ABSTRACT


Palmer amaranth has been one of the most troublesome weeds to manage in cotton and sweetpotato production over the past decade. Furthermore, the evolution of herbicide-resistant weeds has changed weed management programs in numerous cropping systems throughout the southeastern U.S. Management strategies that include diversification of herbicide modes of action and use of non-herbicidal tactics such as deep tillage and rogueing of fields to remove escaped weeds have been required to control GR Palmer amaranth in many production systems. Two research projects were conducted to evaluate alternative control strategies in managing Palmer amaranth. In one experiment, research was conducted in two separate fields from 2011-2014 to determine weed population dynamics and frequency of GR Palmer amaranth with herbicide programs consisting of glyphosate, dicamba, and residual herbicides in dicamba-tolerant cotton. Seven treatments were imposed in this experiment including continuous glyphosate postemergence (POST) and continuous glyphosate plus dicamba POST both with and without preemergence (PRE) herbicides, annual rotations of these treatments, and a final treatment of glyphosate plus dicamba plus acetochlor POST. Ten soil cores were collected at random in each plot after planting and prior to any herbicide application and were used to determine Palmer amaranth density and frequency of glyphosate resistance. Density of Palmer amaranth in the field was determined in August of each year after all herbicides were applied. The highest population of Palmer amaranth was noted when glyphosate was the only POST herbicide throughout the experiment. By the end of the study, diuron plus pendimethalin PRE in a program with only
glyphosate POST were no more effective than glyphosate alone. The lowest population of Palmer amaranth was observed when glyphosate plus dicamba were applied regardless of PRE herbicides. Soil core populations of Palmer amaranth from alternating treatments were intermediate of those continuous programs. Although frequency of glyphosate resistance was lower during the first two years when dicamba was included, by the final two years of the experiment frequency of glyphosate resistance was similar regardless of PRE or POST herbicide treatment. Movement of GR pollen from glyphosate-only treatments most likely contributed to glyphosate resistance across all treatments by the end of the experiment. These data suggest that GR Palmer amaranth can be controlled by dicamba and that dicamba is an effective alternative to glyphosate in fields where GR Palmer amaranth is present.

In the second experiment, research was conducted from 2012-2014 to determine the influence of a single deep tillage operation and hand removal of Palmer amaranth prior to seed production on Palmer amaranth populations and economic returns in cotton and sweetpotato over 3 years. Treatments consisted of moldboard plowing in fall and a no-moldboard plowing control with and without hand removal of Palmer amaranth prior to seed production. In cotton, diuron PRE and glufosinate POST herbicide program was used over the entire test area. Moldboard plowing and hand removal reduced weed populations in subsequent years in some but not all instances. Differences in weed populations with deep tillage or hand removal did not always translate into differences in yield and economic returns. In one of two fields with cotton, cumulative economic return was higher following a single moldboard plowing operation compared with no moldboard plowing regardless of hand removal treatment. In contrast, cumulative economic return was higher following hand removal of Palmer amaranth only when moldboard plowing.
In sweetpotato, weed management programs included pre-transplant herbicide flumioxazin followed by S-metolachlor PRE and bi-weekly inter-row cultivation. Moldboard plowing reduced Palmer amaranth density in subsequent years and increased yield in one of two years. Hand removal reduced weed populations in one of two years but had no effect on yield. Economic return was not affected by moldboard plowing or hand removal of Palmer amaranth in sweetpotato.
Long-Term Management of Palmer Amaranth with Herbicides and Cultural Practices

by
Matthew Darwin Inman

A thesis submitted to the Graduate Faculty of
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DEDICATION

This thesis is dedicated to my loving wife Ashley M. Inman. I would not be where I am without her continuous love, patience, and support.
BIOGRAPHY

Matthew Darwin Inman was born on October 8, 1984 in Winston-Salem, NC. He was raised in East Bend, NC and graduated from Forbush High School in 2002. In 2004, Matthew graduated with an Associate in Applied Science Degree in Horticulture from Haywood Community College in Clyde, NC. From 2006 to 2010, Matthew served active duty in the United States Marine Corps. In the fall of 2010, Matthew started his Bachelor’s Degree in Agronomy at North Carolina State University and completing this degree in the spring of 2013. In the summer of 2013, he was admitted into the graduate school of North Carolina State University where he began to pursue a Master’s of Science degree in Crop Science under the direction of Drs. David Jordan and Katie Jennings. Upon completion, Matthew plans to pursue a PhD.
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CHAPTER ONE

