSPS enzyme prevents the plant from being able to produce essential aromatic amino acids tryptophan, tyrosine, and phenylalanine (WSSA 2019). Glyphosate-resistant Palmer amaranth is one of the biggest issues facing producers as it is one of the most economically impactful glyphosate-resistant weeds in the United States (Beckie 2011). First identified in Georgia (Culpepper et al. 2006), glyphosate-resistant Palmer amaranth has spread across the South (Norsworthy et al. 2008; Steckel et al. 2008). Glyphosate-resistant

Palmer amaranth has since moved out of the South to as far north as Wisconsin (Butts and Davis 2015), as far west as California, and as far east as New Jersey (Heap 2019). The most common mechanism of glyphosate resistance in Palmer amaranth is conferred through a mutation in the coding region of the EPSPS gene, resulting in amplification in the expression of this gene and the synthesis of the EPSPS enzyme. This amplification has been documented to produce as much as 100 times the original amount of EPSPS enzyme, allowing the plant to continue with normal biological functions even after glyphosate binds with and inhibits a substantial amount of EPSPS enzymes (Gaines et al. 2010, 2011; Powles 2010). The overexpression of the EPSPS gene appears to be a unique mechanism of herbicide resistance in weed populations that are also passed on by the pollen of resistant males (Gaines et al. 2012).

PPO Inhibitor (WSSA Group 14)-Resistant Palmer Amaranth

WSSA Group 14 herbicides inhibit the production of protox enzymes, which leads to an accumulation of protoporphyrin IX in the thylakoid. This accumulation leads to a chain reaction of free radical production in the plant cell. These radicals, in turn, attack and oxidize lipids and proteins in the cell, disintegrating membranes within the cell and causing cell death (WSSA 2019). PPO-inhibitor resistance in Palmer amaranth has been attributed to several different mechanisms of resistance, the first being a deletion of a glycine residue at the 210th position of the PPO enzyme (ΔGLY-210 mutation) (Salas et al. 2016). The second known mechanism of resistance discovered in Palmer amaranth is a non-target site mechanism of resistance that allows the plant to metabolize the herbicide internally, causing minimal injury to the plant (Varanasi et al. 2018).

VLCFA Inhibitor (WSSA Group 15)-Resistant Palmer Amaranth

Very Long Chain Fatty Acid (VLCFA) inhibitor herbicides are herbicides that inhibit the fatty acid elongase enzyme (FAE) that is responsible for the production of VLCFAs. The inhibition of the production of VLCFAs inhibits important cellular processes including cell division (Bach et al. 2011). The first populations of VLCFA-resistant Palmer amaranth were discovered in Mississippi and Crittenden counties in Arkansas from *S*-metolachlor escapes in the field during the 2016 and 2017 growing seasons (Brabham et al. 2019).

HPPD Inhibitor (WSSA Group 27) Resistant Palmer Amaranth

The 4-hydroxyphenylpyruvate dioxygenas (HPPD) -inhibiting herbicides are the most recently discovered and commercialized class of chemistry (Lee et al. 1998). These herbicides cause bleaching due to a lack of carotenoid synthesis and lipid peroxidation of cell membranes (Mitchell et al. 2001). Resistance to HPPD-inhibiting herbicides by Palmer amaranth has been documented in Nebraska (Jhala et al. 2014)), Kansas, and North Carolina (Heap 2021). Resistance to HPPD-inhibiting herbicides has been documented to be conferred through both the non-target site mechanism of rapid detoxification and the target site mechanism of increased HPPD gene expression (Nakka et al. 2017).

Integrated Palmer Amaranth Management

With the current state of Palmer amaranth resistance to multiple herbicide groups, an integrated weed management approach is required to successfully manage Palmer amaranth (Schwartz et al. 2016).   Typically, when discussing integrated pest management systems, an economic threshold is established (UC IPM 2020). That is not the case for Palmer amaranth or any other invasive and resistance-prone weed species. As a result, Palmer amaranth in both cotton and soybean production systems should be subjected to a zero-tolerance management policy. In a zero-tolerance management system, no escapes are allowed to reproduce (Barber et al. 2015). A successful integrated weed management program utilizes several different components to ensure a well-rounded approach: mechanical, cultural, chemical, and biological (UC IPM 2020).

Mechanical Control

Mechanical weed control includes the use of tillage, cultivation, mowing, hand-weeding, and harvest weed seed control (HWSC) either to prevent the emergence of a weed or to kill a weed while it is actively growing in the field (Schwartz et al. 2016). These methods of weed control are typically non-selective in practice and indiscriminately remove plants from the treated area. The use of in-crop conventional tillage practices has been shown to be an effective strategy for Palmer amaranth control, especially when coupled with other integrated weed management strategies such as cover crops or layered residual herbicides (DeVore et al. 2012; DeVore et al. 2013; Norsworthy et al. 2016; Price et al. 2011; Price et al. 2016). After the discovery of glyphosate-resistant Palmer amaranth in Georgia in 2004 (Culpepper et al. 2006), the proportion of hectares that utilized in-season tillage to control Palmer amaranth increased from 34% in 2005 to 44% in 2010 (Sosnoskie and Culpepper 2014).

Deep tillage is a subset of tillage practices where the primary goal is to invert the soil and bury weed seed that may be close to the soil surface. Years of conservation tillage as a result of the adoption and effectiveness of glyphosate-resistant cropping systems have allowed for weed seeds to accumulate in the top portion of the soil profile (Barberi and Cascio 2000). Strategic timing of deep tillage using a moldboard plow inverts the soil and places weed seeds deep into the soil profile. In a study investigating how deep tillage would affect Palmer amaranth emergence in double-cropped soybeans, Palmer amaranth emergence was reduced 94% with the use of a moldboard plow over a two-year period compared to plots that were not tilled (DeVore et al. 2013). In cotton, the use of cover crop and deep tillage resulted in an 80% reduction in Palmer amaranth emergence over a two-year period compared to plots without cover crops or tillage (DeVore et al. 2012).

Hand weeding or hoeing of weeds in fields is another practice that has increased after the emergence of glyphosate-resistant Palmer amaranth. In Georgia, the percentage of hectares that utilized hand weeding practices increased from 3 to 66% from 2000 to 2010 with a cost increase of \$25 ha^{-1} (Sosnoskie and Culpepper 2014). Hand weeding is viewed as an effective strategy for improved sanitation in fields to prevent the spread of Palmer amaranth but should be coupled with effective herbicide programs as well as other weed management strategies for effective control and is part of a zero-tolerance weed management policy (Barber et al. 2015; Norsworthy et al. 2018). Producers should use caution when implementing hand weeding strategies as the plasticity of Palmer amaranth allows the weed to re-root and still produce seed (Sosnoskie et al. 2014).

Harvest weed-seed control includes narrow windrow burning, chaff carts, Harrington seed destructors, and bale direct systems (Schwartz et al. 2016). Narrow windrow burning is a simple and effective harvest weed seed control strategy as approximately 40- to 45-cm windrows are produced from the chaff that is dumped from the back end of a combine and burned immediately. It has been shown that narrow windrow burning can reduce Palmer amaranth soil seedbank populations by as much as 62% over three years (Barber et al. 2017). The Harrington Seed Destructor (HSD) is an innovation from Australia that can either be pulled behind or integrated into a combine and works by milling down the chaff that comes out of the back, crushing any weed seeds that pass through (Walsh et al. 2013). Although the HSD is effective on larger seeded weeds such as wild oat (*Avena fatua* L.), ridgid ryegrass (*Lolium rigidum* Gaundin), and wild radish (*Raphanus raphanistrum* L.) (Walsh et al. 2013), there are concerns that as seed size is decreased, the efficacy of the HSD is also decreased, which may be a potential problem for the small seeds of Palmer amaranth (Tidemann et al. 2017). Research conducted where chaff was collected from a harvested soybean field and ran through a HSD effectively destroyed 100% of all Palmer amaranth seed collected in chaff compared to chaff not ran through a HSD (Schwartz-Lazaro et al. 2017b).

Chemical Control

For an effective integrated weed management program, the chemistries that are being utilized must be diverse and be comprised of multiple SOAs. Producers are encouraged to rotate cropping systems, herbicide chemistries, and cultural control methods in a production area (Bagavathiannan et al. 2013; Barber et al. 2015). For a herbicide program to be effective, it is imperative that overlapping residual herbicides are used to control glyphosate-resistant Palmer amaranth in cotton and soybean (Norsworthy et al. 2012). Even with multiple residual herbicides, there will likely be uncontrolled weeds at the end of the season (Everman et al. 2007; Gardner et al. 2006; Meyer et al. 2015). With XtendFlex cotton, a successful postemergence program to control emerged Palmer amaranth includes the use of glufosinate or dicamba as an early POST application followed by glufosinate as a mid-POST application and a late-POST option (Vann et al. 2017). In addition to traditional broadcast applications, a layby application that includes a residual herbicide must be considered to ensure adequate Palmer amaranth control through harvest (Vann et al. 2017). In soybean, a nationwide study was conducted to evaluate the best diverse herbicide programs for Palmer amaranth and waterhemp (*Amaranthus* *tuberculatus* (Moq.) Sauer) control. It was reported that programs that use an aggressive preemergence program of flumioxazin and pyroxasulfone followed by a late POST application of glyphosate, dicamba, and *S*-metolachlor provided the greatest reduction of waterhemp and Palmer amaranth at the end of the season (Meyer et al. 2015).

Cultural Control

Cultural control practices include cover crops as well as alterations to the seeding rate, row spacing, and planting timing of a crop. Field and machinery sanitation practices are also included in cultural practices (Schwartz et al. 2016). Cover crops can work as an effective tool for managing troublesome weeds, with studies finding Palmer amaranth population reductions of as much as 80% by utilizing Austrian winter field pea (*Pisum sativum* L.) and cereal rye (*Secale cereal* L.) cover crops compared to treatments without cover crops (Webster et al. 2013). Cereal rye has also been shown to be effective at reducing total Palmer amaranth emergence by 83% in Arkansas compared to treatments without cover crops (Palhano et al. 2018). When used to complement a glufosinate-based herbicide system in cotton, the cereal rye cover crop increased Palmer amaranth control 18% compared to treatments without cover crops (Webster et al. 2013). One reason that cereal rye is an effective cover crop option is because the allelopathic chemicals that are produced by rye have been found to inhibit Palmer amaranth germination and seedling growth (Burgos and Talbert 2000; Webster et al. 2013).

Altering planting population, planting timing, and row spacing are all effective ways to increase leaf area index (LAI) and directly affect the emergence rate of weeds (Harder et al. 2007; Bertram and Pederson 2004). By increasing the amount of LAI by the crop during the growing season, less light and solar radiation are allowed to reach the soil surface thus keeping the soil surface cooler and darker. By doing so, there is a decrease in weed germination and growth (Harder et al. 2007; Yelverton and Coble 1991). The shading affect created by canopy closure only reduces the number weeds that germinate as established Palmer amaranth will continue to be able to effectively compete with crops. Established Palmer amaranth can compensate and alter its growth pattern in as much as 87% shade by growing more upright and increasing leaf thickness (Jha et al. 2008; Jha and Norsworthy 2009). A study investigating how row spacing, planting population and herbicide programs affect Palmer amaranth fecundity, biomass and emergence found that decreasing soybean row spacing and increasing planting population were both effective at reducing Palmer amaranth fecundity and growth but not emergence (Butts et al. 2016).

One often-overlooked cultural control practice is the practice of keeping equipment and areas around fields clean and free from weed seeds. Oftentimes, roadways, field borders, turnrows, and railroad rights-of-way are sprayed but not planted back with any vegetation, leaving a niche for herbicide-resistant weeds such as Palmer amaranth to flourish and grow to maturity (Bond 2012; Norsworthy et al. 2012). To prevent weed seed production in these areas, it is suggested that these areas be reestablished to a competitive type of vegetation such as ryegrass or native perennials to outcompete Palmer amaranth (Bond 2012).

Dicamba Applications Involving Rope Wick and Roller Wiper Applicators

Concerns about off-target movement of dicamba have led producers and applicators to search for innovative technologies to aid in dicamba applications. Off-target movement is typically categorized into three categories: particle drift, tank contamination, and volatilization (Cundiff et al. 2017; Steckel et al. 2010). Concerns about off-target movement in the form of volatility stem from the volatile nature of dicamba and the salt of dicamba. After application, dicamba has historically been known to vaporize from the applied surface and travel to sensitive crops and cause injury (Behrens and Leuschen 1979). Low doses of dicamba and other herbicides that move onto non-target weeds may promote herbicide-resistance as the result of multiple low dose exposures (Vieira et al. 2020). Off-target movement has also been attributed to the physical drift of droplets from dicamba applications. These droplets have been shown to travel great distances from the intended site of application due to small droplet size, wind, improper boom height, and tank-mix partners (Alves et al. 2017a, 2017b).

Different management practices have been suggested to reduce physical drift from dicamba applications including growing physical barriers such as corn to block physical movement (Vieira et al. 2018) or using a hooded sprayer to prevent particles from escaping the treated area (Foster et al. 2018). One additional application technology that is being considered to reduce particle drift is the use of wicking/wiping type applicators. Wick type applicators were first utilized as a method to remove weeds that grew above the canopy of crops that were not tolerant to the herbicide that was applied (Hoette et al. 1982). Glyphosate was often used in rope-wick applicators to rid soybean and cotton fields of johnsongrass [*Sorghum halepense* (L.) Pers.], shattercane [*Sorghum bicolor* (L.) Moench spp.], and volunteer corn (*Zea mays* L.) (Keeley et al. 1984; Schneider et al. 1982). This method was effective for controlling weeds that had grown above the canopy but could not effectively control weeds that had not yet grown up through the canopy. There were also concerns regarding dripping from these types of applications when the wicks were not properly set up (Hoette et al. 1982; Meyers et al. 2017). Currently, wicks and wipers are used primarily in turf and range situations to apply synthetic auxin herbicides to invasive broadleaf weeds. Studies conducted in-crop found that any weeds contacted by the wiper during application were effectively controlled (Chandran 2009), giving promise to the effectiveness of wick and wiper applications of dicamba.

The purpose of this research was to investigate how different integrated weed management strategies can be implemented in cotton and soybean production systems and how they affect the seedbank of troublesome weed species, particularly Palmer amaranth, in these two cropping systems. This study will also look at how the application of dicamba using ropewick application technology will fit in soybean production systems and the effectiveness of isoxaflutole-resistant cotton systems on weed control. The findings from this study will enable producers to make informed management decisions regarding implementation of diverse integrated pest management strategies for their production systems to control herbicide-resistant Palmer amaranth.

References

Alves GS, Kruger GR, da Cunha JPAR, Henry RS, Vieira BC, Obradovic A, Grujic M (2017a) Spray drift from dicamba and glyphosate application in a wind tunnel. Weed Technol 31:387–395

Alves GS, Kruger GR, da Cunha JPAR, de Santana DG, Pinto LAT, Guimaraes F, Zaric M (2017b) Dicamba spray drift as influenced by wind speed and nozzle type. Weed Technol 31:734–731

Bach I, Gissot I, Marion J, Tellier F, Moreau P, Satiat-Jeunemaitre B, Palauqui JC, Napier JA, Faure JD (2011) Very-long-chain fatty acids are required for cell plate formation during cytokinesis in *Arabadopsis thaliana*. J Cell Sci 124:1–24

Bagavathiannan MV, Norsworthy JK, Scott RC, Barber LT (2013) Answers to frequently asked questions on herbicide resistance management. University of Arkansas Division of Agriculture Fact Sheet FSA2172 http://www.uaex.edu/publications/pdf/FSA2172.pdf. Accessed February 3, 2017

Barber LT, Butts TR, Boyd J, Cunningham K, Selden G, Norsworthy J, Burgos N, Bertucci M, Selden G (2021) MP44: Recommended Chemicals for weed and brush control. University of Arkansas System Division of Agriculture, Cooperative Extension Service

Barber LT, Norsworthy JK, Vangilder AM (2015) A Community-Based Program for Glyphosate- Resistant Palmer Amaranth Management. University of Arkansas Cooperative Extension. https://www.uaex.edu/publications/pdf/FSA2177.pdf. Accessed February 12, 2020

Barberi P, Cascio BL (2000) Long-term tillage and crop rotation effects on weed seedbank size and composition. Weed Res 41:325–340

Beckie HJ, Reboud X (2009) Selecting for weed resistance: herbicide rotation and mixture. Weed Technol 23:363–370

Beckie HJ (2011) Herbicide resistant weeds: management tactics and practices. Weed Technol 20:793-814

Behrens R, Leushen WE (1979) Dicamba volatility. Weed Sci 27:486–493

Bensch CN, Horak MJ, Peterson D (2003) Interference of redroot pigweed (*Amaranthus retroflexus*), Palmer amaranth (*Amaranthus palmeri*), and common waterhemp (*Amaranthus rudis*) in soybean. Weed Sci 51:37–43

Bertram MG, Pedersen P (2004) Adjusting management practices using glyphosate-resistant soybean cultivars. Agron J 96:462-468

Bond JA (2012) Challenges associated with clean turnrows and ditchbanks. Page 5 *in* 2012 Proceedings of the Beltwide Cotton Conference. Cordova, TN: National Cotton Council of America

Brabham C, Norsworthy JK, Houston MM, Varanasi VK, Barber T (2019) Confirmation of S-metolachlor resistance in Palmer amaranth (*Amaranthus palmeri*). Weed Technol 33:720–726

Brinker RJ, Burns WC, Feng PCC, Kendig JA, Leclere S, Lutke J, Malven M (2014) Cotton transgenic event MON 88701 and methods of use thereof. Patent No. US8735661B2

Burgos NR, Kuk YI, Talbert RE (2001) *Amaranthus palmeri* resistance and differential tolerance of *Amaranthus palmeri* and *Amaranthus hybridus* to ALS-inhibitor herbicides. Pest Manag, Sci 57:449-457

Burgos NR, Talbert RE (2000) Differential allelochemicals from *Secale cereale* in seedling bioassays. Weed Sci 48:302–310

Butts T, Davis V (2015) Palmer amaranth (*Amaranthus palmeri*) confirmed glyphosate-resistant in Dane County, Wisconsin. University of Wisconsin-Extension:3

Butts TR, Norsworthy JK, Kruger GR, Sandell LD, Young BG, Steckel LE, Loux MM, Bradley KW, Conley SP, Stoltenberg DE, Arriga FJ, Davis VM (2016) Management of pigweed (*Amaranthus* spp.) in glufosinate-resistant soybean in the Midwest and Mid-South. Weed technol 30:355-365

Chandran RS (2009) New wipers for weed management in pasture and hayfield. https://grassworksmanufacturing.com/wp-content/uploads/2019/12/GrassWorks-Wipers-for-Weed-Control-in-Pasture-and-Hayfields.pdf. Accessed February 10, 2020

Clemente TE, Dumitru R, Feng PCC, Flasinski S, Weeks DP (2007) Modified dicamba monooxygenase enzyme and methods of its use. Patent No. WO2007146706A2

Costea M, Weaver SE, Tardiff FJ (2004) The biology of invasive alien plants in Canadian weeds. 130. *Amaranthus retroflexus* L., *A. powellii* S. Watson and *A. hybridus* L. Cana J Plant Sci 84:631–668

Culpepper A, Grey T, Vencill W, Kichler J, Webster T, York A, Davis J, Hanna W (2006) Glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) confirmed in Georgia. Weed Sci 54:620–626

Culpepper A, Kilcher J, Sosnoskie L, York A, Sammons D, Nichols B (2010) Integrating crop cover residue and moldboard plowing in to glyphosate-resistant Palmer amaranth management programs. Page 1650 *in* 2010 Proceedings of the Beltwide Cotton Conference. National Cotton Council of America. Cordova, TN

Cundiff GT, Reynolds DB, Mueller TC (2017) Evaluation of dicamba persistence among various agricultural hose types and cleanout procedures using soybean (*Glycine max*) as a bio-indicator. Weed Sci 65:305–316

DeVore JD, Norsworthy JK, Brye KR (2012) Influence of deep tillage and a rye cover crop on glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) emergence in cotton. Weed Technol 26:832–838

DeVore JD, Norsworthy JK, Brye KR (2013) Influence of deep tillage, a rye cover crop, and various soybean production systems on Palmer amaranth emergence in soybean. Weed Technol 27:263–270

Everman WJ, Burke IC, Allen JR, Collins J, Wilcut JW (2007) Weed control and yield with glufosinate-resistant cotton weed management systems. Weed Technol 21:695-701

Foster HC, Sperry BP, Reynolds DB, Kruger GR, Claussen S (2018) Reducing herbicide particle drift: effect of hooded sprayer and spray quality. Weed Technol 32:714–721

Franssen AS, Skinner DZ, Al-Khatib K, Horak MJ, Kulakow PA (2001) Interspecific hybridization and gene flow of ALS resistance in *Amaranthus* species. Weed Sci 49:598–606

Gaines TA, Shaner DL, Leach JE, Ward SM, Preston C, Westra P (2011) Mechanism of resistance of evolved glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*). J Agric Food Chem 59:5886–5889

Gaines TA, Ward SM, Bekun B, Preston C, Leach JE, Westra P (2012) Interspecific hybridization transfers a previously unknown glyphosate resistance mechanism in *Amaranthus* species. Evol Applic 5:29-38

Gaines TA, Zhang W, Wang D, Bukun ST, Chisholm ST, Shaner DL, Nissen SJ, Patzodt WL, Tranel PJ, Culpepper AS, Grey TL, Webster TM, Vencill WK, Sammons D, Jiang JM, Preston C, Leach JE, Westra P (2010) Gene amplification confers glyphosate resistance in *Amaranthus palmeri*. Proc Natl Acad Sci USA 107:1029–1034

Gardner AP, York AC, Jordan DL, Monks DW (2006) Management of annual grasses and *Amaranthus* spp. in glufosinate-resistant cotton. J. Cotton Sci 10:428-338

Givens WA, Shaw DR, Kruger GR, Johnson WG, Weller BC, Young BG, Wilson RG, Owen MDK, Jordan D (2009) Survey of tillage trends following the adoption of glyphosate-resistant crops. Weed Technol 23:150–155

Gossett BJ, Murdock EC, Toler JE (1992) Resistance of Palmer amaranth (*Amaranthus palmeri*) to the dinitroaniline herbicides. Weed Technol 6:587–591

Harder DB, Sprague CL, Renner KA (2007) Effect of soybean row width and population on weeds, crop yield, and economic return. Weed Technol 21:744-752

Heap I (2021) International Survey of Herbicide Resistant Weeds. http://www.weedscience.org/Summary/Species.aspx?WeedID=14. Accessed January 22, 2021

Hoette GD, Livingstron SD, Peters EJ (1982) Rope wick applicators. http://extension.missouri.edu/webster/documents/resources/agriculture/ropewick/G4920_Rope_Wick_Applicators.pdf. Accessed February 10, 2020

Hymowitz T (1970) On the domestication of the soybean. Econ Bot 24:408-421

Hymowitz T, Newell CA (1981) Taxonomy of the genus glycine, domestication and uses of soybeans. Econ Bot 35:272-288

Jha P, Norsworthy JK (2009) Soybean canopy and tillage effects on emergence of Palmer amaranth (*Amaranthus palmeri*) from a natural seed bank. Weed Sci 57:644–651

Jha P, Norsworthy JK, Riley MB, Bielenberg DG, Bridges W (2008) Acclimation of Palmer amaranth (*Amaranthus palmeri*) to shading. Weed Sci 56:729–734

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

Jhala AJ, Sandell LD, Rana N, Kruger GR, Knezevic SZ (2014) Confirmation and control of triazine and 4-hydroxyphenylpyruvate dioxygenate-inhibiting herbicide resistant Palmer amaranth (*Amaranthus palmeri*) in Nebraska. Weed Technol 28:28–38

Keeley PE, Carter CH, Thullen RJ (1987) Influence of planting date on growth of Palmer amaranth (*Amaranthus palmeri*). Weed Sci 35:199–204

Keeley PE, Carter CH, Thullen RJ, Miller JH (1984) Comparison of ropewick applicators for control of Johnsongrass (*Sorghum halepense*) in cotton (*Gossypium hirsutum*) with glyphosate. Weed Sci 32:431–435

Klingman TE, Oliver LR (1994) Palmer amaranth (*Amaranthus palmeri*) interference in soybeans (*Glycine max*). Weed Sci 42:523–527

Kniss A (2018) Genetically engineered herbicide-resistant crops and herbicide resistant weed evolution in the United States. Weed Sci 66:260–273

Korres NE, Norsworthy JK, Young BG, Reynolds DB, Johnson WG, Conley SP, Smeda RJ, Mueller TC, Spaunhorst DJ, Gage KL, Loux M, Kruger GR, Bagavathiannan MV (2018) Seedbank persistence of Palmer amaranth (*Amaranthus palmeri*) and waterhemp (*Amaranthus tuberculatus*) across diverse geographical regions of the United States. Weed Sci. 66:446-456

Lee DL, Knudsen CG, Michealy WJ, Chin HL, Nguyen NH, Carter CG (1998) The structure-activity relationships of the triketone class of HPPD herbicides. Pest Manag. Sci. 54:377-384

Meyer CJ, Norsworthy JK, Young BG, Steckel LE, Bradley KW, Johnson WG, Loux MM, Davis VM, Kruger GR, Bararpour MT, Ikley JT, Spaunhorst DJ, Butts TR (2015) Herbicide program approaches for managing glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) and waterhemp (*Amaranthus tuberculatus* and *Amaranthus rudis*) in future soybean-trait technologies. Weed Technol 29:716–729

Meyers SL, Jennings KM, Monks DW (2017) Sweetpotato response to simulated glyphosate wick drip. Weed Technol 31:130–135

Mitchell G, Bartless DW, Fraser TEM, Hawkes TR, Holt DC, Townson JK (2001) Mesotrione: a new selective herbicide for use in maize. Pest Manag. Sci. 57:120-128

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

Nakka S, Godar AS, Wani PS, Thompson CR, Peterson DE, Roelofs J, Jugulam M (2017) Physiological and molecular characterization of hydroxyphenylpyruvate dioxygenase (HPPD)-inhibitor resistance in Palmer amaranth (*Amaranthus palmeri* S. Wats.). Front. Plant Sci. 8:555

NCCA (National Cotton Council of America) (2013) Frequently asked questions. http://www.cotton.org/edu/faq/index.cfm. Accessed February 10, 2020

Norsworthy JK, Griffith GM, Scott RC, Smith KL, Oliver LR (2008) Confirmation and control of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) in Arkansas. Weed Technol 22:108–113

Norsworthy JK, Griffith GM, 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 Sci 62:237-249

Norsworthy, JK, NE Korres, MJ Walsh, SB Powles (2016) Integrating herbicide programs with harvest weed seed control and other fall management practices for the control of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*). Weed Sci 64:540–550

Norsworthy JK, Korres NE, Bagavathiannan MV (2018) Weed seedbank management: revisiting how herbicides are evaluated. Weed Sci 66:415–417

Norsworthy JK, Smith KL, Steckel LE, Koger CH (2009) Weed seed contamination in gin trash. Weed Technol 23:574–580

Norsworthy JK, Ward SM, Shaw DR, Llewellyn R, Nichols RL, Webster TM, Bradley KW, Frisvold G, Powles SB, Burgos NR, Witt W, Barrett M (2012) Reducing the risks of herbicide resistance: best management practices and recommendations. Weed Sci 60 (SI I):31–62

Pallet KE, Little JP, Sheekey M, Veerasekaren P (1998). The mode of action of isoxaflutole I. Physiological effects, metabolism, and selectivity. Pestic. Biochem. Physiol. 62:113-124

Palhano MG, Norsworthy JK, Barber T (2018) Cover crops suppression of Palmer amaranth (*Amaranthus palmeri*) in cotton. Weed Technol 32:60-65

Powles SB (2010) Gene amplification delivers glyphosate-resistant weed evolution. Proc Natl Acad Sci USA 107:179–190

Price AJ, Balkcom KS, Culpepper AS, Kelton JA, Nichols RL, Schomberg H (2011) Glyphosate-resistant Palmer amaranth: a threat to conservation tillage. J Soil Water Conserv 66:265–275

Price AJ, Monks CD, Culpepper AS, Duzy LM, Kelton JA, Marshall MW, Steckel LE, Sosnoskie LM, Nichols RL (2016) High-residue cover crops alone or with strategic tillage to manage glyphosate resistant Palmer amaranth (*Amaranthus palmeri*) in southeastern cotton (*Gossypium hirsutum*). J Soil Water Conserv 71:1-11

Rowland MW, Murray DS, Verhalen LM (1999) Full-season Palmer amaranth (*Amaranthus palmeri*) interference with cotton (*Gossypium hirustum*). Weed Sci 47:305–309

Saari LL, Cotterman JC, Thrill DC (1994) Resistance to acetolactate synthase inhibiting herbicide. Herbicide Resistance in Plants. Pages 83–139 in S. B. Powles and J. A. M. Holtum, eds. Herbicide Resistance in Plants: Biology and Biochemistry. Boca Raton, FL: Lewis Publishers.

