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Glyphosate Resistant Palmer amaranth (*Amaranthus palmeri*) management late-season and POST-harvest in corn production systems

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To the Graduate Council:

I am submitting herewith a thesis written by Whitney D. Crow entitled "Glyphosate Resistant Palmer amaranth (*Amaranthus palmeri*) management late-season and POST-harvest in corn production systems." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Plant Sciences.

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"Trust in the Lord with all your heart, and do not lean on your own understanding. In all your ways acknowledge him, and he will make straight your paths."

Proverbs 3:5-6

Abstract

The objectives of this research were to evaluate control options for glyphosate resistant (GR) Palmer amaranth (*Amaranthus palmeri*) late-season in corn systems and POST-harvest for the prevention of seed production. Our results determined that the best late-season control methods were treatments tank-mixed with dicamba plus diflufenzopyr. These tank-mixtures improved control from 10 to 46% [percent] over treatments without the dicamba premix. Tank-mixtures with dicamba plus diflufenzopyr that provided weed control > [greater than] 96% 28 DAA included *s*-metolachlor plus glyphosate plus mesotrione and tembotrione plus thiencarbazone.

For the prevention of POST-harvest GR palmer amaranth seed production, our results determined that paraquat provides excellent initial control of existing vegetation but regrowth can occur from larger plants. The addition of a residual herbicide may aid in controlling regrowth as well as preventing plant germination. All treatments provided enough control for the prevention of seed production. Through implementation of POST-harvest management practices, 1200 seed per m^2 [meter squared] was prevented from replenishing the soil seed bank. There were no adverse affects on wheat yield.

From these results, we can conclude that when practicing POST only weed management strategies, application timing is vital for the prevention of corn loss and that implementation of late-season weed management programs can effectively reduce weed seed rain, therefore reducing weed seed bank densities.

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Part I.

Introduction

Corn History and Production

Corn, *Zea mays L.*, commonly known as maize in the rest of the world, is a member of the Poaceae family. Corn originated in Meso-America and was rapidly distributed throughout the world as a food crop by the Spanish and Portuguese in the early sixteenth century (Fageria et al, 2011). After rice and wheat, corn is one of the world's most important cereal crops (Danforth, 2009). Of the cereal crops, corn is not only grown in more countries around the world, but also produces the largest grain yield (Fageria et al, 2011). In many parts of the world corn is a primary source of food and feed because of its nutrient content, high yield averages per unit of land and labor (Danforth, 2009). In the United States, corn is primarily produced as an energy source for livestock feed. Of the corn that is produced in the United States, 70% is used as animal feed and 20% is used for industrial processes like ethanol and biofuels. According the United States Department of Agriculture, corn hectrage in the United States was 38,592,846 ha in 2013, and in the state of Tennessee was 331,842 ha (2012).

Corn, being a determinate plant, has separate vegetative and reproductive stages. Its vegetative stages begin at plant emergence and are completed once the tassel is completely visible. The reproductive cycle is represented by six different growth stages. These stages include silking, blister, milk, dough, dent, and physiological maturity (Purdue, 2013).

Corn, unlike rice and wheat, utilizes a C_4 photosynthetic pathway allowing for a different photosynthetic metabolism. C_4 pathways are an adaptation of C_3 pathways (Furbank and Taylor, 1995). Through the utilization of C_4 pathways, plants are able to optimize their growing potential by high photosynthetic rates, low CO_2 compensation, and better use of water which results in more stored carbohydrates.

Palmer Amaranth

Weed management is important for Tennessee corn producers partly because they face numerous issues with Palmer amaranth. Palmer amaranth is one of the most problematic and troublesome weeds of agronomic crops in the southeastern United States (Heap et al, 2013). Several factors have enabled this *Amaranthus* species to develop into a competitive biotype that is augmented by higher water use efficiency, rapid growth rate, high-volume seed production, and herbicide resistance (Chandi et al, 2012).

Palmer amaranth is a dioecious summer annual belonging to the *Amaranthus* genus that is native to the southwestern United States and northern Mexico. Palmer amaranth is a member of the Amaranthaceae family and is one of the ten dioecious species found in a distinct subgroup that is native to North America. For many reasons, Palmer amaranth has developed into a competitive biotype, and, consequently, has become one of the most troublesome and problematic *Amaranthus* species found in corn (Sauer, 1956; Bryson et al, 2009). In the United States, Palmer amaranth seeds may germinate from soils as early as March 1 until as late as October 1. Being a dioecious plant species, female seed heads will be prickly to touch with seed production reaching highs of up to 600,000 seeds per plant (Keeley et al, 1987). Seed production typically ranges between 200,000 and 600,000 seeds per plant. Palmer amaranth seeds are generally smooth and round, and range from 1 to 2 mm in diameter. Seeds are predominantly gravity-dispersed, but due to seed size and prolific production they have the potential to be dispersed via animal and equipment allowing for rapid spread of the species. Like corn, Palmer amaranth utilizes C_4 photosynthetic pathways, photosynthesizing at a more rapid rate than C_3 plants, resulting in higher grow rates and the potential to grow up to 3.5 cm per day (Horak and Loughin, 2000; Norsworthy et al, 2008). This species can grow anywhere from 2m to 3m in height, and may produce non-branching seed heads that can measure up to 0.5m tall (Culpepper et al, 2006).