Long-Term Management of Palmer Amaranth in Dicamba-Tolerant Cotton

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ABSTRACT

Evolution of herbicide-resistant weeds has significantly changed weed management programs in cotton over the past decade. Glyphosate-resistant (GR) Palmer amaranth has become the most troublesome and economically damaging weed in cotton throughout southern United States. Management strategies that include diversification of herbicide modes of action and use of non-herbicidal tactics have been required to control GR Palmer amaranth. Research was conducted in two separate fields from 2011 to 2014 to determine weed population dynamics and frequency of GR Palmer amaranth with herbicide programs consisting of glyphosate, dicamba, and residual herbicides in dicamba-tolerant cotton. The following five treatments were maintained in the same plots over the duration of the experiment: three sequential POST applications of glyphosate with or without pendimethalin plus diuron PRE; three sequential POST applications of glyphosate plus dicamba with and without the PRE herbicides; and a POST application of glyphosate plus dicamba plus acetochlor followed by a another POST application of glyphosate plus dicamba without PRE herbicides. Additional treatments included alternating years with three sequential POST applications of glyphosate only and glyphosate plus dicamba POST with and without PRE herbicides. During May of each year and January of 2015, ten soil cores were collected and used to determine Palmer amaranth density and changes in frequency of glyphosate resistance over time. Density of Palmer amaranth in the field was determined in August of each year after all herbicides were applied. The greatest population of Palmer amaranth was noted when glyphosate was the only POST herbicide throughout the experiment. Although
diuron plus pendimethalin PRE in a program with only glyphosate POST improved control
during the first 2 yr, these herbicides were ineffective by the final 2 yr based on weed counts
from soil cores. The lowest population of Palmer amaranth was observed when glyphosate
plus dicamba were applied regardless of PRE herbicides or inclusion of acetochlor POST.
When POST applications of glyphosate alone or glyphosate plus dicamba were alternated
during years, Palmer amaranth populations from soil cores collected in January 2015 were
intermediate between glyphosate only and glyphosate plus dicamba POST treatments applied
each year. Frequency of GR Palmer amaranth was 8% or less when the experiment was
initiated. Although frequency of GR Palmer amaranth varied by herbicide program during
2012, frequency of glyphosate resistance was similar among all herbicide programs by 2013
and 2014. Similar frequency of GR Palmer amaranth across all treatments at the end of the
experiment most likely resulted from the pollen movement from Palmer amaranth treated
with glyphosate only to any surviving female plants regardless of PRE or POST treatment.
These data suggest that GR Palmer amaranth can be controlled by dicamba and that dicamba
is an effective alternative MOA to glyphosate in fields where GR Palmer amaranth is present.

**NOMENCLATURE:** acetochlor; dicamba; glyphosate; Palmer amaranth, *Amaranthus*

*palmeri* S. Watts; cotton, *Gossypium hirsutum* L.

**KEYWORDS:** Herbicide-resistant weeds, herbicide resistance management, soil seedbank.
INTRODUCTION

Since 2005, GR Palmer amaranth has been one of the most common and troublesome weeds in agronomic crops throughout the southern United States (Culpepper et al. 2006; Culpepper et al. 2008; Webster 2005; Webster 2013). It has also become one of the most economically damaging glyphosate-resistant weed species in the United States (Beckie 2011). A native of arid environments, Palmer amaranth is a dioecious, C4 plant characterized by high rates of photosynthesis ($81 \mu\text{mol m}^{-2} \text{s}^{-1}$ at 42°C) (Ehleringer 1983; Ward et al. 2013). Male Palmer amaranth plants can pollinate a female plant up to 300 m away (Sosnoskie et al. 2012). Palmer amaranth plants have been documented to produce over 500,000 seed, and anecdotal evidence suggests production in excess of 1 million seeds per plant may occur (Culpepper et al. 2010; Keeley et al. 1987). Because of Palmer amaranth’s ability to compete for resources, yield reductions associated with varying weed densities have been well documented, especially in cotton (MacRae et al. 2013; Morgan et al. 2001; Rowland et al. 1999). For example, Morgan et al. (2001) reported that 10 Palmer amaranth plants per 9.1 m of row reduced cotton biomass approximately 50% and reduced lint yield 57%. In addition to interfering with growth and yield, Palmer amaranth adversely affects harvest efficiency (Smith et al. 2000).

