

Integration and management of winter-annual cover crops and herbicides to control glyphosate-resistant Palmer amaranth (*Amaranthus palmeri* S. Wats)

A Dissertation Presented for the
Doctor of Philosophy
Degree
The University of Tennessee, Knoxville

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December 2014

Acknowledgements

I would like to express my gratitude to all those who have supported me throughout my education, research, and preparation of this dissertation.

I wish to express my appreciation to Dr. Larry Steckel for his constant guidance and the opportunity to further my education under his leadership at The University of Tennessee. Thank you for your understanding, sincerity, and patience as I broadened my horizons. To my committee members, Dr. Robert Hayes, Dr. Angela McClure, Dr. Donald Tyler, and Dr. James Larson, I appreciate your support, your willingness to serve, and your guidance over this research.

To The Weed Science Research Team: Kelly Barnett, Patricia Brawley, Shawn Butler, Whitney Crow, Ernest Merriweather, Garret Montgomery, and Julie Reeves, thank you for your friendship and assistance with establishment, maintenance, and harvest of these trials. Also, I would like to thank the remainder of the faculty and staff at the West Tennessee Research and Education Center for their ongoing support of my education and research.

In addition, I wish to acknowledge Adam, Lori, and Colt Duncan, William and Sarah Phillips, Tyler and Heather Simmons, Benjamin and Suzannah Wiggins, and Daniel Wiggins not only for their support, but their camaraderie that made my time at The University of Tennessee enjoyable.

I would also like to thank my parents, Jerry and Katherine Wiggins, and family for their undying support and love.

The Lord is my strength and my song; he has become my salvation. Psalm 118:14...

Abstract

The main objective of this research was to evaluate the integration of high residue winter-annual cover crops with herbicides, both preemergence and postemergence, to control glyphosate-resistant Palmer amaranth. The results of these trials indicated that winter-annual cover crops improved early-season weed suppression. However, cover crops alone or as part of an integrated weed management system including only preemergence or only postemergence herbicides was not sufficient to control of glyphosate-resistant Palmer amaranth. Therefore, winter-annual cover crops should be used in conjunction with existing weed control tactics to achieve adequate glyphosate-resistant Palmer amaranth control, where applicable.

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Part I
Introduction

Introduction

Palmer amaranth (*Amaranthus palmeri* S. Wats) is a dioecious summer-annual weed that is very problematic in agronomic crops in most of the Southeast United States (U.S.) (Main et al. 2012; Norsworthy et al. 2008; Steckel et al. 2012). Its competitiveness in agronomic crops is due to its lengthy germination window, robust growth habit, and the vast numbers of viable seed produced by a single plant (Bond and Oliver 2006; Klingaman and Oliver 1994). Moreover, Palmer amaranth is a confirmed glyphosate-resistant (GR) weed specie in several states in the Southeast and Midsouth U.S., including Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, Missouri, North Carolina, South Carolina, and Tennessee (Heap 2014). The widespread presence, competitiveness, and herbicide resistance of Palmer amaranth make it a difficult weed to manage in agronomic production (Bond and Oliver 2006; Klingaman and Oliver 1994; Main et al. 2012).

Palmer Amaranth

Palmer amaranth is the most prevalent weed specie affecting crop production in the Midsouth and Southeastern U.S. today (Klingaman and Oliver 1994; Main et al. 2012). The initiation of GR crops including corn, cotton, and soybean have provided postemergence (POST) control options for many weeds (Askew et al. 2002; Duke and Powles, 2009). Glyphosate has been heavily utilized in agronomic production systems since its introduction in 1997, due to its broad-spectrum control of many grass and broadleaf weed species (Duke and Powles, 2009; Gianessi, 2008). Foliar applications of glyphosate proved to be an effective control method for many weeds across a wide range of growth stages. Therefore, timely applications were not needed as they previously were with conventional herbicides (Askew et al. 2002; Duke and Powles, 2009; Culpepper and York, 1998). Also, this adoption of a glyphosate-based weed

control programs now allowed producers to adopt a conservation tillage or no-tillage system that provides many benefits for the production system (Duke and Powles, 2009; Fernandez-Cornejo and Caswell 2006; Johnson et al. 2009). Unfortunately, years of intensive selection pressure placed on glyphosate have selected for many resistant weed species, including Palmer amaranth (Culpepper and York 1998; Duke and Powles, 2009; Heap 2014). Currently in Tennessee, there are six identified weed species resistant to glyphosate (Heap 2014). All of these species directly compete for essential resources and can detrimentally affect yield of agronomic crops, but of these six species Palmer amaranth proves the most difficult to control (Culpepper and York 1998; Klingaman and Oliver, 1994). In addition to glyphosate, Palmer amaranth is confirmed resistant to several other herbicides and mode of actions. Currently in the U.S., Palmer amaranth biotypes are confirmed resistant to acetolactate synthase (ALS)-inhibiting herbicides, dinitroanilines, hydroxylphenylpyruvate dioxygenase (HPPD)-inhibiting herbicides, atrazine, and glyphosate (Heap 2014). Fortunately, Palmer amaranth biotypes resistant to atrazine and the HPPD-inhibiting herbicides have not been confirmed in the Midsouth U.S. and these herbicides continue to be an effective control option.

Current difficulties in controlling Palmer amaranth, other than herbicide resistance, can be explained by biological characteristics. Palmer amaranth has a lengthy germination window, robust growth habit, and produces of large quantities of viable seed (Bond and Oliver, 2006; Keeley et al. 1987; Horak et al. 2000; Sellers et al. 2003). Even though Palmer amaranth is considered a summer-annual specie, it has been observed germinating from March 1 until October 1 (Keeley et al. 1987). Also, Palmer amaranth has been observed germinating within 5 d of planting, reaching plant heights of 10.4 cm within 2 wk of planting, developing large amounts of biomass, and producing more than 250,000 seed plant⁻¹, making Palmer amaranth a

very competitive weed specie for resources (Klingaman and Oliver 1994; Sellers et al. 2003). These biological and ecological factors make Palmer amaranth a formidable pest with few efficient control options.

Control Options for Glyphosate-Resistant Palmer amaranth

Cotton

Currently, there are few POST herbicide options that provide adequate control of Palmer amaranth in cotton (Steckel et al. 2012). Registrations of GR and glufosinate-resistant cotton, pyriithiobac, and trifloxysulfuron provided cotton producers with POST control options for many dicot weed species (Everman et al. 2007). Pyriithiobac, like trifloxysulfuron, is an acetolactate synthase (ALS) inhibitor that will control small Palmer amaranth (Branson et al. 2005; Corbett et al. 2004). Unfortunately, Palmer amaranth resistant to ALS-inhibiting herbicides is widespread across the Southeastern U.S., and in many cases this weed has multiple resistance to ALS-inhibiting herbicides and glyphosate (Bond et al. 2006; Culpepper and York 1998; Wise et al. 2009). Therefore, glufosinate-tolerant crops have been widely utilized to attain adequate weed control since introduction to the market in 2004 (Gardner et al. 2006; Steckel et al. 2012). Glufosinate is a nonselective herbicide that provides effective control of Palmer amaranth with a timely application (Steckel et al. 2012). In 2012, 82% of Tennessee cotton hectares were planted with glufosinate-tolerant varieties (USDA-AMS 2012). With no known glufosinate-resistant dicot weed species at this time, glufosinate proves to be an excellent option for controlling GR dicot weeds (Heap 2014).

Since there are very few effective POST options for controlling GR Palmer amaranth, the use of herbicides with residual activity and alternating different modes of actions is important components of an effective management strategy (Whitaker et al. 2011b). Residual

preemergence (PRE) herbicides have been documented to reduce early-season weed interference and increase season-long weed control of Palmer amaranth (Everman et al. 2009, Whitaker et al. 2011b). Herbicides such as acetochlor, diuron, fluometuron, fomesafen, prometryn, and s-metolachlor have been recommended PRE and are effective in managing Palmer amaranth (Everman et al 2007, Steckel 2014). However, effectiveness of these PRE herbicides is dictated by precipitation. Inconsistent Palmer amaranth control can often be attributed to inadequate precipitation when irrigation is not available to activate PRE herbicides. Therefore, best management strategies for GR Palmer amaranth control in cotton include the use of PRE herbicides, overlaying residual herbicides in-season, timely POST applications, and POST-directed applications. (Everman et al. 2009; Price et al. 2011; Whitaker et al. 2011a)

Corn

Controlling GR Palmer amaranth in corn is essential to ensure a successful crop (Massinga et al. 2001). Fortunately, GR Palmer amaranth control is typically easier to attain in corn than other major crops grown in the Midsouth U.S. (Webster and Nichols 2012). Atrazine and hydroxylphenylpyruvate dioxygenase (HPPD)-inhibiting herbicides are the primary herbicides that are used for weed control in corn (Webster and Nichols 2012). Both atrazine and the HPPD-inhibiting herbicides are flexible in that they can be applied PRE or POST and can be tank-mixed with other herbicides for increased efficacy. Moreover, these herbicides offer broad-spectrum weed control including GR Palmer amaranth. However, Palmer amaranth biotypes resistant to atrazine and HPPD-inhibiting herbicides are already present in the U.S. (Heap 2014). Although this is not a current issue in the Midsouth U.S., producers will need to steward these herbicides and incorporate additional control methods to aid in mitigating further development of herbicide resistant Palmer amaranth biotypes.

Cultural and Mechanical Control

Other control options commonly used to remove weed species are mechanical and cultural practices. Tillage and cultivation are frequently used for seedbed preparation and as an in-season method to remove problematic weeds (Edmisten et al. 2010). Tillage can affect weed emergence, weed management practices, weed seed production, and distribution of weed seed in the soil (Buhler 1995). However, much of the Midsouth and Southeastern U.S. has adopted no-tillage or conservation tillage using a glyphosate-based weed control program because many of the soils in production are prone to erosion (Duke and Powles, 2009; Young 2006; Fernandez-Cornejo and Caswell 2006). Other control options are more cultural, such as crop rotation, adjusting row spacing, plant populations, and integration of cover crop residues (Price et al. 2011). All of these control methods promote conservation agriculture by reducing selection pressure from herbicides and by adding residues into the cropping system. In managing problematic weeds, such as Palmer amaranth, the most effective control option is the implementation of an integrated approach. To attain effective and sustainable weed control, integrating chemical, cultural, and mechanical control is needed (Price et al. 2012).

Cover Crops

Winter-annual cover crops have been used in the Southeastern U.S. as a conservation practice. The integration of this cultural technique has long been proven to improve soil quality, increase soil organic matter, increase soil moisture retention, reduce erosion, and provide early-season weed suppression when implemented in an agronomic cropping scenario (Hartwig and Hoffman 1975). Winter-annual grasses and legumes have been implemented as cover crops in crops such as corn, cotton, and soybean (Reddy 2001; White and Worsham 1990). Cover crops have been observed to provide early-season weed suppression by both chemical and physical

interference (Barnes and Putnam 1986; Reddy 2001; Teasdale and Mohler 2000). Cereal rye (*Secale cereale*) and winter wheat (*Triticum aestivum*) are commonly used grass cover crops that reduce weed pressure of several weed species (Liebel et al. 1992; Moore et al. 1994). Other cover crop species such as hairy vetch (*Vicia villosa*) and crimson clover (*Trifolium incarnatum*) have not only been investigated for weed suppression, but also for their ability to biologically fix atmospheric nitrogen that becomes available for the subsequent crop (Duck and Tyler 1996; Fisk et al. 2001; Norsworthy et al. 2010). The purpose of using a winter-annual cover crop for weed suppression is to produce plant residue to create unfavorable growing environments for weeds (Teasdale 1996). The cover crop can reduce light (Teasdale and Mohler, 1993), and moisture available to germinating weeds. Weeds attempting to germinate with a cover crop present would be in direct competition for resources and may not sufficiently develop or survive (Teasdale and Mohler 1993). Typically, cover crops are planted in the autumn of the year, post-harvest of the existing crop. The cover crop continues to grow in the autumn as long as growing conditions in the environment are conducive to plant growth. Eventually, limiting growth factors such as frost and cold temperatures force the cover crops in to a dormant stage until the subsequent spring where growth and biomass accumulation will continue (Fisk et al. 2001). The addition of this dense biomass adds to and is a strong determinate of early-season weed suppression (Ateh and Doll 1996; Teasdale and Mohler 1993; Teasdale 1996). The cover crop is often terminated 2 to 3 wk prior to no-till planting of the subsequent agronomic crop for ease of planting and to ensure seed-soil contact. Although cover crops suppress many winter-annual weed species during the early spring, cover crop residues typically do not provide total in-season weed control for summer crops (Teasdale 1996). Thus, herbicides are commonly needed alongside cover crop residues to achieve adequate weed control.

Winter-Annual Grass Cover Crops

Cereal rye and winter wheat are the two most common grass winter-annual cover crop species implemented in the Southeastern U.S. Cereal rye, the hardiest of cereals, has been documented to accumulate massive amounts of biomass, directly contributing to early-season weed suppression and to the prevention of erosion (Daniel et al. 1999). It can be seeded much later in the fall than other cover crops, and can still accumulate vast amounts of biomass, an extensive root system, and exceptional weed suppression (Clark 2007). Cereal rye or winter wheat as a cover crop can yield high amounts (4,500 kg/ha or greater) of residue, while following the recommended cover crop termination and crop planting schedule (Price et al. 2012; Reiter et al. 2008). Price et al. 2012 found that implementing a rye cover reduced the need for POST herbicides and higher cotton yields were attained. Daniel et al. 1999 observed both rye and wheat covers conserved soil moisture, due to the amount and physical characteristics of the cover crop residue. Although the dense biomass accumulation of these winter cereal crops does provide many benefits for cropping systems, some difficulties can be associated with them. Termination of the dense stands of cereal crops can prove challenging. Glyphosate is commonly used, but can be inconsistent (White and Worsham 1990). Therefore, paraquat is an effective option for controlling these cover crops (White and Worsham 1990). If adequate termination of the cover crops is not obtained, the cover crop can compete with the subsequent crop for moisture and nutrients early in the growing season (Fisk et al. 2001).

Winter-Annual Legume Cover Crops

Crimson clover and hairy vetch are two legume species that have been extensively researched as cover crops (Norsworthy et al. 2010; Reddy 2001; White and Worsham., 1990). Annual legumes also reduce weed pressure of some winter and summer-annual weeds (Fisk et al.

2001; Isik et al. 2009). Research has shown that these species do not accumulate as much biomass as the winter-annual grass species, but when used in combinations with winter-annual grass species, biomass was comparable to that of the grasses (Daniel et al. 1999). In addition to weed suppression benefits, crimson clover and hairy vetch have the ability to fix atmospheric nitrogen and provide the subsequent crop with 56 to 79 kg ha⁻¹ nitrogen (Duck and Tyler 1996). Glyphosate provides inconsistent control of these species, especially hairy vetch, resulting in early-season competition for resources between the cover crop and field crop (Fisk et al. 2001). Therefore, paraquat is a viable option for termination of legume cover crops as it is with the cereal cover crops (White and Worsham 1990).

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Part II

Integrating Cover Crops and POST Herbicides for Glyphosate-Resistant Palmer amaranth (*Amaranthus palmeri* S. Wats) Control in Corn

Abstract

Field experiments were conducted at the West Tennessee Research and Education Center in Jackson, Tennessee, during 2013 and 2014 to evaluate the efficacy of integrating cover crops and POST herbicides in corn to control glyphosate-resistant Palmer amaranth. Cover crop treatments of crimson clover and hairy vetch were established in the autumn of the previous years and allowed to over winter. The cover crops were terminated prior to corn planting and above ground biomass samples were collected. POST herbicide treatments were applied when Palmer amaranth reached a height of 15 cm. Herbicide treatments included glyphosate + s-metolachlor + mesotrione, thienencarbazone-methyl + tembotrione, and glyphosate. All herbicide applications were tanked- mixed with atrazine. Both cover crops accumulated greater than 1600 kg ha⁻¹ of biomass and added to early-season Palmer amaranth suppression. Crimson clover and hairy vetch provided 62% and 58% Palmer amaranth control 14DBA, respectively. Moreover, all evaluated herbicide treatments provided greater than 95% control of Palmer amaranth 28DAA. In addition to Palmer amaranth suppression, hairy vetch as a cover crop increased corn height at V5 and V7 growth stages. Therefore, results of this trial indicate that cover crops are effective in suppressing glyphosate-resistant Palmer amaranth during the early corn growing season and offer an additional weed management strategy that can potentially aid in mitigating further formation of herbicide resistant Palmer amaranth biotypes.