Glyphosate Tolerant Crops

The adoption of glyphosate tolerant crops facilitated an increase in the use of glyphosate for weed control. Traditionally, glyphosate was used as a non-selective herbicide prior to planting. However, once GR crops were rapidly adopted by producers, glyphosate became increasingly used as a postemergence herbicide in annual agronomic crops. This allowed producers to save on input costs and to develop better weed management programs. In 2009, 13 years after the introduction of glyphosate tolerant crops, five different glyphosate tolerant crops were grown in the United States, and of these cotton (*Gossypium hirsutum*), corn (*Zea mays*), canola (*Brassica napus*), and soybeans (*Glycine max*) were being raised in other countries as well (Duke and Powles, 2009). The popularity of glyphosate tolerant crops led to increased use of glyphosate. Many producers relied solely on this herbicide for weed management, thus jeopardizing the longevity of this highly effective tool, ultimately resulting in many glyphosate resistance weeds (Owen, 2008). The first glyphosate resistant weed was discovered in 1997, and to date, worldwide there are 24 glyphosate resistant weed species (Heap, 2013). Of these, Palmer amaranth is one of the most difficult to control and creates issues for many Tennessee producers. The presence of glyphosate resistant Palmer amaranth in Tennessee was confirmed in 2006 (Heap, 2013). Other states in the southeastern region of the United States that have confirmed the presence of glyphosate- resistant Palmer amaranth are Alabama, Arkansas, Florida, Georgia, Louisiana, and Mississippi (Price et. al., 2011). Inhibition of 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS) is one of the five mechanisms of herbicide action to which Palmer amaranth has resistance. Others include but are not limited to photosynthetic inhibitors, and acetolactate synthase (ALS) inhibitors (Chandi et al, 2012; Heap, 2013). In corn, Palmer amaranth has had repeated herbicide resistance to both atrazine and mesotrione, both of which are popular corn herbicides used for weed management.

Weed Management

Weed management in corn production systems in Tennessee is largely dependent on herbicide programs to control problematic weed species. In recent years corn producers often need to control large Palmer amaranth in corn greater than 31 cm tall. A common herbicide found in corn production for the control of Palmer amaranth is atrazine because of its low cost and effective control; however, it is only labeled to be applied up to 31 cm corn (Anonymous). To slow the development of further herbicide resistance in Palmer amaranth, it is important to incorporate multiple mechanisms of action into herbicide programs. Furthermore, producers should employ year-round weed management programs, shifting to programs with less reliance on herbicides-only control for weed management. It is also important to implement practices like crop rotation, and expand the use of various cultural methods of weed control such as manipulating planting dates, preventing seed movement, planting weed-free seed, reducing soil seed bank, enforcing a zero-tolerance seed production policy, and regular scouting. (Vencill et al, 2012; Norsworthy et al, 2012). By implementing and enforcing a zero-tolerance seed policy POST-harvest in corn production systems, weed seed found in the soil seed bank is effectively reduced (Taylor and Oliver 1997; Clay and Griffin 2000; Brewer and Oliver 2007). Additionally, the occurrence of resistance alleles from herbicide resistant weed species is reduced due to the reduction of seed dispersal.

The objective of this research is to evaluate Palmer amaranth weed management programs late-season and POST-harvest in corn production systems. The purpose of this research is to provide the best weed management program to control > 20 cm Palmer amaranth late-season in cornthat will prevent Palmer amaranth reproduction and reduce soil seed bank reservoirs, therefore, reducing the spread of herbicide resistant and problematic species.

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Part II

Evaluation of Non-Atrazine Herbicide Treatments for POST Control of Glyphosate Resistant Palmer amaranth (*Amaranthus palmeri*) in Corn

Abstract

New control strategies must be developed to optimize weed control of glyphosate resistant (GR) palmer amaranth. A study was conducted in 2013 and 2014 in Jackson, TN to evaluate non-atrazine herbicide weed control programs in corn (*Zea mays*) for the control of glyphosate resistant (GR) palmer amaranth greater than 21 cm in height. Treatments consisted of herbicides applied alone and in tank-mixture with dicamba plus diflufenzopyr. Herbicides were applied POST to corn between V5 and V6 growth stages. Dicamba plus diflufenzopy 28 DAA controlled Palmer amaranth > 91%. The herbicides alone or in combinations applied as tank mixtures did not improve control (<76%) over dicamba plus diflufenzopyr alone. Corn yield was not adversely affected by Palmer amaranth interference partly because soil moisture and nutrition were not limiting in these studies.

Nomenclature: Corn [*Zea mays*]; Palmer amaranth [*Amaranthus palmeri*]; Glyphosate resistant, GR; Days after application, DAA.

Keywords: non-atrazine, palmer amaranth, glyphosate resistant, late-season

Introduction

Palmer amaranth has become one of the most problematic and troublesome weeds of agronomic crops, including corn in the southeastern United States (Heap et al, 2013). Weed management in corn production systems in Tennessee is largely dependent on herbicides to control problematic weed species. In 2001, approximately 98% of corn planted across the country received a herbicide application. In recent years, corn producers have been forced to control large Palmer amaranth in corn greater than 21 cm tall whether it be due to environmental conditions or management practices.

It is important to know the critical weed free period of corn to understand how weed interference can adversely affect crop growth and development (Gower, 2002). The critical weed free period is defined as the time in which a weed species may coexist with a crop before there is a reduction in yield due to weed interference (Hall et al, 1992). Many studies have been conducted to determine the critical weed free period of corn. Hall et al (1992), and Page et al (2012) determined that the critical weed free period under North American growing conditions is when corn is between the fourth and eighth leaf (Gantoli et al, 2013), although Halford et al (2001), determined that the critical weed free period usually begins at the six-leaf stage and ends between the ninth- to 13- leaf stage. We can conclude that it is often difficult to define the critical weed free period in corn and often varies with weed species, environment, and cultural practices (Norsworthy and Oliveira, 2004; Myers, 2005).

Several factors have enabled Palmer amaranth to develop into a competitive biotype that is augmented by higher water use efficiency, rapid growth rate, high-volume seed production, and herbicide resistance (Chandi et al, 2012). Palmer amaranth is a dioecious summer annual belonging to the *Amaranthus* genus that is native to the southwestern United States and northern

Mexico. Seeds may germinate from soils as early as March 1 until as late as October 1. Seed production typically ranges between 200,000 and 600,000 seeds per plant. Like corn, Palmer amaranth utilizes C_4 photosynthetic pathways, photosynthesizing at a more rapid rate than C_3 plants, resulting in higher growth rates and the potential to grow up to 3.5 cm per day (Horak and Loughin, 2000; Norsworthy et al, 2008). Studies have shown that Palmer amaranth densities of 0.5 to 8 plants m^{-1} of row reduced corn yield 11 to 91% (Massing et al, 2001).