Glyphosate resistance in Palmer amaranth was first confirmed in 2005 in Georgia and was subsequently confirmed in Arkansas, North Carolina, South Carolina, Tennessee, and many other states in the southern United States (Culpepper et al. 2008; Culpepper et al. 2006; Norsworthy et al. 2008; Steckel et al. 2008; York et al. 2007). Prior to glyphosate resistance,
Palmer amaranth was controlled effectively by glyphosate in GR cotton (Culpepper and York 1998). Fewer herbicide applications were needed in a GR cotton production system and less total herbicide input was required to produce yields and economic returns similar to more intensive programs available prior to GR cotton introduction (Culpepper and York 1998). Weed management programs offered in GR cotton often increased flexibility in future crop rotations compared to herbicides often used prior to GR cotton (Bradley et al. 2001; Fisher et al. 2007; York 1993). Along with glyphosate resistance, acetolactate synthase (ALS)-resistant Palmer amaranth has been confirmed in North Carolina and is now prevalent throughout the mid-west and southern United States, with several states documenting multiple resistance to both herbicide modes of action (MOA) (Heap 2015; Poirier et al. 2014). Resistance to these widely available and frequently used herbicide MOA further reduces growers’ flexibility in rotating herbicide MOA and limits available options to control Palmer amaranth. Management programs that decrease the number of applications of these products are needed to ensure longevity of currently used herbicides.

Since GR cotton became commercially available, the exclusive use of a single herbicide MOA has had a major impact in the evolution of GR Palmer amaranth when more herbicide intensive weed management options were not implemented (Norsworthy et al. 2012). Continuous use of glyphosate can select for resistant biotypes in as few as 4 yr (Culpepper et al. 2006; Legleiter and Bradley 2008; Norsworthy et al. 2012). Significant levels of resistance evolved with as few as five applications of ALS-inhibiting herbicides in some weed populations (Beckie 2006; Norsworthy et al. 2012). Repeated use of the same
MOA and subsequent increases in selection pressure is the single greatest risk component in the evolution of herbicide resistance (Beckie 2006; Powles et al. 1997). Rotating herbicide MOA reduces selection pressure on resistant biotypes by decreasing the frequency of applications of the same MOA (Beckie 2011; Norsworthy et al. 2012).

Rotating herbicide-resistant (HR) varieties to non-HR varieties as well as crop rotation irrespective of HR trait are recommended to help manage HR weed shifts (Culpepper 2006). Availability of herbicides and often management tactics can impact weed population dynamics in subsequent years (Beckie 2011). For example, peanut (Arachis hypogaea L.), sweetpotato [Ipomoea batatas (L.) Lam.], and tobacco (Nicotiana tabacum L.) are often grown in rotation with cotton (Meyers et al. 2010; Fisher et al. 2007). Availability of new technology such as HR traits can be limited during the first few years of introduction and require growers to implement programs that may not be as efficient in weed control. Modeling studies have demonstrated that rotating HR cultivars to non-HR cultivars can delay the evolution of herbicide resistance depending on herbicides used in alternating crops (Neve et al. 2011). Kruger et al. (2009) suggested that rotating to a non-GR crop and subsequent use of non-glyphosate herbicides can be beneficial in controlling summer annual and perennial weeds.