Salas RA, Burgos NR, Tranel PJ, Singh S, Glasglow L, Scott RC, Nichols RL (2016) Resistance to PPO-inhibiting herbicides in Palmer amaranth from Arkansas. Pest Manag Sci 72:864-869

Sauer J (1957) Recent migration and evolution of the dioecious amaranths. Evolution 11:11–31

Schneider GL, Koehler CB, Schepers JS, Burnside OC (1982) Roller applicator for shattercane (*Sorghum bicolor*) control in row crops. Weed Sci 30:301–306

Schwartz LM, Norsworthy JK, Barber TL, Scott RC (2016) Harvest weed seed control- an alternate method for measuring the soil seed bank. University of Arkansas Research and Extension. FSA2180. http://www.uaex.edu/publications/pdf/FSA-2180.pdf Access date: January 24, 2019.

Schwartz-Lazaro LM, Norsworthy JK, Scott RC, Barber LT (2017b) Resistance of two Palmer amaranth populations to multiple herbicide modes of action in Arkansas. Crop Prot 96:158-163

Schwartz-Lazaro LM, Norsworthy JK, Walsh MJ, Bagavathiannan MV (2017b) Efficacy of the integrated Harrington Seed Destructor on weeds of soybean and rice production systems in the southern United States. Crop Sci 57:1-7

Shah DM, Rogers SG, Horsch RB, Fraley RT (1990) Glyphosate-resistant plants. Patent No. US4940835A

Shaner DL, Anderson PC, Stidham MA (1984) Imidazolines: potent inhibitors of acetohydroxy acid synthase. Plant Physiol 76:545–546

Smith CW, Cothren JT (1992) Cotton: origin, history, technology, and production. John Wiley & Sons. 872p

Smith DT, Baker RV, Steele GL (2000) Palmer amaranth (*Amaranthus palmeri*) impacts on yield, harvesting, and ginning in dryland cotton (*Gossypium hirsutum*). Weed Technol 14:122–126

Sosnoskie L, Culpepper A (2014) Glyphosate-Resistant Palmer amaranth (*Amaranthus palmeri*) increases use of herbicide use, tillage and hand-weeding in Georgia cotton. Weed Sci 62:393–402

Sosnoskie LM, Webster TM, Grey TL, Culpepper AS (2014) Severed stems of *Amaranthus palmeri* are capable of regrowth and seed production in *Gossypium hirsutum*. Ann Appl Biol 165:147-154

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

Sosnoskie LM, Webster TM, Culpepper AS (2007) Palmer amaranth pollen viability. University of Georgia. http://www.ugacotton.com/vault/rer/2007/p43.pdf. Accessed February 10, 2020

Sprague CL, Stoller EW, Wax LM, Horak MJ (1997) Palmer amaranth pollen (*Amaranthus palmeri*) and common waterhemp (*Amaranthus rudis*) resistance to selected ALS-inhibiting herbicides. Weed Sci 45:192–197

Steckel LE (2007) The dioecious amaranth spp: here to stay, intriguing world of weeds. Weed Technol 21:567–570

Steckel LE, Chism C, Thompson A (2010) Cleaning plant growth regulator (PGR) herbicides out of field sprayers. https://extension.tennessee.edu/publications/Documents/W071.pdf. Accessed February 10, 2020

Steckel LE, Main CL, Ellis AT, Mueller S (2008) Palmer amaranth (*Amaranthus palmeri*) in Tennessee has low level glyphosate resistance. Weed Technol 22:119–123

Steckel LE, Sprague CL, Stoller EW, Wax LM (2004) Temperature effects on germination of nine Amaranthus species. Weed Sci 52:217–221

Steinmaus SJ, Prather TS, Holt JS (2000) Estimation of base temperatures for nine weed species. J Exp Bot 51:275–286

Stephenson DO, Bond JA (2012) Evaluation of thiencarbazone-methyl– and isoxaflutole-based herbicide programs in corn. Weed Technol 26:37–42

Taiz L, Zeiger E, Moller IM, Murphy A (2014) Plant Physiology and Development. 6th ed. Sinauer Associates. 761 p

Tidemann BD, Hall LM, Harker KN, Beckie HJ (2017) Factors affecting weed seed devitalization with the Harrington seed destructor. Weed Sci 65:650–658

Tranel PJ, Wright TR (2002) Resistance of weeds to ALS-inhibiting herbicides: what have we learned? Weed Sci 50:119–122

UC IPM (2020) What Is Integrated Pest Management (IPM)? / UC Statewide IPM Program (UC IPM). https://www2.ipm.ucanr.edu/What-is-IPM/. Accessed January 24, 2020

USDA-NASS (2017) U.S. Department of Agriculture-National Agricultural Statistics Service Quick Stats. https://quickstats.nass.usda.gov/. Accessed October 31, 2017

USDA-NASS (2019) USDA Quick Stats. https://quickstats.nass.usda.gov/. Accessed February 10, 2020

Van Wychen L (2019) 2019 Survey of the most common and troublesome weeds in broadleaf crops, fruits & vegetables in the United States and Canada. Weed Science Society of America National Weed Survey Dataset. Available: http:/wssa.net/wp-content/uploads/2016_Weed_Survey_Final.xlsx Accessed February 7, 2019

Vann RA, York AC, Cahoon Jr. CW, Buck TB, Askew MC, Seagroves RW (2017) Glufosinate plus dicamba for rescue palmer amaranth control in XtendFlex cotton. Weed Technol 31:666–674

Varanasi VK, Brabham C, Norsworthy JK (2018) Confirmation and characterization of non-target site resistance to fomesafen in Palmer amaranth. Weed Sci 66:702–709

Vieira BC, Butts TR, Rodrigues AO, Golus JA, Schroeder KP, Kruger GR (2018) Spray particle drift mitigation using field corn (*Zea mays* L.) as a drift barrier: field corn as a drift barrier. Pest Manag Sci 74:2038-2046

Vieira BC, Luck JD, Amundsen KL, Werle R, Gaines TA, Kruger GR (2020) Herbicide drift exposure leads to reduced herbicide sensitivity in *Amaranthus* spp. Sci Rep 10:2146

Walsh MJ, Newman P, Powles SB (2013) Targeting weed seeds in-crop: a new weed control paradigm for global agriculture. Weed Technol 27:431–436

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

Webster TM, Scully BT, Culpepper AS (2013) Winter cover crops influence *Amaranthus palmeri* establishment. Crop Prot 52:130-135

WSSA (2019) Summary of Herbicide Mechanism of Action According to the Weed Science Society of America (WSSA). WSSA http://wssa.net/wp-content/uploads/WSSA-Mechanism-of-Action.pdf. Accessed February 12, 2020.

Yelverton FH, Coble HD (1991) Narrow row spacing and canopy formation reduces weed resurgence in soybean (*Glycine max*). Weed Sci 25:73-78

Zimdahl RL (1980) Weed Crop Competition: A Review. International Plant Protection Center 196p

Chapter 2

Utility of Isoxaflutole-based Herbicide Programs in HPPD-Tolerant Cotton Production Systems

Abstract

Palmer amaranth has developed resistance to at least six herbicide sites of action in the Cotton Belt, leaving producers with few options to manage this weed. Previous research in corn and newly commercially released soybean systems have found the use of 4-hydroxyphenylpyruvate dioxygenase (HPPD)-inhibiting herbicides such as isoxaflutole (IFT) to be effective at managing Palmer amaranth. Consequently, a new transgenic cultivar of cotton is being developed with tolerance to IFT, allowing for in-crop applications of the herbicide. Two separate studies were conducted near Marianna, AR, in 2019 and replicated in 2020 to investigate the crop safety and utility of IFT when added to cotton herbicide programs. Herbicide programs featured IFT as a preemergence or early-postemergence option, residual herbicides in subsequent postemergence applications, and the presence or absence of a layby application. The use of IFT did not significantly impact cotton injury or yield while the use of layered residual herbicides, including IFT, increased Palmer amaranth control. Regardless of earlier use of IFT, layby applications were needed for season-long control of Palmer amaranth, entireleaf morningglory, broadleaf signalgrass, and johnsongrass, as evidenced by greater than a 20-percentage point improvement in control of all weeds when a layby application was made. Overall, findings from these studies indicate IFT to be a suitable tool for managing Palmer amaranth and will provide an additional site of action to cotton herbicide programs. Sequential herbicide applications and overlaying residuals were found to be paramount for managing Palmer amaranth throughout the season.

Nomenclature: isoxaflutole; broadleaf signalgrass, *Urochloa platyphylla* (Munro ex C. Wright) R.D. Webster; entireleaf morningglory, *Ipomoea hederacea var. integriuscula*; johnsongrass, *Sorghum halepense* (L.) Pers.; Palmer amaranth, *Amaranthus palmeri* (S.) Wats.; corn, *Zea mays* L.; cotton, *Gossypium hirsutum* L.; soybean, *Glycine max* (L.) Merr.;

Key words: herbicide-resistance; herbicide-tolerance, integrated weed management; resistance management; layby; nonparametric data

Introduction

The ability of Palmer amaranth to adapt and invade cropping systems (Sauer 1972) has enabled it to become the dominant weed of concern in cotton production systems across the Midsouth over the past 50 years (Sauer 1972; Van Wychen 2019). Management concerns with Palmer amaranth have been exacerbated throughout the Midsouth, where resistant populations have evolved to many of the available herbicide options for weed control in cotton production systems. Currently, Palmer amaranth has developed resistance to microtubule-inhibiting herbicides such as pendimethalin (Gossett et al. 1992), acetolactate synthase- (ALS) inhibiting herbicides such as trifloxysulfuron (Burgos et al. 2001; Norsworthy et al. 2008), synthetic auxin herbicides such as dicamba (Steckel 2020; Shyam et al. 2021; Heap 2021), 5-enolpyruvyl-shikimate-3-phosphate- (EPSPS) inhibiting herbicides such as glyphosate (Norsworthy et al. 2008), protoporphyrinogen oxidase- (PPO) inhibiting herbicides such as fomesafen (Varanasi et al. 2018), 4-hydroxyphenylpyruvate dioxygenase (HPPD) herbicides such as mesotrione (Jhala et al. 2014), and very-long-chain fatty acid (VLCFA) inhibiting herbicides such as *S*-metolachlor (Brabham et al. 2019).

Economically, Palmer amaranth can cause dramatic reductions in cotton yield, reducing lint production by 59% at Palmer amaranth densities of 1.1 plants m^{-2} (Morgan et al. 2001). As weed densities increase, cotton lint yield has been found to linearly decrease at rates between 5.9 and 11% with each additional plant m row^{-1} (Rowland et al. 1999). In addition to causing direct yield losses, heavy infestations may also reduce cotton harvest efficiencies. Palmer amaranth densities of 3,260 weeds ha^{-1} have been shown to increase the time to harvest a hectare of cotton by 3 hours (Smith et al. 2000). Reduced harvest efficacy can result in significant economic ramifications, costing producers additional fuel, time, and wear on equipment. The development of herbicide resistance has also exposed the true costs of herbicide-resistant weeds: more expensive herbicide programs, technology fees for herbicide-resistant crops, and the addition of other management practices such as tillage and hand weeding (DeVore et al. 2012).

To offer more herbicide options for cotton producers, BASF has developed a genetically modified line of cotton that is tolerant to glyphosate, glufosinate, and isoxaflutole (IFT). The introduction of IFT to cotton production systems offers producers an additional site of action that had previously not been available for use (Barber et al. 2021). Isoxaflutole (HPPD) herbicide is in the isoxazole chemical family. The addition of IFT provides producers an additional pigment-inhibiting herbicide alongside fluridone, a phytoene desaturase inhibitor. Typically, IFT has been labeled for use in corn production as a PRE or early postemergence (EPOST) herbicide for the control of small-seeded broadleaf weeds and grasses (Anonymous 2019; Pallett et al. 1998). It has been previously reported that IFT is an effective tank-mixture partner with photosystem II (PSII)-inhibiting herbicides for the control of glyphosate-resistant Palmer amaranth when used as a part of a glufosinate-based herbicide programs (Chahal et al. 2019; Chahal and Jhala 2018; Jhala et al. 2014; Stephenson and Bond 2012).

When applied POST, the combination of HPPD- and PSII-inhibiting herbicides has been shown to have a synergistic effect, whereas PRE applications of similar tank-mixtures were additive in nature (Chahal and Jhala 2018; Kohrt and Sprague 2017; Meyer et al. 2016). Although HPPD-resistant populations of Palmer amaranth have been documented, the pairing of HPPD-inhibiting herbicides, such as IFT, with PSII-inhibiting herbicides has been shown to be effective at overcoming resistance to either site of action (Chahal et al. 2019; Chahal and Jhala 2018). In IFT-tolerant cotton, producers will have the flexibility to apply IFT PRE or EPOST.

In 2019 and 2020, field experiments were established to investigate the utility of IFT-tolerant cotton herbicide programs in terms of weed control and crop safety. The objectives of these studies were to determine the effectiveness of different IFT-based herbicide programs on Palmer amaranth and to evaluate crop safety and tolerance of IFT-tolerant cotton to different IFT-based herbicide programs in Arkansas.

Materials and Methods

Crop Safety

A regulated field trial was conducted in the summers of 2019 and 2020 to determine the crop safety of various IFT-based herbicide programs in IFT-tolerant cotton. Field trials were conducted at the Lon Mann Cotton Research and Extension Center near Marianna, AR (-34.73, -90.74), on a Convent silt loam soil with 1% organic matter, 7% clay, 1% sand, and 92% silt (USDA-NRCS 2020). Each plot measured 3.9 m wide and 9.1 m long with 96-cm row spacings, allowing for four rows per plot with the two center rows being utilized for data collection and the outside rows acting as a buffer between applied treatments. Prior to planting, the experimental area was tilled and bedded. The trial was seeded with a four-row cone planter (Almaco, Nevada, IA) at a rate of 114,000 seeds ha^{-1} to a glufosinate, glyphosate, and IFT-tolerant cotton variety (experimental, BASF, Research Triangle, NC) In 2019, the trial was seeded and initiated on May 16th and on May 12th in 2020. The experiment was designed as a single-factor, randomized complete block design with four replications. The entire study and associated buffer area were fertilized based off of typical cotton production practices for the state of Arkansas (Robertson et al. 2021). Supplemental irrigation was provided via in-furrow irrigation when rainfall was not sufficient.

Treatments consisted of different herbicide programs utilizing IFT either PRE or EPOST along with a herbicide program that lacked IFT and a nontreated control for comparison (Tables 1 and 2). Herbicide treatments were applied at 140 L ha^{-1} using a CO_2-pressurized backpack sprayer using TeeJet® AIXR 110015 nozzles (TeeJet Technologies, Springfield IL 62703), and layby applications were made using a single-nozzle boom with a TeeJet® XR8002E even flat fan nozzle. Herbicide programs were applied according to standard cotton production practices with the PRE applications being applied at planting (0 days after planting), the EPOST were made 21 days after planting, the mid-postemergence applications (MPOST) being applied at 42 days after planting, and the layby applications being made prior to canopy closure (approximately 63 days after planting). In addition to herbicide applications, plots were hand-weeded as needed to prevent weed interference with cotton. A 20-m buffer of Deltapine 1518XF (Bayer Crop Science, St. Louis, MO) cotton was planted in all directions from the trial and destroyed prior to harvest to prevent outcrossing from the experimental seed.

Stand counts were taken at 14 days after planting from 2 meters of row in each plot. To evaluate phytotoxic crop injuries, visual estimations of crop injury (ratings)were taken weekly until 28 days after the layby application. Ratings were based on a 0 to 100 scale, with 0 representing no injury and 100 representing plant death. Days to 70% boll opening were taken prior to maturity and were made relative to the nontreated check in each block. Seedcotton yield was determined at cotton maturity using a two-row cotton picker, and 40 representative bolls collected per plot for fiber quality analysis (Kothari et al. 2017). Fiber quality analysis was conducted at the west Tennessee Research and Extension Center in Jackson, TN and resulted in measurements for micronaire, fiber length, uniformity, fiber strength, and elongation.

Weed Control

To evaluate the efficacy of the addition of IFT into cotton herbicide programs, studies were conducted during the summers of 2019 and 2020 at the Lon Mann Cotton Research and Extension Center near Marianna, AR, on a Convent silt loam soil similar to the crop tolerance study. In both site-years, herbicide programs were applied in bare ground conditions, which were tilled and bedded prior to PRE applications. Plots measured 1.9 m wide by 6.1 m long. The treatments and treatment structure were the same as the crop safety study (Table 2), and all applications were made at the same time as in the crop safety study. Applications were made with a CO_2-pressurized backpack sprayer using TeeJet® AIXR 110015 nozzles at 140 L ha^{-1}. Visual estimations of control of a natural population of weeds were taken every seven days following the first application until 28 days after the layby application. In 2019, Palmer amaranth, entireleaf morningglory, johnsongrass, and broadleaf signalgrass were rated. In 2020, Palmer amaranth and entireleaf morningglory were rated. Groundcover was measured with drone imagery from a height of 55 m taken 14 days after the EPOST and MPOST applications in 2020 and 14 days after the layby application in 2019 using a DGI Phantom 4 PRO (DGI, Shenzhen, China). Percent groundcover was subsequently calculated from field imagery using the Field Analyzer software to compare groundcover coverage between treatments (Turf Analyzer, Fayetteville, AR).

Statistical Analysis

Data were analyzed using R Statistical Software v 4.0.3 (R Foundation, Vienna, Austria). Prior to final model selection, data were evaluated for normality using Shapiro-Wilks tests, and equal variance was determined by plotting the residuals of the model (Kniss and Streibig 2018). Variables that met both normality and homogeneity of variance assumptions were evaluated with linear models using base functions. Variables that failed normality or variance assumptions were then analyzed using a nonparametric factorial model using the *rankFD* package (Brunner et al. 1997, 2019) to test for year-by-treatment interactions, which were not significant for all experimental variables. Treatment effects across year and replication were subsequently determined with a Friedmans test using the *pgirmess* package (Giraudoux et al. 2018). The effect of year was then determined through a non-parametric Kruskal-Wallis Test (Kruskal and Wallis 1952; Shah and Madden 2004) using the *pgirmess* package. Orthogonal contrast analyses were conducted to evaluate Palmer amaranth control to compare the use of IFT to the nontreated, the use of IFT PRE to EPOST, the use of residual herbicides at MPOST, and the use of layby applications. Following model selection, data were then subjected to Type I ANOVA, and means were separated using least significant differences with Tukey's adjustment at α=0.05.

Results and Discussion

Crop Safety

Differences in cotton tolerance were observed over the course of the two site-years for the study (Tables 3 and 4). While cotton stand at 14 days after planting was not significant for herbicide program and site-year (Table 3), preemergence treatments were determined to have a significant influence on cotton injury at 14 days after treatment (Table 3). Across both site-years, stand-alone PRE applications of fluometuron resulted in the lowest crop injury (1%). In contrast, PRE applications of fluridone resulted in higher crop injury in both site-years (6%), though this program was not significantly different than any other program besides the programs that utilized only fluometuron PRE. Crop injury caused by PRE-applied IFT-containing programs was not higher or lower in either site-year to that of other programs (2 to 5% crop injury) (Table 5). All PRE herbicide programs resulted in ≤ 10% crop injury, which has been used as a standard injury threshold in cotton (Jordan et al. 1993). At 14 days after EPOST, crop safety was similar for all herbicide programs averaged over site-years (Table 5), although averaged over treatments, differences were observed between site-years (Table 5). Injury was significantly lower in 2019 than in 2020 (Table 6), presumably due to differences in environmental conditions following application between the two site-years, with more rainfall and cooler conditions following application in 2020 than 2019 (Figures 1). These conditions may have slowed the metabolism of herbicides by the cotton plants and inhibited the recovery of the cotton by slowing the growth rate, especially in the early growth stages of cotton (Reddy et al. 1992).

At 14 days after the MPOST (DAMP), there was a significant treatment-by-site-year interaction (Table 3). In 2019, cotton injury was influenced by herbicide treatment. Three programs caused injury to cotton in 2019; (Program 2) fluometuron followed by glufosinate plus *S*-metolachlor followed by glyphosate + glufosinate+ acetochlor; (Program 9) fluometuron followed by IFT, glufosinate; and glyphosate followed by *S*-metolachlor, glufosinate, and glyphosate; and (Program 10) fluridone with fluometuron followed by IFT, glufosinate, and glyphosate followed by *S*-metolachlor, glufosinate, and glyphosate (2%, 3%, and 1% crop injury, respectively). However, the injury that resulted in programs 2 and 10 was not found to be statistically different than those programs that did not express any injury (Table 5). Injury observed in these programs was most likely due to the addition of chloroacetamide herbicides in the MPOST application. Applications of chloroacetamide herbicides and glufosinate have been shown to be injurious to glufosinate-tolerant cotton, but well within commercial tolerance and not detrimental to yield (Culpepper et al. 2009). Injury in 2019 was also within acceptable levels. In 2020, there were no differences among the programs and all injury was less than the 10% acceptable injury threshold. There was also not a program effect at 14 days following the layby application in either year, although there was a difference between the two site-years of the study. Cotton injury was greater in 2020 than in 2019, presumably due to higher temperatures in 2020 after application compared to 2019 (Figure 1).

Cotton boll opening was also not affected by treatment. Seventy percent boll opening was different between site-years, with 2020 reaching 70% boll opening 1 day later than in 2019 (Table 6). This may be because two hurricanes passed over the trial after defoliation in 2020. Despite the hurricanes and any observed injury in the field, there were no differences in yield among the treatments or between years. Fiber quality measurements did not differ among treatments (Table 4). There was a year effect on fiber length and uniformity, with 2020 having lower fiber length and uniformity (Table 6). These differences are attributed to the environmental conditions post-desiccation, primarily due to the hurricane events.

The above results support that the addition of IFT to cotton weed management herbicide programs is suitable for IFT-tolerant cotton systems. Crop injury measured throughout the growing season in both site-years was within the range of acceptable crop safety. Most injury appeared to be transient and dissipated throughout the season and did not have any impact on cotton yield. Fiber quality was not influenced by the presence or absence of IFT in the herbicide programs either.

Weed Control

At 21 days following planting, Palmer amaranth control among the herbicide programs did not differ, although there was a difference between site-years (Table 7). The difference in year showed that there was greater overall control in 2020 than in 2019 in all programs, potentially because of differences in weed population dynamics and environment, as the experiment were not conducted in the same area of the field in consecutive years (Table 8). At 21 days after EPOST (DAEP), weed control among herbicide treatments did not differ for entireleaf morningglory, broadleaf signalgrass, or johnsongrass (Tables 7 and 9). There was, however, a significant treatment-by-year interaction at 21 DAEP for Palmer amaranth (Table 7). Treatment had an effect on Palmer amaranth control in 2019, whereas all herbicide programs provided similar control in 2020. In 2019, treatments utilizing IFT PRE in combination with fluridone or fluometuron were found to be the most efficacious (Table 10). These findings are similar to those of Chalal and Jhala (2018), where there was greater Palmer amaranth control when IFT was mixed with a PSII herbicide such as fluometuron. Groundcover analysis following the EPOST application was not significant across herbicide program (Table 9). Contrast analyses determined that there was not a difference between the use of IFT PRE or EPOST at 21 DAEP (P=0.189) as well as between the presence or absence of IFT in the program (P=0.841) (Data not shown). While the addition of IFT did not enhance Palmer amaranth control at this location, IFT did add an additional site of action without detriment to weed control, potentially aiding in the delay of herbicide-resistance evolution. In production areas where Palmer amaranth may be resistant to HPPD, PSII, or both sites of action, the use of IFT with a PSII herbicide such as fluometuron may still be able to provide some control where fluometuron alone may not due to the synergistic behavior that has been shown to overcome resistance to these sites of action (Chahal and Jhala 2018; Chahal et al. 2019).

There were differences among herbicide programs and between site-years at 14 DAMP for Palmer amaranth control (Table 7). Herbicide programs 2 (fluometuron PRE followed by glufosinate and *S*-metolachlor EPOST followed by glyphosate, glufosinate, and acetochlor MPOST) and 9 (fluometuron PRE followed by IFT, glufosinate, and glyphosate EPOST followed by *S*-metolachlor, glufosinate, and glyphosate MPOST) resulted in 91% Palmer amaranth control, which was the greatest observed control, but were not different than any other herbicide program besides program 7 (IFT and fluometuron PRE followed by glufosinate and *S*-metolachlor EPOST followed by glyphosate and glufosinate MPOST), which only resulted in 68% Palmer amaranth control (Table 10). Based on contrast analyses comparing programs that included a residual chloroacetamide herbicide at MPOST to those that did not, those programs that included a residual resulted in greater Palmer amaranth control at 14 DAMP and 28 days after layby (Table 12). At 14 DAMP, Palmer amaranth control for those plots utilizing residual herbicides was 89% on average while those that did not resulted in 73% control on average. These results are likely due to the residual weed control activity that chloroacetamide herbicides have, prolonging the control of weeds such as Palmer amaranth (Culpepper et al. 2009; Norsworthy et al. 2012; Riar et al. 2013). While there were differences in observed weed control, there were no differences in weed groundcover at the MPOST timing (Tables 8 and 9).

Entireleaf morningglory control was influenced by herbicide program at 14 DAMP. Programs 2 (fluometuron PRE followed by glufosinate and S-metolachlor EPOST followed by glyphosate, glufosinate, and acetochlor MPOST), 8 (IFT and fluometuron PRE followed by glufosinate and S-metolachlor EPOST followed by glyphosate and glufosinate MPOST) and 9 (fluometuron PRE followed by IFT, glufosinate, and glyphosate EPOST followed by S-metolachlor, glufosinate, and glyphosate MPOST) all resulted in 89% control. These three programs were similar to all other programs besides Program 3 (isoxaflutole with diuron followed by dimethenamid-P with glufosinate fb glyphosate with glufosinate) and Program 10 (fluridone with fluometuron followed by IFT, glufosinate, and glyphosate followed by *S*-metolachlor, glufosinate, and glyphosate) with 73 and 68% control, respectively (Table 10). Lack of control was likely the result of newly emerged weeds at this time period as the residuals in these two programs at PRE and EPOST are not completely effective at controlling morningglory species, particularly fluometuron (Anonymous 2019), isoxaflutole (Stephenson and Bond 2012), and diuron (Anonymous 2021). The control from Program 10 was similar to control provided by Program 4 and 5 while Program 3 resulted in similar entireleaf morningglory control as Programs 4, 5, 6, and 7 (Table 10). Unlike Palmer amaranth, contrast analysis of the use of residual herbicides in the MPOST applications were not significant, as the addition of chloroacetamide herbicides did not provide any additional benefit for morningglory control (Table 12). This is expected, as typically, morningglory species are not controlled by chloroacetamide herbicides (Anonymous 2018, 2020). Control for the two grass species, johnsongrass and broadleaf signalgrass, were not impacted by herbicide program or by the inclusion of a residual at the MPOST application at 14 DAMP as control for all programs was greater than 95% (Table 11).

The observed Palmer amaranth, entireleaf morningglory, johnsongrass, and broadleaf signalgrass control following the layby applications was different among treatments. Programs that utilized a layby application had the greatest Palmer amaranth control ranging from 67 to 85%, while Palmer amaranth control in programs without layby applications ranged from 35 to 36% (Table 10). Similar trends were seen in broadleaf signalgrass, johnsongrass (Table 12), and entireleaf morningglory (Table 10). Contrast analysis comparing the use of layby applications to not resulted in a significant increase in average weed control for all species evaluated. With the addition of a layby application, Palmer amaranth control increased from 36 to 78%, entireleaf morningglory control increased from 49 to 80%, broadleaf signalgrass control increased from 64 to 88% and johnsongrass control increased from 47 to 83% at 28 days after layby applications (Table 12).

Aerial imagery data suggests that the weedy groundcover was also influenced by treatment following the layby application. Just as with the observed Palmer amaranth control, the treatments that utilized a layby application decreased weedy groundcover relative to no layby application (Table 11). The use of the additional herbicide application provided plots with greater weed control primarily due the longer residual activity of the herbicides applied as well as additional postemergence weed control. Although the study was conducted in a bare ground setting, similar results would likely be observed in a row-crop environment, though potentially to a lesser extent due to the added benefit of crop canopy closure. Despite this limitation, use of additional successful herbicide applications and layered residuals have been shown previously to improve weed control in cotton (Price et al. 2008).