Key Words: atrazine; corn, *Zea mays* L.; cover crop; crimson clover, *Trifolium incarnatum*; cultural weed control; glyphosate; glyphosate-resistance; hairy vetch, *Vicia villosa*; Palmer amaranth, *Amaranthus palmeri* (S.) Wats.

Introduction

Corn (*Zea mays*) is the most widely cultivated crop in the United States (U.S.), with a planted area of more than 37 million ha (USDA-NASS 2014). Even though corn is largely grown in the Midwestern states, producers in the Midsouth are increasing hectares devoted to this crop. Tennessee producers planted over 360 thousand ha in 2014, making it a major crop in Tennessee agriculture (USDA-NASS 2014). As with the other major crops grown in Tennessee, in-season weed control is essential for producing a successful corn crop. Glyphosate-resistant (GR) weeds continue to be the most challenging weeds to manage, specifically GR Palmer amaranth (*Amaranthus palmeri* S. Wats) (Culpepper and York 1998; Klingaman and Oliver, 1994).

Palmer amaranth is a dioecious, summer-annual specie that is originally native to the desert southwest region of the U.S. (Franssen et al. 2001; Sauer 1957). Despite its origin, Palmer amaranth is able to flourish in most any environment due to its ultracompetitive biological characteristics (Klingaman and Oliver 1994; Sellers et al. 2003). Palmer amaranth has a lengthy germination window, robust growth habit, and is a prolific seed producer (Bond and Oliver 2006; Horak et al. 2000; Keeley et al. 1987; Sellers et al. 2003). These characteristics make adequate and timely control of this formidable pest a difficult task.

Current difficulties in controlling Palmer amaranth, other than its biological characteristics, can be explained by herbicide resistance. Presently in the U.S., Palmer amaranth biotypes are confirmed resistant to acetolactate synthase (ALS)-inhibiting herbicides, dinitroanilines, hydroxylphenylpyruvate dioxygenase (HPPD)-inhibiting herbicides, atrazine, and glyphosate (Heap 2014). Palmer amaranth has been confirmed as a glyphosate-resistant weed specie in several states in the Midsouth U.S., including Alabama, Arkansas, Kentucky,

Louisiana, Mississippi, Missouri, and Tennessee and in many cases has multiple resistance to ALS-inhibiting herbicides (Bond et al. 2006; Culpepper and York 1998; Heap 2014; Wise et al. 2009). Fortunately, biotypes resistant to atrazine and HPPD-inhibiting herbicides are not presently in the Midsouth U.S. (Heap 2014). As a result, producers are relying on atrazine and HPPD-inhibiting herbicides for broad-spectrum weed control in corn.

Compared to cotton (*Gossypium hirsutum*) and soybean (*Glycine max*), adequate weed control in corn is easier to attain (Webster and Nichols 2012). Atrazine and HPPD-inhibiting herbicides are some of the most commonly used herbicides for weed control in corn and are effective in controlling GR weeds, including Palmer amaranth (Sutton et al. 2002; Swanton et al. 2007; Vyn et al. 2006). Atrazine can be applied preemergence (PRE) or postemergence (POST) alone or in tank-mixtures with several herbicides (Walsh et al. 2012). The HPPD-inhibiting herbicides have become popular among corn producers due to their broad-spectrum weed control, flexible application timings, tank-mix compatibilities, and crop safety (Bollman et al. 2008; Stephenson and Bond 2012; Walsh et al. 2012). However, this widespread adoption and repeated use of atrazine and HPPD-inhibiting herbicides is a concern, as other corn producing areas of the U.S. have confirmed Palmer amaranth resistant to these herbicides.

Mechanical and cultural control methods are commonly used in addition to herbicides to aid in weed control. Tillage and cultivation are frequently used for seedbed preparation and as an in-season weed control method (Edmisten et al. 2010). However, much of the Midsouth U.S. has adopted a no-tillage or conservation tillage system because many of the soils are prone to erosion and the adoption of a glyphosate-based weed control programs (Duke and Powles, 2009; Young 2006; Fernandez-Cornejo and Caswell 2006). Cultural control methods such as crop rotation, adjusting row spacing and plant populations, and integration of high residue cover crops

all promote conservation agriculture and are effective in the management of GR weeds. Currently, the Natural Resources Conservation Service in Tennessee is promoting the use of cover crops and is offering a cost-share program with area producers to provide incentive to use cover crops as part of a conservation tillage system (Anonymous 2014). Therefore, interest in integrating high residue cover crop species into production systems is increasing (Price et al. 2012).

Winter-annual cover crops have long been used as a conservation tillage practice to prevent soil erosion, water runoff, improve soil structure, soil quality, organic carbon and nitrogen (Krutz et al. 2009; Teasdale 1996). However, recent interest in winter-annual cover crops in the Midsouth region of the U.S. is primarily attributed to the potential for early-season weed control (Norsworthy et al. 2011; Price et al. 2012). Cover crops have demonstrated early-season weed control in several crops, including cotton, corn, and soybean (Reddy 2001; White and Worsham 1990). Cover crop residues can reduce available light and moisture to germinating weeds, creating an unfavorable growing environment (Teasdale 1996). Even though cover crops suppress many winter-annual weed species during the early spring, cover crop residues typically do not provide total in-season weed control for summer crops (Teasdale 1996). Herbicides are commonly needed alongside cover crop residues to achieve adequate weed control.

Research is limited in the area of cover crop residue and POST herbicide integration for controlling Palmer amaranth in corn. Therefore, a study was conducted to evaluate the effectiveness of high residue cover crops with POST herbicide applications of atrazine tank-mixes. The objective of this research is to identify which integrated herbicide and cover crop system offers corn producers the greatest amount of Palmer amaranth control.

Materials and Methods

A field experiment to determine efficacy of high residue cover crops, integrated with POST herbicides to control glyphosate-resistant Palmer amaranth in a no-till corn system was conducted at the West Tennessee Research and Education Center in Jackson, TN during the 2013 and 2014 growing seasons (Table 1). The location chosen for this trial was infested with nearly 100% GR Palmer amaranth (unpublished data). Corn cultivars P1412-HR and P1319-HR (Pioneer Hi-Bred, Johnston, IA) were planted in 2013 and 2014, respectively. These corn hybrids were selected for their performance. Seed corn was planted 7 cm deep with a seed population of 79,000 seed ha⁻¹ into an existing cover crop residue using a no-tillage planter. The cover crops were crimson clover and hairy vetch seeded at rates of 17 kg ha⁻¹ and 22 kg ha⁻¹, respectively. A no cover check was included which was made up of native winter vegetation consisting of henbit (*Lamium amplexicaule*), annual bluegrass (*Poa annua*), and horseweed (*Conyza canadensis*). Plots in this trial were two rows by 9.1 m, with a row spacing of 76 cm. This trial was implemented as a randomized block design with a three by four factorial arrangement of treatments with four replications. Treatment factors included a main treatment effect of cover crop specie and a secondary treatment of herbicide regime, consisting of atrazine tank-mixes. All production practices, other than weed control and nitrogen recommendations, followed University of Tennessee Extension recommendations for corn production. Current nitrogen recommendations following a legume cover crop that has reached early bloom stage is to reduce nitrogen rate by 67 to 90 kg ha⁻¹ (Savoy and Joines 2009). However, in this trial an application of 32-0-0 liquid nitrogen at a rate of 202 kg ha⁻¹ was applied to the entire plot area at the V4 growth stage using a side-dressing implement. Nitrogen rates were not adjusted for the

legume covers to reduce the potential for cover crop and herbicide treatments to be confounded by nitrogen rates.

The cover crops were drilled in the autumn of 2012 and 2013 using a no-till drill and allowed to over winter (Table 2). Shortly before chemical desiccation of cover crops, biomass samples were clipped from a 0.1 m² quadrat above the ground. These cover crop samples were then dried in a forced-air oven at 60°C and weights were recorded after drying for 48 hrs. Approximately 3 wk prior to estimated corn planting, the entire test area was desiccated using paraquat at 851 g ai ha⁻¹ plus 0.25% VV⁻¹ non-ionic surfactant. This herbicide application adequately controlled all cover crops and the winter-annual weeds present in the no cover plots.

Corn was planted once cover crops were effectively terminated (Table 1). The POST herbicide applications commenced when Palmer amaranth reached a height of 15 cm (Table 2). Herbicide treatments included glyphosate + s-metolachlor + mesotrione (1048 + 1048 + 105 g ai ha⁻¹), thienencarbazone-methyl + tembotrione (15 + 75 g ai ha⁻¹), and glyphosate (1532 g ae ha⁻¹). All herbicide applications were tanked-mixed with atrazine (1671 g ai ha⁻¹). Herbicides were applied using a CO₂-pressurized backpack sprayer calibrated to deliver 140 L ha⁻¹. Backpack sprayers were equipped with AIXR11002 nozzles (AIXR TeeJet Air Induction Extended Range Flat Fan Spray Tips, TeeJet Technologies, Wheaton, IL).

Palmer amaranth control was visually estimated weekly for 6 wk, starting 14 days before application (DBA) of the herbicide treatment using a scale of 0 (no control) to 100 (complete control). Palmer amaranth density was recorded after visual rating of weed control had been completed. Because a visual height difference was observed, corn plant heights were collected at the V5 and V7 growth stages to record growth differences among treatments. Corn was

harvested from this trial during both years of the study. Two center rows of each plot were harvested using a combine adapted for small-plot harvesting. Grain weights were recorded from each plot and later adjusted for moisture content to 15%.

Data were subjected to analysis of variance using the PROC MIXED procedure of SAS (ver. 9.3; SAS Institute; Cary, NC). ANOVA was used to test for significant main effects and interactions. Means were separated using Fishers Protected LSD procedure at the 0.05 significance level. Cover crop specie and herbicide regime were considered fixed effects. Replication and year were treated as random effects as well as any interactions containing these random effects.

Results and Discussion

Cover Crop Biomass and Early-Season Palmer amaranth Control

Winter-annual cover crop biomass accumulation was variable in this trial ranging from 890 to 3,090 kg ha⁻¹, depending on cover crop specie (Table 3). Both legume cover crops produced more above ground biomass than areas of typical native winter vegetation. Hairy vetch accumulated the greatest amount of biomass, accumulating 3,090 kg ha⁻¹. Other researchers correlate the accumulation of biomass to the amount of early-season weed control (Teasdale and Mohler 1993; Teasdale1996). In our research, the lower biomass cover crimson clover actually provided the best early-season weed suppression. The authors would suggest this is due to the prolonged persistence of the residue of this specie on the soil surface which would be consistent with other research. Waggoner (1989) found that hairy vetch had a lower C/N ratio and more rapidly decomposed when compared to crimson clover. Similar results were observed in this research and affected early-season weed control assessments. At the 14DBA Palmer amaranth

control ranged from 42% to 62%, with crimson clover providing 62% control. Palmer amaranth control at the 7DBA evaluation timing ranged from 41% control to 29% control. Therefore, both cover crop species added to early-season Palmer amaranth control in the two growing seasons. Moreover, in 2013 and 2014 POST herbicide treatments were made when Palmer amaranth was 15 cm tall which was delayed 61 and 45 days, respectively, from the time of cover crop termination (Table 2). From a Palmer amaranth resistance management standpoint, this delay in POST herbicide application timing and reduced weed pressure is beneficial. This system could aid producers in making more timely and effective POST herbicide applications. Unfortunately, the amount Palmer amaranth control diminished rapidly during the early cropping season making timely applied POST herbicides essential for season-long control of Palmer amaranth.

In-Season Palmer amaranth Control

Palmer amaranth control varied throughout the assessment period by POST herbicide treatments (Table 4). Cover crop ($P > f = 0.0837$) and the interaction of cover crop ($P > f = 0.2267$) and herbicide treatment had no effect on Palmer amaranth control 7DAA. At the 7DAA assessment, both premix herbicides containing HPPD-inhibitors provided the greatest amount of control. The premix containing glyphosate + s-metolachlor + mesotrione provided 96% control of Palmer amaranth, whereas the premix containing thienencarbazone-methyl + tembotrione provided 91% control. In this study, glyphosate had 77% POST control of Palmer amaranth 7DAA. However, all herbicide treatments were tank-mixed with 1671 g ai ha⁻¹ of atrazine. Therefore, it is highly probable that the POST control of Palmer amaranth with the glyphosate treatment can be attributed to the POST activity of atrazine.

Control of Palmer amaranth at 14DAA and 21DAA followed a trend similar to previous observations. POST herbicide did have an effect on control 14DAA and 21DAA, whereas cover crop (14DAA= $\text{Pr}>\text{f}=0.2266$; 21DAA= $\text{Pr}>\text{f}=0.1789$) and the interaction of cover crop and herbicide application (14DAA= $\text{Pr}>\text{f}=0.3078$; 21DAA= $\text{Pr}>\text{f}=0.2945$) had no significant effect. Premix herbicides containing HPPD-inhibiting herbicides provided greater than 96% control. Glyphosate plus atrazine controlled Palmer amaranth 89% and 86% at 14DAA and 21DAA, respectively. However, Palmer amaranth control at 28DAA indicated no significant differences among herbicide treatments. All herbicide treatments had provided greater than 95% control, effectively managing the GR Palmer amaranth present in this trial. Cover crop ($\text{Pr}>\text{f}=0.1118$) and the interaction of main effects ($\text{Pr}>\text{f}=0.0914$) had no significant impact on Palmer amaranth control 28DAA.

Palmer amaranth Density and Corn Heights

Palmer amaranth densities differed only between the herbicide treated and untreated check treatments (Table 4). Cover crop ($\text{Pr}>\text{f}=0.7046$) and the interaction effect of cover crop and POST herbicide treatments ($\text{Pr}>\text{f}=0.9721$) had no effect on Palmer amaranth densities. Palmer amaranth populations followed a similar trend to visual assessment at 28DAA. All POST herbicide treatments at this evaluation timing had greater than 95% control with 1 or less Palmer amaranth escapes m^{-2} . Therefore, the results of this trial demonstrate that there are effective POST herbicide control options when used as part of an integrated weed management program for controlling GR Palmer amaranth.

Corn plant heights did not vary among herbicide treatments ($\text{Pr}>\text{f}=0.5442$), but did differ according to cover crop specie ranging from 54 cm to 48 cm at V5 growth stage (Table 3).

There was no interaction between main effects at V5 ($P > 0.9906$) or V7 ($P > 0.9915$) growth stages. Corn plant heights were the highest (54 cm) in the hairy vetch areas. A similar trend was observed at V7. Herbicide treatment had no effect on plant height at V7 ($P > 0.5263$). Plant height at V7 ranged from 138 cm to 121 cm, with the tallest corn plants in the hairy vetch cover crop. There was no difference in corn plant height between crimson clover and the untreated check. These findings are different than results of other researchers. Reddy and Koger (2004) found that corn plant height was reduced when using a hairy vetch cover crop. However, hairy vetch in this trial accumulated more biomass than seen by Reddy and Koger (2004), suggesting that this legume cover crop fixed atmospheric nitrogen which became available for the subsequent corn crop, even with the early termination date (Table 2). Waggener (1989) found that hairy vetch more readily releases nitrogen and in greater quantities than that of crimson clover when terminated at the same time. Therefore, hairy vetch can be a substantial nitrogen source for corn and can affect plant height if adequate cover crop biomass is accumulated. However, more research is needed to definitively determine nitrogen sourcing and availability.