Best management practices have shifted, and the focus is to preserve efficacy of herbicides by decreasing selection pressure on herbicides currently used in cotton and other crops. Diversifying effective herbicide programs can prolong the sustainability of weed management (Norsworthy et al. 2012). Transgenic cotton cultivars resistant to dicamba
(event MON88701) are now commercially available in the United States. (USDA-APHIS 2015). This technology was developed through insertion of the dicamba monoxygenase gene from *Stenotrophomonas maltophilia* resulting in demethylation of dicamba to a non-phytotoxic metabolite (Behrens et al. 2007). Dicamba is an auxin-mimicking herbicide that controls GR Palmer amaranth and other broadleaf weeds alone or in combination with glyphosate or glufosinate (Cahoon et al. 2015; Green and Owen 2010; Merchant et al. 2013; Samples et al. 2013; Sanders and Marshall 2014; York et al. 2012). Research (Cahoon et al. 2015; Sanders and Marshall 2014; York et al. 2012) suggests that dicamba is most effective in a program with other herbicides. Application of dicamba provides an alternate herbicide MOA in weed management programs and can further delay selection for resistance to widely used herbicides in cotton such as glufosinate and protoporphyrinogen-oxidase (PPO) inhibiting herbicides (York et al. 2012).

A major challenge in managing weeds is minimizing the return of weed seed to the soil seed bank (Swanton and Booth 2004). Menges (1987) reported that maintaining fields weed-free for 6 yr reduced the soil seedbank of Palmer amaranth by 98%; however 18 million seed ha$^{-1}$ remained in the soil. Palmer amaranth seed viability is decreased when buried below the depth of optimal germination for at least 36 mo (Sosnoskie et al. 2013). Most experiments comparing herbicide programs are completed during a single season without evaluation of treatment effects on the soil seedbank. Determining the effect of long-term management of GR Palmer amaranth with dicamba would be of value in determining utility of this herbicide in a comprehensive weed management program. Eliminating yearly
contributions of weed seed to the soil seed bank would be effective; however, effectiveness is limited with a single-year management approach (Coble and Mortensen 1992; Cousens 1987; Norsworthy et al. 2012). The objective of this research was to compare Palmer amaranth population dynamics and frequency of glyphosate resistance over 4 yr with herbicide programs that included glyphosate, dicamba, and residual herbicides.

MATERIALS AND METHODS

The experiment was established in two fields approximately 340 m apart, separated by planting date, during 2011 in North Carolina at the Upper Coastal Plain Research Station located near Rocky Mount (35.893N, -77.681W). Soil was a Aycock very fine sandy loam (fine-silty, siliceous, subactive, thermic Typic Paleudults) with 0.5% humic matter and Norfolk loamy sand (fine-loamy, kaolinitic, thermic Typic Kandiudults) with 0.5% humic matter in field 1 and an Aycock very fine sandy loam (fine-silty, siliceous, subactive, thermic Typic Paleudults) with 0.5% humic matter in field 2. Plot size was six rows (91-cm spacing) by 15 m in field 1 and eight rows by 11 m in field 2. Alleys between plots were 2.4 m. Plot size varied because of field size and isolation requirements for compliance with USDA-APHIS regulations. Both fields were naturally infested with Palmer amaranth with a mixture of glyphosate-susceptible (GS) and ALS-susceptible Palmer amaranth and GR and ALS-resistant Palmer amaranth. Cotton (BollGard II® Xtend Flex™) resistant to dicamba, glufosinate, glyphosate, and lepidopteran insects (events MON88701 x MON88913 x MON15985) (ISAAA 2015) was planted in conventionally tilled, raised beds at a seeding
rate designed to provide a final in-row population of 17 plants per m of row. Cotton was planted 24-25 May, 16-17 May, 22-23 May, and 8-9 May in 2011, 2012, 2013, and 2014, respectively, at a depth of 2 cm. Fields were irrigated periodically to maintain cotton growth using overhead sprinkler irrigation.

Seven herbicide treatments were compared in the experiment and were applied at the manufacturer’s suggested use rate (Tables 1 and 2). Preemergence herbicides were applied immediately after planting with POST herbicides applied 2 (POST-1), 4 (POST-2), and 6 (POST-3) wk after planting (WAP). Five of the treatments were maintained in the same plots for the duration of the experiment (2011 to 2014). These treatments included diuron plus pendimethalin PRE or no PRE herbicides followed by three POST applications of glyphosate or three POST applications of glyphosate plus dicamba and glyphosate plus dicamba plus acetochlor applied POST-1 followed by glyphosate plus dicamba applied POST-2 and POST-3. Two additional herbicide programs included alternating years between glyphosate plus dicamba and glyphosate only at all three POST timings with or without diuron plus pendimethalin PRE in all 4 yr. Herbicides were applied using a CO2-pressurized backpack sprayer equipped with flat-fan nozzles (AIXR 11002 TeeJet® Air Induction XR flat-spray nozzles, TeeJet Technologies, Wheaton, IL) calibrated to deliver 140L ha⁻¹ at 152 kPa.