The findings from these studies indicate that the integration of IFT into cotton herbicide programs provide comparable control of weeds such as Palmer amaranth without sacrificing yield or fiber quality in IFT-tolerant cotton systems. The addition of IFT will provide an additional herbicide site of action for cotton production acres while planted to cotton, which will be paramount for combating further herbicide resistance evolution. It should be noted that successful, season-long weed control was only attained through the use of complete herbicide programs and these strategies, as well as the incorporation of holistic integrated weed management strategies, will need to be implemented to aid in the longevity of these new technologies (Norsworthy et al. 2012).

Acknowledgments

Funding for this research was provided by BASF Corporation.

References

Anonymous (2018) Warrant Herbicide Label. Monsanto Company, St. Louis, MO. https://s3-us-west-1.amazonaws.com/agrian-cg-fs1-production/pdfs/Warrant_Herbicide1c_Label.pdf. Accessed February 17, 2021

Anonymous (2019) Brake Herbicide Label. SePRO Corporation, Carmel, IN. https://www.sepro.com/Documents/Brake-Herbicide_Label.pdf, Accessed February 17, 2021

Anonymous (2020) Dual II Magnum Herbicide. Syngenta Crop Protection LLC, Greensboro, NC. https://www.syngenta-us.com/current-label/dual_ii_magnum. Accessed February 17, 2021.

Anonymous (2021) Direx 4L Herbicide Label. ADAMA, Raleigh, NC. https://assets.greenbook.net/L119813.pdf, Accessed February 17, 2021.

Barber L, Boyd J, Norsworthy J, Burgos N, Bertucci M, Selden G (2021) MP44: Recommended Chemicals for weed and brush control. University of Arkansas System Division of Agriculture, Cooperative Extension Service

Brabham C, Norsworthy JK, Houston MM, Varanasi VK, Barber T (2019) Confirmation of *S*-metolachlor resistance in Palmer amaranth (*Amaranthus palmeri*). Weed Technol 33:720-726

Brunner E, Bathke AC, Konietschke F (2019) Designs with three and more factors. Pages 333–355 *in* Rank and pseudo-rank procedures for independent observations in factorial designs. Springer

Brunner E, Dette H, Munk A (1997) Box-type approximations in nonparametric factorial designs. J Am Statistical Assoc 92:1494-1502

Burgos NR, Kuk YI, Talbert RE (2001) *Amaranthus palmeri* resistance and differential tolerance of *Amaranthus palmeri* and *Amaranthus hybridus* to ALS-inhibitor herbicides. Pest Manag Sci 57:449-457

Chahal PS, Jugulam M, Jhala AJ (2019) Basis of atrazine and mesotrione synergism for controlling atrazine- and HPPD inhibitor-resistant Palmer amaranth. Agron J 111:3265-3273

Chahal PS, Jhala AJ (2018) Interaction of PS II- and HPPD-inhibiting herbicides for control of Palmer amaranth resistant to both herbicide sites of action. Agron J 110:2496-2506

Culpepper AS, York AC, Robert P, Whitaker JR (2009) Weed control and crop response to glufosinate applied to “PHY 485 WRF” cotton. Weed Technol 23:356-362

DeVore JD, Norsworthy JK, Brye KR (2012) Influence of deep tillage and a rye cover crop on glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) emergence in cotton. Weed Technol 26:832-838

Giraudoux P, Antonietti JP, Beale C, Pleydell D, Treglia M (2018) pgirmess: spatial analysis and data mining for field ecologists. https://cran.r-project.org/web/packages/pgirmess/index.html. Accessed February 1, 2021

Gossett BJ, Murdock EC, Toler JE (1992) Resistance of Palmer amaranth (*Amaranthus palmeri*) to the dinitroaniline herbicides. Weed Technol 6:587-591

Heap I (2021) International Survey of Herbicide Resistant Weeds. http://www.weedscience.org/Summary/Species.aspx?WeedID=14. Accessed January 22, 2021

Jhala AJ, Sandell LD, Rana N, Kruger GR, Knezevic SZ (2014) Confirmation and control of triazine and 4-hydroxyphenylpyruvate dioxygenate-inhibiting herbicide resistant Palmer amaranth (*Amaranthus palmeri*) in Nebraska. Weed Technol 28:28-38

Jordan DL, Frans RE, McClelland MR (1993) Cotton (*Gossypium hirsutum*) response to DPX-PE350 applied postemergence. Weed Technol 7:159-162

Kniss AR, Streibig JC (2018) Statistical analysis of agricultural experiments using R. https://Rstats4ag.org. Accessed February 1, 2021

Kohrt JR, Sprague CL (2017) Herbicide management strategies in field corn for a three-way herbicide-resistant Palmer amaranth (*Amaranthus palmeri*) population. Weed Technol 31:364-372

Kothari N, Hinze L, Dever J, Hague S (2017) Boll sampling protocols and their impact on measurements of cotton fiber quality. Ind Crops Prod 109:248-254

Kruskal WH, Wallis WA (1952) Use of ranks in one-criterion variance analysis. J Am Statisitical Assoc 47:583-621

Meyer CJ, Norsworthy JK, Young BG, Steckel LE, Bradley KW, Johnson WG, Loux MM, Davis VM, Kruger GR, Bararpour MT, Ikley JT, Spaunhorst DJ, Butts TR (2016) Early-season Palmer amaranth and waterhemp control from preemergence programs utilizing 4-hydroxyphenylpyruvate dioxygenase-inhibiting and auxinic herbicides in soybean. Weed Technol 30:67-75

Morgan GD, Bautmann PA, Chandler JM (2001) Competetive impact of Palmer amaranth (*Amaranthus palmeri*) on cotton. Weed Technol 15:408-412

Norsworthy JK, Griffith GM, Scott RC, Smith KL, Oliver LR (2008) Confirmation and control of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) in Arkansas. Weed Technol 22:108-113

Norsworthy JK, Ward SM, Shaw DR, Llewellyn R, Nichols RL, Webster TM, Bradley KW, Frisvold G, Powles SB, Burgos NR, Witt W, Barrett M (2012) Reducing the risks of herbicide resistance: best management practices and recommendations. Weed Sci 60 (SI I):31-62

Price AJ, Koger CH, Wilcut JW, Miller D, van Santen E (2008) Efficacy of residual and non-residual herbicides used in cotton production systems when applied with glyphosate, glufosinate, or MSMA. Weed Technol 22:459-466

Reddy KR, Reddy VR, Hodges HF (1992) Temperature effects on early season cotton growth and development. Agron. J. 84:229-237

Riar DS, Norsworthy JK, Steckel LE, Stephenson DO, Eubank TW, Scott RC (2013) Assessment of weed management practices and problem weeds in the midsouth United States-soybean: a consultant's perspective. Weed Technol 27:612-622

Robertson B, Barber T, Lorenz G (2021) 2021 Arkansas Cotton Quick Facts. University of Arkansas System Division of Agriculture Research and Extension. Online. Accessed October 5, 2021. Accessed at https://www.uaex.edu/farm-ranch/crops-commercial-horticulture/verification/2021_Arkansas_Cotton_Quick_Facts_final_accessible.pdf

Rowland MW, Murray DS, Verhalen LM (1999) Full-season palmer amaranth (*Amaranthus palmeri*) interference with cotton (*Gossypium hirsutum*). Weed Sci 47:305-309

Sauer, JD 1972. The dioecious amaranths: a new species name and major range extensions. Madrono 21:426-434

Shah DA, Madden LV (2004) Nonparametric analysis of ordinal data in designed factorial experiments. Phytopathology 94:33–42

Shyam C, Borgato EA, Peterson DE, Dille JA, Jugulam M (2021) Predominance of metabolic resistance in a six-way-resistant Palmer amaranth (*Amaranthus palmeri*) population. Front Plant Sci 11:614618

Smith DT, Baker RV, Steele GL (2000) Palmer amaranth *(Amaranthus palmeri*) impacts on yield, harvesting, and ginning in dryland cotton (*Gossypium hirsutum*). Weed Technol 14:122-126

Steckel, LE (2020) Dicamba-resistant Palmer amaranth in Tennessee: stewardship even more important. The University of Tennessee Institute of Agriculture. Available. https://news.utcrops.com/2020/07/dicamba-resistant-palmer-amaranth-in-tennessee-stewardship-even-more-important/. Accessed February 1, 2021

Stephenson DO, Bond JA (2012) Evaluation of thiencarbazone-methyl and isoxaflutole-based herbicide programs in corn. Weed Technol 26:37-42

USDA-Natural Resources Conservation Service (NRCS), United States Departments of Agriculture. (2020) Web Soil Survey. Available: http://websoilsurvey.sc.egov.usda.gov/. Accessed February 1, 2021

Van Wychen L (2019) 2019 Survey of the most common and troublesome weeds in broadleaf crops, fruits & vegetables in the United States and Canada. Weed Science Society of

America National Weed Survey Dataset. Available: http:/wssa.net/wp-content/uploads/2016_Weed_Survey_Final.xlsx Accessed February 7, 2020

Varanasi VK, Brabham C, Norsworthy JK (2018) Confirmation and characterization of non-target site resistance to fomesafen in Palmer amaranth. Weed Sci 66:702-709

Tables and Figures

Table 1. Herbicide information for all products used in both experiments.

Common name	**Product name**	**Manufacturer**	**Address**
Acetochlor	Warrant	Bayer Crop Science	Research Triangle Park, NC
Dimethenamid-P	Outlook	BASF	Research Triangle Park, NC
Diuron	Direx	Adama	Raleigh, NC
Flumioxazin	Valor	Valent	Walnut Creek, CA
Fluometuron	Cotoran	Syngenta Crop Protection LLC	Greensboro, NC
Fluridone	Brake	SePRO Corp.	Carmel, IN
Glufosinate	Liberty	BASF	Research Triangle Park, NC
Glyphosate	Roundup PowerMax	Bayer Crop Science	Research Triangle Park, NC
Isoxaflutole	ALITE 27	BASF	Research Triangle Park, NC
MSMA	MSMA	Drexel Chemical Co.	Memphis, TN
Pendimethalin	Prowl H2O	BASF	Research Triangle Park, NC
S-metolachlor	Dual Magnum	Syngenta Crop Protection LLC	Greensboro, NC

Table 2. Treatment structure for both experiments in 2019 and 2020 at the Lon Mann Cotton Research Station near Marianna, AR.[a]

Program	Timing	Common name(s)	Product name(s)	Rate (g ai or ae ha^{-1})
1	None	-------	--------	-------
2	PRE	Fluometuron	Cotoran	1120
	EPOST	Glufosinate + *S*-metolachlor	Liberty + Dual Magnum	656 + 1068
	MPOST	Glyphosate + Glufosinate +Acetochlor	Roundup Powermax + Liberty + Warrant	1260 + 656 + 1052
	LAYBY	Diuron + MSMA	Direx + MSMA	560 + 1963
3	PRE	Isoxaflutole + Diuron	ALITE 27 + Direx	105 + 560
	EPOST	Dimethenamid-P + Glufosinate	Outlook + Liberty	840 + 880
	MPOST	Glufosinate + Glyphosate	Liberty + Roundup PowerMax	880 + 1740
4	PRE	Isoxaflutole + Pendimethalin	ALITE 27 + Prowl H20	105 + 1065
	EPOST	Dimethenamid-P + Glufosinate	Outlook + Liberty	840 + 880
	MPOST	Glufosinate + Glyphosate	Liberty + Roundup PowerMax	880 + 1740
5	PRE	Isoxaflutole + Diuron + Pendimethalin	ALITE 27 + Direx + Prowl H20	105 + 560 + 1065
	EPOST	Dimethenamid-P + Glufosinate	Outlook + Liberty	840 + 880
	MPOST	Glufosinate + Glyphosate	Liberty + Roundup PowerMax	880 + 1740
6	PRE	Isoxaflutole + Prometryn	ALITE 27 + Caparol	105 + 1120
	EPOST	Glufosinate + *S*-metolachlor	Liberty + Dual Magnum	880 + 1068
	MPOST	Glufosinate + Glyphosate	Liberty + Roundup PowerMax	880 + 1740
	LAYBY	Flumioxazin + MSMA	Valor + MSMA	72 + 1963
7	PRE	Isoxaflutole + Fluometuron	ALITE 27 + Cotoran	105 + 1120
	EPOST	Glufosinate + *S*-metolachlor	Liberty + Dual Magnum	880 + 1068
	MPOST	Glufosinate + Glyphosate	Liberty + Roundup PowerMax	880 + 1740
	LAYBY	Flumioxazin + MSMA	Valor + MSMA	72 + 1963
8	PRE	Isoxaflutole + Fluridone	ALITE 27 Brake	105 + 168
	EPOST	Glufosinate + *S*-metolachlor	Liberty + Dual Magnum	880 + 1068
	MPOST	Glufosinate + Glyphosate	Liberty + Roundup PowerMax	880 + 1740
	LAYBY	Flumioxazin + MSMA	Valor + MSMA	72 + 1963
9	PRE	Fluometuron	Cotoran	1120
	EPOST	Isoxaflutole + Glufosinate + Glyphosate	ALITE 27 + Liberty + Roundup PowerMax	105 + 880 + 1740
	MPOST	*S*-metolachlor + Glufosinate + Glyphosate	Dual Magnum + Liberty + Roundup PowerMax	1068 + 880+ 1740
	LAYBY	Flumioxazin + MSMA	Valor + MSMA	72 + 1963
10	PRE	Fluridone + Fluometuron	Brake + Cotoran	168 + 1120
	EPOST	Isoxaflutole + Glufosinate + Glyphosate	ALITE 27 + Liberty + Roundup PowerMax	105 + 880 + 1740
	MPOST	*S*-metolachlor + Glufosinate + Glyphosate	Dual Magnum + Liberty + Roundup PowerMax	1068 + 880+ 1740
	LAYBY	Flumioxazin + MSMA	Valor + MSMA	72 + 1963

[a] Abbreviations PRE=preemergence, EPOST=first postemergence application, MPOST=second postemergence application

Table 3. P-values for cotton crop safety by treatment and year for cotton injury at 14 days after preemergence, early-postemergence, mid-postemergence, and layby application, stand, boll opening, and yield at the Lon Mann Cotton Research Center near Marianna, AR.[a,b]

Source	Cotton injury						
	14 DAP	14 DAEP	14 DAMP	14 DA Layby	Stand	Boll opening	Yield
	---------- P-values ----------						
Treatment	**0.0067**	0.5110	0.5204	0.6678	0.7827	0.3007	0.7843
Year	0.8401	**<0.0001**	**<0.0001**	**<0.0001**	0.3054	**0.0380**	0.1069
Treatment*Year	0.4977	0.7374	**0.0353**	0.6660	0.9376	0.5430	0.8485

[a] Abbreviations: DAP=days after preemergence, DAEP=days after first postemergence application, DAMP=days after second postemergence application, DA Layby=days after layby application

[b] Bolded values are statistically significant at α<0.05.

Table 4. P-values for cotton fiber quality by treatment and year for micronaire, fiber length, fiber uniformity, fiber strength, and fiber elongation at the Lon Mann Cotton Research Center near Marianna, AR.

Source	Micronaire	Fiber length	Uniformity	Fiber strength	Fiber elongation
	---------- P-values ----------				
Treatment	0.8964	0.8667	0.9535	0.9716	0.8719
Year	0.1276	**<0.0001**[a]	**0.0342**	0.4197	0.1016
Treatment*Year	0.9612	0.9551	0.9321	0.6994	0.6331

[a] Bolded values are statistically significant at α<0.05.

Table 5. Injury to isoxaflutole-tolerant cotton at 14 days after preemergence applications, averaged over 2019 and 2020 and injury 14 days after mid-POST application in 2019 at the Lon Mann Cotton Research Station near Marianna, AR.[a,b]

	Cotton injury	
Herbicide program	14 DAP	14 DAMP 2019
	---------------- % -----------------	
2: Fluo PRE fb Glu+Smoc EPOST fb Gly+Glu+Ace MPOST fb Diuron+MSMA Layby	1 b	2 ab
3: IFT+Diuron PRE fb Dim+Glu EPOST fb Gly+Glu MPOST	2 ab	0 b
4: IFT+Pendimethalin PRE fb Dim+Glu EPOST fb Gly+Glu MPOST	3 ab	0 b
5: IFT+Diuron+Pendimethalin PRE fb Dim+Glu EPOST fb Gly+Glu MPOST	4 ab	0 b
6: IFT+Prometryn PRE fb Glu+Smoc EPOST fb Glu+Ggly MPOST fb Flum+MSMA Layby	3 ab	0 b
7: IFTt+Fluo PRE fb Glu+Smoc EPOST fb Gly+Glu MPOST fb Flum+MSMA Layby	5 ab	0 b
8: IFT+Fluridone PRE fb Glu+Smoc EPOST fb Gly+Glu MPOST fb Flum+MSMA Layby	5 ab	0 b
9: Fluo PRE fb IFT+Glu+Gly EPOST fb Smoc+Glu+Gly MPOST fb Flum+MSMA Layby	1 b	3 a
10: Fluridone+Fluo PRE fb IFT+Glu+Gly EPOST fb Smoc+Glu+Gly MPOST fb Flum+MSMA Layby	6 a	1 ab

[a] Abbreviations: fluo=fluometuron, glu=glufosinate, smoc=*S*-metolachlor, gly=glyphosate, ift=isoxaflutole, dim=dimethenamid-P, flum=flumioxazin, PRE=preemergence, DAP=days after preemergence, EPOST= first postemergence application; MPOST=second postemergence application, DAMP=days after second postemergence application

[b] Means followed by the same letter within a column are not statistically different based on Tukey's (α=0.05)

Table 6. Cotton injury at 14 days after early-postemergence and layby, visual emergence at 14 days after planting, relative boll opening, fiber length, and fiber uniformity averaged over treatment at the Lon Mann Cotton Research Station near Marianna, AR, in 2019 and 2020.[a,b]

	Cotton injury				
Year	14 DAEP	14 DA Layby	Relative 70% boll opening	Relative fiber length	Relative fiber uniformity
	--------------------%--------------------		Days	---------------------------%---------------------------	
2019	3 b	0 b	+1 b	100 a	100 a
2020	8 a	4 a	+2 a	97 b	99 b

[a] Abbreviations: DAEP=days after first postemergence application, DA Layby=days after layby application

[b] Means followed by the same letter within a column are not statistically different based on Tukey's (α=0.05).

Table 7. P-values for Palmer amaranth and entireleaf morningglory control at the Lon Mann Cotton Research Station near Marianna, AR, in 2019 and 2020.[a,b]

Source	Palmer amaranth control				Entireleaf morningglory control		
	21 DAP	21 DAEP	14 DAMP	28 DA Layby	21 DAEP	14 DAMP	28 DA Layby
	-- P-values ---						
Treatment	0.2018	0.4529	**0.0002**	**<0.0001**	0.3172	**0.0234**	**<0.0001**
Year	**0.0002**	**<0.0001**	**0.0003**	0.1786	**<00.001**	**<0.0001**	0.0931
Treatment*Year	0.3713	**0.0233**	0.5064	0.2536	0.4192	0.4392	0.5840

[a] Abbreviations: DAP=days after preemergence, DAEP=days after first postemergence application, DAMP=days after second postemergence application

[b] Bolded values are statistically significant at α=0.05 based on Tukey's.

Table 8. Palmer amaranth control by year at 21 days after preemergence and 14 days after mid-postemergence applications and entireleaf morningglory control at 14 days after mid-postemergence and 28 days after layby at the Lon Mann Cotton Research Station near Marianna, AR averaged over treatment.[a,b]

	Palmer amaranth control		Entireleaf morningglory control	
Year	21 DAP	14 DAMP	14 DAEP	14 DAMP
	-- % --			
2019	84 b	86 a	93 a	75 a
2020	95 a	72 b	72 b	65 b

[a] Abbreviations: PRE=preemergence, DAP=days after preemergence application, DAEP=days after first postemergence application, DAMP=days after second postemergence application

[b] Means followed by the same letter within a column are not statistically different based on Tukey's (α=0.05).

Table 9. P-values for weed groundcover at 14 days after early-postemergence in 2020, 14 days after mid-postemergence in 2019, 14 days after layby in 2019; johnsongrass control 21 days after early-postemergence, 14 days after mid-postemergence, and 28 days after layby in 2019; and broadleaf signalgrass control 21 days after early-postemergence, 14 days after mid-postemergence, and 28 days after layby in 2019 at the Lon Mann Cotton Research Station near Marianna, AR[a,b]

Source	Groundcover			Johnsongrass			Broadleaf signalgrass		
	14 DAEP 2020	14 DAMP 2019	14 DA Layby 2019	21 DAEP 2019	14 DAMP 2019	28 DA Layby 2019	21 DAEP 2019	14 DAMP 2019	28 DA Layby 2019
	---- P-values ----								
Treatment	0.3350	0.3863	**0.0001**	0.4613	0.2654	**<0.0001**	0.4735	**0.0289**	**0.0044**

[a] Abbreviations: DAEP=days after first postemergence application, DAMP=days after second postemergence application, DA Layby=days after layby application

[b] Bolded values are statistically significant at α=0.05.

Table 10. Observed control of Palmer amaranth at 21 days after early-POST in 2019, 14 days after mid-postemergence and 28 days after layby averaged over 2019 and 2020; entireleaf morningglory at 14 days after mid-POST and 28 days after layby averaged over 2019 and 2020 at the Lon Mann Cotton Research Center near Marianna, AR.[a,b]

Herbicide program	Palmer amaranth control				Entireleaf morningglory control	
	21 DAEP 2019	21 DAEP 2020	14 DAMP	28 DA Layby	14 DAMP	28 DA Layby
	%					
2: Fluo PRE fb Glu+Smoc EPOST fb Gly+Glu+Ace MPOST fb Diuron+MSMA Layby	79 b	70	91 a	84 a	89 a	85 a
3: IFT+Diuron PRE fb Dim+Glu EPOST fb Gly+Glu MPOST	95 ab	60	72 ab	36 b	73 bc	53 bc
4: IFT+Pendimethalin PRE fb Dim+Glu EPOST fb Gly+Glu MPOST	93 ab	55	74 ab	36 b	82 abc	48 c
5: IFT+Diuron+Pendimethalin PRE fb Dim+Glu EPOST fb Gly+Glu MPOST	89 ab	62	75 ab	35 b	80 abc	47 c
6: IFT+Prometryn PRE fb Glu+Smoc EPOST fb Glu+Ggly MPOST fb Flum+MSMA Layby	74 b	50	70 ab	74 a	85 ab	79 a
7: IFTt+Fluo PRE fb Glu+Smoc EPOST fb Gly+Glu MPOST fb Flum+MSMA Layby	98 a	56	68 b	80 a	85 ab	81 a
8: IFT+Fluridone PRE fb Glu+Smoc EPOST fb Gly+Glu MPOST fb Flum+MSMA Layby	98 a	60	79 ab	79 a	89 a	79 a
9: Fluo PRE fb IFT+Glu+Gly EPOST fb Smoc+Glu+Gly MPOST fb Flum+MSMA Layby	84 ab	71	91 a	85 a	89 a	83 a
10: Fluridone+Fluo PRE fb IFT+Glu+Gly EPOST fb Smoc+Glu+Gly MPOST fb Flum+MSMA Layby	92 ab	73	84 ab	67 a	68 c	76 ab

[a] Abbreviations: fluo=fluometuron, glu=glufosinate, smoc=*S*-metolachlor, gly=glyphosate, ace=acetachlor, ift=isoxaflutole, dim=dimethenamid-P, flum=flumioxazin, PRE = preemergence, DAP=days after preemergence application, DAEP=days after first postemergence application, DAMP=days after second postemergence application, DA Layby=days after layby application

[b] Means followed by the same letter within a column are not statistically different based on Tukey's (α=0.05)

Table 11. Visible estimates of broadleaf signalgrass control at 14 days after mid-postemergence and 28 days after layby in 2019; johnsonsgrass control at 28 days after layby in 2019 and groundcover at 14 days after layby at Marianna, AR[a,b]

	Broadleaf signalgrass control		Johnsongrass control	
Herbicide program	14 DAMP 2019	28 DA Layby 2019	28 DA Layby 2019	Layby groundcover
	%			
2: Fluo PRE fb Glu+Smoc EPOST fb Gly+Glu+Ace MPOST fb Diuron+MSMA Layby	99 a	99 a	99 a	0.354 ab
3: IFT+Diuron PRE fb Dim+Glu EPOST fb Gly+Glu MPOST	98 b	72 cd	50 c	11.215 a
4: IFT+Pendimethalin PRE fb Dim+Glu EPOST fb Gly+Glu MPOST	99 a	59 d	41 c	8.539 a
5: IFT+Diuron+Pendimethalin PRE fb Dim+Glu EPOST fb Gly+Glu MPOST	98 b	64 d	50 c	11.164 a
6: IFT+Prometryn PRE fb Glu+Smoc EPOST fb Glu+Ggly MPOST fb Flum+MSMA Layby	99 a	71 cd	74 b	0.090 ab
7: IFTt+Fluo PRE fb Glu+Smoc EPOST fb Gly+Glu MPOST fb Flum+MSMA Layby	99 a	78 bcd	89 ab	0.000 b
8: IFT+Fluridone PRE fb Glu+Smoc EPOST fb Gly+Glu MPOST fb Flum+MSMA Layby	99 a	89 abc	75 b	0.000 b
9: Fluo PRE fb IFT+Glu+Gly EPOST fb Smoc+Glu+Gly MPOST fb Flum+MSMA Layby	99 a	97 ab	79 b	0.000 b
10: Fluridone+Fluo PRE fb IFT+Glu+Gly EPOST fb Smoc+Glu+Gly MPOST fb Flum+MSMA Layby	99 a	95 ab	83 ab	0.003 b

[a] Abbreviations: fluo=fluometuron, glu=glufosinate, smoc=*S*-metolachlor, gly=glyphosate, ace=acetachlor, ift=isoxaflutole, dim=dimethenamid-P, flum=flumioxazin, PRE = preemergence, DAP=days after preemergence application, DAEP=days after first postemergence application, DAMP=days after second postemergence application, DA Layby=days after layby application

[b] Means followed by the same letter within a column are not statistically different based on Tukey's (α=0.05)

Table 12. Results of contrast analyses comparing the use of residuals or no residual in the mid-postemergence applications and the presence or absence of layby applications for Palmer amaranth, entireleaf morningglory, broadleaf signalgrass, and johnsongrass control averaged over year at the Lon Mann Cotton Research Station near Marianna, AR.[a,b,c]

	Palmer amaranth control			Entireleaf morningglory control			Broadleaf signalgrass control			Johnsongrass control		
Contrasts	With	Without	P-value	With	Without	P-value	With	Without	P-value	With	Without	P-value
	--------%---------			----------%----------			--------%----------			--------%--------		
MPOST Residual – No MPOST Residual 14 DAMP	89 a	73 b	**<0.001**	-	-	0.996	-	-	0.051	-	-	0.669
Layby- No Layby 28 DA Layby	78 a	36 b	**<0.001**	80 a	49 b	**<0.001**	88 a	64 b	**0.001**	83 a	47 b	**<0.001**

[a] DAMP=days after second postemergence application

[b] Bolded values are statistically significant at α=0.05.