Corn Yield

Corn yield did not differ by cover crop ($P > 0.1586$), POST herbicide treatment ($P > 0.5482$), or by the interaction of cover crop and herbicide treatments ($P > 0.2596$). Adequate heat unit accumulation and precipitation were received during 2013 and 2014 and resulted in a high yield scenario (Table 1). Corn yields were greater than $12,950 \text{ kg ha}^{-1}$ regardless of cover crop and POST herbicide treatment. Conceivably, differences in corn yield between cover crop treatments and POST herbicide treatments would be more prevalent in a yield limiting environment where less than adequate precipitation was received and in areas of increased Palmer amaranth density. Steckel and Sprague (2004) found that optimum growing

conditions mitigated corn yield loss compared to yield limiting years when evaluating common waterhemp (*Amaranthus rudis*) interference. Therefore, recommendations are to continue to use POST herbicides and integrated weed control methods, such as cover crops, to ensure adequate weed control and to prevent yield loss.

Conclusions

Fortunately, there are effective means to control GR Palmer amaranth including high-residue cover crops and POST herbicide treatments as part of an integrated weed management system in corn. Cover crop residues did provide early-season weed suppression due to biomass accumulation. Herbicide applications were delayed 61 and 45 days from cover crop termination in 2013 and 2014, respectively, which could potentially increase corn producers POST herbicide application flexibility by reducing and delaying Palmer amaranth emergence. Results of this trial also suggest that cover crops are not a means of season-long control of GR Palmer amaranth. Moreover, corn yield was not impacted by cover crop or POST herbicide treatments. However, it is going to be essential to incorporate timely applied POST herbicides, multiple modes of actions, and cultural weed control tactics to ensure adequate weed control. The herbicide treatments evaluated in this trial were very effective in controlling GR Palmer amaranth, especially those containing HPPD-inhibiting herbicides. The POST herbicide treatment of glyphosate tank-mixed with atrazine was effective in controlling Palmer amaranth. However, this tank-mixture has only a single effective mode of action to control GR Palmer amaranth. Unfortunately, Palmer amaranth biotypes resistant to atrazine are already present in Georgia, Kansas, Nebraska, and Texas (Heap 2014). As corn production increases in the Midsouth U.S. and in Tennessee, the reliance on atrazine alone for controlling GR Palmer amaranth is concerning. From a resistance management perspective additional weed control options such as

using premix herbicides with multiple modes of action, atrazine tank-mixes, and high residue cover crops should aid in mitigating the further selection for herbicide resistant biotypes of Palmer amaranth.

Acknowledgments

The authors would like to thank Kelly Barnett, Patricia Brawley, Shawn Butler, Ernest Merriweather, Garret Montgomery, and Whitney Crow for their assistance in establishment, maintenance, and harvest of these trials.

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Part III

Integrating Cover Crops and POST Herbicides for Glyphosate-Resistant Palmer amaranth (*Amaranthus palmeri* S. Wats) Control in Cotton

Abstract

Field experiments were conducted at the West Tennessee Research and Education Center in Jackson, Tennessee, during 2013 and 2014 to evaluate the efficacy of integrating cover crops and POST herbicides in cotton to control glyphosate-resistant Palmer amaranth. Cover crop treatments of cereal rye, crimson clover, hairy vetch, and winter wheat were established in the autumn of the previous year using a no-till drill and allowed to grow until terminated prior to cotton planting. Above ground biomass samples were collected prior to cover crop termination. POST herbicide treatments were applied when Palmer amaranth reached a height of 10 cm. Herbicide treatments included glufosinate and glyphosate. All of the evaluated cover crops accumulated biomass and improved early-season weed suppression. The winter-annual grass species that accumulated the greatest amount of biomass also provided the greatest amount of Palmer amaranth control. However, weed suppression provided by the cover crops was not adequate for season-long control of Palmer amaranth and POST herbicides were needed. The glufosinate-based weed control system provided greater control (75% vs. 31%) of Palmer amaranth than the glyphosate system. These results indicate that a POST herbicide weed management system will not provide adequate control of Palmer amaranth, even when used in conjunction with a high residue cover crop. Therefore, recommendations for GR Palmer amaranth control will include integrating cover crops with PRE herbicides, over laying residual herbicides in-season, and timely POST herbicide applications in order to provide season-long control of this formidable pest.

Key Words: cereal rye, *Secale cereal*; cotton, *Gossypium hirsutum*; cover crop; crimson clover, *Trifolium incarnatum*; cultural weed control; glufosinate; glyphosate; glyphosate-resistance;

hairy vetch, *Vicia villosa*; Palmer amaranth, *Amaranthus palmeri* S. Wats.; winter wheat, *triticumastivum*.

Introduction

Glyphosate-resistant (GR) weeds continue to dominate the weed management strategies of cotton producers in the Midsouth and Southeast regions of the United States (U.S.) (Klingaman and Oliver 1994; Steckel 2007; Webster and Sosnoskie 2010). Palmer amaranth (*Amaranthus palmeri* S. Wats) is currently the most prolific GR weed affecting cotton cropping systems. This weed has an ultracompetitive growth habit and commonly reduces yields of agronomic crops if adequate control is not obtained (Klingaman and Oliver 1994; MacRae et al. 2013; Morgan et al. 2001).

The release of GR crops have changed cotton production and weed management (Duke and Powles 2009). This technology was eagerly accepted due to the broad-spectrum weed control, ease of crop maintenance, and increased crop rotation options (Culpepper and York 1998; Duke and Powles 2009; Gianessi 2008). This system also helped many producers adopt a conservation tillage system that provides many benefits for cotton production (Duke and Powles 2009; Fernandez-Cornejo and Caswell 2006; Johnson et al. 2009). Foliar applications of glyphosate proved to be an effective control method for many weeds across a wide range of growth stages. Therefore, timely applications were not needed as they previously were with conventional herbicides (Askew et al. 2002; Duke and Powles 2009; Culpepper and York 1998). This ease of application and control eventually led to intense selection pressure for GR weeds, including GR Palmer amaranth (Powles 2008).

Palmer amaranth is a dioecious, summer-annual specie native to the southwest region of the U.S. (Franssen et al. 2001; Sauer 1957). Palmer amaranth has a wide germination window, aggressive growth habits, and produces numerous viable seed (Bond and Oliver 2006; Horak and

Loughin 2000; Keeley et al. 1987; Sellers et al. 2003). Even though Palmer amaranth is considered a summer-annual specie, it has been observed germinating from March 1 until October 1 (Kelley et al. 1987). Moreover, Palmer amaranth has been observed germinating within 5 days of planting, reaching plant heights of 10.4 cm within 2 wk of planting, developing large amounts of biomass, and is capable of producing more than 250,000 seed plant⁻¹. These biological characteristics make Palmer amaranth a very competitive for resources and make timely postemergence (POST) herbicide applications a challenge (Klingaman and Oliver 1994; Sellers et al. 2003).

Currently there are few POST options for controlling GR Palmer amaranth in cotton. Glufosinate, pyriithiobac, and trifloxysulfuron have shown utility in controlling Palmer amaranth (Branson et al. 2005; Corbett et al. 2004; Culpepper et al. 2009; Everman et al. 2007; Gardner et al. 2006; Whitaker et al. 2011). Pyriithiobac, like trifloxysulfuron, is an acetolactate synthase (ALS)-inhibiting herbicide that will control small Palmer amaranth. Unfortunately, Palmer amaranth populations resistant to ALS-inhibiting herbicides are widespread across the southeastern U.S. and in many cases this weed has multiple resistance to ALS-inhibiting herbicides and glyphosate. (Bond et al. 2006; Culpepper and York 1998; Wise et al. 2009). The registration of glufosinate-resistant cotton cultivars has provided cotton producers with success in controlling GR Palmer amaranth (Gardner et al. 2006). Like glyphosate, glufosinate is a non-selective herbicide that provides broad-spectrum control of monocot and dicot weeds (Corbett et al 2004, Steckel 1997). Glufosinate must be applied to Palmer amaranth in a timely manner (Coetzer et al. 2002; Culpepper et al. 2010), and thorough coverage must be achieved to ensure adequate control (Corbett et al 2004; Steckel 2007). Effective application of glufosinate can

prove difficult to accomplish due to the robust growth habit of Palmer amaranth (Coetzer et al. 2002).

Mechanical and cultural control methods such as tillage, crop rotation, row spacing, and integration of high residue cover crops have proved beneficial in controlling problematic weed species (Edmisten et al. 2010; Price et al. 2011). Many cotton producers in the Midsouth and Southeastern regions of the U.S. have adopted a conservation tillage approach due to the use of a glyphosate-based weed control program (Duke and Powles 2009; Fernandez-Cornejo and Caswell 2006; Young 2006). Currently, the Natural Resources Conservation Service in Tennessee is promoting the use of cover crops and is offering a cost-share program with area producers to provide incentive to use cover crops as part of a conservation tillage system (Anonymous 2014). Therefore, interest in integrating high residue cover crop species in cotton production systems is increasing (Price et al. 2012).

Winter-annual cover crops have readily been used as a conservation practice. Cover crops improve soil quality, increase soil organic matter, increase soil moisture retention, reduce erosion, and provide early-season weed control (Hartwig and Hoffman 1975). Cereal rye (*Secale cereale*) and winter wheat (*Triticum aestivum*) are commonly used winter-annual grass cover crops that reduce weed pressure of several weed species (Liebel et al. 1992; Moore et al. 1994). Other cover crop species such as hairy vetch (*Vicia villosa*) and crimson clover (*Trifolium incarnatum*) have not only been investigated for weed suppression, but also for their ability to biologically fix atmospheric nitrogen that becomes available for the subsequent crop (Duck and Tyler 1996; Fisk et al. 2001; Norsworthy et al. 2010). Winter-annual grasses and legumes have been implemented in several crops, including corn, cotton, and soybean (Reddy 2001; White and Worsham 1990). Although cover crops suppress many winter-annual weed species during the

early spring, cover crop residues typically do not provide total in-season weed control for agronomic crops (Teasdale 1996). Thus, POST herbicides are commonly needed alongside cover crop residues to achieve adequate weed control.

Research is limited in the area of cover crop residue and herbicide integration for controlling Palmer amaranth during the growing season. Therefore, we conducted a field experiment to evaluate the effectiveness of integrating high residue cover crops into a glyphosate and glufosinate-based weed control system in cotton. The intent of this research is to identify which integrated herbicide and cover crop system offers cotton produces the greatest amount of Palmer amaranth control.

Materials and Methods

A field experiment to determine efficacy of high residue cover crops, integrated with POST herbicides to control glyphosate-resistant Palmer amaranth was conducted at the West Tennessee Research and Education Center in Jackson, TN during the 2013 and 2014 growing seasons (Table 5). The location chosen for this trial was infested with nearly a 100% GR Palmer amaranth population (unpublished data). Cotton cultivar FM 1944GLB2 Bayer CropScience, Research Triangle Park, NC), selected for performance and tolerance to glyphosate and glufosinate, was planted 2 cm deep with a seed population of 10-12 seed m⁻¹ of row into an existing cover crop residue using a no-tillage system. The cover crops evaluated were cereal rye, winter wheat, crimson clover, and hairy vetch. Cover crop seeding rates were 67 kg ha⁻¹, 67 kg ha⁻¹, 17 kg ha⁻¹, and 22 kg ha⁻¹, respectively. These cover crops were compared to check plots with native winter vegetation consisting of henbit (*Lamium amplexicaule*), annual bluegrass (*Poa annua*), and horseweed (*Conyza canadensis*). Plots in this trial were two rows by 9.1 m, with a row spacing of 97 cm. This trial was implemented as a randomized block design with a factorial

arrangement of treatments. Treatment factors included a main treatment effect of cover crop specie and a secondary treatment of herbicide regime. All production practices, other than weed control and nitrogen application, followed University of Tennessee Extension recommendations for cotton production. Current nitrogen recommendations for cotton following a legume cover crop that has reached early bloom stage is to reduce nitrogen rate by 67 to 90 kg ha⁻¹ (Savoy and Joines 2009). However, in this trial an application of 32-0-0 liquid nitrogen at a rate of 90 kg ha⁻¹ was applied to the entire plot area when the cotton had six true leaves using a side-dressing implement. Nitrogen rates were not adjusted for the legume covers to reduce the potential for cover crop and herbicide treatments to be confounded by nitrogen rates.

The cover crops were drilled in September and October of 2012 and 2013, respectively, (Table 6) using a no-till drill and allowed to over winter. The authors experience with planting cotton in cover crops has been that acquiring good seed soil contact and subsequent good cotton stands is difficult. Therefore, a banded early burndown application was applied to row area 90 days before the cotton was to be planted. This allowed the cotton seed to be planted into much less robust residue and obtain good seed soil contact. In order to burndown the intended cotton row a modified shielded sprayer adjusted to spray two identical 25 cm bands on 97cm centers was utilized on a tractor with real-time kinematic (RTK) (John Deere Greenstar 2, John Deere, Moline, IL) capabilities to apply paraquat at 851 g ai ha⁻¹ plus 0.25% non-ionic surfactant within the aforementioned bands. Paraquat effectively desiccated all plants within the applied band and intended planted row. Shortly before complete chemical desiccation of cover crops, cover crop biomass yields were obtained by clipping a 0.1 m² quadrat above the ground from the untreated area between the two rows. Therefore, reported biomass values have been adjusted to reflect biomass absence in the row strips. These cover crop samples were then dried in a forced-air

oven at 60°C and weights were recorded after drying for 48 hrs. Approximately 3 wk prior to estimated cotton planting date, the entire test area was treated with glyphosate at a rate of 887 g ae ha⁻¹. Evaluations of the efficacy of this herbicide application resulted in the need for a sequential burndown application, since glyphosate did not control the cover crops effectively (Fisk et al. 2001). The sequential application consisted of paraquat at 851 g ai ha⁻¹ plus 0.25% non-ionic surfactant. This application adequately controlled all cover crops and the winter-annual weeds present in the native vegetation plots.

Cotton was planted 3 to 4 wk after initial burndown herbicide application. The POST herbicide applications commenced when Palmer amaranth reached a height of 10 cm. Herbicide treatments of glyphosate at 1277 g ae ha⁻¹, glufosinate at 602 g ai ha⁻¹, and a nontreated check were evaluated. Herbicide applications were applied using a CO₂-pressurized-backpack sprayer calibrated to deliver 140 L ha⁻¹. Backpack sprayers were equipped with AIXR11002 nozzles (AIXR TeeJet Air Induction Extended Range Flat Fan Spray Tips, TeeJet Technologies, Wheaton, IL).

Palmer amaranth control was visually estimated weekly for 4 wk, starting 7 days after application (DAA) of the herbicide treatments using a scale of 0 (no control) to 100 (complete control). Palmer amaranth density was recorded prior to POST application and after the fourth visual rating of Palmer amaranth control. A sequential, broadcast application of glufosinate (602 g ai ha⁻¹) and glyphosate (1277 g ae ha⁻¹) was applied to all plots after all assessment data was gathered for grass control and to remove some smaller Palmer amaranth to ensure harvestable plots. Cotton was harvested from this trial during both years of the study. Two center rows of each plot were harvested using a spindle cotton picker adapted for small-plot harvesting. Cotton lint yields were calculated using a 35.5% gin turnout.

Data were subjected to analysis of variance using the PROC MIXED procedure of SAS (ver. 9.3; SAS Institute; Cary, NC). ANOVA was used to test for significant main effects and interactions. Means were separated using Fishers Protected LSD procedure at the 0.05 significance level. Cover crop specie and herbicide regime were considered fixed effects and replication and years were considered random.