In May of each year and in January 2015, weed diversity and density were determined by collecting 10 soil cores (10.2 cm by 7.6 cm) for a total volume of 4,630 ml from each plot immediately after planting and prior to application of PRE herbicides. Soil was transported to a greenhouse in plastic bags and placed in flats to a depth of 4 cm with a
total surface area of 1,550 cm$^2$. Greenhouse was climate controlled for favorable conditions conducive for optimum weed seed germination (33 to 40 C at 80 to 90% relative humidity). Soil was irrigated with overhead sprinklers to promote germination of seed and adequate growth of seedlings. Approximately 3 wk after establishment, seedling diversity and density were recorded. Plants were then treated with glyphosate at 946 g ha$^{-1}$ (Roundup WeatherMAX, Monsanto Co. St Louis, MO) to determine the frequency of GR Palmer amaranth, the predominant weed in the study. Under greenhouse conditions, 280 g ha$^{-1}$ reflects a rate of glyphosate that would provide a lethal dose to GS Palmer amaranth biotypes (Chandi et al. 2013; Poirier 2014; Whitaker 2009). Two wk after herbicide application, frequency of GR Palmer amaranth was determined by calculating the percentage of plants surviving glyphosate relative to the number of plants present when glyphosate was applied. In the field, density of Palmer amaranth was determined in late August of each year from the center two rows (plots with six rows) or the center four rows (plots with eight rows). The exception was plots receiving glyphosate only applied POST, regardless of PRE herbicide, where three sections of 1 m$^2$ each were counted in each plot. Density of Palmer amaranth in the field was converted to plants ha$^{-1}$.

Cotton yield was not determined in these experiments because of concern over movement of plant material and weed seed from plot to plot. Palmer amaranth seeds were allowed to mature prior to disk ing fields twice in late September at a slow speed to minimize soil and seed movement from plot to plot. Prior to planting each spring, fields received two
passes parallel to rows with a disc-harrow and a field cultivator followed by in-row subsoiling and bedding.

The experimental design was a randomized complete block and treatments were replicated four times in both fields. Data for Palmer amaranth density from soil cores and density in the field during late August were converted to the common log prior to being subjected to ANOVA (PROC GLM SAS version 9.3; SAS Institute Inc., Cary, NC). Three analyses were performed on the data. In one analysis, data for Palmer amaranth density and frequency of resistance associated with glyphosate or glyphosate plus dicamba with or without PRE herbicides were subjected to ANOVA to determine if these treatments were influenced by interactions with fields. Data for these treatments were also subjected to regression procedures using the PROC REG (SAS Version 9.3; SAS Institute Inc., Cary, NC) procedure of SAS testing for linear, quadratic, and cubic functions for common log of Palmer amaranth density versus months after experiment initiation and frequency of glyphosate resistance as well as standard errors of each data point. In a final analysis, data from soil cores collected in January 2015 for Palmer amaranth density and soil cores collected in 2014 for frequency of resistance from all seven herbicide treatments were subjected to ANOVA. Means for all treatments from soil cores collected in January 2015 were separated using Fisher’s Protected LSD at $p \leq 0.05$. 
RESULTS AND DISCUSSION

**Palmer amaranth population.** The interaction of field by treatment for Palmer amaranth density from soil cores or field observations in August was not significant for treatments including no PRE or diuron plus pendimethalin PRE followed by glyphosate or glyphosate plus dicamba except for 2011 in the field (Table 3). Therefore, data were pooled over both fields for regression analyses.