[c] Values not shown due to insignificance

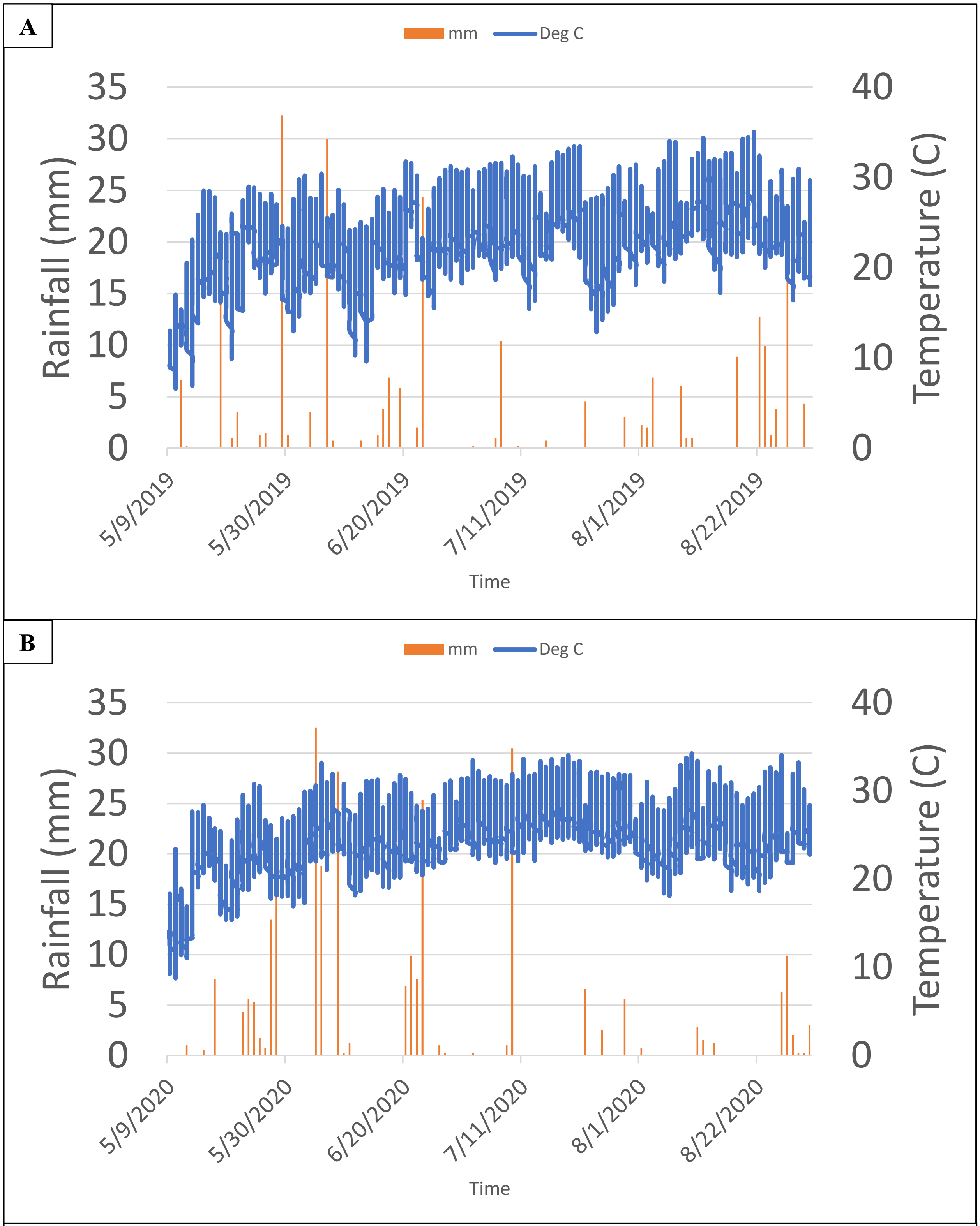

Figure 1: Rainfall and temperature data over the growing season at the Lon Mann Cotton Research Center near Marianna, AR in 2019 (a) and 2020 (b)

Chapter 3

Utility of Roller Wiper Applications of Dicamba for Palmer Amaranth Control in Soybean

Abstract

The commercialization of dicamba-resistant soybean has resulted in increased concern for off-target movement of dicamba onto sensitive vegetation. To mitigate the off-target movement through physical drift, one might consider use of rope wicks and other wiper applicators. Although wiper-type application methods have been efficacious in pasture settings, the utility of dicamba using wiper applicators in agronomic crops has not been investigated. To determine the utility of roller wipers for dicamba applications in dicamba-resistant soybean, two separate experiments were conducted in the summer of 2020 and replicated in both Keiser and Fayetteville, AR. The first study (Herbicide rate study) was designed as a randomized complete block with a three-factor factorial treatment structure, where the first factor was target height of the Palmer amaranth, the second factor was concentration of herbicide applied, and the third factor was number of directions wiped by the applicator. Utilizing multiple application directions and a 2:1:1 ratio of water:formulated glyphosate:formulated dicamba were the most efficacious practices for controlling Palmer amaranth. The high herbicide concentrations and wiping multiple directions increased soybean injury when the wiper contacted the crop, but no yield loss was observed becasue of this injury. The second study (Herbicide placement study) was designed as a three-factor factorial where the first factor was the placement of the application, the second factor was preemergence herbicide used, and the third factor was presence or absence of a second sequential application of dicamba 14 days following the initial application. Broadcast applications resulted in greater Palmer amaranth mortality than roller wiper applications, and the most effective roller wiper treatments were when two sequential applications were made inside the crop canopy. Roller wiper applications did not reduce soybean yield, thus wiper-type applications may be safely used in dicamba-resistant soybean, albeit the likelihood for off-target damage caused by volatilization of these treatments would need to be investigated.

Nomenclature: Dicamba; Palmer amaranth, *Amaranthus palmeri* (S.) Wats.; soybean, *Glycine max* (L.) Merr.

Key words: herbicide application techniques, herbicide-resistance, weed wiper, rope wick, wick applicator, spray drift management, herbicide coverage, resistance management

Introduction

Dicamba is a synthetic auxin herbicide (WSSA Group 4) that has been primarily used for broadleaf weed management. The use of dicamba in North America has been an integral aspect of weed management programs in corn (*Zea mays* L.), small grains, pasture, and rangeland for more than 50 years (Hartzler 2017; Keelin and Abernathy 1988; Schroeder and Banks 1989). The evolution of herbicide-resistant weeds such as Palmer amaranth, waterhemp [*Amaranthus tuberculatus* (Moq.) J. D. Sauer], and horseweed (*Conyza canadensis* L. Cronq.) in soybean has forced producers to seek alternative options for broadleaf weed management in broadleaf crops, such as the addition of dicamba (Heap 2020; Kruger et al. 2010; Norsworthy et al. 2008). In response to the growing number of herbicide-resistant broadleaf weeds in cotton (*Gossypium hirsutum* L.) and soybean, Monsanto, now owned by Bayer, developed crops that were resistant to both glyphosate and dicamba (Clemente et al. 2007). The commercialization of the herbicide Xtendimax plus VaporGrip and dicamba-resistant soybean branded as RoundupReady 2 Xtend Soybean in 2016 enabled producers to apply dicamba in-crop for broadleaf weed control.

Combinations of glyphosate and dicamba controlled 90 to 100% of glyphosate-resistant waterhemp, Palmer amaranth, and horseweed (Johnson et al. 2010). Applications of dicamba in dicamba-resistant cotton controlled 88 to 90% of protoporphyrinogen oxidase (PPO)-resistant Palmer amaranth in Arkansas at 21 days after treatment (DAT) (Coffman et al. 2021). Growers in Nebraska reported that the addition of dicamba to soybean herbicide programs resulted in improved weed control for 93% of growers surveyed (Werle et al. 2018). Concurrent with the commercialization of dicamba for in-crop use over soybean in 2016, there was an increase in complaints for auxin damage on non-dicamba resistant soybean. The off-target movement of dicamba was deemed to be caused primarily by three factors, volatilization, physical spray drift, and tank contamination (Cundiff et al. 2017; Steckel et al. 2010).

In order to prevent off-target movement of dicamba onto sensitive crops and vegetation, producers and researchers began to seek alternative management practices that would mitigate physical spray drift and tank contamination. The use of growing physical barriers such as corn (Vieira et al. 2018) and the use of hooded sprayers (Foster et al. 2018) to avert spray droplets from leaving the treated area have been shown to be viable options for mitigating physical, off-target herbicide movement. An additional method being considered by producers to reduce physical spray drift is the utilization of application technology that does not depend on broadcasting spray solution to control weeds. Rather than spraying droplets on weeds, wipers and wicks directly apply the herbicide onto the leaves of vegetation via contact with a saturated surface, such as a rope or fabric material (Ozkan 1995). By applying herbicide directly only to the targeted plants, the risk of off-target movement via physical drift is greatly decreased (Davison and Derrick 1983).

Wiper type applicators were initially utilized for applying auxin herbicides, such as 2,4-D, above broadleaf crops to selectively control broadleaf weeds that grew above the crop canopy (Hoette et al. 1982; Wills and McWhorter 1981). Prior to the development of glyphosate-resistant crops, rope wicks and wipers were used to apply glyphosate above crop canopies to effectively control weeds such as johnsongrass [*Sorghum halepense* (L.) Pers.], shattercane [*Sorghum bicolor* (L.) Moench spp.], and volunteer corn as long as the target weed remained above the crop canopy (Keeley et al. 1984: Schneider et al. 1982). However, to prevent potential crop injury, care had to be taken to prevent leaking or dripping of herbicide from pipes or improperly calibrated systems (Grekul et al. 2005; Hoette et al. 1982; Meyers et al. 2017; Moyo et al. 2008).

By using wiper-type applicators in crops resistant to herbicides such as dicamba, the risk for crop injury would be reduced and would potentially allow for producers to use a wiper type application within the crop canopy. To effectively assess the utility and feasibility of dicamba applications using a wiper-type applicator in dicamba-resistant soybean, two separate studies were conducted in the summer of 2020. The objectives of these studies were to determine optimal practices for a roller-wiper application, evaluate application timing, and measure coverage methods for maximizing Palmer amaranth control and evaluate crop safety from roller-wiper applications in dicamba-resistant soybean.

Materials and Methods

Two separate field experiments were both conducted in 2020 at the Northeast Research and Extension Center near Keiser, AR (35.68, -90.08) and at the Milo J. Schult Arkansas Agricultural Experiment Station at in Fayetteville, AR (36.09, -94.17). The purpose of these experiments was to investigate (1) the influence of weed height, herbicide concentration, and application direction on Palmer amaranth control in dicamba-resistant soybean (herbicide rate study) and (2) the impact that application method and the use or non-use of sequential herbicide applications has on weed control in dicamba-resistant soybean (herbicide placement study). Dicamba-resistant soybean (Asgrow 46X6, Bayer CropScience, St. Louis, MO) was planted on May 20 at both Keiser and Fayetteville. These locations are more 375 km apart. Row spacings were 97 cm in Keiser and 91 cm in Fayetteville. Both locations were furrow-irrigated to supplement natural rainfall. The soil texture at Fayetteville was a Captina silt loam (fine-silty, siliceous, active, mesic Typic Fragiudult) with a pH of 6.4. The soil texture at Keiser was a

Steele loamy sand (Sandy over clayey, mixed, superactive, nonacid, thermic Aquic Udifluvent) with a pH of 6.7 (USDA-NRCS 2021). Both sites had natural populations of glyphosate-resistant Palmer amaranth (Norsworthy 2021 personal communication).

The herbicide rate experiment was designed as a randomized complete-block design using a three-factor factorial (3 x 2 x 2) treatment structure that included a nontreated control and an additional comparison treatment where plots were subjected to a typical postemergence dicamba-based broadcast spray application. The broadcast program consisted of dicamba at 560 g ae ha^{-1} (Xtendimax Bayer Crop Science, St. Louis MO) plus glyphosate at 1260 g ae ha^{-1} (Roundup PowerMax II Bayer Crop Sciences, St. Louis MO) plus pyroxasulfone at 120 g ai ha^{-1} (Zidua WDG, BASF, Research Triangle Park, NC) followed by dicamba at 560 g ha^{-1} dicamba + glyphosate at 1260 g ha^{-1} + acetochlor at 1260 g ai ha^{-1} (Warrant, Bayer Crop Sciences, St. Louis, MO). The three factors of the experiment were target weed height at application (20-30 cm, 40-50 cm, 60-70 cm), herbicide concentration [1 part Xtendimax:1 part Roundup PowerMax:6 parts water (v:v:v) or 1 part Xtendimax:1 part Roundup PowerMax:2 parts water (v:v:v)], and application direction (one direction or two). Plots receiving applications from multiple directions were applied for the first time as the tractor moved down the rows and the second application was made in the opposite direction immediately after the tractor moved completely through the field and had turned to travel in the opposite direction. The plots measured 6.1 m in length and were two rows wide (1.8 m wide in Fayetteville and 1.9 m wide in Keiser) with a two-row non-treated running check on either side of the treated rows.

All plots excluding the nontreated control were treated with *S*-metolachlor at 562 g ha^{-1} (Dual Magnum, Syngenta Crop Protection, Basel Switzerland) at planting using a CO_2-pressurized backpack sprayer at 140 L ha^{-1} using AIXR 110015 nozzles (TeeJet Technologies, Wheaton, IL) to slow emergence of Palmer amaranth. Roller wiper treatments were made when Palmer amaranth were the appropriate heights in plots. The comparative broadcast treatment was made as a salvage treatment when Palmer amaranth reached a 20- to 30-cm height, and a sequential application was made 14 days after final treatment (DAFT). At time of the initial postemergence application, ten Palmer amaranth plants were measured and marked with paint at the base of the plant to aid identification and location of targeted plants at a later date ((Butts et al. 2018, 2019; Franca et al. 2020). In the case where there were not ten Palmer amaranth plants in the plot, all Palmer amaranth in the plot were measured and marked. Palmer amaranth densities and heights were recorded at the time of the first postemergence application (Table 1). Temperature was recorded throughout the season using a Watch Dog 2000 Series permanent weather station (Spectrum Technologies INC. Aurora, IL) located on site (Figure 1). Roller wiper applications were made using a Grassworks™ 3-point tractor-mounted weed wiper (Grassworks USA LLC, Lincoln AR) (Figure 2) where the wiper was wetted prior to entering the plot and was consistently rolling as the tractor moved through the plot. The carpet on the wiper is wetted using spray nozzles inside of closed system that prevents herbicide physical drift. The wiper was placed 10 cm into the crop canopy and was moved through the plot at a speed of 8.5 kph. Treatments were wiped in succession as the tractor traveled down the rows, lowering the wiper into the canopy for plots receiving treatments and raising the wiper above the canopy to avoid treating plots not receiving treatments.

The herbicide placement experiment was designed as a three factor (3 x 2 x 2) factorial with the first factor being the placement of the application (over the top broadcast, at canopy roller wiper, and roller wiper 10 cm inside the soybean canopy), the second factor being the preemergence herbicide used [*S*-metolachlor at 534 g ai ha^{-1} (Dual Magnum, Syngenta Crop

Protection, Greensboro, NC) and a combination of flumioxazin at 35 g ai ha^{-1} and pyroxasulfone at 45 g ai ha^{-1} (Fierce, Valent, Walnut Creek, CA)], and the third factor being the presence or absence of a sequential application 14 days following the initial application. At time of initial postemergence application ten Palmer amaranth plants were measured, marked, and counted as described for the previous experiment. Palmer amaranth densities and heights were recorded at the time of the first postemergence application (Table 1) and temperature was recorded throughout the season using a Watch Dog 2000 Series permanent weather station (Spectrum Technologies INC. Aurora, IL) located on site (Figure 1).

Preemergence and broadcast applications were made using a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} at 276 kPa. Preemergence applications were made using TeeJet AIXR 110015 nozzles and broadcast postemergence applications were made using TeeJet TTI 110015 nozzles. Roller wiper applications were made as previously described using the Grassworks™ weed wiper. The wiper was placed 10 cm into the crop canopy for the in-canopy treatments and touching the crop canopy for the canopy treatments. Ground speed of the tractor was 8.5 kph. Initial applications were made when Palmer amaranth measured 30 to 40 cm in height.

For both studies, visible estimates of Palmer amaranth control were rated at 7, 14, 21, and 28 days after final treatment (DAFT) on a scale of 0-100, where 0 represents no plant symptomology and 100 represents plant death. At 28 DAFT, marked Palmer amaranth plants were individually evaluated for mortality (dead or alive) and the total number of deceased Palmer amaranth were divided by the number of marked plants to provide mortality proportion for each plot (Butts et al. 2018; Franca et al. 2020). Visible soybean injury was rated at 7, 14, and 21 DAFT in the herbicide placement study and at 14 and 21 DAFT in the herbicide rate study on a similar scale to that used for Palmer amaranth control. Soybean grain from the two treated rows of each plot was harvested at maturity using an ALMACO© SPC40 (ALMACO, Nevada, IA) and adjusted to 13% moisture.

Data Analysis

Data for both trials were analyzed in R version 4.0.3 (R Foundation for Statistical Computing, Vienna, Austria). Data were evaluated for normality using Shapiro-Wilks tests and equal variance was determined by plotting the residuals of the model prior to final model selection (Kniss and Streibig 2018). Variables which met both normality and homogeneity of variance assumptions were evaluated with linear models using base functions. Those models that did not satisfy the assumptions of equal variance or normal distribution were analyzed using a nonparametric factorial model using the *rankFD* package (Brunner et al. 1997, 2019). Initially, models were tested with site-year as a factor to test for interactions between site-year and other factors. Exploratory model testing of Palmer amaranth data for the herbicide placement study resulted in site-year by factor interaction for all variables. As a result, data were analyzed separately by site-year. Conversely, exploratory model testing found only two site-year by factor interactions for the herbicide rate study. As a result, the herbicide placement study data were pooled over site-year. One-way ANOVA analyses were conducted using data from the herbicide rate study to compare results from the roller wiper treatments to a broadcast comparison. Data in the herbicide placement study were subjected to Type I ANOVA, and means were separated using least significant differences with Tukey's adjustment at α=0.05. Data in the herbicide rate study were subjected to Type III ANOVA using Palmer amaranth height relative to the height of the roller wiper at time of application as a covariate, and means were separated using least significant differences with Tukey's adjustment at α=0.05.

Results and Discussion

Herbicide rate study

Generally, there were differences between the two site-years, primarily as it related to Palmer amaranth control, but there were no significant interactions between site-year and any other factor, except between site-year and target height for Palmer amaranth control and mortality at 28 DAFT (Table 2). As a result, data were pooled across site-years rather than analyzing the data separately.

Visible Palmer amaranth control at 14 and 21 DAFT were both influenced by site-year (Table 2). When averaged over all treatments, Palmer amaranth control in Fayetteville resulted in 86 and 78% control at 14 and 21 DAFT, respectively, whereas in Keiser, Palmer amaranth control was only 59 and 62% for the same periods (Table 3). The varied response between locations may be attributed to differences in weed densities (Table 1) and climatic conditions (Figure 1) at the two locations that were 368 km apart. The greater densities of Palmer amaranth in Keiser may have allowed for some of the Palmer amaranth to be protected by other weeds in front of them as the wiper moved through the plot and subsequently pushing Palmer amaranth over with the physical wiper. The reduction in contact with the wiper would have resulted in lower coverage, decreasing weed control (Moyo 2008).

Visible Palmer amaranth control at 14 DAFT was influenced by an interaction between number of application directions and the concentration of herbicide applied (Table 2). The greatest control was observed when the high concentration of herbicide was wiped from two different directions, which averaged 82% control (Table 4). The lowest control was observed when dicamba was wiped in a single direction at either herbicide concentration. Palmer amaranth plants in plots wiped only once with the high concentration were controlled 66% and those receiving the low concentration only once were controlled 70%, with both levels of control being statistically similar. Control of Palmer amaranth that received the low concentration of herbicide from two directions was statistically similar to other combinations of concentration and direction (Table 4). At 21 DAFT, Palmer amaranth control was influenced by the number of application directions the treatment received (Table 2). Palmer amaranth receiving applications from two directions resulted in 75% control, which was greater than the 65% control that resulted from the single application direction (Table 3). At 14 and 21 DAFT, the number of application directions increased Palmer amaranth control, most likely due to an increase in herbicide coverage on the weeds similar to findings by others (Butts et al. 2018; Meyer et al. 2015, 2016; Moyo 2008; Ramsdale and Messersmith 2001). Passing over the weeds twice with the roller wiper allowed for contact on both sides of the larger Palmer amaranth plants in the plots.

Visible Palmer amaranth control and mortality were influenced by the interaction between target weed height and site-year at 28 DAFT (Table 2). Palmer amaranth control at 28 DAFT for the two smallest target heights in Fayetteville were similar, resulting in 81 and 80% control for the 20-30 cm and 40-50 cm target heights respectively (Table 4). These levels of control were greater than those at Keiser for the same target heights, where 59 and 58% Palmer amaranth control occurred following treatment at the 20-30 cm and 40-50 cm target heights, respectively. At the tallest target weed height, Palmer amaranth control was 72% at both Keiser and Fayetteville, although the control was not different from that of the smaller target weed heights (Table 4).

Palmer amaranth mortality followed a similar trend to Palmer amaranth control at 28 DAFT. An improvement in mortality occurred in Fayetteville for the two smallest target heights with 53 and 60% mortality for the 20-30 and 40-50 cm target heights compared to the 60-70 cm target height where only 31% mortality was achieved. At Keiser, mortality did not vary among the three target heights (Table 4). These discrepancies in control between the two locations may be attributed to differences in weed density (Table 1). The reduced density in Fayetteville would have allowed for greater contact between the wiper and individual weeds instead of some weeds being shielded from the wiper by other weeds in a denser population such as that in Keiser (Moyo et al. 2008b).

Soybean manifested chlorosis and necrosis following roller wiper applications (Figure 3). Slight but significant differences were ascertained between the two herbicide concentrations at 14 and 21 DAFT (Table 2), where the high concentration of herbicide resulted in 9 and 6% injury as opposed to the low concentration, which resulted in 6 and 4% injury at 14 and 21 DAFT, respectively (Table 3). Greater phytotoxicity could be expected at higher concentrations due to the increased adjuvant load from the glyphosate formulation used, as at high concentrations, adjuvants may illicit plant injury (Wixson and Shaw 1991). Chlorosis may have also been the result of increased aminomethylphosphonic acid (AMPA) concentrations, a byproduct of the metabolism of glyphosate by glyphosate-resistant soybean, that may have been caused by the increased concentration of glyphosate by the roller wiper (Reddy et al. 2004). Soybean injury at 21 DAFT was also slightly influenced by the number of directions of the herbicide applications (Table 2). Applications from two directions resulted in 5% injury, whereas those with a single application direction resulted in 4% injury (Table 3). Although the injury could be associated with adjuvant burn, the difference in injury can be attributed to differences in coverage that resulted from applying herbicide to both sides of the plant. Injury was low and appeared to be transient and had no effect on soybean yield.

When compared to a typical broadcast herbicide application, the roller wiper provided inferior Palmer amaranth control and mortality (Table 5). At 14, 21, and 28 DAFT, broadcast applications controlled Palmer amaranth 86 to 94% compared to 70 to 72% control with the roller wiper applications. Greater Palmer amaranth mortality resulted from the broadcast application (83%) than from the roller wiper applications (37%) (Table 5). Deviations in mortality may be attributed to differences in herbicide coverage, where the broadcast applications were able to evenly distribute herbicide throughout the crop canopy while the roller wiper applications were only able to place herbicide at the point of contact and not place any herbicide on weeds below the height of the roller wiper. Similar results have been observed in studies investigating the effects of different droplet sizes from broadcast applications where less uniform distribution of herbicide reduced weed control (Cuvaca et al. 2020; Butts et al. 2018; Meyer et al. 2015, 2016). Soybean visible injury, although so low as to have no significant effect on yield, was slightly higher with the broadcast application than the roller wiper applications (Table 5). Other research (Wixson and Shaw 1991; Reddy et al 2004; Bernards 2011) also suggests that the degree of injury in this study would not affect soybean yield.

Herbicide placement study

Results for the herbicide placement study varied between locations, partially because of differences in weed population densities (Table 1) and climate (Figure 1) between the two locations. At Keiser, Palmer amaranth populations were 22 plants m^{-2} compared to the 8 plants m^{-2} in Fayetteville (Table 1). Keiser was also generally warmer than Fayetteville throughout the growing season (Figure 1), resulting in greater Palmer amaranth growth during the season (Guo and Al-Khatib 2003). As a result, several site-year by treatment factor interactions emerged (data not shown); thus, the two locations were analyzed separately to better understand the results from the study (Table 6).

At Keiser, Palmer amaranth control was influenced by two factors, herbicide placement and the number of applications at 14, 21, and 28 DAFT (Table 6). In terms of herbicide placement, the broadcast application provided the greatest weed control of all three placements at 14 and 21 DAFT with 71 and 73% respectively. The inside- and at-canopy roller wiper treatments were similar to each other at 14 and 21 DAFT with, 47 and 55% control for the at-canopy treatment and 53 and 54% control for the inside canopy treatment, respectively. At 28 DAFT, the broadcast treatment resulted in greater control compared to the at-canopy treatment only, while the inside-canopy treatment was similar to both other placements at 28 DAFT (Table 7). The lower Palmer amaranth control by the roller wiper treatments can be attributed to inferior herbicide coverage of all weeds in the plot. The roller wiper applications were limited the height of the applicator, whereas the broadcast applications were made to all weed sizes. The lack of uniformity of coverage onto weeds and the inability to reach weeds below the canopy has been a shortfall of wiper-based applications as previously reported by Moyo et al. (2016). With the wiper-based applications, the herbicides were primarily applied to the top leaves of the Palmer amaranth.

Previous research has found that dicamba typically translocates only to the nutrient sinks of the plant (Andersen 2004; Meyer et al. 2020; Zaccaro et al. 2020), which at the time of application was limited to the upper Palmer amaranth leaves and inflorescence. As a result, dicamba, does not typically translocate to the lower parts of the plant, resulting in symptomology being primarily concentrated near the area of application for the roller wiper applications. Conversely, the broadcast applications provided a more uniform distribution of herbicide on the plant, thus increasing the amount of the plant that was exposed to dicamba and resulting in more uniform dicamba uptake and Palmer amaranth control, as seen by Cuvaca et al. 2020; Butts et al. 2018; and Meyer et al. 2015, 2016.

Palmer amaranth control in Keiser was also influenced by the number of herbicide applications (with or without the sequential treatment) (Table 6). Averaged over all other factors, the addition of a second application resulted in 66, 77, and 83% Palmer amaranth control at 14, 21, and 28 DAFT, respectively (Table 7). Control with only the single application of dicamba was significantly lower (45 to 63%). These results are similar to those by Priess et al. (2020a) in which a single application of dicamba resulted in 50% Palmer amaranth control and a sequential application increased control to 95% when a 14-day interval was implemented on 18-cm Palmer amaranth.

At Fayetteville, Palmer amaranth control at 14 DAFT was also influenced by the number of herbicide applications (Table 6). A second application controlled Palmer amaranth 90% compared with 75% control in plots receiving only a single application (Table 7). At 21 and 28 DAFT, Palmer amaranth control and mortality were influenced by an interaction between the placement of the herbicide and the number of applications (Table 6). At 21 DAFT, herbicide application placements were similar when two dicamba applications were applied; however, one application applied at canopy failed to control Palmer amaranth compared with control from inside the canopy and broadcast applications (Table 7). At 28 DAFT at Fayetteville, Palmer amaranth was controlled 85 and 89% with a single application of dicamba if it was applied with the roller wiper inside the canopy or if it was broadcast. However, control with two roller wiper applications did not differ between placement at canopy and inside the canopy. Mortality data were somewhat variable, but two applications placed at canopy increased control over one application (Table 7). Although not different from most other application placements, dicamba applied in two broadcast applications was numerically higher than other treatments.

The reduced control and mortality from the single at-canopy treatment may stem from the height of the roller wiper placement at which the herbicide only reached weeds that would be at or above the canopy, whereas the in-canopy placement would reach weeds just below the crop canopy, and the broadcast placement could make contact with all weeds in the crop canopy. The lack of a significant difference between the single and sequential applications with the in-canopy placement as opposed to at-canopy placement may be a function of Palmer amaranth growth patterns following dicamba applications. Following the first application, the shorter plants that had not contacted the wiper potentially grew taller. As a result, a greater number of Palmer amaranth may have come in contact with the wiper as it moved through the plots. Meanwhile the plants that had been wiped with the previous application may have grown downwards as the result of epinasty from the prior dicamba application (Van De Stroet 2018). With the second application taking place at a greater distance from the ground due to the continued growth of the soybean crop, the plants that had previously been wiped did not get wiped with the second in-canopy application. Conversely, with the at-canopy application, the wiper was able to contact more weeds that had grown taller because fewer weeds were treated with the first application as a result of their uninterrupted growth.

The same interaction was observed for Palmer amaranth mortality in Keiser, where there were no differences among the different placements following a single application (Table 7). There was, however, a difference between the broadcast herbicide placement and the two roller wiper placements following two postemergence applications; the at-canopy and in-canopy applications resulted in reduced mortality compared to the broadcast treatment (Table 7). Due to dense weed populations at Keiser, the benefits of the broadcast placement may not have been completely materialized following a single application, possibly due to a great number of larger Palmer amaranth that protected smaller Palmer amaranth underneath. This taller overgrowth may have allowed for those plants underneath to survive the single application. With the addition of the second application, those larger Palmer amaranth plants that were initially treated by the broadcast would have significantly reduced their surface area after 14 days following the dicamba application (Priess et al. 2021) allowing for the second application to contact the weeds that had previously been shielded.