Weed management in corn is largely dependent on atrazine, a common herbicide used in many areas, because of its low cost and effective weed control (Gower, 2002). Atrazine continues to be used on more than 65% of the corn production areas in the southeastern region of the United States (Frenandez-Cornejo and Jans, 1999). However, according to the label, atrazine can only be applied to corn less than 31 cm in height (Anonymous, 2014). After corn reaches 31 cm, producers must rely on other POST herbicides for effective weed management. According to Gower et al (2002), a total POST herbicide program in corn allows growers the opportunity to determine weed density and composition of weeds present in the location of interest to assist in herbicide selection and application timing. However, application timing is crucial. Ideally, Palmer amaranth should be controlled when it is less than 5 cm tall; however with variable environmental conditions and timing factors, herbicide applications cannot always be made until Palmer amaranth is larger and thus more difficult to control. When using a POST only herbicide program, producers should be mindful not to make the application too soon after both the crop and weeds emerge as this could result in poor control of later weed emergence. Conversely, making the application too late after weed emergence could allow for weed interference resulting in yield reduction (Gower et al, 2002).

The objective of this research is to evaluate non-atrazine premixes alone and tank-mixed with dicamba plus diflufenzopyr to determine the efficacy for GR Palmer amaranth greater than 21 cm in corn productions systems.

Materials and Methods

Field experiments were conducted at the in Jackson, TN (35.632227, -88.857739) in 2013 and 2014 to evaluate control on late GR Palmer amaranth (>21cm) using non-atrazine herbicide applications applied alone and with a premix of dicamba plus diflufenzopyr plus [isoxadifen-ethyl, corn saferner]. Corn was planted at a depth of 3 cm and a population of 79,000 seeds per ha^{-1} on May 13, 2013 and April 2, 2014 in a conservation tillage system. Standard production practices according to the University of Tennessee were followed (McClure, 2009).

Herbicides were applied alone and in combination with a premix of dicamba plus diflufenzopyr plus isoxadifen-ethyl. All herbicide treatments can be found in Table 1. Herbicide rates were applied at the full rate according to the label. POST applications were made to corn between V5 and V6 growth stages. Applications were made on June 5, 2013 and May 27, 2014. Treatments were applied to two rows of each 1.5m by 9m plot. Herbicides applications were applied using a pressurized CO_2 backpack sprayer calibrated to deliver 168 L per ha^{-1} using AIXR 10002 fan flat nozzles at 275 kPa. Herbicide applications were made to a 30% glyphosate resistant and 70% susceptible population of Palmer amaranth, as well as, cross-resistance to ALS inhibiting herbicides. Population densities were greater than 50 plants per m^2 in 2013 and less than 30 plants per m^2 in 2014.

The field study was implemented as a randomized complete block design with four replications. Year and replication were considered to be random effects, and treatments were considered to be fixed effects. Data were analyzed using the PROC MIXED procedure of SAS (ver. SAS 9.3; SAS Institute; Cary, NC). Means were separated using Fisher's Protected LSD procedure at the 0.05 level of significance.

Palmer amaranth control was evaluated at 7, 14, 21, and 28 days after application (DAA) using a scale of 0 (no control) to 100 (complete control) based on visual estimates of stand reduction in the treated area compared with the non-treated checks. Palmer amaranth counts were taken 14 DAA within a 0.5 m^{-2} quadrant between the treated portions of each plot. Corn yield was determined by harvesting the treated portion of each plot.

Results and Discussion

GR Palmer amaranth control. Herbicide treatments provided different levels of Palmer amaranth control across the rating timings ($p>0.0001$) (Table 2). Of the alone herbicide mode of action treatments, Dicamba + diflufenzopyr provided the most complete control of 82 to 91%. Glufosinate initially provided moderate control. However, due to Palmer amaranth size at application, regrowth did occur which resulted in limited control 28 DAA. This result would be consistent with the glufosinate label (Anonymous 2014) which states the cut off height for good control is 10 cm. The glyphosate treatment provided level of Palmer control (67 to 73%) which would be consistent for a mixed population of 30% glyphosate resistant population. The HPPD inhibiting herbicides, tembotrione and mesotrione, alone provided limited control <58%. Limited control from these herbicides are likely due to the timing application. Like glufosiante, the label recommended cutoff height is 5 cm for tembotrione and 8 cm for mesotrione (Anonymous 2014).

There was an increase in Palmer amaranth control, when dicamba + diflufenzopyr was tankmixed with either glyphosate, tembotrione or mesotrione (Table 2). Glyphosate, tembotrione, and mesotrione tank-mixed with dicamba + diflufenzopyr provided about 80% control at the 7 DAA evaluation. This Palmer amaranth control increased to about 90% at the 28 DAA evaluation timing. Tembotrione and thiencarbazone provided 76% control 28 DAA. The addition of theincarbzone helped provide control of the mixed ALS-susceptible population. Of the two-way herbicide treatments, mesotrione and rimsulfuron provided the least amount of control.

Throughout this study, treatments containing tankmixtures of tembotrione + thiencarbazone and *S*-metolachlor + glyphosate + mesotrione tank-mixed with dicamba + diflufenzopyr have provided the greatest control of GR Palmer amaranth. While *S*-metolachlor + glyphosate + glyphosate alone provided considerable less control.

Dicamba + diflufenzopyr alone controlled 91% of GR Palmer amaranth 28 DAA bringing into question the necessity of an additional herbicide. There was an increase in the amount of weed control with dicamba + diflufenzopyr than herbicide treatments applied alone which provided only 51 to 76% control. We can conclude from a single degree of freedom contrast that dicamba + diflufenzopyr tank-mixes help provide additional control of Palmer amaranth 7 DAA, but provides no residual control thereafter (Table 4). Although, 91% of Palmer amaranth is controlled by dicamba + diflufenzopyr 28 DAA, no residual control is provided resulting in limited control of newly germinated plants post application. Moreover, adding an additional mode of action that has some activity on Palmer amaranth should help delay resistance to dicamba (Norsworthy et al. 2012). With the introduction of dicamba-tolerant crops, it will be imperative to not rely solely on dicamba for management of GR Palmer Amaranth. Implementation of good resistance management will be necessary to protect this valuable herbicide (Norsworthy et al. 2012). Of course, the proven strategy is to us premergence herbicides in conjunction with early postemergence control before Palmer amaranth reaches 21 cm.