Results and Discussion

Cover Crop Biomass and Early-Season Palmer amaranth Control

Cover crop biomass accumulation was variable in this trial and differed among cover crop specie ($P > 0.0001$) (Table 7). Dry biomass in this trial ranged from 570 to 3,320 kg ha⁻¹. All cover crop species evaluated accumulated 2,000 kg ha⁻¹ of biomass or greater. The winter-annual grass crops evaluated produced the greatest amount of biomass with winter wheat producing 3,320 kg ha⁻¹ and cereal rye producing 2,870 kg ha⁻¹. Hairy vetch accumulated comparable amounts of biomass in this trial to that of the winter-annual grass crops, whereas crimson clover produced the least amount of biomass of the evaluated cover crop species. However, all of the cover crop species evaluated accumulated more biomass than the areas of native winter vegetation and added to early-season weed suppression. In 2013 and 2014 POST herbicide treatments were delayed 42 and 52 days, respectively, from cover crop termination until POST herbicide application when Palmer amaranth reached a height of 10 cm (Table 6). Results of this trial indicate that cover crops can provide some suppression of problematic weeds in the Midsouth region of the U.S. This added weed suppression can reduce and delay germination of Palmer amaranth and increase efficacy of POST herbicide applications.

However, Palmer amaranth was still prevalent in areas where these cover crop species were grown and POST herbicide applications were needed for season-long control.

In-Season Palmer amaranth Control

In-Season Palmer amaranth control varied throughout the assessment period differing among herbicide and cover crop treatments. No interaction effect between cover crop species and herbicide treatment were observed 7DAA ($P > 0.9103$), 14DAA ($P > 0.9938$), 21DAA ($P > 0.3470$), or 28DAA ($P > 0.4953$). Minimal control of Palmer amaranth was observed in-season due to cover crops (Table 7). All of the cover crop species in this trial had less than <56% control. However, in-season weed suppression by the cover crops is directly related to the amount of biomass accumulated by the cover crop. The winter-annual grass species that produced the greatest amount of biomass provided the greatest amount of weed suppression across the assessment period. Palmer amaranth control at the 28DAA assessment ranged from 31% to 48%. Winter wheat and cereal rye provided the most in-season weed suppression with 48% and 45%, respectively. Even though the legumes evaluated in this trial produced similar biomass as that of cereal rye, they allowed more Palmer amaranth to emerge (Table 7) and provided similar weed suppression to that of areas of native winter vegetation. However, the legume cover crops can be important from a soil quality perspective, but the winter-annual grasses are more effective when selecting cover crop species for weed control.

Control of Palmer amaranth also differed across herbicide treatments ($P > 0.0001$) (Table 8). Glufosinate provided greater than 75% control throughout the assessment period while control with glyphosate was less than 34% indicative of a GR Palmer amaranth population (unpublished data). Control at the 7DAA evaluation timing ranged from 10% to 83%.

Glufosinate herbicide treatment had 83% control, while the glyphosate herbicide treatment had 34% control. Palmer amaranth control decreased at the next assessment period of 14DAA. A sequential herbicide treatment application was made at this timing to control larger and newly emerged Palmer amaranth. Palmer amaranth control at 21DAA and 28DAA followed a similar trend to previous observations made at 7DAA and 14DAA. The glufosinate herbicide treatment had the greatest amount (75%) of control at 28DAA. Therefore, the results of this trial verify that a POST herbicide weed management system is not a viable option for producers in the Midsouth U.S. who have GR Palmer amaranth, as 75% control of GR Palmer amaranth is not adequate control of this formidable pest (MacRae et. al 2013). Using preemergence (PRE) herbicides with residual activity and cultural control tactics, such as cover crops, will aid in stewarding the glufosinate based weed management system and improving season-long weed control.

Palmer amaranth Densities

Early-season Palmer amaranth densities were variable, depending on cover crop specie, ranging from 52 weeds m⁻² to 112 weeds m⁻² (Table 7). This evaluation of Palmer amaranth density followed similar trends to that of in-season Palmer amaranth control and was correlated to biomass accumulation. Winter wheat and cereal rye accumulated 4510 kg ha⁻¹ and 3890 kg ha⁻¹ of biomass, respectively, which increased in-season Palmer amaranth suppression and decreased density. However, none of the evaluated cover crop species suppressed Palmer amaranth sufficiently to where no herbicide application would be needed (MacRae et al. 2013; Morgan et al. 2001). The legume cover crops evaluated produced large amounts of biomass, but had higher Palmer amaranth density than the winter-annual grass cover crops. These results suggest that Palmer amaranth germination and populations could be affected by the legume

cover crops, either from additional nitrogen from nitrogen fixation or by the rapid decomposition of the legume plant tissue.

Palmer amaranth density at the 28DAA assessment varied by herbicide treatment and ranged from 32 weeds m⁻² to 70 weeds m⁻² (Table 8). Cover crop effect and the interaction effect of cover crop (Pr>f=0.5981) and herbicide treatment (Pr>f=0.1978) were not significant. Glufosinate had the greatest in-season weed control and the lowest Palmer amaranth density, 32 weeds m⁻². However, this level of control is inadequate and required additional control measures to ensure a harvestable crop (MacRae et al. 2013; Morgan et al. 2001). There were no differences in Palmer amaranth density between the glyphosate herbicide treatment and the untreated check.

Cotton Yield

Cotton yield was evaluated in both years of the trial to determine if cover crop and herbicide treatments impacted cotton yield. Cotton lint yield differed by herbicide treatment (Pr>f=0.0013) (Table 8). Cover crop specie (Pr>f=0.1054) and the interaction of main effects (Pr>f=0.9459) had no effect on cotton yield. Cotton yield ranged from 980 kg ha⁻¹ to 720 kg ha⁻¹. The glufosinate herbicide treatment had the highest lint yield of 980 kg ha⁻¹. The glyphosate treatment had yields that were no different than the untreated check, as expected when growing cotton in areas with high populations of GR Palmer amaranth. Therefore, glufosinate is recommended in situations where GR Palmer amaranth is numerous. However, the widespread use of glufosinate as a single effective mode of action for controlling GR Palmer amaranth in cotton is concerning. Current recommendations for cotton production, other than timely POST herbicide applications, include applying and overlapping residual herbicides with activity on

Palmer amaranth and integrating additional control measures such as winter-annual cover crops that can aid in weed suppression.

Conclusions

Using winter-annual cover crops did increase suppression of Palmer amaranth in both years of this study. Winter wheat and cereal rye provided the greatest amount of Palmer amaranth suppression due to the large amounts of dry biomass produced. Both of these cover crops reduced early-season Palmer amaranth density and provided in-season weed control, albeit inadequate. One or more POST herbicide treatment is needed for additional control. The glufosinate-based system had the greatest GR Palmer amaranth control, as it was the only effective mode of action that was evaluated in this trial. Unfortunately, like the cover crops evaluated in this study, the POST herbicide treatments provided marginal Palmer amaranth control and would need additional control efforts, such as PRE residual herbicides, to ensure a harvestable crop. Therefore, this study suggests that integrating PRE herbicides with residual activity on GR Palmer amaranth, timely applications of glufosinate, and cultural tactics, such as cover crops, are all useful in the management of GR Palmer amaranth. Using all of these different control tactics is beneficial from a resistance management perspective. Integrating cover crops and using residual PRE herbicides could aid in reducing the selection pressure of glufosinate and help preserve this technology as an effective POST mode of action to control GR Palmer amaranth.

Acknowledgments

The authors would like to thank Kelly Barnett, Patricia Brawley, Shawn Butler, Ernest Merriweather, Garret Montgomery, and Whitney Crow for their assistance in establishment, maintenance, and harvest of these trials.

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Part IV

Evaluating Cover Crops and PRE Herbicides for Glyphosate-Resistant Palmer amaranth (*Amaranthus palmeri* S. Wats) Control in Cotton

Abstract

The onset of glyphosate-resistant (GR) weeds, especially GR Palmer amaranth, continues to be problematic in areas of cotton production the Midsouth region of the United States. Cotton producers in this area rely heavily on the use of preemergence (PRE) residual herbicides with activity on Palmer amaranth since there are few effective postemergence (POST) weed control options. Moreover, there is increased interest in integrating high residue cover crops with existing herbicide programs for GR weed problems. Therefore, research was conducted at the West Tennessee Research and Education Center in Jackson, TN, during the 2013 and 2014 growing season to evaluate GR Palmer amaranth control when integrating cover crops and PRE residual herbicides. Cover crop treatments of cereal rye, crimson clover, hairy vetch, winter wheat, and all possible combinations of grass and legume cover crops were evaluated for GR Palmer amaranth control. Cover crops were established in late September to early October using a no-till drill and allowed to grow until terminated 3 weeks prior to cotton planting when biomass samples were collected. PRE herbicide treatments of fluometuron and acetochlor were applied immediately following cotton planting. Combinations of grass and legume cover crops accumulated the most biomass ($>3,500 \text{ kg ha}^{-1}$) and had the greatest amount of Palmer amaranth control 28DAA (58%). The PRE herbicides evaluated in this trial were initially effective in controlling GR Palmer amaranth. Fluometuron had 95% GR Palmer amaranth control at 14DAA. However, the encapsulated formulation of acetochlor added the most to GR Palmer amaranth control 28DAA, providing 62% control. Unfortunately, control provided by the best cover crop treatment (58%) and the best herbicide treatment (62%) 28DAA is not adequate GR Palmer amaranth control. However, results of this integrated system using cover crops and PRE herbicides suggest that this system does add to early-season weed suppression and could allow

producers to be more flexible in their herbicide applications by delaying PRE or early POST herbicide applications.

Keywords: acetochlor; cereal rye, *Secale cereal*; cotton, *Gossypium hirsutum*; crimson clover, *Trifolium incarnatum*; cultural weed control; fluometuron; glyphosate-resistance; hairy vetch, *Vicia villosa*; Palmer amaranth, *Amaranthus palmeri* (S.) Wats.; winter wheat, *Triticum astivum*.

Introduction

Winter-annual cover crops have long been used to prevent soil erosion, water runoff, improve soil structure, soil quality, organic carbon and nitrogen (Krutz et al. 2009; Teasdale 1996). However, recent interest in winter-annual cover crops in the Midsouth region of the United States (U.S.) is primarily attributed to the potential for early-season weed control (Norsworthy et al. 2011, Price et al. 2012). Currently, the primary method of weed control in cotton (*Gossypium hirsutum* L.) is almost exclusively herbicidal and includes the use of preemergence (PRE) herbicides, applying timely postemergence (POST) herbicides, and overlaying residual herbicides for season-long weed control (Culpepper et al. 2009). Introducing a cultural practice, such as cover crops, is a way for producers to be more integrated and sustainable in their weed management practices (Mortensen et al. 2012).

Cover crops have demonstrated early-season weed control in several crops, including cotton, corn (*Zea mays* L.) and soybean (*Glycine max*) (Reddy 2001; White and Worsham 1990). The purpose of using a winter-annual cover crop for weed suppression is to produce plant residue, which creates unfavorable growing environments for weeds (Teasdale 1996). The cover crop residue can reduce available light and moisture to germinating weeds. Thus, weeds germinating with a cover crop present are in direct competition for resources and typically will not survive (Teasdale and Mohler 1993). Winter-annual cover crops accumulate above ground

biomass from emergence in the autumn of the year until terminated in the spring of the subsequent year (Fisk et al. 2001). The accumulation of plant biomass is a strong determination of early-season weed control (Ateh and Doll 1996; Teasdale and Mohler 1993; Teasdale 1996). Although cover crops suppress many winter-annual weed species during the early spring, cover crop residues typically do not provide total in-season weed control for summer crops (Teasdale 1996). Herbicides are commonly needed alongside cover crop residues to achieve adequate weed control.

Adequate weed control in cotton production areas continues to be difficult to achieve due to the widespread populations of glyphosate-resistant (GR) weeds that are dominating weed management decisions across the U.S (Johnson et al. 2009, Webster and Sosnoskie 2010). Palmer amaranth (*Amaranthus palmeri* S. Wats) proves to be the most difficult GR weed to manage (Culpepper and York 1998; Klingaman and Oliver, 1994). The challenges associated with controlling Palmer amaranth can be attributed to its biological characteristics and herbicide resistance. Palmer amaranth is a summer-annual weed with a lengthy germination window, robust growth habit, and is capable of prolific seed production (Bond and Oliver, 2006; Keeley et al. 1987; Horak et al. 2000; Sellers et al. 2003). These characteristics make it very detrimental to cotton yield (MacRae et al. 2013; Morgan et al. 2001). In addition to its ultracompetitive biology, Palmer amaranth has been documented to be resistant to acetolactate synthase (ALS)-inhibiting herbicides and glyphosate (Bond et al. 2006; Culpepper and York 1998; Wise et al. 2009) making POST control difficult. Therefore, heavy reliance on PRE residual herbicides is essential in managing Palmer amaranth.

Currently there are effective PRE herbicide options for controlling small-seeded dicot weeds in cotton. Fluometuron is a substituted urea herbicide commonly used to control many

annual monocot and dicot weeds in cotton. Fluometuron can be used pre-plant incorporated (PPI), PRE, POST, and POST directed in cotton with minimal crop injury (Anonymous 2014a, Snipes and Byrd 1994, Senseman 2007a). The recent registration of an encapsulated formulation of acetochlor has given producers another PRE herbicide option in cotton. Acetochlor is a chloroacetimide herbicide that offers control of annual monocot grasses and certain small-seeded dicot weeds (Senseman 2007b). Acetochlor can be used PRE, POST, and POST-directed in cotton with minimal cotton injury (Anonymous 2014b; Cahoon et al. 2014)

Research is limited in the area of cover crop residue and PRE herbicide integration for controlling Palmer amaranth. Therefore, a study was conducted to evaluate the effectiveness of integrating high residue cover crops with PRE fluometuron and encapsulated acetochlor. The objective of this research is to identify which integrated herbicide and cover crop system offers cotton producers the greatest amount of early-season Palmer amaranth control.

Materials and Methods

A field experiment to determine efficacy of high residue cover crops, integrated with PRE herbicides to control GR Palmer amaranth was conducted at the West Tennessee Research and Education Center (WTREC) in Jackson, TN during the 2013 and 2014 growing seasons (Table 9). The location chosen for this trial was infested with nearly a 100% GR Palmer amaranth population (unpublished data). Cotton cultivar FM 1944GLB2 (Bayer CropScience, Research Triangle Park, NC), selected for its performance in the Midsouth was planted 2 cm deep with a seed population of 10-12 seed m⁻¹ of row into an existing cover crop residue using a no-tillage system. The cover crops evaluated were cereal rye (*Secale cereale*), winter wheat (*Triticum aestivum*), crimson clover (*Trifolium incarnatum*), hairy vetch (*Vicia villosa*) and all possible combinations of those grass and legume species. Cover crop seeding rates were 67 kg

ha⁻¹, 67 kg ha⁻¹, 17 kg ha⁻¹, and 22 kg ha⁻¹, respectively. All of these were compared to areas of native winter vegetation consisting of henbit (*Lamium amplexicaule*), annual bluegrass (*Poa annua*), and horseweed (*Conyza canadensis*). Plots in this trial were two rows by 9.1 m, with a row spacing of 97 cm. This trial was implemented as a randomized block design with a factorial arrangement of treatments with four replications. Treatment factors included a main treatment effect of cover crop specie and a secondary treatment of herbicide regime. All production practices, other than weed control, followed University of Tennessee Extension recommendations for cotton production.

The cover crops were drilled in the autumn of each year using a no-till drill and allowed to over winter. The authors experience with planting cotton in cover crops has been that acquiring good seed soil contact and subsequent good cotton stands is difficult. To facilitate a good uniform stand of cotton, a 25 cm band of paraquat was applied over each row 90 days before anticipated cotton planting using a tractor with real-time kinematic (RTK) (John Deere Greenstar 2, John Deere, Moline, IL). Paraquat at 851 g ai ha⁻¹ plus 0.25% non-ionic surfactant was applied in the bands. Paraquat effectively desiccated all plant growth within the applied band. Shortly before complete chemical desiccation of cover crops, cover crop biomass yields were obtained from the untreated area between the previously desiccated strips by clipping a 0.1 m² quadrat above the ground. Biomass results reported were adjusted to address missing biomass from the early banded herbicide application. These cover crop samples were then dried in a forced-air oven at 60°C and weights were recorded after drying for 48 hrs. Approximately 3 wk prior to anticipated cotton planting date, the entire test area was treated with glyphosate at a rate of 887 g ae ha⁻¹. Evaluations of the efficacy of this herbicide application resulted in the need for a sequential burndown application, as glyphosate did not control the cover crops effectively

(Fisk et al. 2001). The sequential application of paraquat at 851 g ai ha⁻¹ plus 0.25% non-ionic surfactant adequately controlled all cover crops and the winter-annual weeds present in the areas of native vegetation.