Palmer amaranth control at 28 DAFT and mortality in Fayetteville were significantly influenced by an interaction between herbicide placement and the preemergence option (Table 6). Broadcast treatments of flumioxazin + pyroxasulfone PRE controlled Palmer amaranth 95%, which was similar to control with S-metolachlor PRE followed by at-canopy, in-canopy, and broadcast postemergence placements (Table 7). Both roller wiper treatments, at-canopy and in-canopy, that followed flumioxazin + pyroxasulfone PRE resulted in lower Palmer amaranth control than the broadcast applications. The differences between the two application methods (roller wiper compared to broadcast) as influenced by the PRE option and the mortality of the Palmer amaranth may be attributed to the differences in efficacy of the PRE options. The premix of flumioxazin + pyroxasulfone may have provided a longer residual compared to *S*-metolachlor; pyroxasulfone has a half-life of 71 days compared to a half-life of 27 days for *S*-metolachlor (Mueller and Steckel 2011). Residual activity may have delayed growth of Palmer amaranth in the plots treated with flumioxazin + pyroxasulfone PRE. Therefore, for the roller wiper applications, weeds may have been shorter at application following flumioxazin + pyroxasulfone compared to Palmer amaranth following *S*-metolachlor, resulting in reduced contact by the roller wiper and decreased Palmer amaranth control.

Visible soybean injury at Fayetteville was influenced by herbicide placement at 7 DAFT (Table 6). The at-canopy and broadcast treatments both resulted in 4% injury while the in-canopy treatments resulted in 8% injury (Table 7). The increased injury from the in-canopy treatments may be attributed to the increased contact by the roller wiper in these plots as the wiper was placed deeper into the soybean canopy than the other treatments. Soybean injury was once again significant at 21 DAFT as a function of the number of herbicide applications (Table 6), where 2% soybean injury was recorded following the single application while there was only 1% injury following the second application, potentially due to higher temperatures following the first application (Figure 1) these greater temperatures may have attributed to greater adjuvant injury as opposed to the cooler temperatures that followed the second application in Fayetteville (Wixon and Shaw 1991). Conversely, at 14 DAFT in Keiser, there was 2% soybean injury following the use of two applications where there was no injury following the use of a single application. Warmer temperatures in Keiser (Figure 1) following the first application, relative to the second application, may have allowed for the soybean to recover and grow faster (Purcell et al 2014). At 7 DAFT in Keiser, visible soybean injury was dependent on an interaction between application placement and the number of herbicide applications (Table 6). Following the single application, both roller wiper placements resulted in 5% injury while no injury was observed in the broadcast treatment (Table 7). The presence of injury as the result of the roller wiper applications may be attributed to the brute force of the roller wiper and small sized tractor moving through the plots coupled with the increased concentrations of adjuvants from higher concentrations of formulated product that may have caused most of the injury, (chlorotic or necrotic leaves) (Wixson and Shaw 1991). There was no visible injury at 21 DAFT in Keiser and no differences in soybean grain yield were observed in both studies (Table 6). It can be inferred by these results that any injury observed at seven days after application was cosmetic and did not impact the grain production of the soybean. These results are not unlike previous works that have shown that low levels of injury from labeled applications do not correlate to yield loss (Priess et al 2020b; Kapusta et al. 1986).

Findings from these studies suggest that the use of roller wiper applicators for weed control are not as effective as broadcast applications of dicamba. If roller wiper applicators are to be used, it is recommended that these applications be done in a way that maximizes herbicide coverage onto target weed species. The use of multidirectional applications with increased herbicide concentrations as well as sequential applications may be necessary for adequate control and to deliver a lethal rate in an attempt to curb herbicide resistance development through sub-lethal doses of dicamba (Norsworthy et al. 2012; Tehranchian et al. 2017; Vieira et al. 2020). During these studies, many of the weeds were above labeled heights according to current labels for dicamba herbicides. Further research may need to be conducted to investigate if applications may be optimized earlier in the season when both soybean and Palmer amaranth are smaller than 20 cm. At this point, broadcast applications of residual herbicides should be utilized to prevent any further weed emergence before canopy closure by the soybean (Norsworthy 2012; Sarangi and Jhala 2018). The use of roller wipers was found to be relatively safe for soybean production systems as yields were not reduced because of roller wiper applications.

References

Andersen SM, Clay SA, Wrage LJ, Matthees D (2004) Soybean foliage residues of dicamba and 2,4-D and correlation to application rates and yield. Agron J 96:750-760

Butts TR, Samples CA, Franca L, Dodds DM, Reynolds DB, Adams JW, Zollinger RK, Howatt KA, Fritz BK, Hoffmann C, Kruger GR (2018) Spray droplet size and carrier volume effect on dicamba and glufosinate efficacy. Pest Manag Sci 74:2020-2029

Butts TR, Samples CA, Franca LX, Dodds DM, Reynolds DB, Adams JW, Zollinger RK, Howatt KA, Fritz BK, Hoffmann CW, Luck JD, Kruger GR (2019) Droplet size impact on efficacy od a dicamba-plus-glyphosate mixture. Weed Technol 33:66-74

Bernards M (2011) Yellow flash in soybean. Plant Health Exchange. American Pathological Society. Accessed at: https://www.planthealthexchange.org/soybean/Pages/GROW-SOY-05-11-062.aspx. Accessed April 24, 2021

Brunner E, Bathke AC, Konietschke F (2019) Designs with three and more factors. Pages 333–355 *in* Rank and pseudo-rank procedures for independent observations in factorial designs. Springer

Brunner E, Dette H, Munk A (1997) Box-type approximations in nonparametric factorial designs. J Am Statisitical Assoc 92:1494–1502

Clemente TE, Dumitru R, Paul C, Feng C, Flasinski S, Weeks DP, inventors; University of Nebraska and Monsanto Technology LLC, assignee (2007) Modified dicamba monooxygenase enzyme and methods of its use. US patent US7884262B2

Coffman W, Barber LT, Norsworthy JK, Kruger GR (2021) Effect of dicamba rate and application parameters on protoporphyrinogen oxidase inhibitor-resistant and -susceptible Palmer amaranth (*Amaranthus palmeri*) control. Weed Technol 35:22-26

Cundiff GT, Reynolds DB, Mueller TC (2017) Evaluation of dicamba persistance among various agricultural hose types and cleanout procedures using soybean (*Glycine max*) as a bio-indicator. Weed Sci 65:305–316

Cuvaca I, Currie R, Roozeboom K, Fry J, Jugulam M (2020) Increased absorption and translocation contribute to improved efficacy of dicamba to control early growth stage Palmer amaranth (*Amaranthus palmeri*). Weed Sci 68:27-32

Davison JG, Derrick PM (1983) Weed Response to spray and “wiper” applications of translocated herbicides. Page 520 *in* 10th International Congress of Plant Protection. Brighton, England

Foster HC, Sperry BP, Reynolds DB, Kruger GR, Claussen S (2018) Reducing herbicide particle drift: effefct of hooded sprayer and spray quality. Weed Technol 32:714–721

Franca L, Dodds DM, Butts TR, Kruger GR, Reynolds DB, Mills JA, Bond JA, Catchot AL, Peterson DG (2020) Evaluation of optimal droplet size for control of Palmer amaranth (*Amaranthus palmeri*) with aciflorfen. Weed Technol 34:1–30

Grekul CW, Cole DE, Bork EW (2005) Canada thistle (*Circium arvense*) and pasture forage responses to wiping with various herbicides. Weed Technol 19:298–306

Guo P and Al-Khatib K (2003) Temperature effects on germination and growth of redroot pigweed (*Amaranthus retroflexus*), Palmer amaranth (*A. palmeri*), and common waterhemp (*A. rudis*). Weed Sci 51:869-875

Hartzler B (2017) A historical perspective on dicamba. Page 98 *in* 2017 Proceedings of the 72nd Annual Meeting of the North Central Weed Science Society.

Heap I (2020) International Survey of Herbicide Resistant Weeds. http://www.weedscience.org/Summary/Species.aspx?WeedID=14. Accessed September 22, 2020

Hoette GD, Livingstron SD, Peters EJ (1982) Rope wick applicators. http://extension.missouri.edu/webster/documents/resources/agriculture/ropewick/G4920_Rope_Wick_Applicators.pdf. Accessed February 10, 2020

Johnson WG, Young BG, Marquardt P, Bradley KW, Culpepper AS, Al-Khatib K, Steckel LE, Loux MM, Bernards ML, Smeda RJ, Matthews J, Slack C, York A, Hager A, Moechnig M (2010) Weed control in dicamba-resistant soybeans. Crop Manag 9:1-23

Kapusta G, Jackson LA, Mason DS (1986) Yield response of weed-free soybeans (*Glycine max*) to injury from postemergence broadleaf herbicides. Weed Sci 34:644-651

Keeley PE, Carter CH, Thullen RJ, Miller JH (1984) Comparison of ropewick applicators for control of Johnsongrass (*Sorghum halepense*) in cotton (*Gossypium hirsutum*) with glyphosate. Weed Sci 32:431–435

Keelin J, Abernathy J (1988) Woollyleaf bursage (*Ambrosia grayi*) and Texas blueweed (*Helianthus ciliaris*) control by dicamba. Weed Technol 2:12–15

Kniss AR, Streibig JC (2018) Statistical analysis of agricultural experiments using R. Accessed https://Rstats4ag.org. Accessed February 1, 2021

Kruger GR, Davis VM, Weller DC, Johnson WG (2010) Control of horseweed (*Conyza canadensis*) with growth regulator herbicides. Weed Technol 24:425–429

Meyer CJ, Norsworthy JK, Kruger GR, Barber T (2015) Influence of droplet size on efficacy of the formulated products Engenia, Roundup Powermax, and Liberty. Weed Technol 29:641- 652

Meyer CJ, Norsworthy JK, Kruger GR, Barber LT (2016) Effect of nozzle selection and spray volume on droplet size and efficacy of Engenia tank-mix combinations. Weed Technol 30:377-390

Meyer CJ, Peter F, Norsworthy JK, Beffa R (2020) Uptake, translocation, and metabolism of glyphosate, glufosinate, and dicamba mixtures in *Echinochloa crus-galli* and *Amaranthus palmeri*. Pest Manag Sci 76:3078-3087Moyo C (2008a) Improving the efficiency of herbicide application to pasture weeds by weed-wiping and spot-spraying. Ph.D dissertation. Palmerston North NZ: Massey University 227 p

Moyo C, Harrington KC, Kemp PD, Erens JPJ (2008b) Wiper application of herbicides to Californian thistle. N Z Plant Prot 59:361

Moyo C, Harrington KC, Ghanizadeh H, Kemp PD, Eerens JPJ (2016) Spectrophotometric technique for measuring herbicide deposition from wiper applicators. New Zeal. J. Agri. Res. 59:412-421

Mueller TC, Steckel LE (2011) Efficacy and dissipation of pyroxasulfone and three chloroacetamides in a Tennessee field soil. Weed Sci. 59:574-579

Norsworthy JK, Griffith GM, Scott RC, Smith KL, Oliver LR (2008) Confiramtion and control of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) in Arkansas. Weed Technol 22:108–113

Norsworthy JK, Ward S, Shaw D, Llewellyn R, Nichols R, Webster T, Bradley K, Frisvold G, Powles S, Burgos N, Witt W, Barrett M (2012) Reducing the risks of herbicide resistance: best management practices and recommendations. Weed Sci 60 (SI):31-62

Ozkan HE (1995) Herbicide application equipment. Pages 155–216 *in* Smith, A.E. (Ed.), Handbook of Weed Management System. New York, USA: Marcel Dekker Inc.

Purcell LC, Salmeron M, Ashlock L (2014) Soybean Growth and Development. https://www.uaex.edu/publications/pdf/mp197/chapter2.pdf. Accessed November 17, 2020

Priess GL, Norsworthy JK, Barber LT, Castner MC (2020a) Timing between sequential applications of dicamba and glufosinate. Pages 57-60 *in* Bourland F. Summaries of Arkansas Cotton Research 2019

Priess GL, Norsworthy JK, Roberts TL, Gbur EE Jr. (2020b) Impact of postemergence herbicides on soybean injury and canopy formation. Weed Technol. 34:1-26

Priess GL, Norsworthy JK, Farr RB, Mauromoustakos A, Butts TR, Robers TL (2021) Impact of auxin herbicides on Palmer amaranth groundcover. Weed Technol. Preproof. DOI 10.1017/wet.2021.74

Ramsdale BK, Messersmith (2001) Drift-reducing nozzle effects on herbicide performance. Weed Technol 15:453-460

Reddy KN, Rimando AM, Duke SO (2004) Aminomethylphosphonic acid, a metabolite of glyphosate, causes injury in glyphosate-treated, glyphosate-resistant soybean. J. Agric. Food Chem 52:5139-5143

Sarangi D and Jhala AJ (2018) Palmer amaranth (*Amaranthus palmeri*) and velvetleaf (*Abutilon theophrasti*) control in no-tillage conventional (non-genetically engineered) soybean using overlapping residual herbicide programs. Weed Technol 33:95-105

Schneider GL, Koehler CB, Schepers JS, Burnside OC (1982) Roller applicator for shattercane (*Sorghum bicolor*) control in row crops. Weed Sci 30:301–306

Schroeder J, Banks P (1989) Soft red winter wheat (*Triticum aestivum*) response to dicamba and dicamba plus 2,4-D. Weed Technol 3:67–71

Steckel LE, Chism C, Thompson A (2010) Cleaning plant growth regulator (PGR) herbicides out of field sprayers. https://extension.tennessee.edu/publications/Documents/W071.pdf. Accessed February 10, 2020

Tehranchian P, Norsworthy JK, Powles S, Bararpour MT, Bagavathiannan MV, Barber T, Scott RC (2017) Recurrent sublethal-dose selection for reduced susceptibility of Palmer amaranth (*Amaranthus palmeri*) to dicamba. Weed Sci. 65:206-212

USDA-Natural Resources Conservation Service, United States Departments of Agriculture. Web Soil Survey. Available: http://websoilsurvey.sc.egov.usda.gov/. Accessed February 1, 2021

Van De Stroet, BM (2018) Palmer amaranth in South Dakota: Growth, Herbicidal Control, and Soybean Yield Loss. Thesis, https://openprairie.sdstate.edu/cgi/viewcontent.cgi?article=3493&context=etd. Accessed November 17, 2020

Vieira BC, Butts TR, Rodrigues AO, Golus JA, Schroeder KP, Kruger GR (2018) Spray particle drift mitigation using field corn (*Zea mays* L.) as a drift barrier. Pest Manag Sci 74:2038-2046

Vieira BC, Luck JD, Amundsen KL, Werle R, Gaines TA, Kruger GR (2020) Herbicide drift exposure leads to reduced herbicide sensitivity in *Amaranthus* spp. Sci. Reports 10:2146

Werle R, Oliveira MC, Jhala AJ, Proctor CA (2018) Survey of Nebraska farmers' adoption of dicamba-resistant soybean technology and dicamba off-target movement. Weed Technol 32:754–761

Wills GD, McWhorter CG (1981) Developments in post-emergence herbicide applicators. Outlook Agric 10:337–341

Wixson MB, Shaw DR (1991) Effect of adjuvants on weed control and soybean (*Glycine max*) tolerance with AC 263,222. Weed Technol 5:817-822

Zaccaro ML, Norsworthy JK, Brabham CB (2020) Dicamba translocation in soybean and accumulation in seed. Weed Sci 68:333-339

Tables and Figures

Table 1: Average Palmer amaranth height and density at the time of initial application for both the herbicide rate and herbicide placement experiments in Fayetteville and Keiser, AR, in 2020

Location	Experiment	Height	Density
		average (range)	average (range)
		cm	plants m^{-2}
Fayetteville	Herbicide rate	-*	8 (1-16)
	Herbicide placement	44 (8-72)	8 (1-16)
Keiser	Herbicide rate	-	27 (20-52)
	Herbicide placement	50 (37-71)	22 (12-36)

*Herbicide rate experiments included target heights of 20-30, 40-50, and 60-70 cm as factors

Table 2: P-values from analysis of covariance for soybean injury at 14 and 21 days after final treatment (DAFT), soybean yield, Palmer amaranth control at 14, 21, and 28 DAFT, and Palmer amaranth mortality 28 DAFT from 2020 in Fayetteville and Keiser, AR[a]

	Soybean injury		Soybean yield	Palmer amaranth control			Palmer amaranth mortality
Source	14 DAFT	21 DAFT		14 DAFT	21 DAFT	28 DAFT	
				---------------*P>F*---------------			
Height	0.1972	0.1930	0.8512	0.0661	0.9787	0.7689	0.2487
Rate	**0.0009**	**0.0018**	0.6108	0.3293	0.7141	0.0634	**0.0008**
Direction	0.6314	**0.0119**	0.5511	**0.0016**	**0.0449**	**0.0338**	**0.0047**
Site-Year	0.9054	0.3324	**0.0001**	**<0.0001**	**<0.001**	**<0.0001**	**<0.0001**
Height:Rate	0.0935	0.0775	0.6215	0.5186	0.9505	0.7941	0.4521
Height:Direction	0.3833	0.9527	0.6443	0.9437	0.7320	0.9681	0.5824
Rate:Direction	0.2441	0.6960	0.8724	**0.0213**	0.4388	0.9948	0.4995
Height:Site-Year	0.2539	0.9150	0.4447	0.4701	0.1162	**0.0131**	**0.0001**
Rate:Site-Year	0.1356	0.1390	0.4908	0.6028	0.3820	0.4206	0.4258
Direction:Site-Year	0.2966	0.6043	0.8684	0.2399	0.3952	0.0634	0.1577
Height:Rate:Direction	0.8165	0.7720	0.5331	0.7260	0.9915	0.5655	0.8378
Height:Rate:Site-Year	0.8426	0.4404	0.5635	0.2627	0.6632	0.4289	0.9588
Height:Direction:Site-Year	0.2488	0.6243	0.9084	0.0681	0.5000	0.5928	0.5151
Rate:Direction:Site-Year	0.1265	0.6043	0.9840	0.2399	0.6077	0.3724	0.4272
Height:Rate:Direction:Site-Year	0.2210	0.3079	0.5968	0.3964	0.8611	0.7697	0.4034

[a] Bolded values indicate statistical significance at α=0.05

Table 3: Soybean injury at 14 and 21 days after final treatment (DAFT), soybean yield, Palmer amaranth control at 14, 21, and 28 DAFT, and Palmer amaranth mortality at 28 DAFT by rate, direction, and location in Keiser and Fayetteville, AR in 2020[a]

	Soybean injury		Yield	Palmer amaranth control			Mortality
Treatment	14 DAFT	21 DAFT		14 DAFT	21 DAFT	28 DAFT	
	-----------%----------		kg ha^{-1}	--------------------------%--------------------------			
Rate							
High	9 a	6 a	2844	74	71	73	44 a
Low	6 b	4 b	3052	71	69	67	30 b
Direction							
One	7	4 b	2973	68	65 b	66 b	31 a
Two	8	5 a	2923	77	75 a	74 a	43 b
Site-Year							
Fayetteville	8	5	2760 b	86 a	78 a	77	48
Keiser	7	4	3136 a	59 b	62 b	63	26

[a]Means followed by the same letter are not statistically different based on Tukey's (α=0.05)

Table 4: Palmer amaranth control at 14 and 28 DAFT and Palmer amaranth mortality at 28 DAFT by interactions of direction by rate and location by Palmer amaranth at time of application in 2020 at Fayetteville and Keiser, AR.[a]

Treatment		Palmer amaranth control		Palmer amaranth mortality
		14 DAFT	28 DAFT	
		---------------------------%	----------------------------	
Direction x rate				
Direction	Rate			
One	High	66 b	69	34
	Low	70 b	63	25
Two	High	82 a	77	52
	Low	73 ab	71	34
Location x Palmer amaranth height				
Site-Year	Palmer amaranth height			
Fayetteville	20-30 cm	87	81 a	53 ab
	40-50 cm	87	80 a	60 a
	60-70 cm	83	72 ab	31 c
Keiser	20-30 cm	58	59 b	17 c
	40-50 cm	66	58 b	24 c
	60-70 cm	54	72 ab	38 bc

[a] Means followed by the same letter are not statistically different based on Tukey's (α=0.05)

Table 5. Palmer amaranth mortality, visual control at 14, 21 and 28 days after application, visible soybean injury 7 days after application and soybean yield for contrast analyses comparing broadcast applications of dicamba to roller wiper applications of dicamba at Fayetteville and Keiser, AR in 2020[a,b]

Broadcast vs. Wiper	Palmer amaranth mortality	Palmer amaranth control			Soybean injury		Soybean yield
		14 DAFT	21 DAFT	28 DAFT	14 DAFT	21 DAFT	
	---------------------------------------%	---------------------------------------					kg ha^{-1}
Broadcast	82.5 a	89 a	86 a	94 a	2 b	2 b	2900
Wiper	37.1 b	72 b	70 b	70 b	7 a	5 a	3100
P-value	**0.0002**	0.0024	0.0089	**<0.0001**	**0.0004**	0.0135	0.6786

[a] Means followed by the same letter are not statistically different based on Tukey's (α=0.05)

[b] Bolded values indicate statistical significance at α=0.05

Table 6: P-values from analysis of variance for soybean injury at 7, 14 and 21 days after final treatment (DAFT), soybean yield, Palmer amaranth control at 14, 21, and 28 DAFT, and Palmer amaranth mortality 28 DAFT from 2020 in Fayetteville and Keiser, AR[a,b]

	Source	Palmer amaranth control			Palmer amaranth mortality	Soybean injury			Soybean yield
		14 DAFT	21 DAFT	28 DAFT		7 DAFT	14 DAFT	21 DAFT	
		----	----	----	----	*P>F*	----	----	----
Keiser	PRE	0.0762	0.4984	0.7633	0.3009	0.7084	0.2831	0.3246	0.4435
	Placement	**0.0013**	**0.0130**	**0.0109**	**0.0075**	**0.0006**	0.8086	0.3788	0.1745
	Num.app	**0.0017**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**0.0043**	0.3246	0.8269
	PRE:Placement	0.8565	0.7820	0.3346	0.6909	0.7680	0.7415	0.3788	0.0878
	PRE:Num.app	0.0732	0.1868	0.7534	0.6227	0.7084	0.7607	0.3246	0.4004
	Placement:Num.app	0.0880	0.5451	0.1587	**0.0343**	**0.0006**	0.7398	0.3788	0.3380
	PRE:Placement:Num.app	0.2244	0.1015	0.9686	0.9512	0.7680	0.2201	0.3788	0.1461
Fayetteville	PRE	0.1416	0.1932	**0.0270**	**0.0041**	0.8136	0.5701	0.9999	0.3418
	Placement	0.0727	**0.0070**	**0.0038**	**0.0008**	**0.0019**	0.1120	0.0879	0.4420
	Num.app	**0.0077**	**0.0105**	0.0826	**0.0157**	0.2044	0.4802	**0.0109**	0.4894
	PRE:Placement	0.3636	0.0595	**0.0078**	**0.0046**	0.3117	0.4867	0.3569	0.6384
	PRE:Num.app	0.3593	0.4540	0.3698	0.4421	0.1492	0.3373	0.8277	0.1121
	Placement:Num.app	0.0881	**0.0222**	**0.0287**	**0.0209**	0.3362	0.3335	0.4294	0.4898
	PRE:Placement:Num.app	0.9063	0.3207	0.1043	0.2492	0.8943	0.8098	0.1058	0.2269

[a] Abbreviations: PRE=preemergence herbicide option, Place=herbicide placement, Num.app=number of herbicide applications

[b] Bolded values indicate statistical significance at α=0.05

Table 7: Visible Palmer amaranth control at 14, 21, and 28 days after final treatment (DAFT), Palmer amaranth mortality, visible soybean injury at 7, 14, and 21 DAFT and soybean grain yield from Fayetteville and Keiser AR in 2020[a].

Location	Treatment		Palmer amaranth control			Palmer amaranth mortality	Soybean injury			Soybean Yield
			14 DAFT	21 DAFT	28 DAFT		7 DAFT	14 DAFT	21 DAFT	
			----------------	----------------	----------------	%	----------------	----------------	----------------	kg ha^{-1}
Fayetteville	Herbicide placement									
	At-canopy		80	76	76	47	4b	3	1	2500
	Inside canopy		87	85	82	48	8a	4	2	2400
	Broadcast		81	92	92	80	4b	2	1	2700
	Premergence option									
	S-metolachlor		80	87	89	70	5	3	1	2500
	Flumioxazin + pyroxasulfone		86	82	77	47	6	3	1	2600
	Number of applications									
	One		90 a	79	80	49	5	3	1 b	2600
	Two		75 b	90	86	68	6	4	2 a	2500
	Placement x number of applications									
	Number of Application	Herbicide placement								
	One	At canopy	84	63 b	65 c	23 c	5	3	1	2600
		Inside canopy	92	85 a	87 ab	50 abc	6	3	3	2600
		Broadcast	95	89 a	88 ab	74 ab	4	3	2	2600
	Two	At canopy	77	89 a	87 ab	71 ab	3	3	0	2500
		Inside canopy	81	85 a	77 bc	46 bc	10	6	1	2300
		Broadcast	77	94 a	95 a	86 a	4	2	0	2700
	Preemergence x herbicide placement									
	Preemergence option	Herbicide placement								
	S-metolachlor	At canopy	81	84	85 a	59 ab	4	4	1	2300
		Inside canopy	81	88	94 a	75 a	8	5	2	2400
		Broadcast	78	89	89 a	75 a	3	2	1	2700
	Flumioxazin + pyroxosulfone	At canopy	80	69	67 b	34 b	5	2	0	2700
		Inside canopy	93	83	70 b	22 b	8	4	2	2500
		Broadcast	84	95	95 a	86 a	5	3	2	2700

Table 7 cont.: Visible Palmer amaranth control at 14, 21, and 28 days after final treatment (DAFT), Palmer amaranth mortality, visible soybean injury at 7, 14, and 21 DAFT and soybean grain yield from Fayetteville and Keiser AR in 2020[a].

Location	Treatment		Palmer amaranth control			Palmer amaranth mortality	Soybean injury			Soybean Yield
			14 DAFT	21 DAFT	28 DAFT		7 DAFT	14 DAFT	21 DAFT	
Keiser	Herbicide placement									
	At-canopy		47 b	55 b	66 b	19	3	1	0	3800
	Inside canopy		53 b	54 b	69 ab	21	3	1	0	3900
	Broadcast		71 a	73 a	83 a	43	0	1	0	4100
	Number of applications									
	One		48 b	45 b	63 b	12	4	2 a	0	3900
	Two		66 a	77 a	83 a	43	0	0 b	0	3900
	Placement x number of applications									
	Number of Application	Herbicide placement								
	One	At canopy	39	39	50	6 b	5 a	0	1	3700
		Inside canopy	38	34	64	14 b	5 a	0	0	4100
		Broadcast	69	61	75	15 b	0 b	0	0	4100
	Two	At canopy	58	71	83	32 b	0 b	2	0	3800
		Inside canopy	69	75	74	28 b	0 b	2	0	3700
		Broadcast	73	85	92	70 a	0 b	1	0	4200

[a]Means followed by the same letter within a factor or for multiple factors are not statistically different based on Tukey's (α=0.05).

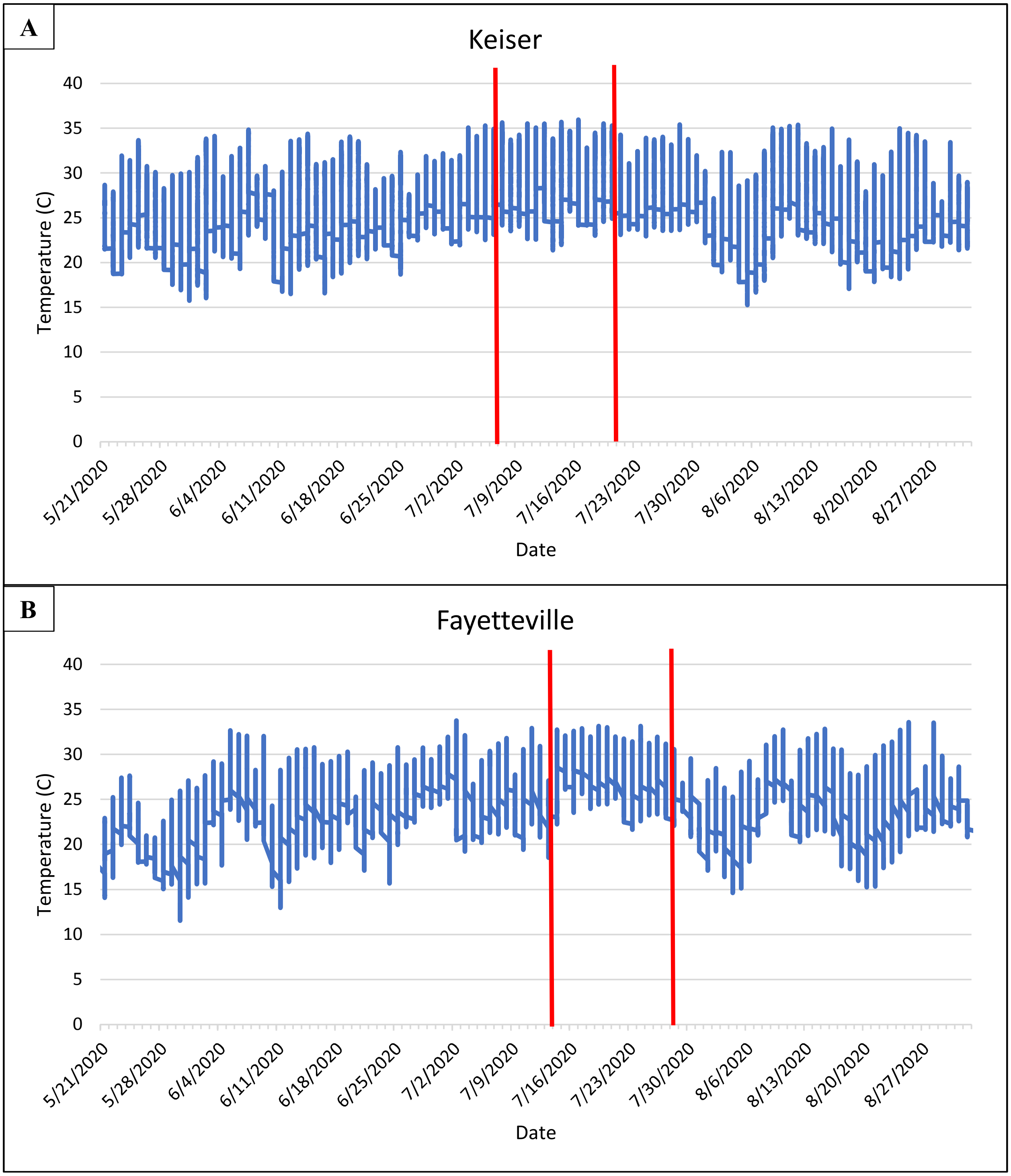

Figure 1: Air temperature in degrees Celsius during the during the growing season at (A) Keiser and (B) Fayetteville, AR. Vertical red lines indicate herbicide application dates.