No difference in Palmer amaranth density was noted among treatments during 2011 at the inception of the experiment (Figure 1). These data suggest that distribution of Palmer amaranth was uniform within and across both fields. In 2012, after 1 yr of herbicide programs in place, the glyphosate-only treatments resulted in an increase of Palmer amaranth density from 25 to 37 plants and 25 to 69 plants when following PRE herbicides or in absence of PRE herbicides, respectively. PRE herbicides applied resulted in fewer weeds 12 and 24 mo after the experiment was initiated when glyphosate was the only herbicide applied post compared with the no-PRE treatment. However, by 36 and 44 mo after experiment initiation, Palmer amaranth density was similar when glyphosate was the only herbicide applied irrespective of PRE treatments. After 4 yr of glyphosate as the only herbicide, Palmer amaranth density increased approximately nine-fold compared to Palmer amaranth density at the beginning of the experiment. Whitaker et al. (2011) reported that residual herbicides at planting improve weed control and contribute to delaying development of herbicide resistance in experiments conducted during a single year. Our results indicate that over an extended period of time, residual herbicides most likely are ineffective in preventing a rapid
increase in GR Palmer amaranth populations when POST herbicides effective against GR Palmer amaranth are not included in the system. In contrast, Palmer amaranth density did not increase over the duration of the experiment from 2011 levels when glyphosate plus dicamba was applied over the experiment regardless of PRE herbicide treatment.

By the end of the experiment, alternating between years with glyphosate plus dicamba and glyphosate only resulted in Palmer amaranth densities intermediate between glyphosate-only POST and glyphosate plus dicamba (Table 4). The reduction of Palmer amaranth control in subsequent years following programs including dicamba can be attributed to the glyphosate-only program replenishing the soil seedbank. This provides further evidence of how quickly weed species can be restored when ineffective weed management strategies are implemented (Burnside et al. 1986).

In most instances, Palmer amaranth density observed in the field at the end of each year reflected results noted from evaluation of soil cores (Figures 1 and 2). However, in the field, PRE herbicides were beneficial in controlling Palmer amaranth and reducing populations each year throughout the duration of the experiment compared with glyphosate only (Figure 2). Applying only glyphosate resulted in a Palmer amaranth density of approximately 2.5 million plants ha\(^{-1}\). Including PRE herbicides in the program with glyphosate only POST resulted in lower Palmer amaranth densities after 4 yr, with approximately 500,000 Palmer amaranth plants ha\(^{-1}\) present. No difference in Palmer amaranth density was noted for herbicide programs that included glyphosate plus dicamba irrespective of PRE herbicides. Results over the course of the experiment with glyphosate
only as the POST treatment were expected. The reduction in contribution to the soil seedbank when the combination of glyphosate plus dicamba was applied also was expected because dicamba controls GR Palmer amaranth (Cahoon et al. 2015; Merchant et al. 2013; Samples et al. 2013; Sanders and Marshall 2014; York et al. 2012; York et al. 2015).

**Frequency of resistance.** Frequency of GR Palmer amaranth ranged from 1 to 8% when the experiment was initiated (Figure 3). After all years of herbicides, frequency of GR Palmer amaranth increased when glyphosate was the only herbicide applied. When PRE herbicides were included with glyphosate only, frequency of GR Palmer amaranth was lower than glyphosate only without PRE herbicides but still exceeded frequency resulting from treatments including glyphosate plus dicamba. However, by 36 mo after experiment initiation, the frequency of GR Palmer amaranth was similar for all treatments (Figure 3). Results from 2011 and 2012 were expected because glyphosate plus dicamba controlled the majority of Palmer amaranth and this resulted in lower contribution of GR seed to the soil seedbank. Similarly, PRE herbicides in the glyphosate only program resulted in a lower frequency of GR Palmer amaranth. However, the increase in GR frequency for all treatments and similarity of GR frequency for all treatments by 36 mo most likely resulted from contributions of GR pollen from the adjacent plots to escaped female plants even when dicamba was included. Sosnoskie et al. (2012) reported that GR Palmer amaranth pollen disperses up to 300 m under normal field conditions. Although not documented, it is suspected that pollen from surrounding fields may have affected frequency. Glyphosate was not applied to these crops and pollen from both GR and GS Palmer amaranth most likely
moved to plants in our experiment and may have increased the frequency of GS Palmer amaranth progeny.