GR Palmer amaranth counts. The number of Palmer amaranth plants per 1.0 m^{-2} differed between herbicide treatments and the non-treated control, but did not differ among treatments (p=0.0001, Table 3).

Effect of herbicide applications on corn yield. Crop loss due to Palmer amaranth competition was not evident (p=0.6695, Table 3). Although control for Palmer amaranth differed among treatments (Table 2), yield was not adversely affected by weed competition. Studies have determined that a reduction in corn yields is possible with *Amaranthus* competition between the V6 and V8 growth stages and with low to moderate plant densities. Massinga et al. found that Palmer amaranth densities of 0.5 to 8 plants per m^{-2} could lead to an 11 to 91% reduction in corn yield (2003). Steckel and Sprague (2004) found that common waterhemp competition through V6 reduced corn yields. Although, Palmer amaranth densities and competition timing could have potentially reduced yield, it is important to remember that the critical period for weed interference is often difficult to define because it is dependent on environment, weed species, and weed density (Hall et al. 1992). Environmental conditions play a vital role in the magnitude of weed interference and had this study been conducted under drought stress conditions then the Palmer amaranth densities could have had a greater impact on yield reduction. Over the course of this study, we had adequate amount of rainfall during the critical period (Table 5)

Historically, Palmer amaranth management in corn has been highly dependent on soil-applied herbicides, largely due to the low cost and high effectiveness of atrazine. Generally, POST herbicides have been used following soil-applied herbicides to achieve the desired level of weed control; however, in the Southeast, POST only programs may be sufficient to achieve adequate control (Gower, 2003; Norsworthy, 2004). The potential advantage of POST only systems is the opportunity to evaluate weed populations and densities before making a herbicide application (Myers et al, 2005; Gower et al, 2003). Unlike soil-applied herbicides, POST herbicides generally do not require rainfall for activation, thus there is less dependence on environmental conditions for optimum herbicide performance (Myers et al, 2005). Casey and Kells (1995), Gower et al (2002), and Tapia et al (1997) suggest that timely POST applications may be an effective alternative to soil-applied herbicides for weed control, but these management strategies do come at a greater risk due to increased opportunity for weed interference and yield loss. Furthermore, POST only programs do not always prevent weed competition in a timely manner. As weed termination is often dependent on growing conditions, species, and growth stages, application timing is vital for an effective weed management program (Carey and Kells, 1995). Therefore, careful management is required if a POST only program is to be used for weed control in corn.

Many studies have shown that the addition of dicamba has increased weed control. Spaunhorst and Bradley (2013) found that a sequential EPOST application that included dicamba provided greater control of GR waterhemp than glyphosate applied alone sequentially. Glyphosate applied sequentially provided 30% control of GR waterhemp, while glyphosate plus dicamba provided approximately 88%. Steckel et al (2006) found that tank-mixing glufosinate plus dicamba (0.28 kg/ha) increased the control of GR horseweed by 39% when compared with using glufosinate alone. Throughout this study, control for Palmer amaranth was greater with treatments containing dicamba.. Overall, Palmer amaranth control was increased from 10 to 46% when a treatment was tank-mixed with dicamba. We can conclude from this study and others that the addition of dicamba has the potential to provide increased Palmer amaranth control.

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Part III

Evaluation of POST- harvest herbicide applications for seed prevention of glyphosate resistant Palmer amaranth

Abstract

Recent increases in the prevalence of glyphosate resistant (GR) palmer amaranth mandate that new control strategies be developed to optimize weed control and crop performance. A field study was conducted in 2012 and 2013 at the West Tennessee Research and Education Center in Jackson, TN to evaluate POST-harvest corn weed management programs for prevention of seed production from glyphosate resistance (GR) Palmer amaranth, and to evaluate herbicide carryover to winter wheat. Treatments were applied POST-harvest to corn stubble, with three applications followed by a preemergence herbicide applied at wheat planting. Paraquat alone controlled 93% of existing Palmer amaranth 14 DAT but did not control regrowth or emergence of new plants. Paraquat tank-mixed with a residual herbicide, metribuzin, *s*-metolachlor, pyroxasulfone, saflufenacil, or flumioxazin, improved control of regrowth or new emergence compared to the paraquat alone. All residual herbicide treatments were equivalent in terms of GR Palmer amaranth control. All treatments prevented seed production of GR Palmer amaranth. Through implementation of POST-harvest management practices, the addition of 1200 seed per m^2 or approximately 12 million seed ha^{-1} to the soil seed bank was prevented. Overall, the addition of the residual herbicide provided only 3 to 6% more GR Palmer amaranth control than paraquat. Wheat injury was evident (<10%) in 2012 from the PRE applications, but not in 2013. Wheat yield was not adversely affected by any herbicide applications.

Nomenclature: Corn [*Zea Mays*]; Palmer amaranth [*Amaranthus palmeri*]; Glyphosate Resistant, GR, Days after treatment, DAT.

Key Words: herbicide resistance, palmer amaranth, glyphosate resistance

Introduction

Weed management in corn production systems in Tennessee is largely dependent on herbicide programs to control problematic weed species. In order to slow the development of further herbicide resistance in Palmer amaranth, it is important to incorporate multiple mechanisms of actions into herbicide programs (Norsworthy et al., 2012). Furthermore, producers should employ year-round weed management programs and shift to programs with less reliance on herbicides for weed control. Therefore, POST-harvest Palmer amaranth control is an important aspect of sustainable management to prevent seed production and the subsequent spread of herbicide resistance species. Current corn production systems that rely heavily on herbicides are not effective for the control of late-season escapes or new plant germination (Vangessel et al., 2001).