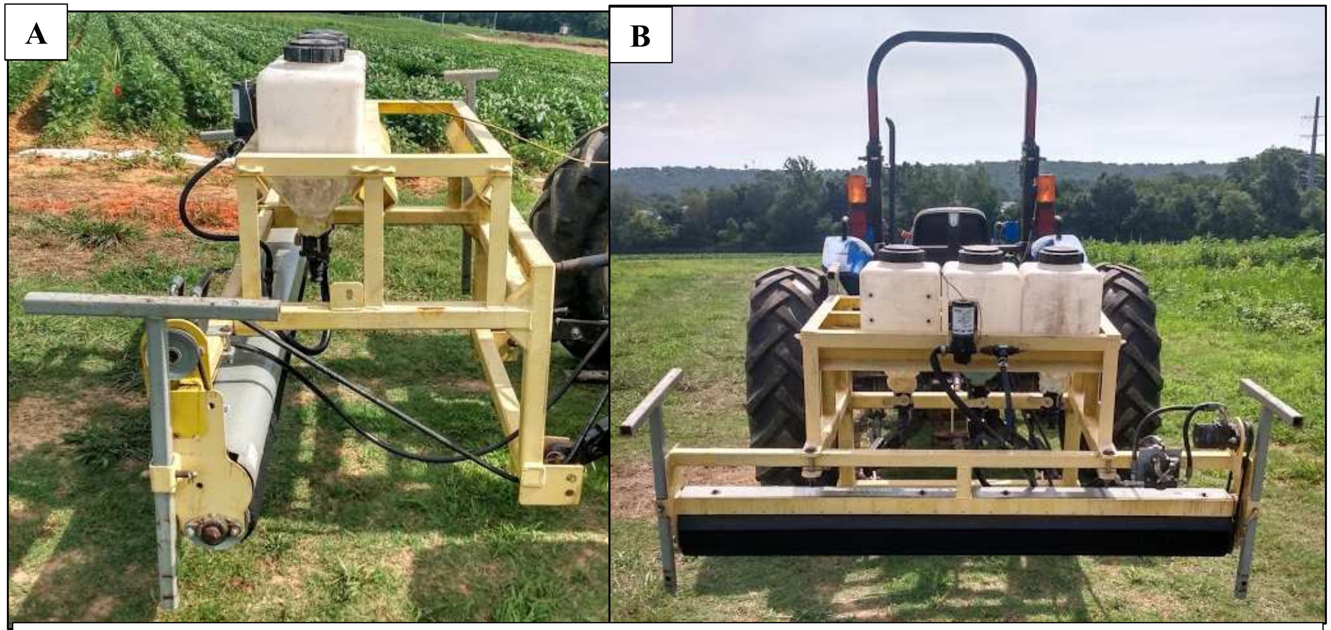

Figure 2. Side (A) and rear (B) view of the two-row Grassworks® roller wiper used for both studies.

Figure 3. Image of chlorotic soybean injury 14 days after final treatment as a result of roller wiper application of dicamba.

Chapter 4

Integration of Multiple Weed Management Practices on Cotton Economics and Palmer Amaranth (*Amaranthus palmeri*) Populations

Abstract

The threat of herbicide-resistant weed species, such as Palmer amaranth, has driven the development of robust weed management programs that rely on more than chemicals for weed control. Previous research has shown that the use of cover crops, deep tillage, and diverse herbicide programs are all effective strategies for controlling Palmer amaranth. Findings from preliminary work hve also suggested that adopting a zero-tolerance mindset and not allowing Palmer amaranth to return seeds to the soil seedbank is effective at controlling weed populations in the long term. Unfortunately, research investigating the integration of all four of these weed management strategies in a system is lacking. To understand how to best leverage these integrated weed management strategies in cotton production systems, a study was initiated in the fall of 2018 near Marianna, AR, with zero-tolerance, deep-tillage, a cereal rye cover crop, and either a dicamba or non-dicamba in-crop herbicide program as factors. There was rarely an interaction among factors for the Palmer amaranth assessments taken, indicating a cumulative effect of each practice on the weed. The use of deep tillage reduced Palmer amaranth emergence and inflorescence-producing plants by 76 and 74% in the first year, respectively. In the second year, when rainfall was limited following planting, the inclusion of dicamba as part of the herbicide program resulted in an 87% reduction in inflorescence-producing Palmer amaranth and a 13% increase in cotton lint yield. Cotton lint yields and partial returns were also greater in the second year becasue of greater cover crop growth when compared to the previous year. Subsequently, lint yields and profits decreased for the short term when hand-weeding was utilized to fulfill a zero-tolerance weed management approach, possibly because of damage to the crop caused by hand removal of large Palmer amaranth and the additional expense associated with this practice. While the use of various combinations of strategies were effective at reducing Palmer amaranth emergence and optimizing resources, timeliness and environmental conditions were also factors in dictating the effectiveness of these strategies.

Nomenclature: dicamba; Palmer amaranth, *Amaranthus palmeri* S. Watson; cotton, *Gossypium hirsutum* L.

Key Words: Integrated weed management; herbicide-resistance, resistance management, cereal rye, moldboard plow, no-till, hand-weeding, economics, zero-tolerance, split-split-split plot

Introduction

The evolution of herbicide-resistant weeds is one of the largest threats to agriculture across the United States and the world (Gaines et al. 2010; Peterson et al. 2018; Westwood et al. 2018). Palmer amaranth has already established itself as a major concern for cotton producers in the Midsouth due to its aggressive competitiveness and adaptability (Sauer 1972; Morgan et al. 2001; Berger et al. 2015). Previous research has shown yield reductions by as much as 59% at Palmer amaranth densities of 1.1 plants m^{-2} (Morgan et al. 2001). Besides the reduction in cotton lint yield, Palmer amaranth also impacts producers in the form of reductions in harvest efficiencies. Palmer amaranth densities of 3260 plants ha^{-1} can increase the time to harvest by 200 min ha^{-1} (Smith et al. 2000).

Cotton producers have adopted various chemical weed management strategies to combat these weeds, centered around the use of genetically modified cultivars resistant to herbicides that had previously not been available for use in the crop such as glyphosate, glufosinate, dicamba, and 2,4-D (Kniss 2018). Over time, Palmer amaranth has systematically evolved resistance to various herbicide sites of action (SOAs), such as acetolactate synthase- (ALS) inhibiting herbicides including trifloxysulfuron (Burgos et al 2001; Norsworthy et al. 2008), microtubule assembly-inhibiting herbicides including pendimethalin (Gossett et al. 1992), synthetic auxin herbicides such as dicamba (Steckel et al 2020; Shyam et al. 2021), the 5-enolpyruvyl-shikimate-3-phosphate- (EPSPS) inhibiting herbicide glyphosate (Norsworthy et al. 2008), the glutamine synthetase-inhibiting herbicide glufosinate (Heap 2021), protoporphyrinogen oxidase- (PPO) inhibiting herbicides such as fomesafen (Varanasi et al. 2018), and very-long-chain fatty acid elongase- (VLCFA) inhibiting herbicides such as *S*-metolachlor (Brabham et al. 2019), leaving few options for cotton producers in the Midsouth. To preserve the few chemical options remaining, alternative options are being sought for Palmer amaranth management.

The adoption of cultural and mechanical weed management practices in addition to chemical weed control methods have been found effective in delaying or preventing the development of herbicide resistance by troublesome weeds (Beckie and Reboud 2009; Beckie 2011). In cotton production, the use of cover crops, such as cereal rye (*Secale cereale* L.), has been shown to be an effective option for aiding in the management of Palmer amaranth, reducing Palmer amaranth densities by 63 to 83% (DeVore et al. 2012; Palhano et al. 2018). Historically, the use of tillage has been a primary, non-chemical method of weed control in cotton production (DeVore et al. 2012). The use of a onetime practice such as deep-tillage through use of a moldboard plow has potential to drastically reduce Palmer amaranth emergence, especially when densities have reached high numbers. The weed management benefit of using a moldboard plow centers around reduction in Palmer amaranth viability over time, as seed of the weed that has been buried can lose as much as 80% viability after three years and as much as 98% after four years (Jha et al. 2014; Korres et al. 2018). Previous research has shown that the use of deep tillage has been effective at reducing Palmer amaranth emergence by 76 to 86% when used alone and by 86 to 94% when used in combination with a cereal rye cover crop (DeVore et al. 2012; 2013). Effectiveness of these management strategies can be primarily associated with the reduction in alterations of light and heat that the Palmer amaranth seed may experience due to the burial of the seed by the deep tillage event and the shading of the soil by the cover crop (Jha et al. 2010).

A newly emerging management practice for Palmer amaranth in the Midsouth is the implementation of a “zero-tolerance” threshold for Palmer amaranth. Zero-tolerance is a mindset that producers may utilize with the main goal being that no seed should return or replenish the soil seedbank (Norsworthy et al. 2012; Norsworthy et al. 2014). These management strategies can be achieved through a multitude of methods, including but not limited to hand weeding and various techniques of harvest weed seed destruction. The concept of zero-tolerance was born out of studies suggesting that the economic consequences of allowing a single weed, such as Palmer amaranth, to produce and disperse seed outweigh the costs of management in the long-run (Norris 1999; Norsworthy et al. 2014). By not allowing more seed to replenish the soil seedbank, Palmer amaranth populations may approach depletion within four years (Jha et al. 2014). Preliminary field-scale trials in Northeast Arkansas have shown promising results where a zero-tolerance approach led to as much as a 65% reduction in Palmer amaranth seedbanks after the first year (Barber et al. 2015).

Implementation of integrated weed management strategies is predominantly a decision based on economics for producers (Moss 2019). A long-term study conducted over 29 years in western Tennessee found that the cash crop yield benefit of cereal rye cover crops was not enough to offset the cost of implementation, thus resulting in a net negative compared to not utilizing cereal rye cover crops at all (Zhou et al. 2017). Other studies have found that the use of cereal rye cover crops may improve cotton yield and partial returns in some instances, while in others there are no differences (DeVore et al. 2012; DeLaune et al. 2020; Price et al. 2021). The use of cereal rye cover crops reduces cotton yield in some instances, primarily because of losses in cotton stand due to allelopathy from cereal rye and difficult planting conditions (Palhano et al. 2018: Price et al. 2021). In the Southeastern United States, the use of deep tillage with a moldboard plow for weed management has had minimal effect on cotton yield, especially when paired with cereal rye cover crops. In terms of profitability, the use of deep tillage and cover crops together were found to be too costly and reduced profitability compared to production practices without tillage (Price et al. 2016). Findings from research in Arkansas has suggested that cotton yield is not affected by using a moldboard plow, but no comparisons were made regarding partial returns (DeVore et al. 2012). For producers to implement these strategies, there needs to be an economic incentive either in the short-term or long-term for the producers to remain viable. While research has been conducted investigating the weed management potential of cereal rye cover crops, deep tillage, and zero-tolerance thresholds with the use of effective herbicide programs, research investigating the combination of more than two of these practices is lacking in the Midsouth, necessitating research where all four of these factors can be investigated for their economic and ecological impact.

Materials and Methods

A large-plot, five-year study in cotton was initiated in the Fall of 2018 at the Lon Mann Cotton Research Station near Marianna, AR (-34.73, -90.74) on a Convent silt loam soil (1% organic matter, 7% clay, 1% sand, and 92% silt) (USDA-NRCS 2021). In this paper, observations and data collection from the 2019 and 2020 growing seasons are reported. The experiment was designed as a randomized complete block with a split-split-split plot arrangement with four replications. The whole-plot factor was the presence or absence of a zero-tolerance threshold. The sub-plot factor was the presence or absence of a one-time deep-tillage event using a moldboard plow at initiation of the experiment in fall of 2018. The sub-sub-plot factor was the presence or absence of a cereal rye cover crop, and the sub-sub-sub-plot factor was the use of either a dicamba in-crop or non-dicamba in-crop-based herbicide program. The plots measured 37 m long and 8 m wide, which allowed for 8 rows on 1.0 m row centers.

The moldboard plow inverted the soil to a 20- to 25-cm depth. Following the one-time deep-tillage event, plots were bedded and treated as no-till for the next two years. ‘Wrens Abruzzi’ cereal rye was drill-seeded during the fall of 2018 and 2019 at 84 kg ha^{-1}. Cereal rye was planted in mid-November in 2018 because of earlier wet conditions, and a more typical planting date of mid-October in 2019. In 2019, cereal rye biomass was not taken due to a lack of establishment. In 2020, cereal rye biomass was estimated by collecting four random 1 m^2 samples of rye prior to planting. Samples were placed in a dryer for a week and then weighed to determine the average biomass. At 21 days prior to planting cotton in both years, the cereal rye cover crop was terminated with glyphosate at 1260 g ae ha $^{-1}$ (Roundup PowerMax II, Bayer Crop Sciences, St. Louis, MO) plus dicamba at 560 g ae ha^{-1} (Clarity, BASF Research Triangle, NC). Deltapine® 1518 B2XF cotton (Bayer Crop Sciences, St. Louis, MO) was planted in both years at 114,000 seed ha^{-1} on May 16th in 2019 and May 12th in 2020 using a 4-row vacuum planter. Cotton was planted on raised beds, fertilized according to local production practices, and was furrow-irrigated to supplement rainfall during the growing season beginning at the 5- to 6-leaf stage.

The two herbicide programs for this study both consisted of a pre-plant burndown (described above), preemergence (PRE) application at planting, early postemergence (EPOST) application at 21 days after planting (DAP), a mid-postemergence (MPOST) application at 42 DAP, and a layby post-directed application at 63 DAP (Table 2). The burndown, PRE, and EPOST applications were made at 140 L ha^{-1} using a Bowman MudMaster (Bowman Manufacturing, Newport, AR) with an effective spray swath of 7.3 m. The second postemergence application was made using a tractor-mounted hooded sprayer and the layby application was made using a tractor-mounted post-directed sprayer at 140 L ha^{-1}. All applications containing dicamba were made using TeeJet TTI 11006 nozzles, the layby applications were made using TeeJet XR 11006E flat fan nozzles, and all other applications were made using TeeJet AIXR 11006 nozzles (TeeJet Technologies, Wheaton, IL). The non-dicamba, in-crop herbicide program consisted of fluometuron at 1120 g ai ha^{-1} plus paraquat at 700 g ai ha^{-1} plus glyphosate at 1260 g ae ha^{-1} (PRE) followed by glufosinate at 656 g ai ha^{-1} plus glyphosate at 1260 g ae ha^{-1} plus *S*-metolachlor at 1068 g ai ha^{-1} (EPOST) followed by glufosinate at 656 g ai ha^{-1} plus glyphosate at 1260 g ae ha^{-1} plus acetochlor at 1260 g ai ha^{-1} (MPOST) followed by flumioxazin at 71.5 g ai ha^{-1} plus MSMA at 2240 g ai ha^{-1} and 0.25% v/v nonionic surfactant (Induce, Helena Agri-Enterprises LLC, Collierville TN) at layby (Tables 1 and 2). The dicamba in-crop program consisted of fluometuron at 1120 g ai ha^{-1} plus dicamba at 1120 g ae ha^{-1} plus glyphosate at 1260 g ae ha^{-1} (PRE) followed by a premixture of dicamba at 560 g ae ha^{-1} and *S*-metolachlor at 1068 g ai ha^{-1} (Tavium® with VaporGrip®, Syngenta Crop Protection Greensboro, NC) plus glyphosate at 1260 g ae ha^{-1} (EPOST) followed by glufosinate at 656 g ai ha^{-1} plus glyphosate at 1260 g ae ha^{-1} plus acetochlor at 1260 g ai ha^{-1} (MPOST) followed by flumioxazin at 71.5 g ai ha^{-1} plus MSMA at 2240 g ai ha^{-1} and 0.25% v/v nonionic surfactant (Induce, Helena Agri-Enterprises LLC, Collierville TN) at layby (Tables 1 and 2). Zero-tolerance thresholds were executed using a one-time hand weeding event 14 days after the layby application. Hand weeding was conducted using four graduate students per plot and the time to hand weed each plot was recorded in seconds using a stopwatch.

Prior to each growing season, ten, 347 mL soil cores were taken from each plot at depths of 0 to 7.6 cm and 7.6 to 15.2 cm to measure soil seedbank densities through exhaustion in a greenhouse. Soil from within the same plots were mixed to homogenize the sample. Equal parts based on volume of field soil and potting mix were then placed in 52 x 40 x 5 cm black plastic flats with the weight of the field soil being recorded prior to combining with the potting soil. The flats were then placed in the greenhouse and watered twice daily to promote weed germination. Emerged weeds were counted every other week. Every four weeks the soil flats were placed into a -17 C freezer for two weeks to break dormancy of weed seeds. These procedures were repeated until no more emergence occurred for two weeks following removal from the freezer. In both years, this was achieved after three cycles of freezing and thawing. Throughout the season, total weed emergence was determined by counting emerged weeds in four seasonally established, 1 m^2 quadrats per plot. Individual Palmer amaranth were counted at 21, 42, 63, and 70 DAP prior to each herbicide application and again 7 days prior to the hand-weeding event. Immediately prior to cotton harvest, the total number of inflorescence-producing Palmer amaranth within each plot was counted and 40 bolls were collected per plot, homogenized, and subsequently analyzed for percent turnout to determine the amount of lint produced. Seedcotton was harvested using a two-row cotton harvester, harvesting the center six rows of cotton from each plot, and seedcotton was weighed in-field using a weigh wagon.

The seedcotton, percent turnout, as well as the inputs and their associated costs for each management strategy were taken into consideration to conduct an economic analysis of each management program (Table 3). Turnout was assumed to 40% based on local practices and costs for each management practice were attained using the University of Arkansas Extension Crop Enterprise Budgets (University of Arkansas Extension Service 2021), which report the costs for labor and horsepower for various practices associated with Arkansas agriculture. Cotton prices were based on the 10-year average for cotton lint, set at \$1.79/kg (USDA-AMS 2016; 2021) Chemical costs were obtained from University of Arkansas Extension Enterprise Budgets, which were comprised from an average of at least ten different chemical retailers in the Arkansas

Mississippi Delta growing region. Costs of chemicals, adjuvants, or additives not included in these budgets were obtained from an average of three different chemical suppliers in the Midsouth and Midwest similar to procedures done by Striegel et al. (2020) for economic analysis of herbicide programs.

All data were analyzed using R version 4.0.2 R Foundation for Statistical Computing, Vienna, Austria). Shapiro-Wilks tests were conducted using the base R *shapiro.test* function to determine if data fulfilled the assumption of normality and equal variance was determined by plotting the residuals of the models prior to final model selection (Kniss and Streibig 2018). Data were analyzed using linear mixed effect models in the *"nlme"* package (Pinheiro 2021; Stoup 2014). Total Palmer amaranth emergence was analyzed separately by year due to the measurements of total Palmer amaranth emergence being done prior to the implementation of zero-tolerance strategies in 2019 while in 2020 the Palmer amaranth seedbank had been subjected to these strategies. As a result, the 2019 total Palmer amaranth emergence model did not include zero-tolerance. Greenhouse soil seedbank exhaustion data were analyzed using an additional factor of depth as the whole-plot factor in the mixed effect model. Data were then subjected to ANOVA, and means were separated using a least significant difference with Tukey's adjustment with an α=0.05. Correlation estimates were made between the quantitative variables total Palmer amaranth emergence, inflorescence-producing Palmer amaranth, time to hand weed, partial return, yield, and weed management costs to determine the relationships, if any, between each variable. A correlation coefficient matrix was created using the "rcorr" function in the "*Hmisc*" package (Harrell Jr. 2021).

Results and Discussion

Impact on weed ecology

Total Palmer amaranth emergence was influenced by different factors in both years. In 2019, total Palmer amaranth was affected by the presence or absence of the one-time deep tillage event (Table 4). The use of the moldboard plow in the previous fall reduced Palmer amaranth to 63,000 plants ha^{-1} from 260,000 plants ha^{-1} in its absence, averaged over other factors (Table 5). Similarly, in 2020, total Palmer amaranth emergence was impacted by an interaction between tillage practices and the use of a zero-tolerance weed management approach. For the treatments that utilized a zero-tolerance weed management strategy the previous year, there were no differences between those that included deep tillage and those that did not. Conversely, when zero-tolerance was not utilized, the effect of the one-time deep tillage event was still noticeable, as Palmer amaranth emergence was reduced from 130,0000 plants ha^{-1} in the absence of tillage to 35,000 plants ha^{-1} in plots deep-tilled in fall of 2018. The reduction of Palmer amaranth emergence by 76% in year one and 73% in year two is similar to findings by DeVore et al. (2012; 2013) and Aulakh et al. (2012) where the inversion of the soil reduced Palmer amaranth emergence 70 to 81% in crop production situations.

Total Palmer amaranth emergence was also impacted by the presence of a cereal rye cover crop in 2019 as well as an interaction between zero-tolerance, cover crop use, and herbicide program in 2020 (Table 4). The use of a cereal rye in 2019 resulted in greater Palmer amaranth emergence relative to absence of the cover crop. The average number of emerged Palmer amaranth in cover crop plots was 180,000 plants ha^{-1} compared to 150,000 plants ha^{-1} in plots without cereal rye cover crops (Table 5). These results are dissimilar to other cover crop studies where cereal rye cover crops were used. Previous research has shown that the use of cereal rye typically reduces Palmer amaranth emergence or does not significantly effect weed emergence (DeVore et al. 2012 and 2013; Wiggins et al. 2016; Palhano et al. 2018; Price et al. 2021). It should be noted that in 2019, the cereal rye cover crop was not planted until mid-November, where there was very little time for cover crop growth and establishment prior to dormancy. Consequently, the cereal rye biomass and groundcover were greatly reduced when compared to the cereal rye in 2020 where the cereal rye in 2019 measured less than 40 cm in height and the cereal rye in 2020 was approximately 150 cm tall. Cereal rye biomass at planting was not measured in 2019, but biomass of the cereal rye at planting in 2020 averaged 4500 kg ha^{-1}, which is similar to biomass recovered in other studies where weed emergence was suppressed at biomass levels ≥3120 kg ha^{-1} (Palhano et al. 2018; Price et al 2021).

In 2020, an interaction between the use of cover crop, herbicide program, and zero-tolerance impacted Palmer amaranth emergence (Table 4). Where zero-tolerance and cereal rye were utilized, as well as when neither were utilized, there were no differences between the use or absence of a dicamba-based herbicide program. Alternatively, when either of these cultural practices were negated, there was a significant difference between Palmer amaranth emergence on a basis of herbicide program. When zero-tolerance was implemented but the cereal rye was not, dicamba-based herbicide programs resulted in lower Palmer amaranth densities than in the absence of dicamba (20,000 plants ha^{-1} vs 73,000 plants ha^{-1}) (Table 5). A similar result occurred when cereal rye was utilized while zero-tolerance was not, where the dicamba-based herbicide program reduced Palmer amaranth emergence from 63,000 plants ha^{-1} in plots receiving no dicamba compared to 14,000 plants ha^{-1} for those with the dicamba-based program (Table 5). Based on these interactions, no statement can be made whether zero-tolerance or cereal rye provided improved weed suppression, though both practices did result in a numeric reduction in Palmer amaranth emergence.

The decreased weed emergence in the dicamba-based herbicide program in 2020 but not 2019 can be primarily attributed to differences in climatic conditions between the two years (Figure 1). Within five days of planting in 2019, there were a series of rainfall events that activated the preemergence herbicide fluometuron (Figure 1; Anonymous 2020), which was included in both herbicide programs and subsequently allowed for similar Palmer amaranth control the first 21 days after planting, a critical time-period for cotton growth and development (Klingaman and Oliver 1994; Zimdahl 2004; Korres and Norsworthy 2015). Conversely, there were no rainfall events for the first 11 days after planting in 2020 (Figure 1). The lack of rainfall did not allow for the fluometuron to become activated, thus vanquishing the activity of this herbicide. Meanwhile, the dicamba that was utilized in the dicamba-based herbicide program was readily active at the time of application, as similarly observed by Smith et al. 2018, where the herbicidal activity of dicamba on Palmer amaranth emergence was not impacted by the lack of irrigation or rainfall following application. The immediate activity of dicamba allowed for the suppression of weeds by this herbicide program as similarly seen in other studies investigating the use of dicamba as a preemergence suppressor of weeds (Johnson et al. 2010; Byker et al. 2013; Meyer et al. 2015). With new updates to dicamba product labels in 2021, the use of 1120 g ae ha^{-1} PRE in cotton is no longer permitted, reducing the maximum application rate at this time to 560 g ae ha^{-1} (Anonymous 2021).

With differences between the two herbicide programs not seen when both zero-tolerance and cereal rye were implemented as well as when neither were utilized at the same time, it can be hypothesized that the integration of these two strategies can overcome some issues surrounding poor preemergence herbicide activation. The presence of both the cereal rye cover crop and the zero-tolerance strategy may have resulted in lower seedbank pressures that would have made determining differences difficult. Likewise, the absence of both programs may have resulted in an increased seedbank pressure that may have made determining differences difficult. Findings also suggest that without the use of these strategies, even with effective herbicide activation, Palmer amaranth will continue to emerge in large quantities throughout the season. These results are similar to findings by others, particularly when cereal rye cover crops were utilized as part of integrated weed management systems. Korres and Norsworthy (2015) determined that with the use of a cereal rye cover crop that the initiation of the critical weed-free period could be delayed due to the suppressive characteristics of the cereal rye.

When the hand-weeding treatments were implemented as part of the zero-tolerance management strategy, the time it took to rid plots of Palmer amaranth was influenced by an interaction between year, cover crop use, and herbicide program (Table 4). In 2019, there was not a treatment effect on the time it took to hand-weed each plot. The lack of differences between the use of different herbicide programs and cover crop use can be related to the overall effectiveness of weed control programs up to this point. At 77 days after planting, there were few weed escapes as a result of three successful postemergence herbicide applications in both the non-dicamba and dicamba-based programs, allowing for relatively efficient hand-removal of weeds (Table 6). In 2020, it took 14.9 hr ha^{-1} to hand-weed plots that did not utilize a cereal rye cover crop and used the non-dicamba herbicide program, which was the greatest amount of time required of any treatment (Table 6). When a cereal rye cover crop was utilized, the time to hand-weed ranged from 7.5 hr ha^{-1} for the non-dicamba program to 3.6 hr ha^{-1} for the dicamba program, which was statistically similar to the non-dicamba program. Use of the dicamba program with the absence of cereal rye also required 3.6 hr ha^{-1} to hand-weed, which was similar to the same herbicide program when cereal rye was utilized but lower than the non-dicamba program used in conjunction with cereal rye (Table 6). Correlation analyses indicated that there was a positive relationship between total Palmer amaranth emergence and the time required to hand weed, further suggesting that the time required to hand weed is best reduced by effective management strategies beforehand (Table 7 and Figure 2).