CONCLUSIONS

Results from this experiment are consistent with other research (Culpepper et al. 2006) demonstrating the rapid increase in Palmer amaranth density and frequency of GR Palmer amaranth when glyphosate is the only POST herbicide included. While the PRE herbicides diuron and pendimethalin decreased the rate of increase of Palmer amaranth density and frequency of GR Palmer amaranth, over the length of the experiment these herbicides proved ineffective. Although the initial population density of GR Palmer amaranth was relatively low at the beginning of the experiment, dicamba included with glyphosate further decreased the density of Palmer amaranth. Glyphosate plus dicamba applied in alternating years resulted in lower densities of Palmer amaranth by the end of the experiment compared with treatments including glyphosate only, but this program was less effective than programs including glyphosate plus dicamba during each year. Akers et al. (2014) reported results from an experiment similar to ours but in continuous dicamba-tolerant soybean [Glycine max (L.) Merr.] with GR tall waterhemp [Amaranthus tuberculatus (Moq.) Sauer] and GR giant ragweed (Ambrosia trifida L.) as the dominant weed species. Similar to our results, they reported that glyphosate alone resulted in substantial increases in these GR weeds and that glyphosate plus dicamba controlled these weeds throughout the study irrespective of PRE treatment. However, in contrast to our results, weed populations over the
length of the study remained at the same level when PRE herbicides and glyphosate only were applied. Cotton is often considered more vulnerable to weed interference than soybean and often requires more intensive herbicide programs with more applications than soybean (Culpepper and York 1998).

While results from this experiment indicate dicamba can be an effective management tool in fields where GS and GR Palmer amaranth are present, comprehensive management programs including effective PRE herbicides and rotation of herbicide MOA will be needed to maintain viability of dicamba in cotton production systems (Norsworthy et al. 2012). Use of dicamba in dicamba-tolerant cotton will positively impact resistance management relative to preserving effectiveness of glufosinate and PPO-inhibiting herbicides in sensitive plants (Cahoon et al. 2014; Edmisten et al. 2015; Jalaludin et al. 2014).
ACKNOWLEDGEMENTS

This research was funded by Monsanto. Appreciation is expressed to staff at the Upper Coastal Plains Research Station and C. Cahoon, A. Poirier, and S. Wells for technical assistance.
LITERATURE CITED


Pp 80-130


<table>
<thead>
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<th>Trade name</th>
<th>Formulation concentration</th>
<th>Application rate</th>
<th>Manufacturer</th>
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<td>acetoxychlor</td>
<td>Warrant®</td>
<td>359 g ai L⁻¹</td>
<td>1260 g ai h⁻¹</td>
<td>Monsanto Co.</td>
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<td>clethodim</td>
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<td>Valent</td>
</tr>
<tr>
<td>dicamba diglycolamine salt</td>
<td>Clarity®</td>
<td>480 g ae L⁻¹</td>
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<td>diuron</td>
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<td>840 g ai h⁻¹</td>
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<td>glyphosate potassium salt</td>
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<td>71 g ai ha⁻¹</td>
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<td>trifloxysulfuron</td>
<td>Envoke®</td>
<td>750 g ai L⁻¹</td>
<td>8 g ai ha⁻¹</td>
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Table 2. PRE and POST herbicide treatments and application years.

<table>
<thead>
<tr>
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<th>POST-2</th>
<th>POST-3</th>
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<td>glyphosate</td>
<td>glyphosate</td>
<td>glyphosate</td>
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</tr>
<tr>
<td>None</td>
<td>glyphosate plus dicamba</td>
<td>glyphosate plus dicamba</td>
<td>glyphosate plus dicamba</td>
<td>2011-2014</td>
</tr>
<tr>
<td>Pendimethalin plus diuron</td>
<td>glyphosate</td>
<td>glyphosate</td>
<td>glyphosate</td>
<td>2011-2014</td>
</tr>
<tr>
<td>Pendimethalin plus diuron</td>
<td>glyphosate plus dicamba</td>
<td>glyphosate plus dicamba</td>
<td>glyphosate plus dicamba</td>
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</tr>
<tr>
<td>None</td>
<td>glyphosate plus dicamba plus acetochlor</td>
<td>glyphosate plus dicamba</td>
<td>glyphosate plus dicamba</td>
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</tr>
<tr>
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<td>glyphosate</td>
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<td>2011 and 2013</td>
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<td>glyphosate plus dicamba</td>
<td>2012 and 2014</td>
</tr>
<tr>
<td>Pendimethalin plus diuron</td>
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<td>glyphosate</td>
<td>glyphosate</td>
<td>2011 and 2013</td>
</tr>
<tr>
<td></td>
<td>glyphosate plus dicamba</td>
<td>glyphosate plus dicamba</td>
<td>glyphosate plus dicamba</td>
<td>2012 and 2014</td>
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Table 3. Probability values for herbicide treatments containing PRE or no PRE followed by glyphosate or glyphosate plus dicamba for soil cores and field counts.*