In areas of warm climate, such as the southeastern region of the United States, the interval between harvest and the first killing frost is a sufficient amount of time to allow for new germination or for mechanically damaged Palmer amaranth that have survived harvest operations to reproduce, allowing for replenishment of the soil seed bank (Bagvanthiannan and Norsworthy, 2012). The soil seed bank serves as a reservoir for pernicious weeds, allowing for their dispersal and future reproduction, including herbicide resistance species (Norsworthy, et. al, 2012). A great contributor to the soil seed bank are the late-season weed escapes, making them a major concern for producers seeking to control weed proliferation (Bagvanthiannan and Norsworthy, 2012). These late-season weed escapes are common in weed management programs that utilize only POST applications with no residual herbicides (VanGessel et al, 2001). Weed species with prolific seed production provide significant seed bank replenishment. Studies have shown that the residual population may be sufficient to persist for several years following the implementation of weed management programs that are effective in controlling late-season weeds (Schweizer and Zimdahl, 1984).

For species like Palmer amaranth with prolific seed production, rapid growth, and the ability to produce viable seed from plants that are less than 15 cm in height, a late-season female plant can donate to seed bank replenishment. Palmer amaranth seed production generally averages between 200,000 and 600,000 seeds per plant (Keeley et al. 1987).

Palmer amaranth plants at 12 ha^{-1} have the potential to produce an additional 5 million seed $ha^{-1,}$ effectively replenishing the seed bank (Culpepper and Sosnokie, 2011). These seeds may germinate from soils as early as March 1 until as late as October 1 and will typically flower between September and October (Keeley et al, 1987). Species like Palmer amaranth involve a zero tolerance seed production policy. Studies have shown that after six years of weed free conditions, seed population were reduced 98% with an average of 7.7 seeds 100 g^{-1} of soil (Menges, 1987). However, the remaining population (2%) represented approximately 18 million seed ha^{-1}(Menges, 1987). Such reduction in the soil seed bank is a clear indicator that maintaining zero seed production will diminish the severity of persistent weed species.

In some areas, producers can use POST-harvest tillage as an effective tool for weed management. Tillage reduces the seed bank by stimulating seed germination and killing emerged plants. However, in Tennessee, POST-harvest tillage is not always the best strategy to use due to erosion potential on the rolling topography (NRCS, 2007). In 2012, 94% of corn hectares were planted in no tillage production systems or some form of conservative tillage, while only 6 % was conventional tillage (USDA, 2012). Thus, herbicidal control is the main driver in managing Palmer amaranth POST-harvest and preventing high-volume seed production in no-tillage systems (Nowark, 1983; Koskinen and McWhorter, 1986; Buhler, 1988; Coffman and Frank, 1991). Jones and Medd found that late-season herbicide applications to prevent seed production were very effective in reducing seed densities (2005).

Weed seed rain is the reproduction or dispersal of seed from weed species that contribute to the replenishment of the soil seed bank (Bagvanthiannan and Norsworthy, 2012). By implementing POST-harvest weed management practices, weed seed rain and density are both effectively reduced (Brewer and Oliver 2007; Clay and Griffin 2000; Taylor and Oliver 1997). This decreases the probability of propagation of resistance alleles, and from an herbicide resistance management standpoint, prevents the reproduction of surviving individuals and decreasing the spread of herbicide resistance species (Norsworthy, et al, 2012). This exemplifies the primary objective of POST-harvest weed management practices, which is to prevent seed production by enforcing a zero tolerance seed production policy in order to reduce the soil seed bank and reduced spread of problematic weed species.

The objective of this research is to evaluate POST-harvest weed management programs for the prevention of Palmer amaranth seed production following corn production systems, as well as to evaluate herbicide injury, or carryover, to fall-seeded winter wheat.

Materials and Methods

Field experiments were conducted at the in Jackson, TN (35.632227, -88.857739) in 2012 and 2013 and in Knoxville, TN (35.974659, -83.856105) in 2013 to evaluate POST-corn harvest weed management programs for the control of Palmer amaranth for the prevention of seed production, as well as, evaluation of herbicide injury to fall-seeded winter wheat .

POST-harvest herbicide applications included paraquat applied alone, or in combination with a residual herbicide (Table 6). All POST-harvest herbicide applications also contained non-ionic surfactant (NIS) at 0.25% v v^{-1}. Three POST-harvest herbicide applications were followed by a preemgerence (PRE) herbicide application of pyroxasulfone, flufenacet methyl, or chlorsulfuron plus metsulfuron methyl. Herbicide application rates are presented in Table 1. POST-harvest herbicide applications were made to Palmer amaranth that ranged in height from 6 to 50 cm, while PRE applications were made at wheat planting. Herbicide applications were applied with a pressurized CO_2 backpack sprayer calibrated to deliver 168 L ha^{-1} using XR 110025 flat fan nozzles set at 186 kPa. POST-harvest herbicides were applied made 5 days after corn harvest on August 14, 2012, September 16, 2013, September 19, 2013 at Jackson, and September 24, 2013 at Knoxville. PRE herbicides were applied at wheat planting on October 10, 2012 Jackson and October 14, 2013 at Jackson, and October 17, 2013 at Knoxville.

This field study was implemented as a randomized complete block design with treatment replicated four times. The treated area of each plot was 1.5 m by 9.1 m. Years and replication were considered random effects, and treatments were considered fixed effects. Data were analyzed using the MIXED procedure of SAS (ver. SAS 9.3; SAS Institute; Cary, NC). Means were separated using Fisher's Protected LSD procedure at the 0.05 level of significance.

Palmer amaranth control was evaluated at POST-harvest application timings of 7 and 14 days after application (DAA) using a scale of 0 (no control) to 100 (complete control) based on visual estimates of Palmer amaranth control as compared with the non-treated checks. Palmer amaranth seed was collected in a 0.5 m^2 area from each plot (Table 2). Seed were harvested using a No. C

0.21 cm round (Seedburo Equipment Company; Chicago, IL) by hand threshing. Seeds were then counted by hand 21 DAA. Wheat injury from PRE herbicides was evaluated at crop emergence using a scale of 0 (no injury) to 100 (plant death) based on visual estimates of wheat phototoxcity, compared with the non-treated checks. Wheat biomass was collected as fresh weights in a 0.3 m^2 area within the 1.5m of the treated portion of the plot. Yield was determined by harvesting the treated area of each plot.