Cotton was planted once cover crops were effectively terminated. The PRE herbicides were applied immediately after cotton planting. Herbicide treatments were fluometuron at 1123 g ai ha⁻¹, acetochlor at 1264 g ai ha⁻¹, and a nontreated check.. Herbicides were applied using a CO₂- pressurized backpack sprayer calibrated to deliver 140 L ha⁻¹ and equipped with AIXR11002 nozzles (AIXR TeeJet Air Induction Extended Range Flat Fan Spray Tips, TeeJet Technologies, Wheaton, IL).

Palmer amaranth control was visually estimated weekly for 4 wk, starting 7 days after application (DAA) of the herbicide treatments using a scale of 0 (no control) to 100 (complete control). Palmer amaranth density was recorded after visual rating of control had been completed. A sequential, broadcast application of glufosinate (602 g ai ha⁻¹) was applied to all plots after all assessment data was gathered for grass control and to remove some smaller Palmer amaranth (<15cm) to ensure harvestable plots. Cotton was harvested from this trial during both years of the study. Two rows of each plot were harvested using a spindle cotton picker adapted for small-plot harvesting. Cotton lint yields were calculated using a 35.5% gin turnout.

Data were subjected to analysis of variance using the PROC MIXED procedure of SAS (ver. 9.3; SAS Institute; Cary, NC). ANOVA was used to test for significant main effects and interactions. Means were separated using Fishers Protected LSD procedure at the 0.05 significance level. Cover crop specie and herbicide regime were considered fixed effects and replication and years were considered random.

Results and Discussion

Cover Crop Biomass

Cover crop biomass varied by cover crop treatment ($P < 0.0001$) (Table 10). A wide range of dry biomass was recorded in this trial, ranging from 990 kg ha⁻¹ to 4,960 kg ha⁻¹. Cover crop combinations of grass and legume species had the greatest biomass. Cover crop combinations of cereal rye and hairy vetch accumulated 4,960 kg ha⁻¹, which was the highest amount of biomass. There were no differences in the remainder of the cover crop combination treatments of grasses and legumes, but they all accumulated residue greater than 3,500 kg ha⁻¹. Single cover crop species biomass ranged from 2,440 kg ha⁻¹ to 3,150 kg ha⁻¹. Hairy vetch and winter wheat cover crop treatments accumulated higher amounts of biomass in this trial when compared to the other single cover crop species, including cereal rye. Cereal rye accumulated biomass similar to that of crimson clover. These findings are different than results of Daniel et al. (1999), who found that cereal rye and combinations of cereal rye and hairy vetch yielded similar amounts of biomass. These results suggest that environmental factors may have affected biomass accumulation in the two years of this trial. However, all cover crops had greater amounts of biomass than areas of native winter vegetation. As in previous research, this accumulation of biomass correlated to early-season weed control (Ateh and Doll 1996; Fisk et al. 2001; Teasdale 1996). Palmer amaranth control and densities were both affected by cover crop treatment.

In-Season Palmer amaranth Control

In-season Palmer amaranth control varied by cover crop treatment and herbicide treatment (Table 10; Table 11). An interaction effect of cover crop by herbicide was significant

($P > F = 0.0025$) at the 7DAA evaluation timing (data not shown). No interaction effects were significant at the 14DAA ($P > f = 0.1677$), 21DAA ($P > f = 0.4767$), or 28DAA ($P > f = 0.2914$).

Palmer amaranth control at the 7DAA evaluation timing ranged from 19% to 99%. There were no differences among any cover crop treatment that received an herbicide application. All treatments of cover crops and herbicides had greater than 87% Palmer amaranth control.

However, cover crop treatments receiving no herbicide were significantly less than those that received herbicides, resulting in less than 65% control.

The sequential evaluation timings from 14DAA to 28DAA will be discussed by main effects, as no interaction was observed. Cover crop had a significant effect on Palmer amaranth control at the 14DAA ranging from 59% control to 80%. There were no differences between the winter-annual grass species evaluated and combinations of legume and grass species. The additional accumulation of biomass of the combination treatments improved Palmer amaranth suppression. There were no differences among the legume cover crops and areas of native winter vegetation. Earlier biomass results indicated that hairy vetch accumulated more biomass than cereal rye. However, the cereal rye had more in-season Palmer amaranth suppression than hairy vetch. These results suggest that the crop residue of cereal rye is more persistent than that of hairy vetch and is adding more to in-season control. Results of the 21DAA and 28DAA assessment had similar trends as the 14DAA. The winter-annual grass cover crops and combination treatments of winter-annual grass and legume species are providing the most Palmer amaranth control, however, it was only 57% 28DAA. This indicates the need for additional weed control measures to ensure a harvestable crop.

Herbicide treatments also impacted Palmer amaranth control, ranging from 31% to 95%, with fluometuron having the greatest amount of control. The encapsulated acetochlor treatment

also provided greater Palmer amaranth control (89%) than that of the untreated checks (31%). Palmer amaranth control did not differ at 21DAA among herbicide treatments. The encapsulated formulation of acetochlor controlled Palmer amaranth 62% at 28DAA which is inadequate for many producers in the Midsouth U.S. where GR Palmer amaranth is widespread (Norsworthy et al. 2014). Like cover crops, PRE herbicides add to early-season weed control, but as in this trial, timely other means of control would be needed to adequately control GR Palmer amaranth.

Palmer amaranth Density

Palmer amaranth densities differed by cover crop treatment and herbicide treatment (Table 10; Table 11). There was not a significant interaction between main effects ($P > 0.05$), therefore only the main effects will be discussed. Palmer amaranth density was directly affected by the amount of biomass produced and persistence of the residue on the soil surface. The winter wheat combinations with legumes had the fewest Palmer amaranth. There were no differences observed in the single cover crop species treatments and areas of native winter vegetation. These results suggest that selecting a multiple species cover crop mixture consisting of wheat and a legume cover crop will add to early-season Palmer amaranth suppression when compared to single species cover crops. Others have found that reduced Palmer amaranth biomass as a result of cover crop usage is a good herbicide resistance management tactic by limiting the number of plants that emerge and reduce seed production which lowers the overall probability of selecting for new herbicide resistance (Owen et al. 2014; Riar et al. 2013).

Palmer amaranth density at 28DAA differed by herbicide treatment and ranged from 6 weeds m^{-2} to 35 weeds m^{-2} . No differences were observed between fluometuron and acetochlor.

However, both herbicide treatments provided significant control when compared to the untreated check.

Cotton Yield

Cotton lint yield differed by herbicide treatment (Table 11). Cover crop specie ($P > f = 0.2453$) and the interaction of main effects ($P > f = 0.6075$) had no effect on cotton yield. Cotton yield ranged from 900 kg ha⁻¹ to 650 kg ha⁻¹. Cotton in treatments with PRE herbicide produced higher yields than the untreated check. There were no differences in cotton yield between PRE herbicides. Consequently, residual herbicides are recommended in cotton production. However, additional control measures will be needed in addition to cover crops and PRE herbicides to ensure optimum lint yield.

Conclusions

PRE residual herbicides and winter-annual cover crops increased control of GR Palmer amaranth throughout the evaluation period of this study. The control attributed to the use of cover crops is directly related to accumulation and persistence of the residue. Heavier residues of winter-annual monocots alone or in combination with legume dicots species aided in preventing Palmer amaranth germination and establishment. However, the cover crop mixtures and single specie cover crops failed to provide adequate season-long GR Palmer amaranth control. Initially, the PRE herbicide treatments provided adequate control of Palmer amaranth, but unfortunately control then diminished to unacceptable levels as cotton progressed. Therefore, it can be concluded that both high residue cover crops and PRE herbicides are part of an effective GR Palmer amaranth management strategy. However, additional means of control are necessary from a weed control and an herbicide resistance management perspective. All these

weed control tactics employed together also construct a very effective herbicide resistance management program as has been suggested by others (Riar et al. 2013).

Acknowledgments

The authors would like to thank Kelly Barnett, Patricia Brawley, Shawn Butler, Ernest Merriweather, Garret Montgomery, and Whitney Crow for their assistance in establishment, maintenance, and harvest of these trials.

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Part V

Managing Winter-Annual Cover Crops to Control Glyphosate-Resistant Palmer amaranth (*Amaranthus palmeri* S. Wats)

Abstract

Weed management of glyphosate-resistant (GR) weeds continues to be difficult in much of the Midsouth and Southeast regions of the United States (U.S.). As a result, many producers are looking for additional means of weed control other than herbicides. Winter-annual cover crops have long been used as a conservation practice, but have seldom been managed for their weed control potential. Therefore, field experiments were conducted at the West Tennessee Research and Education Center in Jackson, TN, during the 2013 and 2014 growing season to evaluate cover crop termination timings and termination herbicides in four cover crop species for weed control. Cover crop species of interest were cereal rye, crimson clover, hairy vetch, and winter wheat. Cover crops were allowed to over winter and were terminated on a predetermined biweekly schedule starting in mid-March (Timing 1) and concluding at mid-May (Timing 6). Above ground biomass was collected at each termination timing. The cover crops were terminated with glyphosate or paraquat at each timing. Data of interest was cover crop biomass, effectiveness of cover crop control, Palmer amaranth control, and Palmer amaranth density. Cereal rye accumulated large amounts of biomass across termination timings, with greater than 5,000 kg ha⁻¹ of biomass from Timing 2 to Timing 6. This large amount of biomass added to early-season Palmer amaranth suppression and the later termination timings reduced Palmer amaranth density. The greatest amount of cereal rye control occurred at Timing 5 and Timing 6 where greater than 89% control was observed. Moreover, the glyphosate was the most effective herbicide for terminating cereal rye with 92% control at t 21DAA. Cereal rye can increase Palmer amaranth suppression by delaying termination timing. Crimson clover was successful in accumulating adequate amounts of biomass to improve early-season Palmer amaranth suppression. Crimson clover biomass peaked at Timing 2 with 6,800 kg ha⁻¹ of residue.

Crimson clover proved difficult to control at the early termination timings, regardless of herbicide treatment. Palmer amaranth control and density was variable, but control was increased with increased amounts of biomass and from using paraquat as a termination herbicide. Therefore, crimson clover should be terminated with paraquat at peak vegetative growth to attain adequate biomass for weed suppression. Hairy vetch biomass increased throughout the assessment period and added to Palmer amaranth control. Hairy vetch was controlled adequately at the later termination timings using either herbicide. Palmer amaranth control 21DAA was increased by terminating later and allowing additional biomass to accumulate. Therefore, herbicide termination of hairy vetch can be delayed to improve Palmer amaranth control. Winter wheat biomass ranged from 3,230 kg ha⁻¹ to 7,520 kg ha⁻¹. Palmer amaranth suppression increased as biomass increased with delayed termination. Palmer amaranth density followed a similar trend behind wheat. Suggesting, improved Palmer amaranth control can be attained by delaying winter wheat termination timing. Overall, results of this trial indicate that the evaluated covers provided Palmer amaranth suppression and that they all responded differently to treatments of termination timings and herbicides. Therefore, cover crops will need to be managed by specie to ensure optimum weed control potential is achieved.

Keywords: cereal rye, *Secale cereal*; crimson clover, *Trifolium incarnatum*; cultural weed control; glyphosate; glyphosate-resistance; hairy vetch, *Vicia villosa*; Palmer amaranth, *Amaranthus palmeri* (S.) Wats.; paraquat; winter wheat, *triticumastivum*

Introduction

Winter-annual cover crops have long been used as a conservation practice in agriculture. Cover crops have been used to reduce soil erosion, water runoff, improve soil quality, soil structure, organic carbon, and nitrogen (Krutz et al. 2009, Teasdale 1996). Even though cover

crops have been primarily used for erosion and soil quality benefits, a secondary use is the ability of some cover crops to suppress early-season weeds (Hartwig and Ammon 2002; Teasdale and Mohler 2000). Winter-annual cover crops produce plant residue in the fall and spring of the year, which creates unfavorable growing environments for emerging weeds (Teasdale 1996). High residue cover crops can reduce available light and moisture for emerging weeds (Teasdale and Mohler 1993), including Palmer amaranth (*Amaranthus palmeri* S. Wats). There is a renewed interest in the Midsouth region of the United States (U.S.) in cover crops and their potential to aid in early-season weed suppression.

Palmer amaranth proves to be the most difficult weed to manage in crop production in the Midsouth U.S. (Culpepper and York 1998; Klingaman and Oliver 1994). The challenges associated with controlling Palmer amaranth can be attributed to both its biological characteristics and herbicide resistance. This weed species has the highest growth rate of the weedy Amaranth species in North America making timely and effective herbicide applications difficult. Moreover Palmer amaranth has a wide germination window (Bond and Oliver 2006; Horak and Loughin 2000; Klingaman and Oliver 1994; Keeley et al. 1987; Sellers et al. 2003). Palmer amaranth has documented resistance to many herbicides, including: acetolactate synthase (ALS)-inhibiting herbicides, dinitroanilines, hydroxylphenylpyruvate dioxygenase (HPPD)-inhibiting herbicides, atrazine, and glyphosate (Heap 2014). Reduced herbicide efficacy and monetary incentives have producers pursuing other means of in-season weed control, such as mechanical and cultural practices (Anonymous 2014).

Tillage and cultivation are frequently used for removing problematic weeds from a cropping system (Edmisten et al. 2010). However, many soils that are in production in the Midsouth region of the U.S. and Tennessee are prone to erosion. Therefore, culturally based

control options such as crop rotation, adjusting planting densities and widths, and integrating cover crop residues are a more viable option (Price et al. 2011). Currently, the Natural Resources Conservation Service in Tennessee is recommending cover crops as part of a conservation system and is offering a cost-share program to promote use of cover crops (Anonymous 2014). Therefore, there is interest in using cover crops and managing them for weed control.

Winter-annual cover crops have been researched for several crops, including corn (*Zea mays*), cotton (*Gossypium hirsutum*), and soybean (*Glycine max*) (Reddy 2001; White and Worsham 1990). Cover crops can provide early-season weed control by physical and chemical interference (Barnes and Putnam 1986; Reddy 2001; Teasdale and Mohler 2000). Cereal rye (*Secale cereale*) and winter wheat (*Triticum aestivum*) are commonly used high residue winter-annual cover crops that have been effective in suppressing several weed species (Liebel et al. 1992; Moore et al. 1994). Winter-annual legume cover crop species such as hairy vetch (*Vicia villosa*) and crimson clover (*Trifolium incarnatum*) also have potential to control some winter and summer annual weeds (Fisk et al. 2001, Isik et al. 2009). The amount of weed suppression provided by these winter-annual cover crops is determined by the quantity of biomass accumulated between planting covers in the autumn of the year and termination of the covers in the subsequent spring (Ateh and Doll 1996; Teasdale and Mohler 1993; Teasdale 1996). As with any high residue cropping system, excessive biomass production can result in decreased crop emergence and situations of crop stress due to water or nutrient deficiency (Daniel et al. 1999; Fisk et al. 2001). Therefore, effective termination or burndown is essential when integrating high residue cover crops into a production scenario.

Herbicidal termination is the primary method of desiccation of winter-annual cover crop. Glyphosate and paraquat are the most common herbicides used to control cover crops and

existing winter-annual weeds that are present before no-till planting (Johnson et al. 1993). These non-selective herbicides are effective in controlling winter-annual cover crops and offer broad-spectrum weed control (Griffin and Dabney 1990; Johnson et al. 1993; White and Worsham 1990). However, there have been reports of inconsistent control when using glyphosate to control legume cover crops (Griffin and Dabney 1990; White and Worsham 1990). Researchers have found that adding atrazine to glyphosate or using paraquat increased control of legume cover crop species (Johnson et al. 1993, White and Worsham 1990). Paraquat is a viable option for the termination of both legume and monocot winter-annual cover crops (White and Worsham 1990).