The trends shown with the time to hand-weed are similar to trends observed with total Palmer amaranth emergence in 2020, where poor activation of preemergence herbicides allowed for increased weed emergence in those plots utilizing the non-dicamba herbicide program. These escapes were problematic throughout the season, as the Palmer amaranth that emerged early were 15- to 25-cm tall at the first postemergence application, which consequently resulted in reduced control compared to weeds that would have emerged later and were smaller at application. Similar issues have been observed by Craigmyle et al. (2013), Merchant et al. (2017), and Vann et al. (2017), where weed control and cotton yield decreased as Palmer amaranth height at time of application increased. The use of cereal rye did appear to suppress Palmer amaranth growth, which allowed for fewer weeds to be present at the end of the season, decreasing the time to hand-weed.

At harvest, the number of inflorescence-producing Palmer amaranth was impacted by three separate interactions: year by tillage, year by herbicide program, and year by cover crop use (Table 4). Many of these influences are similar in nature to the same factors that influenced total Palmer amaranth emergence because the high correlation of emergence with number of inflorescence-producing plants (Table 7). Based on correlation, as total Palmer amaranth emergence increased, the number of inflorescence-producing Palmer amaranth also increased

(Figure 2). In terms of tillage, the 2018 use of deep-tillage reduced the number of inflorescence-producing Palmer amaranth from 1400 plants ha^{-1} with the absence of a one-time deep-tillage event, to 360 plants ha^{-1} with tillage, averaged over all other factors in 2019 (Table 8). In 2020, there was not an apparent difference between the use of the one-time deep-tillage event and not utilizing the moldboard plow for deep-tillage. Similar results were found by DeVore et al. (2012) where the benefits of the moldboard plow from the first year of the study appeared to be diminished in the second year. The key difference between these two studies was that in this study, rows were not re-bedded, but a small furrow plow was ran through the row middles prior to cover crop seeding to improve irrigation flow. Similar to total Palmer amaranth emergence, there was not a difference in 2019 between the two different herbicide programs, but in 2020, the use of the dicamba program reduced inflorescence-producing Palmer amaranth (450 plants ha^{-1} without dicamba vs 59 plants ha^{-1} with dicamba) (Table 8). The increased number of Palmer amaranth at the end of the season in the non-dicamba treatments stems from similar circumstances for increased total Palmer amaranth emergence and increased time to hand-weed, where a lack of residual activity at the beginning of the season led to weed escapes that were never fully controlled throughout the season. The interaction between year and cover crop use is similar to that found with total Palmer amaranth emergence, where in 2020 there were no differences but in 2019, the use of a cereal rye cover crop increased the number of Palmer amaranth plants at the end of the season from 640 plants ha^{-1} to 1100 plants ha^{-1} (Table 8).

Results from the soil seedbank exhaustion studies conducted in the greenhouse found no differences between any of the management factors ($p>0.05$). The inconclusiveness of these results is similar to findings by DeVore et al. (2013), Cardina and Sparrow (1996), and Espeland et al. (2010) that suggested that quantifying soil seedbank populations over time using similar methods does not accurately capture the total variability in the field and does not capture the same environmental conditions that would affect those weed populations in the field. A more effective way to capture changes in weed soil seedbank populations may be to monitor total weed emergence the season following completion of the long-term study in the absence of a crop or other management practices.

Impact on Cotton Production Economics

Cotton yield and partial returns were influenced by a multitude of factors throughout the course of this study. Based on multiple correlation analyses, it was determined that yield and partial return were positively and linearly related to each other (Table 7). Cotton lint yields were generally lower in 2020 than in 2019, due to the occurrence of two separate tropical storm events in 2020 prior to harvest (Hurricanes Laura and Delta) that resulted in widespread lodging and dropped bolls across the entire test area. With an R^2 of 0.9808, there is strong evidence that the greatest influence on partial returns as it relates to weed management came from cotton yield (Figure 3). It was determined that the use of a one-time deep tillage event negatively impacted cotton yields (Table 4). The use of tillage reduced cotton lint yield from 1600 kg ha^{-1} to 1500 kg ha^{-1} and consequently reduced partial returns by \$240 ha^{-1}. This is contrary to findings from others where typically the use of a one-time deep tillage results in similar or greater cotton yields (Aulakh et al. 2012; DeVore et al. 2012). A possible explanation for the reduction in cotton yield following the use of a one-time deep tillage event may be due to a reduction in potassium in the top portion of the soil. Where potassium has been typically broadcast applied at the site, potassium levels were likely stratified, with the greatest levels being found near the soil surface (Howard et al. 1999). The deep tillage event likely buried the soil that was rich with potassium to a depth at which the cotton was unable to utilize the nutrient until later in the season, after yield reduction has already occurred (Singh et al 2009).

The use of a cereal rye cover crop also influenced cotton yields during the course of the study, but the effect was dependent on the year (Table 8). In 2019, there were no differences between the presence or absence of a cereal rye cover crop. This result can be predominantly attributed to the lack of adequate cover crop establishment caused by wet conditions in the fall of 2018 that delayed planting until November. In 2020, the use of cereal rye improved cotton yields by100 kg ha^{-1} and profit by \$280 ha^{-1}. The improvement in cotton yield as a result of cereal rye is similar to findings in Tennessee and Alabama where the use of a cover crop did improve cotton yields in some years, while there were negligible differences in others (Zhou 2017; Price et al. 2021). Findings from other studies in Texas and Arkansas suggested that the use of cereal rye cover crops had no effect on cotton yield or net returns (DeVore et al. 2012; DeLaune et al. 2020).

Cotton yield differed by the use of a zero-tolerance threshold as a function of year and herbicide program (Table 4). In 2019, there were no observed differences in cotton lint yield between the presence or absence of a zero-tolerance management strategy or the use of either herbicide program. The opposite was observed in 2020, where the use of the dicamba herbicide program resulted in an increase in cotton lint yield of 200 kg ha^{-1} (Table 8). The increase in cotton yield is likely a direct result of the greater Palmer amaranth control early in the season by the dicamba in-crop herbicide program, which reduced competition for resources between Palmer amaranth and the cotton. Early season weed control is paramount for proper cotton development as well as yield potential (Klingaman and Oliver 1994; Korres and Norsworthy 2015).

Partial return were also impacted by the use of different herbicide programs, with the more profitable program being dependent on the year (Table 4). In 2019, the non-dicamba in-crop program resulted in greater partial returns than the dicamba in-crop program (Table 8). The primary reason for these differences is not likely attributed to yield differences as yield was not significantly different between the two programs, but rather because of differences in program costs, as the cost of herbicides and associated technology fees for the dicamba program was \$63 ha^{-1} greater than that of the non-dicamba program (Table 3). In 2020, partial returns were optimized instead by the dicamba program, as the partial return was \$150 ha^{-1} more than for the non-dicamba program averaged over other parameters (Table 8). These differences were primarily the result of increased early season weed control from the dicamba program, that allowed for greater cotton yields as well as reduced costs associated with hand weeding as part of the zero-tolerance management strategy.

Cotton yields and profitability in 2020 were decreased as a function of the use of a zero-tolerance weed management strategy. Lint yields decreased by 200 kg ha^{-1} and profitability was reduced by \$530 ha^{-1} (Table 8). In regards to the interaction between hand-weeding and herbicide program that influenced cotton yield, there were no differences in yield between the presence or absence of a zero-tolerance management strategy for plots that utilized the dicamba program. Plots that utilized the non-dicamba program experienced a reduction in yield with the use of hand weeding (Table 8). Losses in yield may have been the result of inadvertent cotton damage by the hand-weeding crew that was removing large Palmer amaranth plants near the cotton plants.

Covariance analyses measured during the study indicated several factors influenced cotton yield and partial returns (Table 6). Unsurprisingly, as the cost of weed management increased, partial returns decreased (Figure 4), though the relationship is not near as strong as that between yield and partial returns (Figure 3). As the time to hand weed a plot increased, weed management costs increased while partial returns and lint yield decreased (Figure 5). The increase in weed management costs is directly related to the increased cost of hand weeding. As the time to hand weed increased, the subsequent cost increased by virtue of the cost being based on the hours needed to complete the task. With lint yields, the reduction from the increase in time required may be indicative of two influences; the increase in the number of Palmer amaranth plants in the plots that needed to be removed which were subsequently competing with the cotton for resources and the previously mentioned inadvertent damage to cotton from the hand weeding due to the large densities and size of Palmer amaranth.

Partial returns were reduced as a result of the increase in time required to hand weed plots due to the reduction in cotton yield as well as the increased cost of management. As the cost of weed management increased, partial returns decreased, while cotton lint yields were not significantly impacted, suggesting that the use of simple, low-cost management strategies will result in similar yields and profits as those management strategies that cost more. These results should be taken with context as this study only encompasses two years of management and that changes in soil seedbank dynamics may not be fully observational at this point in time, as Palmer amaranth seed may remain viable for approximately 4 to 5 years (Jha et al. 2014; Korres et al. 2018). The risk of herbicide resistance development also may not be fully understood with this time frame, as previous studies have indicated that it takes at least 2 to 3 generations to develop resistance to herbicides such as dicamba (Tehranchian et al. 2017; Vieira 2019).

Further research should be conducted to understand the long-term implications of these management strategies both ecologically and economically. The environmental conditions that this long-term study were subjected to were drastically different than each other, necessitating for a continuation of this study to more accurately assess the impact of these management factors over a longer period and to generate better predictive and decision-making models for Palmer amaranth management. The findings from this research exemplify the need for integrated weed management practices to effectively manage Palmer amaranth. No single management practice effectively prevented Palmer amaranth from emerging and competing for resources in the field. Climatic factors also impacted the ability for several management factors to be effective. As a result, multiple integrated weed management strategies should be utilized to overcome any shortcomings and failures of other strategies. These recommendations echo and further reiterate the importance of utilizing best management practices when developing weed management programs in cotton (Norsworthy et al. 2012).

References

Anonymous (2021) Cotoran Herbicide Label. ADAMA Group Company. Raleigh, NC https://www.adama.com/documents/444852/445866/cotoran-4l-label.pdf. Accessed May 13, 2021.

Aulakh JS, Price AJ, Enloe SF, van Santen E, Wehtje G, Patterson MG (2012) Integrated Palmer amaranth management in glufosinate-resistant cotton: I. soil-inversion, high-residue cover crops and herbicide regimes. Agronomy 2:295-311

Barber LT, Smith KL, Scott RC, Norsworthy JK, Vanglider AM (2015) FSA2177 Zero-tolerance: a community-based program for glyphosate-resistant Palmer amaranth management. University of Arkansas Cooperative Extension. Accessed at: https://www.uaex.edu/publications/pdf/FSA2177.pdf. Accessed May 12, 2021

Beckie HJ, Reboud X (2009) Selecting for weed resistance: herbicide rotation and mixture. Weed Technol 23:363–370

Beckie HJ (2011) Herbicide resistant weeds: management tactics and practices. Weed Technol 20:793-814

Berger ST, Ferrell JA, Rowland DL, Webster TM (2015) Palmer amaranth (*Amaranthus palmeri*) competition for water in cotton. Weed Sci 63:928-935

Brabham C, Norsworthy JK, Houston MM, Varanasi VK, Barber T (2019) Confirmation of *S*-metolachlor resistance in Palmer amaranth (*Amaranthus palmeri*). Weed Technol 33:720-726

Burgos NR, Kuk YI, Talbert RE (2001) *Amaranthus palmeri* resistance and differential tolerance of *Amaranthus palmeri* and *Amaranthus hybridus* to ALS-inhibitor herbicides. Pest Manag Sci 57:449-457

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 Technol 27:492-496

Cardina J and Sparrow DH (1996) A comparison of methods to predict weed seedling populations from the soil seedbank. Weed Sci 44:46-51

Craigmyle BD, Ellis JM, Bradley KW (2013) Influence of weed height and glufosinate plus 2,4-D combinations on weed control in soybean with resistance to 2,4-D. Weed Technol 27:271-280

DeLaune PB, Mubvumba P, Fan Y, Bevers S (2020) Agronomic and economic impacts of cover crops in Texas rolling plains cotton. Agrosys Geosci Environ 2020:e20027

DeVore JD, Norsworthy JK, Brye KR (2012) Influence of deep tillage and a rye cover crop on glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) emergence in cotton. Weed Technol 26:832-838

DeVore JD, Norswothy JK, Brye KR. (2013) Influence of deep tillage, a rye cover crop, and various soybean production systems on Palmer amaranth emergence in soybean. Weed Technol 27:263-270

Espeland EK, Perkins LB, Leger EA (2010) Comparison of seed bank estimation techniques using six weed species in two soil types. Range Ecol Manag 63:243-247

Gaines TA, Zhang W, Wang D, Bukun B, Chisolm ST, Shaner DL, Nisses SJ, Patzoldt WL, Tranel PJ, Culpepper AS, Grey TL, Webster TM, Vencill WK, Sammons RD, Jiang J, Preston C, Leach JE, Westra P (2010) Gene amplification confers glyphosate resistance in *Amaranthus palmeri*. Proc Natl Acad Sci USA 107:1029-1034

Gossett BJ, Murdock EC, Toler JE (1992) Resistance of Palmer amaranth (*Amaranthus palmeri*) to the dinitroaniline herbicides. Weed Technol 6:587-591

Heap I (2021) International Survey of Herbicide Resistant Weeds. http://www.weedscience.org/Summary/Species.aspx?WeedID=14. Accessed May 12, 2021

Harrell Jr. FE and Dupont C (2021) *Hmisc*: Harrell Miscellaneous. Accessed at: https://cran.r-project.org/web/packages/nlme/nlme.pdf. Accessed May 12, 2021

Howard DD, Essington ME, Tyler DD (1999) Vertical phosphorus and potassium stratification in no-till cotton soils. Agron. J. 91:266-296

Johnson B, Young B, Matthews J, Marquardt P, Slack C, Bradley K, York A, Culpepper S, Hager A, Al-Khatib K, Steckel L, Moechnig M, Loux M, Bernards M, Smeda R (2010) Weed control in dicamba-resistant soybeans. Online. Crop Manag doi: 10.1094/CM-2010-0920-01-RS

Klingaman TE, Oliver LR (1994) Influence of cotton (*Gossypium hirsutum*) and soybean (*Glycine max*) planting date on weed interference. Weed Sci 42:61-65

Kniss AR (2018) Genetically engineered herbicide-resistant crops and herbicide-resistant weed evolution in the United Sates. Weed Sci 66:260-273

Kniss AR, Streibig JC (2018) Statistical analysis of agricultural experiments using R. https://Rstats4ag.org. Accessed February 1, 2021

Korres NE, Norsworthy JK (2015) Influence of a rye cover crop on the critical period for weed control in cotton. Weed Sci 63:346-352

Korres NE, Norsworthy JK, Young BG, Reynolds DB, Johnson WG, Conley SP, Smeda RJ, Mueller TC, Spaunhorst DJ, Gage KL, Loux M, Kruger GR, Bagavathiannan MV (2018) Seedbank persistence of Palmer amaranth (*Amaranthus palmeri*) and waterhemp (*Amaranthus tuberculatus*) across diverse geographical regions in the United States. Weed Sci 66:446-456

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

Merchant RM, Culpepper AS, Eure PM, Richburg JS, Braxton LB (2017) Salvage Palmer amaranth programs can be effective in cotton resistant to glyphosate, 2,4-D, and glufosinate. Weed Technol 28:316-322.

Meyer CJ, Norsworthy JK, Young BG, Steckel LE, Bradley KW, Johnson WG, Loux MM, Davis VM, Kruger GR, Bararpour MT, Ikley JT, Spaunhorst DJ, Butts TR (2015)

Herbicide program approaches for managing glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) and waterhemp (*Amaranthus tuberculatus* and *Amaranthus rudis*) in future soybean-trait technologies. Weed Technol 29:716-729

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

Moss S (2019) Integrated weed management (IWM): why are farmers reluctant to adopt non-chemical alternatives to herbicides? Pest Manag Sci 75:1205-1211

Norris RF (1999) Ecological implications of using thresholds for weed management. Pages 31-58 *in* Buhler DD, ed. Expanding the Context of Weed Management. New York: Hawthorn

Norsworthy JK, Griffith GM, Scott RC, Smith KL, Oliver LR (2008) Confirmation and control of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) in Arkansas. Weed Technol 22:108-113

Norsworthy JK, Griffith GM, Griffin T, Bagavathiannan MV, 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 Technol 62:237-249

Norsworthy JK, Korres NE, Bagavathiannan MV (2018) Weed seedbank management: revisiting how herbicides are evaluated. Weed Sci 66:415-416

Norsworthy JK, Ward SM, Shaw DR, Llewellyn R, Nichols RL, Webster TM, Bradley KW, Frisvold G, Powles SB, Burgos NR, Witt W, Barrett M (2012) Reducing the risks of herbicide resistance: best management practices and recommendations. Weed Sci 60 (SI I):31-62

Palhano MG, Norsworthy JK, Barber T (2018) Cover crops suppression of Palmer amaranth (*Amaranthus palmeri*) in cotton. Weed Technol 32:60-65

Peterson MA, Collavo A, Overjero R, Shivrain V, Walsh MJ (2018) The challenge of herbicide resistance around the world: a current summary. Pest Manag Sci 74:2246-2259

Pinheiro J (2021) *nlme*: linear and nonlinear mixed effects models. Accessed at: https://cran.r-project.org/web/packages/nlme/nlme.pdf. Accessed May 12, 2021.

Price AJ, Monks CD, Culpepper AS, Duzy LM, Kelton JA, Marshall MW, Steckel LE, Sosnoskie LM, Nichols RL (2016) High-residue cover crops alone or with strategic tillage to manage glyphosate resistant Palmer amaranth (*Amaranthus palmeri*) in southeastern cotton (*Gossypium hirsutum*). J Soil Water Conserv 71:1-11

Price AJ, Nichols RL, Morton TA, Balkom KS, Grey TL, Li S (2021) Effect of cover crop biomass, strip-tillage, residue disturbance width, and PRE-herbicide placement on cotton weed control, yield, and economics. Weed Technol 35:385-393

Sauer, JD 1972. The dioecious amaranths: a new species name and major range extensions. Madrono 21:426-434

Shyam C, Borgato EA, Peterson DE, Dille JA, Jugulam M (2021) Predominance of metabolic resistance in a six-way-resistant Palmer amaranth (*Amaranthus palmeri*) population. Front Plant Sci 11:614618

Singh D, Brar MS, Brar AS (2009) Critical concentrations of potassium in cotton (*Gossypium hirsutum*) J. Agric. Sci. 118:71-75

Smith DT, Baker RV, Steele GL (2000) Palmer amaranth *(Amaranthus palmeri*) impacts on yield, harvesting, and ginning in dryland cotton (*Gossypium hirsutum*). Weed Technol 14:122-126

Smith HC, Ferrell JA, Webster TM, Ferandez JV, Dittmar PJ, Munoz PR, MacDonald GE (2016) Impact of irrigation volume on PRE herbicide activity. Weed Technol 30:793:800

Steckel, LE (2020) Dicamba-resistant Palmer amaranth in Tennessee: stewardship even more important. The University of Tennessee Institute of Agriculture. Available. https://news.utcrops.com/2020/07/dicamba-resistant-palmer-amaranth-in-tennessee-stewardship-even-more-important/. Accessed February 1, 2021

Striegel A, Eskridge KM, Lawrence NC, Knezevic SZ, Kruger GR, Proctor CA, Hein GL, Jhala AJ (2020) Economics of herbicide programs for weed control in conventional, glufosinate, and dicamba/glyphosate-resistant soybean across Nebraska. Agron J 112:5158-5179

Tehranchian P, Norsworthy JK, Powles S, Barapour MT, Bagavathiannan MV, Barber T, Scott RC (2017) Recurrent sublethal-dose selection for reduced susceptibility of Palmer amaranth (*Amaranthus palmeri*) to dicamba. Weed Sci 65:206-212

University of Arkansas Cooperative Extension Service (2021) Arkansas field crop enterprise budgets. Online. https://www.uaex.edu/farm-ranch/economics-marketing/farm-planning/budgets/crop-budgets.aspx. Accessed April 15, 2021.

USDA-Agricultural Marketing Service, United States Department of Agriculture (2017) Cotton Price Statistics 2016-2017. Available: https://apps.ams.usda.gov/Cotton/AnnualCNMarketNewsReports/CottonPriceStatistics/ACPS-2016-2017.PDF. Accessed November 18, 2021

USDA-Agricultural Marketing Service, United States Department of Agriculture (2021) Cotton Price Statistics 2020-2021. Available: https://www.ams.usda.gov/mnreports/cnaacps.pdf. Accessed November 18, 2021

USDA-Natural Resources Conservation Service, United States Departments of Agriculture. Web Soil Survey. Available: http://websoilsurvey.sc.egov.usda.gov/. Accessed February 1, 2021

Vann RA, York AC, Cahoon CW, Buck TB, Askey MC, Seagroves RW (2017) Effect of delayed dicamba plus glufosiante application on Palmer amaranth (*Amaranthus palmeri*) control and XtendFlex™ cotton yield. Weed Technol 31:633-640

Varanasi VK, Brabham C, Norsworthy JK (2018) Confirmation and characterization of non-target site resistance to fomesafen in Palmer amaranth. Weed Sci 66:702-709

Vieira BC, Luck JD, Amundsen KL, Gaines TA, Werle R, Kruger GR (2019) Response of *Amaranthus* spp. Following exposure to sublethal herbicide rates via spray particle drift. PLoS ONE 14: e0220015

Westwood JH, Charudattan R, Duke SO, Fennimore SA, Marrone P, Slaughter DC, Swanton C, Zollinger R (2018) Weed management in 2050: perspectives on the future of weed science. Weed Sci 66:275-285

Wiggins MS, Hayes RM, Steckel LE (2016) Evaluating cover crops and herbicides for glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) control in cotton. Weed Technol 30:414-422

Zhou XV, Larson JA, Boyer CN, Roland KR, Tyler DD (2017) Tillage and cover crop impacts on economics of cotton production in Tennessee. Agron J 109:2087-2096

Zimdahl RL (2004) Weed-crop competition: a review. 2nd edn. Ames IA: Blackwell Publishing. Pp 39-46

Tables and Figures

Table 1. Herbicide information for all weed management chemicals and adjuvants used in Marianna, AR in 2019 and 2020.

Common Name	**Product Name**	**Manufacturer**	**Address**
Acetochlor	Warrant	Bayer Crop Science	Research Triangle Park, NC
Dicamba	Clarity	BASF	Research Triangle Park, NC
Dicamba	Xtendimax plus VaporGrip	Bayer Crop Science	Research Triangle Park, NC
Dicamba + *S*-metolachlor	Tavium plus VaporGrip	Syngenta Crop Protection LLC	Greensboro, NC
Drift Reduction Agent	Intact	Precision Laboratories, LLC	Waukegen, ILL
Flumioxazin	Valor	Valent	Walnut Creek, CA
Fluometuron	Cotoran	Syngenta Crop Protection LLC	Greensboro, NC
Glufosinate	Liberty	BASF	Research Triangle Park, NC
Glyphosate	Roundup PowerMax	Bayer Crop Science	Research Triangle Park, NC
MSMA	MSMA	Drexel Chemical Co.	Memphis, TN
Non-ionic Surfactant	Induce	Helena Agri-Enterprises, LLC	Collierville, TN
Paraquat	Gramoxone 2SL	Syngenta Crop Protection LLC	Greensboro, NC
S-metolachlor	Dual Magnum	Syngenta Crop Protection LLC	Greensboro, NC

Table 2. Herbicide weed management programs for 2019 and 2020 in Marianna, AR[a]

Program	Timing	Product name	Common name	Rate g ai or ae ha^{-1}
Dicamba in-crop	Burndown	Roundup PowerMax + Clarity	Glyphosate + dicamba	1260 + 280
	PRE	XtendiMax plus VaporGrip + Cotoran + Roundup PowerMax	Dicamba + Fluometuron + Glyphosate	1120 + 1120 + 1260
	EPOST	Tavium plus VaporGrip + Roundup PowerMax	Dicamba + *S*-metolachlor + Glyphosate	560 + 1068 + 1260
	MPOST	Liberty + Roundup PowerMax + Warrant	Glufosinate + Glyphosate + Acetochlor	656 + 1260 + 1260
	Layby	Valor + MSMA	Flumioxazin + MSMA	71.5 + 2240
Non-dicamba in-crop	Burndown	Roundup PowerMax + Clarity	Glyphosate + dicamba	1260 + 280
	PRE	Gramoxone + Cotoran + Roundup PowerMax	Paraquat + Fluometuron + Glyphosate	700 + 1120 + 1260
	EPOST	Liberty + Roundup PowerMax + Dual [illegible]um	Glufosinate + Glyphosate + *S*-metolachlor	656 + 1260 + 1068
	MPOST	Liberty + Roundup PowerMax + Warrant	Glufosinate + Glyphosate + Acetochlor	656 + 1260 + 1260
	Layby	Valor + MSMA	Flumioxazin + MSMA	71.5 + 2240

[a] Abbreviations: PRE = preemergence, EPOST = early postemergence, MPOST = mid-postemergence

Table 3. Weed management programs and the costs associated with each weed management strategy for 2019 and 2020 near Marianna, AR[a,b]

Year	Program				Cost				
	Deep tillage	Cover crop	Herbicide program	Zero-tolerance	Deep tillage	Cover crop	Herbicide program	Zero-tolerance	
	---y/n---		Dicamba/non-dicamba[a]	y/n	----------------- $\$\ \text{ha}^{-1}$ -------------------			hr ha^{-1}[b]	$\$\ \text{ha}^{-1}$[b]
2019	y	n	non-dicamba	y	39.52	0.00	542.34	4.20	50.40
	y	n	Dicamba	y	39.52	0.00	605.96	3.96	47.52
	y	y	non-dicamba	y	39.52	86.63	542.34	4.06	48.72
	y	y	Dicamba	y	39.52	86.63	605.96	4.99	59.88
	n	n	non-dicamba	y	0.00	0.00	542.34	4.82	57.84
	n	n	Dicamba	y	0.00	0.00	605.96	4.71	56.52
	n	y	non-dicamba	y	0.00	86.63	542.34	5.93	71.16
	n	y	Dicamba	y	0.00	86.63	605.96	4.96	59.52
	y	n	non-dicamba	n	39.52	0.00	542.34	0.00	0.00
	y	n	Dicamba	n	39.52	0.00	605.96	0.00	0.00
	y	y	non-dicamba	n	39.52	86.63	542.34	0.00	0.00
	y	y	Dicamba	n	39.52	86.63	605.96	0.00	0.00
	n	n	non-dicamba	n	0.00	0.00	542.34	0.00	0.00
	n	n	Dicamba	n	0.00	0.00	605.96	0.00	0.00
	n	y	non-dicamba	n	0.00	86.63	542.34	0.00	0.00
	n	y	Dicamba	n	0.00	86.63	605.96	0.00	0.00

Table 3 cont. Weed management programs and the costs associated with each weed management strategy for 2019 and 2020 near Marianna, AR[a,b]

Year	Program				Cost				
	Deep tillage	Cover crop	Herbicide program	Zero-tolerance	Deep tillage	Cover crop	Herbicide program	Zero-tolerance	
	---y/n---		Dicamba/non-dicamba[a]	y/n	----------------- $ ha^{-1} -------------------			hr ha^{-1b}	$ ha^{-1b}
2020	y	n	non-dicamba	y	0.00	0.00	542.34	16.06	192.72
	y	n	dicamba	y	0.00	0.00	605.96	3.27	39.24
	y	y	non-dicamba	y	0.00	86.63	542.34	6.99	83.88
	y	y	dicamba	y	0.00	86.63	605.96	3.70	44.46
	n	n	non-dicamba	y	0.00	0.00	542.34	13.78	165.36
	n	n	dicamba	y	0.00	0.00	605.96	3.86	46.32
	n	y	non-dicamba	y	0.00	86.63	542.34	7.93	95.16
	n	y	dicamba	y	0.00	86.63	605.96	3.52	42.24

Table 3 cont. Weed management programs and the costs associated with each weed management strategy for 2019 and 2020 near Marianna, AR[a,b]

Year	Program				Cost				
	Deep tillage	Cover crop	Herbicide program	Zero-tolerance	Deep tillage	Cover crop	Herbicide program	Zero-tolerance	
	---y/n---		Dicamba/non-dicamba[a]	y/n	---------------- $ ha^{-1} ------------------			hr ha^{-1b}	$ ha^{-1b}
2020	y	n	non-dicamba	n	0.00	0.00	542.34	0.00	0.00
	y	n	dicamba	n	0.00	0.00	605.96	0.00	0.00
	y	y	non-dicamba	n	0.00	86.63	542.34	0.00	0.00
	y	y	dicamba	n	0.00	86.63	605.96	0.00	0.00
	n	n	non-dicamba	n	0.00	0.00	542.34	0.00	0.00
	n	n	dicamba	n	0.00	0.00	605.96	0.00	0.00
	n	y	non-dicamba	n	0.00	86.63	542.34	0.00	0.00
	n	y	dicamba	n	0.00	86.63	605.96	0.00	0.00