Results and Discussion

GR Palmer amaranth control. All treatments had >98% control of GR Palmer amaranth 7 DAA (Table 7). Paraquat plus *S*-metolachlor had 94 to 95% control, while all other tank-mixes provided ≥97% control.

While paraquat desiccated existing Palmer amaranth; regrowth occurred from larger plants, suggesting that adding a residual herbicide may aid in controlling plant regrowth as well as preventing new plants from emerging. In the mid-south, POST-harvest conditions are optimal for Palmer amaranth germination, given enough rainfall; therefore this pest is still very much a problem, even when crops are no longer present.

Seed Collection. Rapid buildup of viable seed in the soil seed bank is critical for resistant populations, including herbicide resistant species. To reduce long-term weed pressure from weeds like Palmer amaranth, it is vital to enforce a zero tolerance weed seed program. Therefore, there should be no seed production from these plants, meaning that control measures should extend throughout the growing season. (Norsworthy et al, 2014). All treatments prevented seed production of GR Palmer amaranth, even when weed control was not complete. Replenishment of the soil seedbank was reduced by 1200 seed m^2, or approximately 12 million seeds ha^{-1} (Table 7).

Wheat Injury. Treatments that did not receive a PRE herbicide did not have any wheat injury, based on visual estimates, indicating that there was no herbicide carryover from our POST-harvest applications.

Wheat phototoxcity was only evident from PRE applications in 2012. Thus, the following results on wheat injury are exclusively from 2012. Wheat injury ranged from 5 to 10% at 12 DAA of PRE herbicides (Table 6) based on visual estimates of injury. Treatments receiving a PRE application of pyroxasulfone had the highest wheat injury (10%), while chlorsulfuron plus metsulfuron methyl and flufenacet plus metribuzin caused little injury (<5%). No treatment had >4 % wheat injury at 25 DAA.

The total amount of rainfall from August to October, starting at the initial application and continuing through wheat planting, was 38 cm and 22 cm, respectively, for 2012 and 2013 for a difference between years of 16 cm.(NWS reference) For the month of October, there was 7 cm difference in rainfall between 2012 and 2013. Therefore, wheat injury observed in 2012 could be due to the amount of rainfall and herbicide uptake in October. (Table 9).

In studies conducted to evaluate PRE herbicides for weed management in wheat winter, pyroxasulfone caused <8% wheat injury with no effect on yield (Hulting et al., 2012). Flufenacet methyl plus metribuzin had < 19% wheat injury in a range of 3 to 25 weeks after treatment (Hill et al, 2011). These results were similar to the range of injury we observed from the PRE herbicides.

Wheat Biomass. Wheat biomass ranged from 304 to 579 g m^{2} across years and locations. Therefore, differences in wheat biomass due to wheat injury were not evident (Table 6). In 2012, wheat biomass ranged from 236 to 566 g m^2, and biomass was reduced by PRE herbicide (Table 8).

Effect of herbicide application on yield. There was no wheat yield loss due to wheat injury from either herbicide carryover or injury from the herbicide applications (Table 8). Even in 2012, when wheat injury from PRE herbicides was evident, yield was not adversely affected.

With an increase in the prevalence of conservational tillage, weed control has become more difficult. As tillage has been reduced, the reliance on herbicides for weed management has increased, presenting a new set of challenges for producers. Weed populations tend to increase in conservation tillage, thus for species like Palmer amaranth, enforcing a zero seed tolerance policy is vital (Price et al, 2011). The importance of controlling late-season weed escapes and seed production is critical in effectively managing the long-term soil seed bank. By controlling seed production, the spread of herbicide resistant Palmer amaranth will decrease, preventing the replenishment of the soil seed bank, ultimately allowing for a decrease in the viable population of this problematic species.

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Part IV.
Conclusions

The overall objective of this research was to determine late-season control options for glyphosate-resistant (GR) Palmer amaranth for corn production systems and to determine weed management programs for the prevention of seed production POST-corn harvest. The first part of this research evaluated control options for GR Palmer amaranth using non-atrazine herbicides for Palmer amaranth >20 cm. The second part of this research evaluated control options for prevention of seed production POST-harvest for mechanically damaged or late- emerging Palmer amaranth. In the first study, weed control was evaluated and measured through visual evaluations and weed counts. This research also evaluated crop response by collecting yield. In the second study, weed control was evaluated through visual evaluations. This study also evaluated crop response by collecting visual injury ratings, fresh weights and yield.

Part II.

Herbicides that were tank-mixed with dicamba plus diflufenzopyr performed better than those treatments applied alone. Overall, there was an increase of 10 to 46% in Palmer amaranth control when these herbicides were tank-mixed with dicamba plus diflufenzopyr. At 28 DAA, GR Palmer amaranth control was <91% with dicamba, but was not increased with the addition of other herbicides. When practicing POST only weed management strategies, application timing is vital for the prevention of yield loss. Corn yield was not adversely affected from the varying of amount of weed control provided from the selected herbicide applications, when applications where made between the V5 and V6 growth stages to GR Palmer amaranth > 20 cm.

Part III.

Paraquat provides excellent initial desiccation of existing vegetation. Regrowth occurred from larger plants. The addition of a residual herbicide may aid in controlling plant regrowth as well as preventing new Palmer amaranth emergence. Many studies have shown that implementing late-season weed management programs has been effective in reducing weed seed rain and seed bank densities. All treatments prevented seed bank replenishment. On average, treatments prevented 1200 viable seed m^2, approximately 12 million seed ha^{-1} from going back into the soil seed bank. From visual and biomass measurements, wheat injury only occurred from the PRE applications in 2012, but wheat yield was not impacted. There was no wheat injury from the POST-harvest herbicides.

Appendices

Appendix A
Tables

Table 1. Herbicides, rates, and manufacturer.