Research is limited in the area of managing winter-annual cover crops for weed suppression in the Midsouth region of the U.S. Therefore, a field experiment was conducted to evaluate cover crop termination timings and termination products in commonly used cover crop species. Results of this research are meant to provide producers with more information regarding management of cover crops for weed suppression.

Materials and Methods

A field experiment to evaluate cover crop management techniques for no-till production systems for control of glyphosate-resistant Palmer amaranth was conducted at the West Tennessee Research and Education Center in Jackson, TN during the 2013 and 2014 growing seasons (Table 12). The location chosen for this trial was infested with nearly a 100% GR Palmer amaranth population (unpublished data). Soybean cultivars AG4232 and AG4832 (Monsanto Co., St. Louis, MO) were planted in 2013 and 2014, respectively. These soybeans were planted 5 cm deep with a seed population of 345,000 seed ha⁻¹ into residue from terminated cover crops using a no-tillage planter. The cover crops evaluated were cereal rye, winter wheat,

crimson clover, and hairy vetch. Cover crop seeding rates were 67 kg ha⁻¹, 67 kg ha⁻¹, 17 kg ha⁻¹, and 22 kg ha⁻¹, respectively. Plots in this trial were two rows by 6.1 m, with a row spacing of 76 cm. This trial was implemented as a randomized block design with a split-plot treatment arrangement. Treatment factors included cover crop specie, termination timing, and termination herbicide. All production practices, other than weed control, followed University of Tennessee Extension recommendations for soybean production.

The cover crops were drilled in the autumn of each previous year using a no-till drill and allowed to over winter. Cover crops were terminated at six predetermined dates to evaluate biomass accumulation and herbicide efficacy across the assessment period. Termination dates ranged from the middle of March (timing 1) to the end of May (timing 6) and herbicides were applied at 2 wk intervals. Shortly before complete chemical desiccation of cover crops, cover crop biomass was obtained by clipping a 0.1 m² quadrat above the ground. These cover crop samples were then dried in a forced-air oven at 60°C and weights were recorded after drying for 48 hrs.

Cover crop control was visually estimated weekly for 4 wk, starting 7 days after application (DAA) of the termination treatment. Herbicide treatments were glyphosate (887 g ae ha⁻¹) and paraquat (851 g ai ha⁻¹) + non-ionic surfactant (0.25% V/V). Herbicides were applied using a CO₂- pressurized backpack sprayer calibrated to deliver 93.5 L ha⁻¹. Backpack sprayers were equipped with AIXR11002 nozzles (AIXR TeeJet Air Induction Extended Range Flat Fan Spray Tips, TeeJet Technologies, Wheaton, IL). Palmer amaranth control was visually estimated 1 wk after soybean planting. Palmer amaranth density was recorded after visual rating of Palmer amaranth control was completed.

Soybean was planted once cover crops were effectively terminated. A late-POST herbicide application of s-metolachlor + fomesafen at 1200+270 g ae ha⁻¹ was applied to maintain harvestable plots. Soybean was harvested from this trial during both years of the study. Two center rows of each plot were harvested using a combine adapted for small-plot harvesting. Grain weights were recorded from each plot and later adjusted to 13% moisture content.

Data were subjected to analysis of variance using the PROC MIXED procedure of SAS (ver. 9.3; SAS Institute; Cary, NC). ANOVA was used to test for significant main effects and interactions. Means were separated using Fishers Protected LSD procedure at the 0.05 significance level. Termination timing and termination herbicide were considered fixed effects and replications and years were considered random. Cover crops were not randomized in this trial. Therefore comparisons will not be made across cover crop species.

Results and Discussion

Cereal Rye

Biomass

Cereal rye biomass was impacted by the different termination timings evaluated in this trial (Table 13). Cereal rye biomass ranged from 3,550 kg ha⁻¹ to 7,120 kg ha⁻¹. Cereal rye at termination Timing 1 accumulated the least amount of biomass. Slight differences were also recorded among the remainder of the termination timings. However, greater than 5,000 kg ha⁻¹ biomass was accumulated in all remaining timings. This impressive accumulation of biomass across wide termination timings demonstrates why cereal rye is used extensively as a winter-annual cover crop for conservation and weed control purposes. This high residue system can aid

in preventing erosion, increase soil moisture retention and soil organic matter, and provide weed suppression.

Control

An interaction of herbicide application and termination timing was observed at the 7DAA ($\text{Pr}>\text{F}=0.0009$) and 14DAA ($\text{Pr}>\text{F}=0.0005$) evaluations (Table 15). Therefore, the interaction effect will be discussed for these timings and only main effects will be discussed at the 21DAA assessment. Evaluation of glyphosate and paraquat across these termination timings suggest that these herbicides perform differently depending on timing of application. Initially, paraquat provided better control of the cereal rye across the first three termination timings. There were little or no differences in cover crop control at the fourth and fifth termination timings. The greatest amount of cereal rye control 7DAA occurred at the sixth termination timing, nearing the end of May, regardless of herbicide treatment. A similar trend was present at the 14DAA evaluation timing. Both glyphosate and paraquat were very effective in controlling cereal rye at the late May termination timing, providing greater than 97% control. Additionally, glyphosate applied at the fourth and fifth termination timings controlled cereal rye greater than paraquat at 14DAA. Cover crop control 21DAA varied by termination timing and by herbicide application. Cereal rye control at 21DAA followed a similar trend to that of the other assessment timings (Table 13). The greatest amount of cereal rye control at 21DAA was with the middle- and late-May termination timings providing 89% and 98% control, respectively. The other termination timings had less than 85% control. Herbicide treatments also impacted cereal rye control (Table 14). Glyphosate controlled cereal rye 92%, while paraquat controlled cereal rye 79%. These findings differ from other research in this area in that glyphosate did adequately control cereal rye (White and Worsham 1990). Results of this trial suggest that cereal rye can be difficult to

control at early termination timings and could benefit from a sequential herbicide application to ensure that the cover crop does not compete with the intended rotation crop for essential resources.

Palmer amaranth Control and Density

Palmer amaranth control and density varied by termination timing, herbicide application, and the interaction of these two main effects (Table 15). Palmer amaranth control ranged from 61% to 97%. Paraquat added the most to Palmer amaranth control at the 21DAA. There were no differences among the paraquat applications, all resulting in greater than 87% control. Glyphosate applications at the fifth and sixth termination timings were equivalent to that of the paraquat. Glyphosate provided marginal control at the earlier four termination timings. This result suggests that Palmer amaranth in these plots is GR. Paraquat was effective in managing the emerged Palmer amaranth. Furthermore, additional weed control can be achieved by delaying cover crop termination and allowing the accumulation of additional cereal rye biomass.

Soybean Yield

Termination timing, herbicide, and their interaction in cereal rye had no effect on soybean yield (Table 13; Table 14; Table 15). Similar weed control measures were applied to all plots after the assessment of treatments was completed, thus no difference in soybean yield. These results suggest in environments similar to this study when precipitation is not a limiting factor, cereal rye could be managed for weed control by delaying termination without adverse impacts on soybean yield.

Crimson Clover

Biomass

Crimson clover biomass varied by termination timings (Table 16). Crimson clover biomass ranged from 2,850 kg ha⁻¹ to 6,800 kg ha⁻¹. The mid-March termination timing had 2,850 kg ha⁻¹ of biomass. Biomass accumulation spiked for this specie in early April (Timing 2). No additional biomass accumulated after early April. These biomass findings suggest that crimson clover biomass peaks during vegetative growth, suggesting that producers could managing crimson clover cover crops for biomass by terminating as early as mid-April.

Control

Control of crimson clover as a cover crop varied across termination timings and herbicide treatments at the 7DAA and 14DAA assessments, but there was no interaction effect. An interaction effect of termination timing and herbicide was observed at 21DAA, therefore main effects will not be discussed. Termination timing had similar trends at both the 7DAA and 14DAA assessments (Table 16). Crimson clover control increased as termination date was delayed with the highest amount of control being achieved when terminated from late April through late May (Timing 4 – Timing 6). However, the amount of control suggests that crimson clover is difficult to control. Glyphosate and paraquat had less than 80% control at the 7DAA and 14DAA assessments (Table 17). Paraquat had the greatest amount of initial control, but a sequential herbicide application would be needed to adequately manage the crimson clover residue. Crimson clover control 21DAA ranged from 59% to 92% (Table 18). Results from this assessment suggest that termination timing plays a large role in determining the amount of crimson clover control. The greatest amount of crimson clover control occurred at the three later

termination timings (Timing 4 – Timing 6) and there were no differences between herbicide treatments at these timings. These results indicate that crimson clover is easier to terminate using either glyphosate or paraquat at later growth stages than earlier when it is accumulating an abundance of vegetative biomass.

Palmer amaranth Control and Density

Palmer amaranth control varied by termination timing ($P < 0.0033$) (Table 16). Herbicides and the interaction of herbicides and termination timing had no effect on Palmer amaranth control. Palmer amaranth control ranged from 69% to 94%. Palmer amaranth was controlled best at the latter two termination timings (Timing 5 and Timing 6) and at the early April timing (Timing 2), where the greatest amount of crimson clover residue accumulated before termination. Palmer amaranth density differed by termination timing and the interaction of termination timing and herbicide treatment (Table 18). The interaction of the two main effects suggests that paraquat was more effective in controlling emerged Palmer amaranth. Glyphosate failed to control the Palmer amaranth as indicated by the higher density, as would be expected with GR Palmer amaranth. Moreover, Palmer amaranth density was significantly less at the later termination timings, even though this is not when the greatest amount of crimson clover biomass was accumulated. These results could suggest that the crimson clover residue was not persistent on the soil surface to serve as physical barrier to impede Palmer amaranth germination. Therefore, there could be potential weed control benefits to adding crimson clover to a more persistent residue cover crop such as cereal rye or winter wheat.

Soybean Yield

Termination timing, termination herbicide, and their interaction in a crimson clover cover crop had no effect on soybean yield (Table 16; Table 17; Table 18). Since similar weed control measures were applied to all plots after the assessment of treatments was completed, soybean yield were similar. These results suggest in environments similar to this study when precipitation is not a limiting factor, crimson clover could be managed for weed suppression by delaying termination without adversely impacting soybean yield.

Hairy Vetch

Biomass

Hairy vetch biomass varied by termination timing (Table 19), ranging from 1,720 kg ha⁻¹ to 7,470 kg ha⁻¹. The greatest amount of biomass was measured at the mid-late May termination timings (Timing 5 and Timing 6). However, all timings with the exception of the mid-March timing (Timing 1) accumulated greater than 3,500 kg ha⁻¹. Therefore, these results suggest that delaying termination of hairy vetch could add to early-season weed suppression if managing a hairy vetch cover crop with a weed control mindset.

Control

Hairy vetch control varied by termination timings, herbicide treatments, and there was an interaction effect of the two main effects. There was an interaction effect observed at the 7DAA and 21 DAA assessment timings (Table 21). There was not an interaction effect at the 14DAA evaluation timing, therefore only main effects will be discussed. Hairy vetch 7DAA proved difficult to control, especially at the early termination timings (Timing 1 – Timing 3) regardless

the herbicide treatment. At these earlier timings, hairy vetch was in a vegetative growth stage and rapidly accumulating biomass. This rapidly growing vegetative state made it difficult to attain adequate control. Acceptable control of hairy vetch 7DAA occurred at the late May termination timing (Timing 6) when using paraquat.

Hairy vetch control was impacted at the 14DAA assessment by termination timings (Table 19). Herbicide treatment and an interaction of the two main effects had no effect on hairy vetch control at this assessment. Hairy vetch was controlled at the latter two termination timings (Timing 5 and Timing 6), suggesting that hairy vetch is easier to control as it goes from vegetative to reproductive growth stage. Hairy vetch was controlled of less than 75% at the earlier termination timings. The interaction effect at the 21DAA assessment suggests a similar trend to that at 7DAA and 14DAA. Moreover, early termination timings with paraquat had less control than with glyphosate. However, plots where paraquat treatments were applied regrew as the hairy vetch progressed through the spring. This regrowth could hinder the establishment of the rotation crop and would require a second spray near planting to prevent competition between the hairy vetch and the rotation crop.

Palmer amaranth Control and Density

Palmer amaranth suppression was impacted by termination timing and there was no observed effect of herbicide treatment or interaction of termination timing and herbicide (Table 19). Palmer amaranth control increased as hairy vetch biomass accumulated and termination was delayed to mid-late May. Delaying termination of hairy vetch adds residue to the cropping system and aids early-season Palmer amaranth control. There were no observed differences in Palmer amaranth density by termination timing, herbicide treatment, or an interaction effect.

Soybean Yield

Termination timing, termination herbicide, and the interaction of main effects in a hairy vetch cover crop had no effect on soybean yield (Table 19; Table 20; Table 21). Since similar weed control measures were applied to all plots after the assessment of treatments was completed, soybean yield was not affected. Therefore, these results suggest that hairy vetch could be manipulated for Palmer amaranth suppression by delaying termination when grown in environments similar to this study where precipitation was not a limiting factor.

Winter Wheat

Biomass

Winter wheat biomass accumulation varied by termination timing (Table 22). Winter wheat produced 3,230 kg ha⁻¹ to 7,520 kg ha⁻¹ of biomass. Biomass accumulated throughout the termination timings and resulted in a high residue system. All the termination timings from early April to late May had greater than 5,000 kg ha⁻¹ of biomass. Since winter wheat is a prolific accumulator of biomass, this cover crop species would be a good option for producers who wish to use cover crops for a method of early-season weed suppression. Winter wheat could be flexible in its termination timings in that it provides a vast amount of residue early in the planting season and extending through late May.

Control

Wheat control varied by termination timing and herbicide treatments. An interaction effect was observed at the 7DAA and 14DAA assessment timings (Table 24). There was no interaction among main effects at the 21DAA, therefore only main effects will be discussed.

Paraquat was more effective in controlling the winter wheat than glyphosate at 7DAA. As winter wheat grew, termination with herbicides improved. Herbicides applied at timings from late April to late May (Timing 4 – Timing 6) had greater than 97% control. Control of winter wheat varied by termination timing at the 21DAA (Table 22). Winter wheat was easier to control later in the spring. Timing 4 through Timing 6 had greater than 88% control. Control of winter wheat increased as temperatures increased and as winter wheat was actively growing. Winter wheat control 21DAA also differed by herbicide treatment (Table 23). Glyphosate controlled winter wheat 92% while control with paraquat was less than 80%. The results of this trial suggest that winter wheat can be terminated easily with glyphosate or paraquat at the later termination timings.

Palmer amaranth Control and Density

Palmer amaranth control varied by termination timing, herbicide treatment, and the interaction effect of termination timing and herbicide treatment. Palmer amaranth control was greater than 70% regardless of the treatment. This suggests that winter wheat is a good cover crop option for those managing cover crops for weed suppression. Palmer amaranth was controlled greater than 87% where paraquat was used to control the cover crop species. These results indicate that additional Palmer amaranth control can be achieved by allowing additional biomass to accumulate and delaying termination timing. Palmer amaranth density varied by termination timing, herbicide treatment, and the interaction of the two main effects. Treatments with paraquat for termination of the winter wheat had less than 1 weed m² (Table 24). Later applications of glyphosate were similar to the paraquat treatments, suggesting that the additional accumulation of biomass by delaying winter wheat termination can add to early-season weed suppression.

Soybean Yield

Soybean yield varied by herbicide termination treatment (Table 23), but not by termination timing (Table 22) or the interaction of main effects (Table 24). Soybean yield ranged from 4,260 kg ha⁻¹ to 4,110 kg ha⁻¹, with areas treated with paraquat yielding higher than areas where treated with glyphosate. The winter-wheat cover crop was adequately controlled with applications of paraquat and provided 96% Palmer amaranth control 21DAA. This early-season Palmer amaranth control along with the in-season weed control measures eliminated most GR Palmer amaranth as evidenced by improved soybean yield.