[a] Dicamba in-crop herbicide program or non-dicamba in-crop herbicide program

[b] Values are based on averages for the program

Table 4. P-values for total Palmer amaranth emergence, time to hand weed, inflorescence-producing Palmer amaranth, cotton lint yield, and partial returns by year, zero-tolerance, deep-tillage, cover crop, and herbicide program in Marianna, AR.[a,b]

Source	Total PA emergence		HWT	IPPA	Lint yield	Partial returns
	2019	2020				
	---------------------*P>F*---------------------					
Year	--	--	0.0527	0.1006	0.0571	0.7000
Zero-tolerance	--	0.7747	--	0.4402	**0.0202**	**0.0067**
Deep tillage	**0.0072**	**0.0210**	0.5183	**0.0022**	**0.0085**	**0.0042**
Cover Crop	**0.0334**	0.5402	**0.0027**	**0.0487**	**<0.0001**	**0.0042**
Herbicide Program	0.4999	**<0.0001**	**<0.0001**	**<0.0001**	0.9018	0.4747
Year*Zero-tolerance	--	--	--	0.1727	**0.0161**	**0.0124**
Year*Deep tillage	--	--	0.2630	**0.0082**	0.1798	0.1626
Zero-tolerance*Deep tillage	--	**0.0443**	--	0.7496	0.2448	0.2628
Year*Cover Crop	--	--	**0.0003**	**0.0002**	**0.0174**	**0.0104**
Zero-tolerance*Cover Crop	--	0.0671	--	0.1380	0.1048	0.0812
Deep tillage*Cover Crop	0.2720	0.1311	0.3999	0.9815	0.0643	0.0642
Year*Herbicide Program	--	--	**<0.0001**	**0.0001**	**0.0001**	**0.0001**
Zero-tolerance*Herbicide Program	--	0.8757	--	0.3053	**0.0383**	0.1169
Deep tillage*Herbicide Program	0.6051	0.4100	0.9964	0.8037	0.0849	0.0965
Cover Crop*Herbicide Program	0.3041	0.9056	**0.0045**	0.8371	0.9142	0.9110
Year*Zero-tolerance*Deep tillage	--	--	--	0.8557	0.0663	0.0738
Year*Zero-tolerance*Cover Crop	--	--	--	0.7788	0.8187	0.6383
Year*Deep tillage*Cover Crop	--	--	0.5652	0.8796	0.5256	0.5055
Zero-tolerance*Deep tillage*Cover Crop	--	0.0928	--	0.9271	0.1319	0.1316
Year*Zero-tolerance*Herbicide Program	--	--	--	0.1552	0.9892	0.6967
Year*Deep tillage*Herbicide Program	--	--	0.4769	0.4723	0.1216	0.1475
Zero-tolerance*Deep tillage*Herbicide Program	--	0.1037	--	0.9683	0.1150	0.1294
Year*Cover Crop*Herbicide Program	--	--	**0.0061**	0.8371	0.8802	0.9504

Table 4 cont. P-values for total Palmer amaranth emergence, time to hand weed, inflorescence-producing Palmer amaranth, cotton lint yield, and partial returns by year, zero-tolerance, deep-tillage, cover crop, and herbicide program in Marianna, AR.[a,b]

Source	Total PA emergence		HWT	IPPA	Lint yield	Partial returns
	2019	2020				
	P>F					
Zero-tolerance*Cover Crop*Herbicide Program	--	**0.0489**	--	0.5254	0.8354	0.6769
Deep tillage*Cover Crop*Herbicide Program	0.6790	0.1037	0.2299	0.6502	0.0549	0.0534
Year*Zero-tolerance*Deep tillage*Cover Crop	--	--	--	0.8633	0.8993	0.9353
Year*Zero-tolerance*Deep tillage*Herbicide Program	--	--	--	0.4763	0.2868	0.3250
Year*Zero-tolerance*Cover Crop*Herbicide Program	--	--	--	0.5240	0.8200	0.6695
Year*Deep tillage*Cover Crop*Herbicide Program	--	--	0.6949	0.3759	0.1082	0.1141
Zero-tolerance*Deep tillage*Cover Crop*Herbicide Program	--	0.2097	--	0.0545	0.7379	0.8199
Year*Zero-tolerance*Deep tillage*Cover Crop*Herbicide Program	--	--	--	0.5633	0.4665	0.4718

[a] Abbreviations: PA = Palmer amaranth, HWT = hand weeding time, IPPA = inflorescence-producing Palmer amaranth

[b] Bolded values indicate significant p-values (α=0.05)

Table 5. Total Palmer amaranth emergence in 2019 and 2020 by tillage, cover crop, and zero-tolerance use and herbicide program near Marianna, AR[a]

Factor		Total Palmer amaranth emergence			
		2019		2020	
		-----------------plants ha^{-1}-----------------			
Deep tillage					
Yes		63000	b	62000	
No		260000	a	110000	
Cover Crop					
Yes		180000	a	82000	
No		150000	b	93000	
Zero-tolerance	Deep tillage				
Yes	Yes	-		36000	ab
	No	-		40000	ab
No	Yes	-		14000	b
	No	-		53000	a

Table 5 cont. Total Palmer amaranth emergence in 2019 and 2020 by tillage, cover crop, and zero-tolerance use and herbicide program near Marianna, AR[a]

Factor			Total Palmer amaranth emergence		
			2019	2020	
			-----------------plants ha^{-1}-----------------		
Zero-tolerance	Cover Crop	Herbicide Program			
Yes	Yes	Dicamba in-crop	-	17000	abcd
		Non-dicamba in-crop	-	41000	bd
	No	Dicamba in-crop	-	20000	bd
		Non-dicamba in-crop	-	73000	ac
No	Yes	Dicamba in-crop	-	14000	cd
		Non-dicamba in-crop	-	63000	ac
	No	Dicamba in-crop	-	17000	abcd
		Non-dicamba in-crop	-	40000	abcd

[a] Values followed by the same letter are statistically similar based on Tukey's (α=0.05)

Table 6. Time required to hand-weed plots as a function of year, cover crop use, and herbicide program in Marianna, AR [a]

Year	Cover crop	Herbicide program	Time to hand-weed	
			hrs ha^{-1}	
2019	Yes	Dicamba in-crop	4.97	bc
		Non-dicamba in-crop	4.99	bc
	No	Dicamba in-crop	4.34	bc
		Non-dicamba in-crop	4.51	bc
2020	Yes	Dicamba in-crop	3.61	bc
		Non-dicamba in-crop	7.46	b
	No	Dicamba in-crop	3.57	c
		Non-dicamba in-crop	14.92	a

[a] Values followed by the same letter are statistically similar based on Tukey's (α=0.05)

Table 7. P-values and correlation coefficients for correlation analyses between total Palmer amaranth emergence, inflorescence-producing Palmer amaranth, cotton lint yield, weed management cost, partial return, and time to hand weed in Marianna, AR in 2019 and 2020.^{a,b}

	Total PA emergence	Inflorescence-producing PA	Lint yield	Weed manag. cost	Partial return	Time to hand weed
	---*P>F*---					
Total PA emergence		**<0.0001**	0.0504	0.2145	0.0805	**0.0070**
Inflorescence-producing PA	**<0.0001**		0.0566	0.1093	0.0991	0.0611
Lint yield	0.0504	0.0566		0.5709	**<0.0001**	**<0.0001**
Weed manag. cost	0.2145	0.109	0.5709		**0.0331**	**<0.0001**
Partial return	0.0805	0.0991	**<0.0001**	**0.0331**		**<0.0001**
Time to hand weed	**0.0070**	0.0611	**<0.0001**	**<0.0001**	**<0.0001**	

	Total PA emergence	Inflorescence-producing PA	Lint yield	Weed manag. cost	Partial return	Time to hand weed
	-------------------------------Correlation coefficient-------------------------------					
Total PA emergence	1.00	0.69	0.17	0.11	0.16	0.24
Inflorescence-producing PA	0.69	1.00	0.17	0.14	0.15	0.17
Lint yield	0.17	0.17	1.00	-0.05	0.99	-0.38
Weed manag. Cost	0.11	0.14	-0.05	1.00	-0.19	0.55
Partial return	0.16	0.15	0.99	-0.19	1.00	-0.45
Time to hand weed	0.24	0.17	-0.38	0.55	-0.45	1.00

[a] Abbreviations: PA = Palmer amaranth, mang. = management.

[b] Bolded p-values indicate significant values (α=0.05)

Table 8: Inflorescence-producing Palmer amaranth, cotton lint yield, and partial return based on year, deep tillage, cover crop, zero-tolerance, and herbicide program in Marianna, AR [a,b]

Factor		IPPA		Yield		Partial return	
		plants ha^{-1}		kg ha^{-1}		\$ ha^{-1}	
Deep tillage							
Yes		290		1500	b	760	b
No		860		1600	a	1000	a
Year	Deep tillage						
2019	Yes	360	b	1600		1000	
	No	1400	a	1700		1200	
2020	Yes	220	c	1300		820	
	No	290	c	1500		500	
Year	Cover Crop						
2019	Yes	1100	a	1600	a	1100	a
	No	640	b	1700	a	1100	a
2020	Yes	200	c	1500	a	800	b
	No	310	c	1300	b	520	c
Year	Herbicide Program						
2019	Dicamba in-crop	920	a	1600	a	970	b
	Non-dicamba in-crop	860	a	1700	a	1200	a
2020	Dicamba in-crop	59	c	1500	a	740	c
	Non-dicamba in-crop	450	b	1300	b	590	c
Year	Zero-tolerance						
2019	Yes	470		1700	a	1100	a
	No	480		1700	ab	1100	ab
2020	Yes	210		1300	c	400	c
	No	300		1500	b	930	b

Table 8 cont.: Inflorescence-producing Palmer amaranth, cotton lint yield, and partial return based on year, deep tillage, cover crop, zero-tolerance, and herbicide program in Marianna, AR [a,b]

Factor		IPPA	Yield		Partial return
		plants ha^{-1}	kg ha^{-1}		\$ ha^{-1}
Herbicide Program	Zero-tolerance				
Dicamba in-crop	Yes	710	1500	ab	680
	No	270	1600	a	1000
Non-dicamba in-crop	Yes	800	1400	b	790
	No	510	1600	ab	1000

[a] Abbreviations: IPPA= inflorescence-producing Palmer amaranth

[b] Values followed by the same letter are statistically similar based on Tukey's (α=0.05)

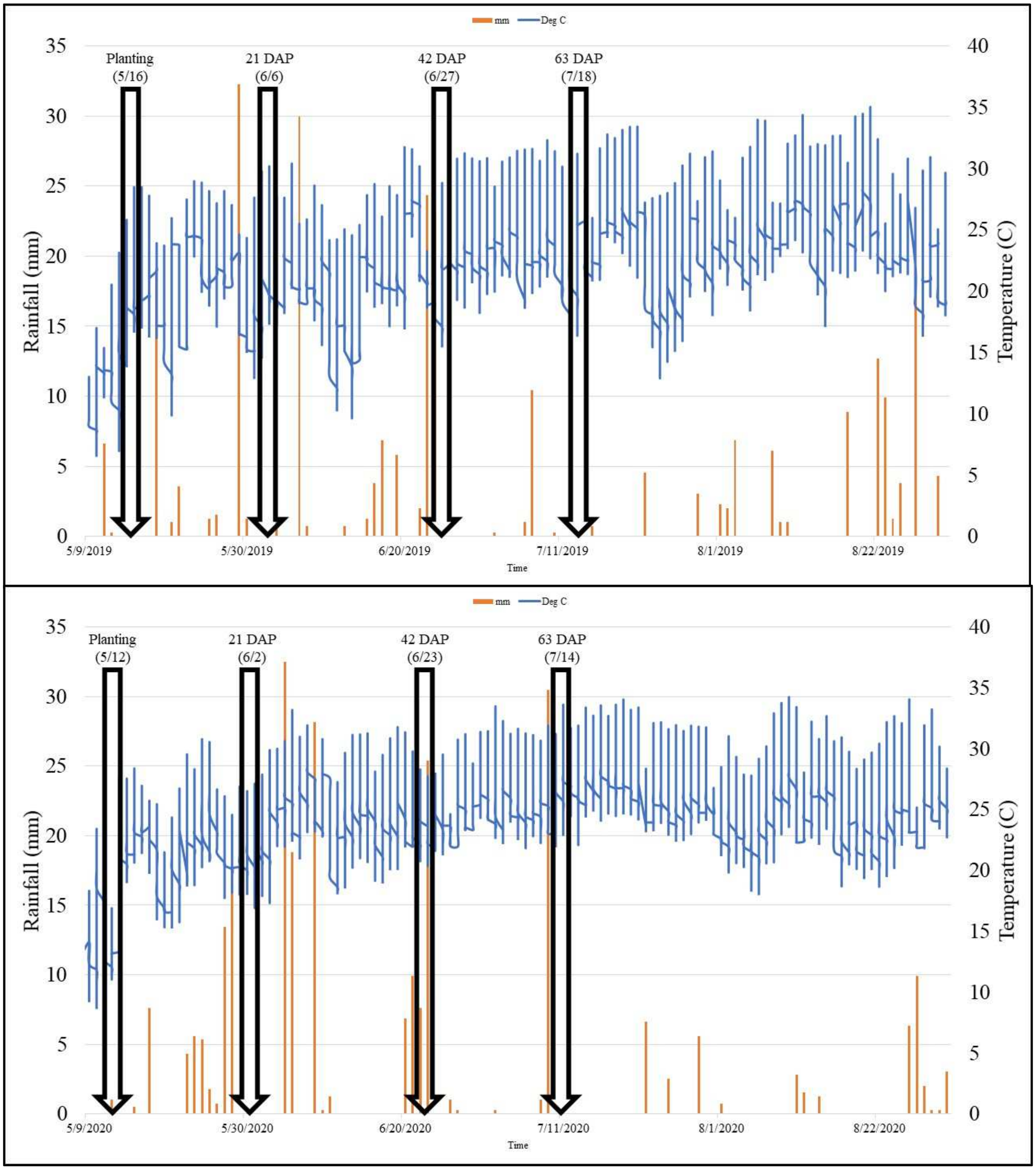

Figure 1. Planting and herbicide application dates, air temperature and rainfall at Marianna, AR in 2019 and 2020. Preemergence herbicide applications occurred immediately after planting.

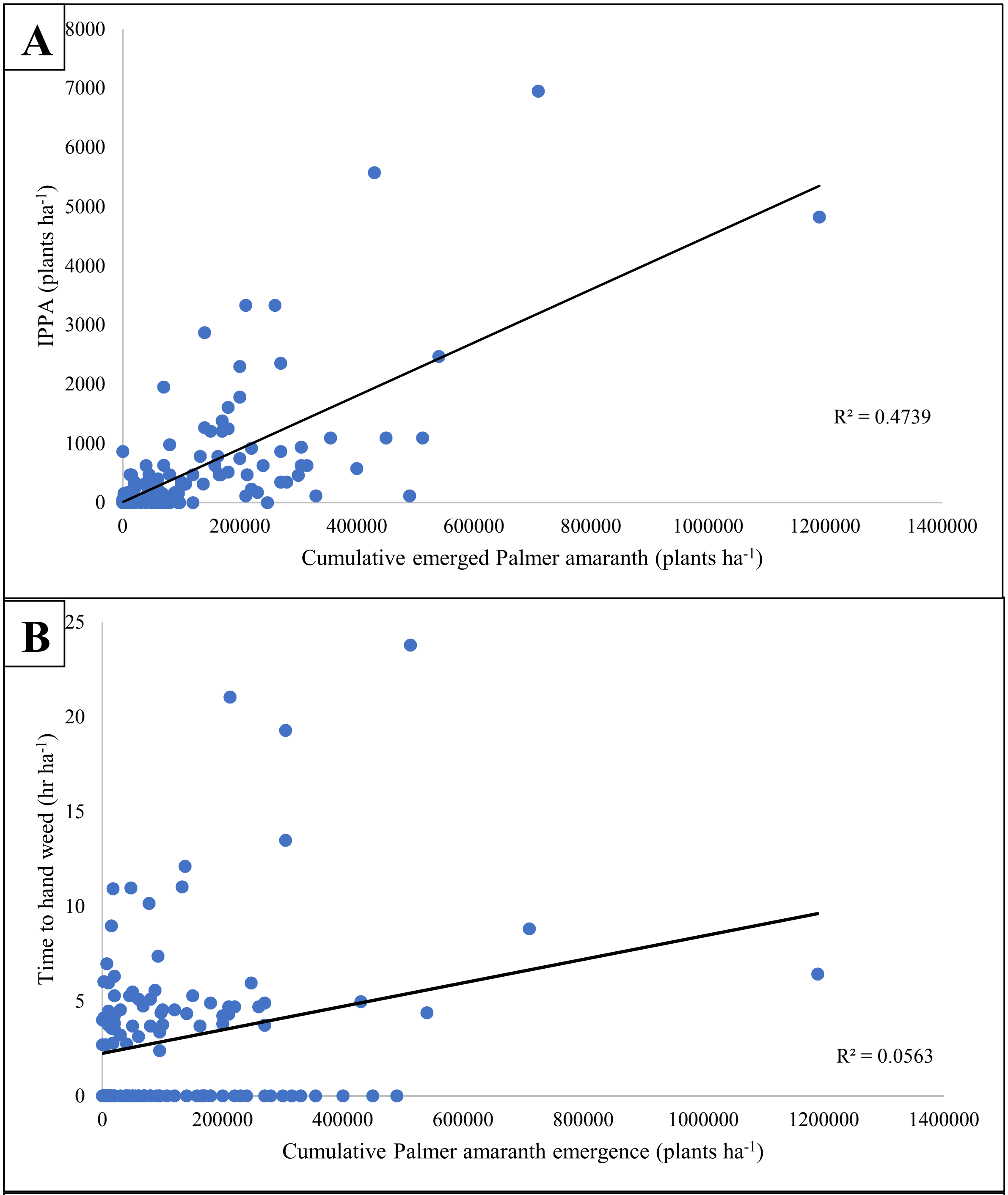

Figure 2. Correlation between cumulative Palmer amaranth emergence and the (A) number of inflorescence-producing Palmer amaranth (IPPA) and (B) the time to hand weed near Marianna, AR

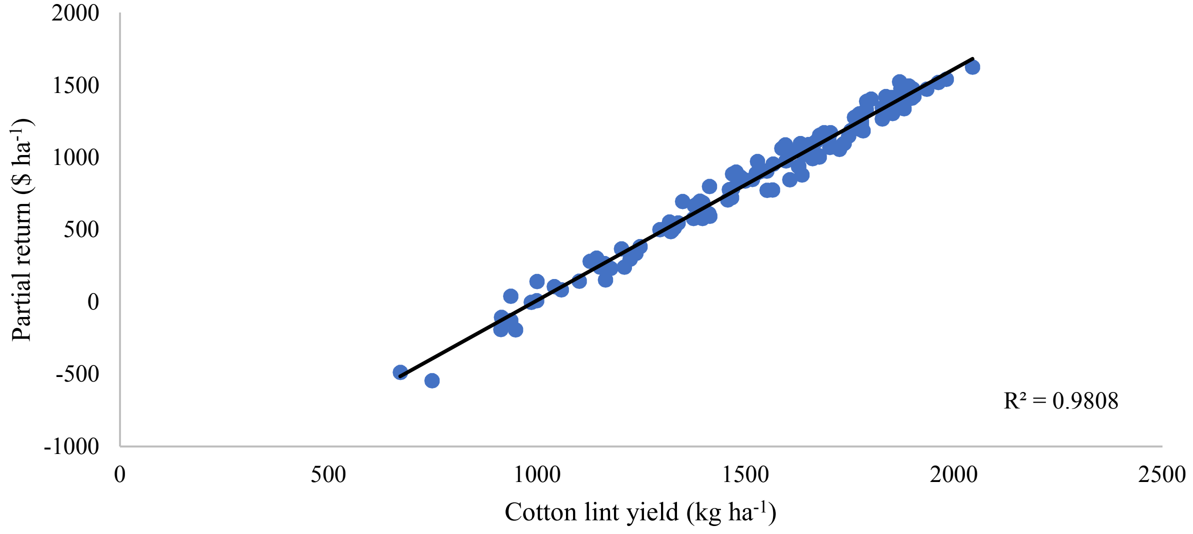

Figure 3. Correlation between cotton lint yield and partial return near Marianna, AR

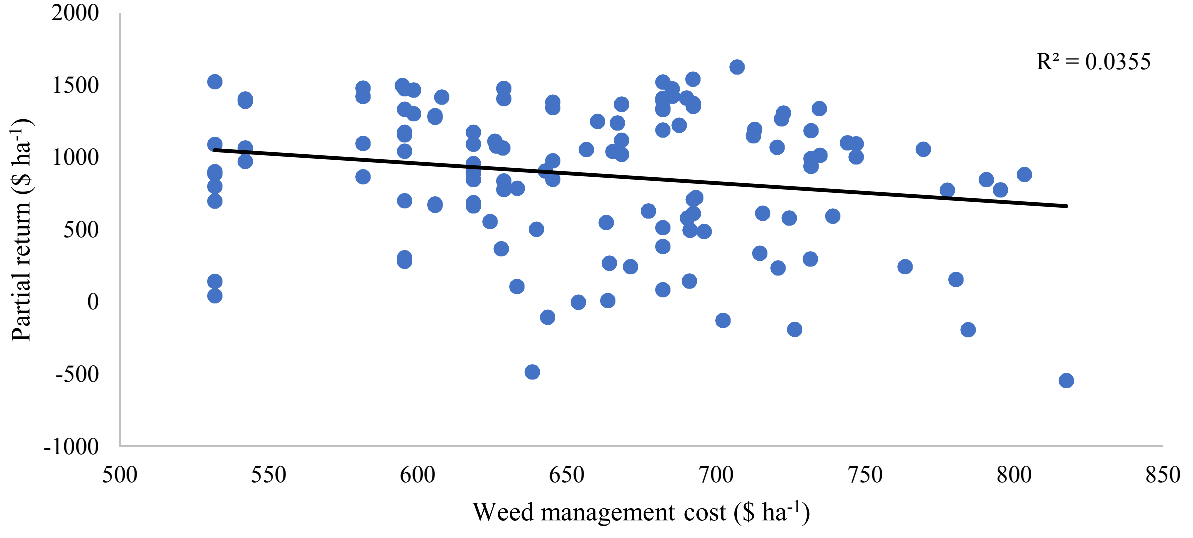

Figure 4. Correlation between weed management cost and partial return near Marianna, AR

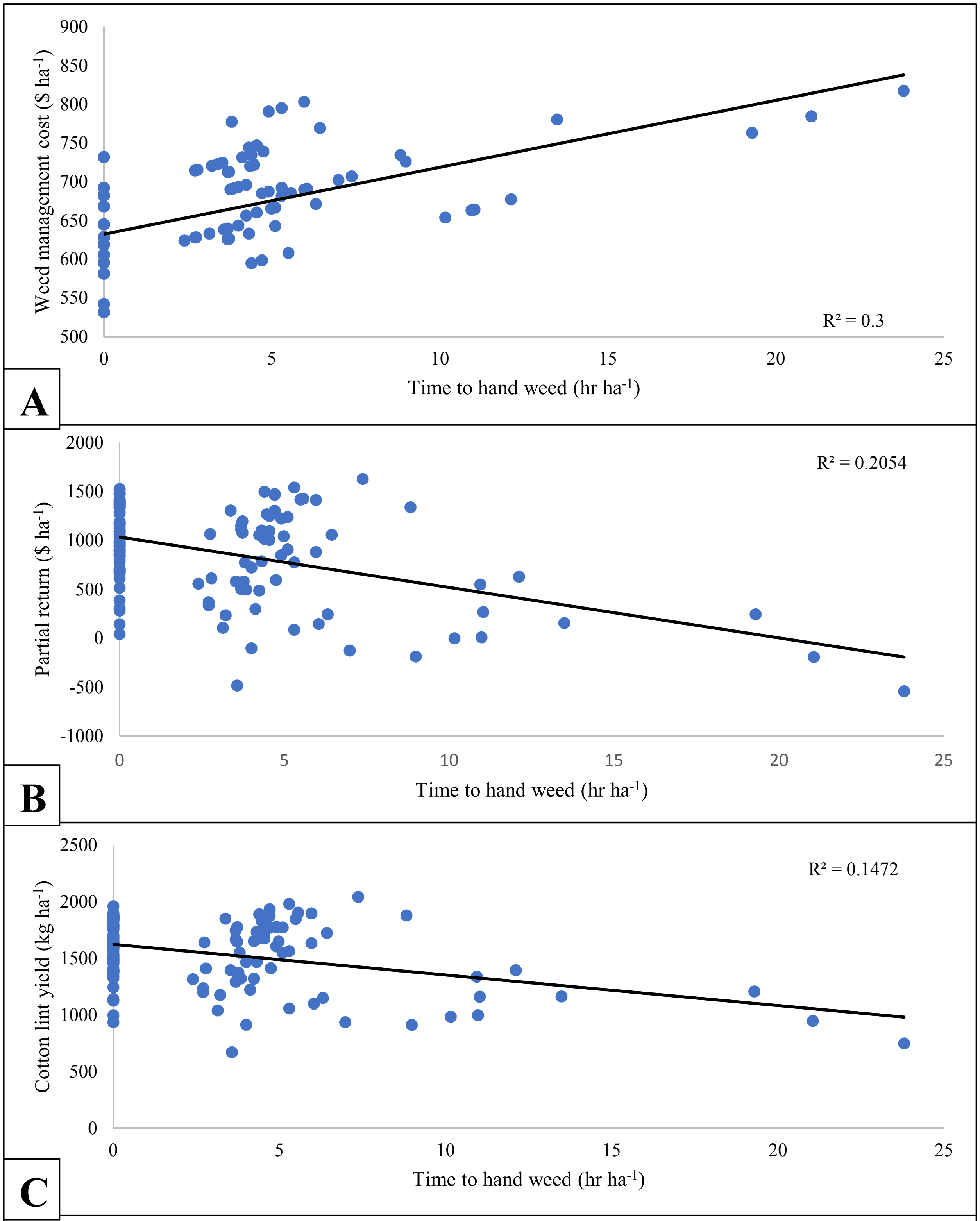

Figure 5: Correlation between the time to hand weed and (A) weed management cost, (B) partial return, and (C) cotton lint yield near Marianna, AR

Summary of Research

Palmer amaranth [*Amaranthus palmeri* (S.) Wats.] is considered to be the most troublesome weed in the United States from both a management and economic perspective. Management of Palmer amaranth in the Midsouth in soybean [*Glycine max* (L.)] and cotton (*Gossypium hirsutam L.*) production systems has become increasingly troublesome due to resistance to many of the commonly utilized herbicides in these systems. To combat this troublesome weed, researchers have investigated multiple tactics, such as developing new genetically modified crops that allow for new herbicides to be applied in-season as well as integrated weed management strategies that lessen the reliance on chemical weed control. While these tactics have been found to aid in the control Palmer amaranth, questions have risen given the economic feasibility or effectiveness of these new strategies, especially when used in combination with each other. Additionally, regulation has limited producers' abilities to utilize some herbicide chemistries. As a result, experiments were conducted to 1) understand the utility of isoxaflutole in isoxaflutole-tolerant cotton systems, 2) investigate the potential for roller wiper-based applications of dicamba in dicamba-tolerant soybean systems, and 3) optimize the use of various integrated weed management practices for dicamba-tolerant cotton production systems. The addition of isoxaflutole to cotton weed management programs garnered comparable and effective Palmer amaranth control with minimal crop injury and no yield reductions. These findings will allow producers to use an additional site of action for weed control previously not utilized in cotton and help mitigate herbicide resistance by Palmer amaranth to the few effective chemistries remaining. Roller wiper applications of dicamba were generally not as efficacious for Palmer amaranth control compared to broadcast applications, limiting their potential as a substitution for over-the-top applications of dicamba. The results from the roller wiper studies also aiding in understanding the importance of herbicide coverage for weed control, even with systemic herbicides. The use of integrated weed management practices showed great potential for weed population reductions, primarily with the use of one-time deep tillage and dicamba-based herbicide programs. Economically, the use of hand-weeding as part of a zero-tolerance strategy for weed management was inhibitive as the cost appeared to outweigh the benefits provided in the short term, not including the price of herbicide resistance evolving. However, weed populations were numerically reduced when hand-weed was utilized. Findings for this research will better enable producers to make informed management decisions when looking to adopt new technologies and strategies in their production systems aimed at combating Palmer amaranth among other weeds.