Herbicide Treatment		Rate	Manufacturer
Trade Name	Common Name	g ai ha^{-1}	
Roundup Powermax	glyphosate	1264	Monsanto Co., St. Louis, MO
Liberty 280	glufosinate	660	Bayer CropScience, Research Triangle Park, NC
Halex GT	*S*-metolachlor glyphosate mesotrione	1174 1174 117	Syngenta Crop Protection Inc., Greensboro, NC
Capreno	tembotrione thiencarbzone	76 15	Bayer CropScienes, Research Triangle Park, NC
Callisto	mesotrione	105	Syngenta Crop Protection Inc., Greensboro, NC
Laudis	tembotrione	92	Bayer CropScienes, Research Triangle Park, NC
Realm Q	mesotrione rimsulfuron	88 21	DuPont Crop Protection Co., Wilmington, ME
Status	dicamba diflufenzopyr	247 96	BASF Corporation, Research Triangle Park, NC

Table 2. GR Palmer amaranth control with herbicides applied at V5 to V6.

Herbicide Treatment	Rate	Palmer amaranth control[a] %			
Active ingredient(s)	g ai ha^{-1}	7 DAA	14 DAA	21 DAA	28 DAA
Glyphosate[c]	1264	73 ab[b]	67 de	72cde	69 d
Glufosinate	660	81 a	74 cde	74 cde	70 d
Tembotrione	92	48 cd	52 fg	59 ef	58 e
Mesotrione	105	45 d	44 gh	48 f	51 e
Dicamba[d]	247, 96	82 a	87 abc	90 ab	91 abc
Glyphosate plus dicamba[d]	1264 + 247, 96	83 a	86 abc	90 ab	89 bc
Tembotrione plus dicamba[d]	92 + 247, 96	78 a	83 abc	85 abc	87 c
Mesotrione plus dicamba[d]	105 + 247, 96	79 a	84 abc	85 abc	92 abc
Mesotrione and rimsulfuron	88, 21	35 d	35 h	48 f	51 e
Tembotrione and thiencarbzone	76, 15	46 cd	64 def	67 de	76 d
Mesotrione and rimsulfuron plus dicamba[d]	88, 21 + 247, 96	77 a	77 bcd	80 bcd	87 c
Tembotrione and thiencarbzone plus dicamba[d]	760, 15 + 247, 96	80 a	89 ab	95 a	98 a
S-metolachlor, glyphosate, and mesotrione	1174, 1174, 117	61 bc	63 ef	70 de	72 d
S-metolachlor, glyphosate, and mesotrione plus dicamba[d]	1170, 1170, 120 + 247,96	84 a	91 a	97 a	96 ab
p-values		p>0.0001	p>0.0001	p>0.0001	p>0.0001

[a] Palmer amaranth control was rated at 7, 14, 21 and 28 days after application using a visual scale of 0 to 100 (0= no injury and 100 = plant death).
[b] Means followed by the same letter are not different according to Fisher's Protected LSD at $p \leq 0.05$
[c] Glyphosate is denoted in g ae ha^{-1}
[d] Dicamba treatments contain diflufenzopyr and isoxadifen-methyl

Table 3. GR Palmer amaranth counts and corn yield.

Herbicide Treatment	Rate	Palmer amaranth	Corn
Active ingredient(s)	g ai ha^{-1}	Counts[a]	Yield[b]
		plants 1.0 m^2	kg ha^{-1}
Glyphosate[e]	1264	16 b [c]	10300 a[d]
Glufosinate	660	17 b	10900 a
Mesotrione	105	19 b	10200 a
Tembotrione	92	13 b	9500 ab
Dicamba[f]	247, 96	9 b	10660 a
Glyphosate plus dicamba[f]	1264 + 247, 96	8 b	10300 a
Mesotrione plus dicamba[f]	105 + 247, 96	10 b	9900 ab
Tembotrione plus dicamba[f]	92 + 247, 96	8 b	10470 a
Tembotrione and thiencarbzone	76, 15	10 b	10200 a
Mesotrione and rimsulfuron	88, 21	21 b	10220 a
Mesotrione and rimsulfuron plus dicamba[f]	88, 21 + 247, 96	8 b	9760 a
Tembotrione and thiencarbzone plus dicamba[f]	760, 15 + 247, 96	4 b	9930 a
S-metolachlor, glyphosate, and mesotrione	1174, 1174, 117	13 b	10900 a
S-metolachlor, glyphosate, and mesotrione plus dicamba[f]	1170, 1170, 120 + 247, 96	5 b	10900 a
Non-treated Check		122 a	8500 b
p-values		p>0.0001	NS

[a] Pigweed counts were taken from 0.5m between the treatment portion of each plot
[b]Corn yield collected from the treated portion of each plot (1.5m by 9m)
[c]Means followed by the same letter are not different according to Fisher's Protected LSD at $p \leq 0.05$
[d]Means were not statistically significant using Fisher's Protected LSD at $p \leq 0.05$
[e] Glyphosate is denoted in g ae ha^{-1}
[f] Dicamba treatments contain diflufenzopyr and isoxadifen-methyl

Table 4. Single degree of freedom contrasts comparing the effect of herbicide application of dicamba plus diflufenzopyr on Palmer amaranth control at application timing 7, 14, 21 and 28 DAA, counts, and corn yield

	Palmer amaranth					Corn
	Control				Counts	Yield
	%				plants per m^2	Kg ha^{-1}
Contrast	7 DAA	14 DAA	21 DAA	28 DAA	14 DAA	
With Dicamba	80	84	87	92	6	10233
Without Dicamba	51	55	61	63	15	10206
Pr > F	0.0202	0.0809	0.1258	0.0625	0.9209	0.9892

Table 5. Rainfall in cm per week after application

Weeks after application	Jackson, TN 2013	2014
	centimeters	
0	2.10	1.20
1	2.10	9.00
2	3.70	12.0
3	0.40	0.10
4	1.80	1.50
5	1.20	7.00
6	2.80	1.30
7	9.50	5.80
8	0.70	0.50
9	2.20	0
10	2.00	6.00
11	0.80	0.70
12	0	6.30

Table 6. Herbicides, rates, and manufacturer.