Conclusions

Results of these trials indicate that each winter-annual cover crop specie responded differently to termination timing treatments and herbicide application. Therefore, management systems for cover crops will need to differ among cover crop specie to maximize their weed suppression potential. Each of the evaluated species demonstrated some measure of weed suppression. Cereal rye, winter wheat, and hairy vetch all accumulated vast amount of biomass and improved early-season weed suppression. Cereal rye and winter wheat accumulated large amounts of residue early in the termination regimes and would be a good cover crop choice for problematic GR Palmer amaranth fields for early and late cropping systems. Hairy vetch would be a good choice for a later cropping system since it continues to accumulate biomass throughout the evaluated termination timings. Crimson clover obtained peak biomass accumulation in early April, making it a potential weed management choice for an earlier cropping system. These cover crop species also responded differently to termination herbicides. Generally, all the cover crop species were easier to control at the later termination timings than at the earlier termination

timings. This increased control at these timings could be due to environmental factors, such as increased temperatures and sunlight intensity that stimulate plant growth and increase herbicide efficacy. The early termination timings had marginal cover crop control and would need a sequential application to achieve adequate control. It is important to control the cover crop to prevent competition for resources between the cover crop and rotational crop. Each of the evaluated cover crops offers some Palmer amaranth suppression, either by visual assessment or from reducing Palmer amaranth density. As one would expect, Palmer amaranth suppression was greatest when termination timings occurred as cover crop biomass accumulation reached a maximum. In conclusion, each of the evaluated cover crop species can offer weed suppression along with other soil benefits not discussed in this manuscript. The degree of weed suppression is often going to depend on environmental conditions and management techniques.

Acknowledgements

The authors would like to thank Kelly Barnett, Patricia Brawley, Shawn Butler, Ernest Merriweather, Garret Montgomery, and Whitney Crow for their assistance in establishment, maintenance, and harvest of these trials.

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Part VI
Conclusions

Conclusions

Fortunately, there are effective means to control GR Palmer amaranth including high-residue cover crops and POST herbicide treatments as part of an integrated weed management system in corn. Cover crop residues evaluated in this study suppressed Palmer amaranth during the early-season due to biomass accumulating and forming a mulch and unfavorable condition for the weed to establish. POST herbicide applications were delayed 61 and 45 days from cover crop termination in 2013 and 2014, respectively, which could potentially reduce the need for a PRE herbicide application. Also, this would extend the window of opportunity for growers that often encounter unfavorable conditions for POST herbicide application. Results of this trial also suggest that cover crops are not a means of season-long control of GR Palmer amaranth. Moreover, corn yield was not impacted by cover crop or POST herbicide treatments. However, it is going to be essential to incorporate timely applied POST herbicides, multiple modes of actions, and cultural weed control tactics to ensure adequate Palmer Amaranth control. The herbicide treatments evaluated in this trial were very effective in controlling GR Palmer amaranth, especially those containing HPPD-inhibiting herbicides. The POST herbicide treatment of glyphosate tank-mixed with atrazine was effective in controlling Palmer amaranth. However, this tank-mixture has only a single effective mode of action to control GR Palmer amaranth. Unfortunately, Palmer amaranth biotypes resistant to atrazine are already present in Georgia, Kansas, and Nebraska. As corn production increases in the Midsouth U.S. and in Tennessee, the reliance on atrazine for controlling GR Palmer amaranth is concerning. From a resistance management perspective additional weed control options such as, using premix herbicides with multiple modes of action, atrazine tank-mixes, and high residue cover crops

should aid in mitigating the further development of herbicide resistant biotypes of Palmer amaranth.

Using winter-annual cover crops and POST herbicides increased control of Palmer amaranth in both years. Winter wheat and cereal rye produced the most biomass and had the greatest suppression of Palmer amaranth. However, this amount of in-season Palmer amaranth suppression was minimal and a POST herbicide was needed for additional control.

Understandably, the glufosinate-based system provided the greatest amount of herbicidal control, as it was the only effective mode of action that was evaluated in this trial. Unfortunately, like the cover crops evaluated in this study, the POST herbicide treatments provided marginal Palmer amaranth control and would need additional control efforts, such as PRE herbicides, to ensure a harvestable crop. Therefore, this study suggests that integrating PRE herbicides with residual activity on GR Palmer amaranth, timely applications of glufosinate, and cultural tactics, such as cover crops, are all important in the management of GR Palmer amaranth. Using all of these different control tactics is beneficial from a resistance management perspective. Integrating cover crops and using residual PRE herbicides could aid in reducing the selection pressure on glufosinate and help preserve this technology as an effective POST mode of action to control GR Palmer amaranth.

PRE residual herbicides and winter-annual cover crops increased the control of GR Palmer amaranth. The control attributed to the use of cover crops was directly related to the accumulation of residue and the persistence of that residue. The heavier residue combination treatments and winter-annual grass species added the most to weed suppression and reduced Palmer amaranth density. This large amount of cover crop residue aided in preventing Palmer amaranth germination and establishment. However, the cover crop mixtures and single specie

cover crops failed to provide adequate season-long GR Palmer amaranth control. Initially, the PRE herbicide treatments controlled Palmer amaranth. Unfortunately, Palmer amaranth control diminished to unacceptable levels as the crop progressed through the assessment period. Therefore, it can be concluded that both high residue cover crops and PRE herbicides are part of an effective Palmer amaranth management strategy. However, additional means of weed control are necessary from both a weed control and an herbicide resistance management perspective.

Results of the cover crop management trial indicated that each winter-annual cover crop species responded differently to termination timing treatments and herbicide application. Therefore, management systems for cover crops will need to differ among cover crop species to utilize these covers to their upmost weed control potential. Each of the evaluated species demonstrated some measure of weed suppression. Cereal rye, winter wheat, and hairy vetch all accumulated vast amount of biomass and improved early-season Palmer amaranth suppression. Cereal rye and winter wheat accumulated a large amount of residue early in the evaluation periods and would be a good cover crop choice for problematic GR Palmer amaranth fields for early and late cropping systems. Hairy vetch would be a good choice for a later cropping system since biomass continued to accumulate throughout the evaluation periods. In this trial crimson clover biomass accumulation peaked in early April, making it a potential weed management choice for an earlier cropping system. These cover crop species also responded differently to termination applications. Generally, all the cover crop species were easier to control at the later termination timings than at the earlier termination timings. The early termination timings had marginal cover crop control and would need a sequential application to achieve adequate control. It is important to control the cover crop to prevent competition between the cover crop and intended rotation crop for resources. All of the evaluated cover crops offered some weed

suppression, either by visual assessment or from reducing Palmer amaranth density. As one would expect, weed suppression was typically increased later in the season as biomass accumulation reached a maximum. In conclusion, each of the evaluated cover crop species can offer weed suppression along with other soil health benefits. The degree of weed control is often going to depend on environmental conditions and management techniques.

Appendices

Appendix A

Tables

Table 1. Location, environmental conditions, corn planting dates, and corn harvest dates.

Location	Year	Soil series/texture	Planting date	Harvest date	Total precipitation ^a	Growing Degree Days ^a	Average Precipitation ^b
					cm	DD50's	cm
WTREC	2013	Lexington silt loam ^c	04/10/2013	09/13/2013	81	3,424	66
WTREC	2014	Lexington silt loam	04/21/2014	09/20/2014	87	3,499	

^a Climate information recorded from planting date to harvest date.

^b Historical average rainfall from April through September from 1980-2009 recorded at WTREC.

^c Fine-Silty, Mixed, Active, Thermic Ultic Hapludalfs.

Table 2. Cover crop planting dates, termination dates, herbicide application dates, and early-season Palmer amaranth control.

Year	Planting date	Termination date	POST herbicide application date ^a	Early-season Palmer amaranth control ^b no. days
2013	09/28/2012	03/22/2013	05/23/2013	61
2014	10/10/2013	04/15/2014	05/30/2014	45

^a Postemergence herbicides were applied when Palmer amaranth reached a height of 15cm.

^b Number of days from cover crop termination to POST herbicide application.

Table 3. Cover crop dry biomass, early-season Palmer amaranth control, and corn plant height.^a

Cover crop	Biomass kg ha ⁻¹	Corn				Yield kg ha ⁻¹
		Palmer amaranth control		Plant height		
		14DBA	7DBA	V5	V7	
		-----%		-----cm-----		
hairy vetch	3,090 a	58 a	36 ab	54 a	138 a	13,760
crimson clover	1,600 b	62 a	41 a	49 b	124 b	13,180
untreated check ^b	890 c	42 b	29 b	48 b	121 b	13,060
Pr > F	<0.0001	0.0004	0.0432	<0.0001	<0.0001	NS

^a Means within a column followed by the same letter are not significantly different according to Fisher's protected LSD a P < 0.05.

^b Areas included in the untreated check consisted of henbit (*Lamium amplexicaule*), annual bluegrass (*Poa annua*), and horseweed (*Conyza canadensis*).

Table 4. In-season Palmer amaranth control and density and corn yield.^a

Herbicide treatments ^b	Palmer amaranth				Density	Corn yield
	Control ^c					
	7DAA	14DAA	21DAA	28DAA	28DAA	
	-----%-----				no. m ⁻²	kg ha ⁻¹
glyphosate + s-metolachlor + mesotrione	96 a	98 a	98 a	99 a	0b	13,570
thiencarbazone-methyl + tembotrione	91 a	96 ab	97 a	98 a	0b	13,420
glyphosate	77 b	89 b	86 b	95 a	1b	13,380
untreated check	16 c	31 c	26 c	26 b	15a	12,950
Pr > F	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	NS

^a Means within a column followed by the same letter are not significantly different according to Fisher's protected LSD a P < 0.05.

^b All POST herbicide treatments were applied when Palmer amaranth reached a height of 15 cm and were tank-mixed with 1671 g ai ha⁻¹ of atrazine.

Table 5. Location, environmental conditions, cotton planting dates, and cotton harvest dates.

Location	Year	Soil Series/Texture	Planting Date	Harvest Date	Total Precipitation ^a	Heat Accumulation ^a	Average Precipitation ^b
					cm	DD60's	cm
WTREC	2013	Dexter clay loam ^c	05/09/2013	10/01/2013	57	2,174	64
WTREC	2014	Dexter clay loam	05/05/2014	10/06/2014	83	2,130	

^a Climate information recorded from planting date to harvest date.

^b Historical average rainfall from May through October from 1980-2009 recorded at WTREC.

^c Fine-Silty, Mixed, Active, Thermic Ultic Hapludalfs.

Table 6. Cover crop planting dates, termination dates, herbicide application dates, and early-season Palmer amaranth control.

Year	Planting Date	Termination Date	POST Herbicide Application Date ^a	Sequential POST Herbicide Application Date	Early-season Palmer amaranth Control ^b no. days
2013	09/28/2012	04/19/2013	05/24/2013	06/07/2013	42
2014	10/10/2013	04/15/2014	05/30/2014	06/13/2014	52

^a Postemergence herbicides were applied when Palmer amaranth reached a height of 10cm.

^b Number of days from cover crop termination to POST herbicide application.

Table 7. Cover crop dry biomass, early-season Palmer amaranth density and control as affected by cover crop specie.^a

Cover Crop	Biomass kg ha ⁻¹	Palmer amaranth				
		Density at application ^b no. m ⁻²	Control			
			7DAA	14DAA ^c	21DAA	28DAA
			-----%-----			
cereal rye	2,870 ab	60 b	44	45 a	47 b	45 a
crimson clover	2,211 b	107 a	38	34 bc	39 c	34 b
hairy vetch	2,660 ab	112 a	44	30 c	40 bc	35 b
winter wheat	3,320 a	52 b	47	43 ab	56 a	48 a
untreated check ^d	570 c	75 ab	38	33 bc	36 c	31 b
Pr > F	<0.0001	0.0027	NS	0.0193	<0.0001	<0.0001

^a Means within a column followed by the same letter are not significantly different according to Fisher's protected LSD a $P < 0.05$.

^b Early-season weed Palmer amaranth density prior to POST herbicide treatment application.

^c A sequential herbicide application was applied 14DAA of the same initial herbicide treatment.

^d Areas included in the untreated check consisted of henbit (*Lamium amplexicaule*), annual bluegrass (*Poa annua*), and horseweed (*Conyza canadensis*).

Table 8. In-season Palmer amaranth control and density 28DAA as affected by POST herbicide treatments.^a

Herbicide Treatments ^b	Palmer amaranth					Cotton lint yield kg ha ⁻¹
	Control				Density	
	7DAA	14DAA ^c	21DAA	28DAA	28DAA	
	-----%-----				no. m ²	
glufosinate	83 a	65 a	87 a	75 a	32 b	980 a
glyphosate	34 b	32 b	30 b	31 b	70 a	830 b
untreated check	10 c	14 c	12 c	10 c	65 a	720 b
Pr > F	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0013

^a Means within a column followed by the same letter are not significantly different according to Fisher's protected LSD a $P < 0.05$.

^b All POST herbicide treatments were applied when Palmer amaranth reached a height of 10 cm.

^c A sequential herbicide treatment was applied 14DAA of the same initial herbicide treatment.

Table 9. Location, environmental conditions, cotton planting dates and harvest dates, cover crop planting dates and termination dates.

Location	Year	Soil Series/Texture	Cotton Planting Date	Cotton Harvest Date	Cover Crop Planting Date	Cover Crop Termination Date	Total Precipitation ^a cm	Heat Accumulation ^a DD60's	Average Precipitation ^b cm
WTREC	2013	Lexington silt loam ^c	05/09/2013	10/05/2013	09/28/2012	04/19/2013	57	2,174	64
WTREC	2014	Lexington silt loam	05/05/2014	10/06/2014	10/10/2013	04/15/2014	83	2,130	

^a Climate information recorded from cotton planting date to cotton harvest date.

^b Historical average rainfall from May through October from 1980-2009 recorded at WTREC.

^c Fine-Silty, Mixed, Active, Thermic Ultic Hapludalfs.

Table 10. Cover crop dry biomass, Palmer amaranth control and density 28DAA as affected by cover crop specie.^a

Cover Crop	Biomass kg ha ⁻¹	Palmer amaranth				
		Control				Density
		7DAA	14DAA ^c	21DAA	28DAA	28DAA
		-----%-----				no. m ⁻²
cereal rye	2,440 e	81 ab	80 a	64 a	57 a	17 abc
cereal rye + crimson clover	3,900 b	80 ab	76 a	54 abc	45 bc	15 bc
cereal rye + hairy vetch	4,690 a	85 a	75 a	59 ab	48 abc	14 bc
crimson clover	2,450 e	72 c	59 b	35 e	32 d	24 ab
hairy vetch	3,150 cd	76 bc	64 b	39 de	27 d	27 a
winter wheat	3,080 d	82 ab	78 a	59 ab	54 ab	17 abc
winter wheat + crimson clover	3,530 bc	80 ab	74 a	52 bc	45 bc	11 c
winter wheat + hairy vetch	3,620 b	85 a	78 a	55 abc	48 abc	10 c
untreated check ^b	990 f	68 c	62 b	48 cd	44 c	22 ab
Pr > F	<0.0001	0.0003	<0.0001	<0.0001	<0.0001	0.0146

^a Means within a column followed by the same letter are not significantly different according to Fisher's protected LSD a P < 0.05.

^b Areas included in the untreated check consisted of henbit (*Lamium amplexicaule*), annual bluegrass (*Poa annua*), and horseweed (*Conyza canadensis*).

Table 11. In-season Palmer amaranth control and density 28DAA as affected by PRE herbicide treatments.^a

Herbicide Treatments ^b	Palmer amaranth					Cotton lint yield
	Control				Density	
	7DAA	14DAA ^c	21DAA	28DAA	28DAA	
	-----%-----				no. m ²	kg ha ⁻¹
acetochlor	97 a	89 b	70 a	62 a	6 b	890 a
fluometuron	93 a	95 a	66 a	54 b	11 a	900 a
untreated check	47 b	31 c	19 b	17 c	35 a	650 b
Pr > F	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

^a Means within a column followed by the same letter are not significantly different according to Fisher's protected LSD a P < 0.05.

Table 12. Location, environmental conditions, and soybean planting and harvest dates.

Location	Year	Soil Series/Texture	Planting Date	Harvest Date	Total Precipitation ^a (cm)
WTREC	2013	Lexington Silt Loam ^b	05/24/2013	10/05/2013	44
WTREC	2014	Lexington Silt Loam	06/16/2014	10/9/2014	53

^a Precipitation information recorded from planting date to harvest date.

^b Fine-Silty, Mixed, Active, Thermic Ultic Hapludalfs

Table 13. Cereal rye dry biomass and control ratings, Palmer amaranth control and density, and soybean yield as affected by termination timing.^a

Termination timing ^b	Biomass kg ha ⁻¹	Cereal rye			Palmer amaranth		Soybean Yield kg ha ⁻¹
		Control			Control	Density	
		7DAA	14DAA	21DAA	21DAA	21DAA	
		-----%-----			%	no. m ⁻²	
1	3,490 c	74 bc	74 d	73 c	79 bc	5 b	3,950
2	6,540 ab	65 c	77 cd	84 b	78 bc	17 a	4,030
3	5,170 bc	65 c	79 cd	82 bc	74 c	5 b	3,690
4	5,570 ab	82 b	86 bc	85 b	88 ab	7 ab	3,740
5	7,120 a	75 bc	88 b	89 ab	95 a	1 b	3,850
6	6,250 ab	96 a	97 a	98 a	96 a	0 b	3,780
Pr > F	0.0077	<0.0001	<0.0001	0.0006	0.0022	0.0188	NS

^a Means within a column followed by the same letter are not significantly different according to Fisher's protected LSD a $P < 0.05$.

^b Termination timings: Timing 1: mid-March; Timing 2: early April; Timing 3: mid-April; Timing 4: late April; Timing 5: mid-May; Timing 6: late May.

Table 14. Cereal rye control ratings, Palmer amaranth control and density 21DAA, and soybean yield as affected by herbicide.^a

Herbicide	Cereal rye			Palmer amaranth		Soybean yield kg ha ⁻¹
	Control			Control	Density	
	7DAA	14DAA	21DAA	21DAA	21DAA	
	-----%-----			%	no. m ⁻²	
glyphosate	72 b	88 a	92 a	77 b	10 a	3,770
paraquat	80 a	79 b	79 b	93 a	1.5 b	3,910
Pr > F	0.0079	0.0073	0.0096	0.0045	0.0024	NS

^a Means within a column followed by the same letter are not significantly different according to Fisher's protected LSD a $P < 0.05$.

Table 15. Cereal rye control ratings, Palmer amaranth control and density 21DAA, and soybean yield as affected by the interaction of termination timing and burndown herbicide.^a

Termination timing ^b	Herbicide	Cereal rye			Palmer amaranth		Soybean yield kg ha ⁻¹
		Control			Control	Density	
		7DAA	14DAA	21DAA	21DAA	21DAA	
		-----%-----			%	no. m ⁻²	
1	glyphosate	67 de	77 b	78	72 cd	5 bc	4,070
2	glyphosate	56 ef	74 b	89	62 d	33 a	4,010
3	glyphosate	49 f	82 b	90	61 d	10 bc	3,820
4	glyphosate	90 abc	99 a	99	79 bcd	14 b	3,840
5	glyphosate	75 d	99 a	96	95 ab	1 bc	3,740
6	glyphosate	95 ab	98 a	99	95 ab	0 c	3,980
1	paraquat	81 bcd	71 b	69	87 abc	5 bc	3,830
2	paraquat	73 d	81 b	79	95 ab	1 bc	4,050
3	paraquat	81 bcd	75 b	75	88 abc	1 bc	3,560
4	paraquat	74 d	72 b	72	98 a	1 bc	3,640
5	paraquat	76 cd	77 b	82	94 ab	2 bc	3,960
6	paraquat	97 a	97 a	98	97 ab	0 c	3,570
Pr > F		0.0009	0.0005	NS	0.0483	0.0050	NS

^a Means within a column followed by the same letter are not significantly different according to Fisher's protected LSD a P < 0.05.

^b Termination timings: Timing 1: mid-March; Timing 2: early April; Timing 3: mid-April; Timing 4: late April; Timing 5: mid-May; Timing 6: late May.

Table 16. Crimson clover dry biomass and control ratings, Palmer amaranth control and density, and soybean yield as affected by termination timing.^a

Termination timing ^b	Biomass kg ha ⁻¹	Crimson clover			Palmer amaranth		Soybean yield kg ha ⁻¹
		Control			Control	Density	
		7DAA	14DAA	21DAA	21DAA	21DAA	
		-----%-----			%	no. m ⁻²	
1	2,850 c	60 bc	65 b	60 c	70 bc	9 ab	2,830
2	6,800 a	62 bc	59 b	72 bc	82 ab	8 ab	2,700
3	5,010 ab	56 c	66 b	65 c	69 c	12 a	2,800
4	4,000 bc	70 abc	81 a	84 ab	70 bc	6 b	2,850
5	3,200 bc	73 ab	92 a	91 a	94 a	0 c	2,940
6	5,030 ab	82 a	87 a	91 a	93 a	0 c	2,970
Pr > F	0.0033	0.0054	<0.0001	<0.0001	<0.0001	<0.0001	NS

^a Means within a column followed by the same letter are not significantly different according to Fisher's protected LSD a P < 0.05.

^b Termination timings: Timing 1: mid-March; Timing 2: early April; Timing 3: mid-April; Timing 4: late April; Timing 5: mid-May; Timing 6: late May.

Table 17. Crimson clover control ratings, Palmer amaranth control and density 21DAA, and soybean yield as affected by herbicide.^a

Herbicide	Crimson clover			Palmer amaranth		Soybean yield kg ha ⁻¹
	Control			Control	Density	
	7DAA	14DAA	21DAA	21DAA	21DAA	
	-----%-----			%	no. m ⁻²	
glyphosate	58 b	72 b	77	79	7	2,800
paraquat	76 a	79 a	77	80	5	2,900
Pr > F	<0.0001	0.0008	NS	NS	NS	NS

^a Means within a column followed by the same letter are not significantly different according to Fisher's protected LSD a P < 0.05.

Table 18. Crimson clover control ratings, Palmer amaranth control and density 21DAA, and soybean yield as affected by the interaction of termination timing and burndown herbicide.^a

Termination timing ^b	Herbicide	Crimson clover			Palmer amaranth		Soybean yield kg ha ⁻¹
		Control			Control	Density	
		7DAA	14DAA	21DAA	21DAA	21DAA	
		-----%-----			%	no. m ⁻²	
1	glyphosate	49	61	59 de	64	13 ab	2,860
2	glyphosate	54	52	68 cde	80	12 abc	2,490
3	glyphosate	48	65	71 cd	71	17 a	2,660
4	glyphosate	61	78	80 abc	78	1 de	2,750
5	glyphosate	61	89	92 a	93	0 de	2,900
6	glyphosate	75	85	90 a	90	0 de	3,120
1	paraquat	70	70	60 de	76	5 cde	2,800
2	paraquat	70	67	75 bc	84	4 cde	2,910
3	paraquat	64	68	59 e	69	7 bcd	2,940
4	paraquat	79	85	87 ab	63	11 ab	2,960
5	paraquat	85	94	91 a	94	0 e	2,990
6	paraquat	89	89	91 a	95	1 de	3,120
Pr > F		NS	NS	0.0414	NS	0.0012	NS

^a Means within a column followed by the same letter are not significantly different according to Fisher's protected LSD a P < 0.05.

^b Termination timings: Timing 1: mid-March; Timing 2: early April; Timing 3: mid-April; Timing 4: late April; Timing 5: mid-May; Timing 6: late May.

Table 19. Hairy vetch dry biomass and control ratings, Palmer amaranth control and density, and soybean yield as affected by termination timing.^a

Termination timing ^b	Biomass kg ha ⁻¹	Hairy vetch			Palmer amaranth		Soybean yield kg ha ⁻¹
		Control			Control	Density	
		7DAA	14DAA ^c	21DAA	21DAA	21DAA	
		-----%-----			%	no. m ⁻²	
1	1,720 d	71 b	70 c	67 b	82 ab	6	3,730
2	4,280 bc	71 b	64 c	76 b	75 b	6	3,550
3	3,780 c	58 c	74 c	76 b	74 b	7	3,530
4	4,340 bc	76 b	75 bc	80 ab	70 b	5	3,740
5	6,060 ab	78 ab	89 a	93 a	86 ab	4	3,580
6	7,470 a	86 a	88 ab	91 a	95 a	0	3,430
Pr > F	<0.0001	<0.0001	0.0029	0.0059	0.0381	NS	NS

^a Means within a column followed by the same letter are not significantly different according to Fisher's protected LSD a $P < 0.05$.

^b Termination timings: Timing 1: mid-March; Timing 2: early April; Timing 3: mid-April; Timing 4: late April; Timing 5: mid-May; Timing 6: late May.

Table 20. Hairy vetch control ratings, Palmer amaranth control and density 21DAA, and soybean yield as affected by herbicide.^a

Herbicide	Hairy vetch			Palmer amaranth		Soybean yield kg ha ⁻¹
	Control			Control	Density	
	7DAA	14DAA ^c	21DAA	21DAA	21DAA	
	-----%-----			%	no. m ⁻²	
glyphosate	63 b	75	82	75	6	3,650
paraquat	84 a	78	79	86	3	3,530
Pr > F	<0.0001	NS	NS	NS	NS	NS

^a Means within a column followed by the same letter are not significantly different according to Fisher's protected LSD a P < 0.05.

Table 21. Hairy vetch control ratings, Palmer amaranth control and density 21DAA, and soybean yield as affected by the interaction of termination timing and burndown herbicide.^a

Termination timing ^b	Herbicide	Hairy vetch			Palmer amaranth		Soybean yield kg ha ⁻¹
		Control			Control	Density	
		7DAA	14DAA	21DAA	21DAA	21DAA	
		-----%-----			%	no. m ⁻²	
1	glyphosate	61 e	75	72 def	70	9	3,540
2	glyphosate	68 cde	59	79 bcdef	64	8	3,790
3	glyphosate	39 f	76	85 abcd	64	9	3,580
4	glyphosate	63 e	71	79 bcde	72	4	3,850
5	glyphosate	66 de	84	91 ab	87	6	3,590
6	glyphosate	79 bcd	85	88 abc	93	1	3,530
1	paraquat	81 abc	64	63 f	93	3	3,920
2	paraquat	74 cde	69	73 cdef	87	4	3,300
3	paraquat	77 bcd	72	67 ef	85	5	3,470
4	paraquat	88 ab	79	81 abcde	68	7	3,630
5	paraquat	89 ab	94	96 a	85	2	3,560
6	paraquat	93 a	91	94 ab	96	0	3,300
Pr > F		0.0353	NS	0.0071	NS	NS	NS

^a Means within a column followed by the same letter are not significantly different according to Fisher's protected LSD a P < 0.05.

^b Termination timings: Timing 1: mid-March; Timing 2: early April; Timing 3: mid-April; Timing 4: late April; Timing 5: mid-May; Timing 6: late May.

Table 22. Winter wheat dry biomass and control ratings, Palmer amaranth control and density, and soybean yield as affected by termination timing.^a

Termination timing ^b	Biomass kg ha ⁻¹	Winter wheat			Palmer amaranth		Soybean yield kg ha ⁻¹
		Control			Control	Density	
		7DAA	14DAA ^c	21DAA	21DAA	21DAA	
		-----%-----			%	no. m ⁻²	
1	3,230 c	66 c	70 e	71 d	85 c	9 a	4,170
2	5,440 b	66 c	74 de	82 bc	86 bc	8 a	4,220
3	5,880 ab	66 c	80 cd	77 cd	85 c	6 a	4,280
4	6,860 ab	84 ab	86 bc	88 ab	94 ab	1 b	4,260
5	7,520 a	80 b	95 ab	96 a	97 a	0 b	4,000
6	7,380 ab	93 a	97 a	97 a	96 a	0 b	4,160
Pr > F	0.0007	<0.0001	<0.0001	<0.0001	0.0101	<0.0001	NS

^a Means within a column followed by the same letter are not significantly different according to Fisher's protected LSD a P < 0.05.

^b Termination timings: Timing 1: mid-March; Timing 2: early April; Timing 3: mid-April; Timing 4: late April; Timing 5: mid-May; Timing 6: late May.

Table 23. Winter wheat control ratings, Palmer amaranth control and density 21DAA, and soybean yield as affected by herbicide.^a

Herbicide	Winter wheat			Palmer amaranth		Soybean yield kg ha ⁻¹
	Control			Control	Density	
	7DAA	14DAA ^c	21DAA	21DAA	21DAA	
	-----%-----			%	no. m ⁻²	
glyphosate	72 b	86	92 a	86 b	7 b	4,110 b
paraquat	79 a	82	79 b	96 a	0 a	4,260 a
Pr > F	0.0259	NS	<0.0001	0.0028	0.0064	0.0168

^a Means within a column followed by the same letter are not significantly different according to Fisher's protected LSD a P < 0.05.

Table 24. Winter wheat control ratings, Palmer amaranth control and density 21DAA, and soybean yield as affected by the interaction of termination timing and burndown herbicide.^a

Termination timing ^b	Herbicide	Winter wheat			Palmer amaranth		Soybean yield kg ha ⁻¹
		Control			Control	Density	
		7DAA	14DAA	21DAA	21DAA	21DAA	
		-----%-----			%	no. m ⁻²	
1	glyphosate	58 ef	68 d	73	71 d	16 a	4,240
2	glyphosate	61 def	70 cd	94	75 cd	15 a	4,140
3	glyphosate	48 f	83 bc	87	84 bc	11 a	4,200
4	glyphosate	96 a	97 a	99	92 ab	2 b	4,220
5	glyphosate	84 abc	99 a	99	97 ab	0 b	3,870
6	glyphosate	88 ab	98 a	99	95 ab	0 b	3,980
1	paraquat	74 bcd	72 cd	68	99 a	1 b	4,110
2	paraquat	71 cde	78 cd	70	97 ab	0 b	4,300
3	paraquat	84 abc	78 cd	68	87 abc	0 b	4,340
4	paraquat	73 bcde	75 cd	77	97 a	0 b	4,310
5	paraquat	76 bcd	91 ab	94	97 a	0 b	4,150
6	paraquat	97 a	97 a	96	98 a	0 b	4,340
Pr > F		<0.0001	0.0070	NS	0.0096	0.0003	NS

^a Means within a column followed by the same letter are not significantly different according to Fisher's protected LSD a P < 0.05.

^b Termination timings: Timing 1: mid-March; Timing 2: early April; Timing 3: mid-April; Timing 4: late April; Timing 5: mid-May; Timing 6: late May.

Vita

Matthew S. Wiggins was born August 8, 1988, in Jackson, TN. He is the son of Mr. and Mrs. Jerry Wiggins of Friendship, TN. He attended Crockett County High School and graduated in May 2006. He then enrolled at Tennessee Technological University in August 2006 and received a Bachelor of Science in Agriculture, with an emphasis in Agricultural Engineering Technology in December 2009. Upon graduation, he accepted the position of Graduate Research Assistant in the graduate program at The University of Tennessee working under Dr. Christopher Main, Cotton and Small Grains Extension Specialist, and achieved a Master of Science degree in Plant Sciences in May 2012. Upon graduation, Matthew continued his education at the University of Tennessee pursuing a Ph. D. in Plant, Soils, and Insects with an emphasis in weed science under the direction of Dr. Larry Steckel. Matthew has been the recipient of numerous awards during his undergraduate and graduate career. He has also presented at numerous extension and professional meetings and won awards at the Beltwide Cotton Conference, North Central Weed Science Society, and the Southern Weed Science Society annual meetings. To date, Matthew is the author of 2 peer review manuscripts and 14 non-peer reviewed publications. After completion of his Ph. D. degree, Matthew will begin a position with Monsanto Company as a Technology Development Representative Associate in Huxley, IA.