Herbicide		Rate	Manufacturer
trade name	common name	g ha^{-1}	
Gramoxone SL	paraquat	840	Syngenta Crop Protection, Greensboro, NC
Sencor	metribuzin	263	Bayer CropScience, Research Triangle Park, NC
Dual Magnum	*S*-metolachlor	1070	Syngenta Crop Protection, Greensboro, NC
Valor SX	flumioxazin	72	Valent BioSciences Corporation, Walnut Creek, CA
Sharpen	saflufenacil	50	BASF Corporation, Research Triangle Park, NC
Zidua	pyroxasulfone	149	BASF Corporation, Research Triangle Park, NC
Finesse	chlorsulfuron metsulfuron	33 7	DuPont Crop Protection, Wilmington, DE
Axiom	flufenacet methyl metribuzin	228 57	Bayer CropScience, Research Triangle Park, NC
Fierce	pyroxasulfone flumioxazin	70 89	Valent BioSciences Corporation, Walnut Creek, CA
Anthem	pyroxasulfone fluthiacet	128 4	FMC Corporation, Philadelphia, PA

Table 7. GR Palmer amaranth control and seed counts.

Herbicide Treatment	Rate	Palmer amaranth		
		control[a] (%)		seed counts
Active ingredient(s)	g ai ha^{-1}	7 DAA	14 DAA	per m^2
Paraquat	840	98 a[b]	91 b	0 b
Paraquat plus metribuzin	840, 263	99 a	97 a	0 b
Paraquat plus s-metolachlor	840, 1070	98 a	97 a	0 b
Paraquat plus metribuzin followed by chlorsulfuron, metsulfuron	840, 263 fb 33, 7	98 a	98 a	0 b
Paraquat plus s-metolachlor followed by pyroxasulfone	840, 1070 fb 149	98 a	95 ab	0 b
Paraquat plus s-metolachlor followed by flufenacet, metribuzin	840, 1070 fb 228, 57	99 a	95 ab	0 b
Paraquat plus flumioxazin	840, 72	98 a	98 a	0 b
Paraquat plus saflufenacil	840, 50	99 a	99 a	0 b
Paraquat plus pyroxasulfone	840, 149	98 a	98 a	0 b
Paraquat plus flumioxazin and pyroxasulfone	840, 70, 89	99 a	99 a	0 b
Paraquat plus pyroxasulfone and fluthiacet	840, 128, 4	99 a	99 a	0 b
Non-treated Check		0 b	0 c	1200 a
p-values		$p<0.0001$	$p<0.0001$	$p<0.0001$

[a] Palmer amaranth control at 7 and 14 days after application based on a visual scale of 0 (no control) to 100 (complete control)

[b] Means followed by the same letter are not different according

Table 8. Wheat response, wheat biomass, and wheat yield.

Herbicide Treatment	Rate	Wheat					
		2012 Only				2012 and 2013	
		Injury[a]		Biomass[c]	Yield[d]	Biomass[c]	Yield[d]
Active ingredient(s)	g ai ha^{-1}	12 DAP	25 DAP	g 1.0 m^2	kg ha^{-1}	g 1.0 m^2	kg ha^{-1}
Paraquat	840			570 ab[e]	3770 ab[ef]	420 a[ef]	4830 b[ef]
Paraquat plus metribuzin	840, 263			450 abcd	3820 ab	400 a	5250 ab
Paraquat plus s-metolachlor	840, 1070			500 abc	4210 a	420 a	5250 ab
Paraquat plus metribuzin fb chlorsulfuron, metsulfuron[b]	840, 263, 33, 7	5 b[e]	1 b[e]	240 e	3600 b	300 a	4950 ab
Paraquat plus s-metolachlor fb pyroxasulfone[d]	840, 1070 149	10 a	4 a	280 de	3730 ab	330 a	5210 ab
Paraquat plus s-metolachlor fb flufenacet-methly, metribuzin[d]	840, 1070 228, 57	5 b	3 a	350 cde	3890 ab	380 a	5240 ab
Paraquat plus flumioxazin	840, 72			390 bcd	3560 b	360 a	5220 ab
Paraquat plus saflufenacil	840, 50			630 a	3840 ab	470 a	5050 ab
Paraquat plus pyroxasulfone	840, 149			530 abc	3430 b	410 a	4870 ab
Paraquat plus flumioxazin and pyroxasulfone[g]	840, 70, 89					360 a	4910 ab
Paraquat plus pyroxasulfone and fluthiacet[g]	840, 128, 4					580 a	5570 a
Non-treated Check				570 ab	3670 b	420 a	5230 ab
p-values				p=0.0042	p=0.2579	p=0.1030	p=0.119

[a] Wheat injury was evaluated using a scale of 0 to 100 (0= no injury and 100= plant death)at 12 and 25 DAP.
[b] Herbicide treatments that had a follow up application of a PRE at planting
[c] Wheat biomass collected and weighted in grams m^2 in each plot.
[d] Wheat yield collected from 1.5m by 9 m of treated area..
[e] Means followed by the same letter are not different according to Fisher's Protected LSD at $p \leq 0.05$
[f] Means were not statistically significant using Fisher's Protected LSD at $p \leq 0.05$
[g]pyroxasulfone premixes were only studied in 2013

Table 9. Rainfall in cm per week after application

Weeks after Application	Jackson, TN 2012	Jackson, TN 2013	Knoxville, TN 2013
	centimeters		
0	7.4	0.20	0.50
1	0	6.25	0
2	0	0.20	0
3	12.30	3.90	0
4	2.70	1.20	0
5	0.20	0.25	0.20
6	5.00	4.50	0.05
7	3.20	0.50	0.45
8	4.40		
9	0.90		
10	0		

Vita

Whitney Desiree Crow was born on June 23, 1991 in Decatur, AL. She is the daughter of Randall and Anne Crow of Atoka, TN and the eldest of their five children. She graduated from Brighton High School in May of 2009, and then she attended the University of Tennessee at Martin. In May of 2013, she received her Bachelor of Science in Agriculture with a concentration in Crop and Soil Management. After graduation, she accepted a position at the University of Tennessee as a Graduate Research Assistant in the Plant Sciences Department with Dr. Larry Steckel, UT Extension Weed Specialist. She achieved her Master of Science degree in Plant Sciences with a concentration in weed science in December of 2014. Upon graduation, Whitney will continue her education by pursuing a Doctorate of Philosophy. in entomology at Mississippi State University.