<table>
<thead>
<tr>
<th>Source of variation</th>
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<td>Field</td>
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<td>0.5263</td>
<td>0.8157</td>
<td>0.5021</td>
<td>0.0419</td>
<td>0.0172</td>
<td>0.2369</td>
<td>0.1456</td>
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<tr>
<td>Herbicide</td>
<td>0.0835</td>
<td>&lt;.0001</td>
<td>&lt;.0001</td>
<td>&lt;.0001</td>
<td>&lt;.0001</td>
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<td>&lt;.0001</td>
<td>&lt;.0001</td>
<td>&lt;.0001</td>
<td></td>
</tr>
<tr>
<td>Field*Herbicide</td>
<td>0.3058</td>
<td>0.3300</td>
<td>0.6201</td>
<td>0.3711</td>
<td>0.2668</td>
<td>0.0002</td>
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<td>0.0558</td>
<td>0.9881</td>
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<tr>
<td>Coefficient of variation (%)</td>
<td>20.6</td>
<td>22.1</td>
<td>26.2</td>
<td>27.2</td>
<td>34.3</td>
<td>19.5</td>
<td>24.9</td>
<td>16.5</td>
<td>27.9</td>
<td></td>
</tr>
</tbody>
</table>

*Significance at p < 0.05 for means within a treatment factor.
<table>
<thead>
<tr>
<th>Herbicide Treatments</th>
<th>Years</th>
<th>Palmer amaranth density No. 10 cores⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRE</td>
<td>POST</td>
<td></td>
</tr>
<tr>
<td>None</td>
<td>glyphosate</td>
<td>2011-2014</td>
</tr>
<tr>
<td>None</td>
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<td>2011-2014</td>
</tr>
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</tr>
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<td>Pendimethalin plus diuron</td>
<td>glyphosate plus dicamba</td>
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</tr>
<tr>
<td>None</td>
<td>glyphosate plus acetochlor fb glyphosate plus dicamba</td>
<td>2011-2014</td>
</tr>
<tr>
<td>None</td>
<td>glyphosate plus dicamba</td>
<td>2011 and 2013</td>
</tr>
<tr>
<td>Pendimethalin plus diuron</td>
<td>glyphosate plus dicamba</td>
<td>2011 and 2013</td>
</tr>
</tbody>
</table>

aMeans followed by the same letter are not significantly different according to Fisher’s Protected LSD test at p ≤ 0.05. Data are pooled over fields. Data for actual density of Palmer amaranth are presented with mean separation based on transformed data.

bGlyphosate resistance determined as percentage of Palmer amaranth surviving glyphosate at 946 g ha⁻¹.
Figure 1. Density of Palmer amaranth from soil cores collected over 44 months after experiment initiation. Regression expressions: glyphosate, $y=1.3+0.08x-0.003x^2+0.00005x^3$; $p=0.039$; $r^2 =0.55$; glyphosate plus dicamba, $y=22.8-0.43x$; $p=0.03$; $r^2 =0.35$; diuron plus pendimethalin fb glyphosate, $y=1.27+0.018x$; $p=0.0011$; $r^2 =0.25$; diuron plus pendimethalin fb glyphosate plus dicamba, $y=1.05-0.05x+0.005x^2-0.000075x^3$; $p=0.004$; $r^2 =0.40$. 

![Graph showing density of Palmer amaranth over time with regression lines for each treatment.](image-url)
Figure 2. Palmer amaranth density in the field during August of each year. Regression expressions: glyphosate, \( y = 9.93 + 0.14x; p < 0.0001; r^2 = 0.81 \); glyphosate plus dicamba, \( y = 4.4 - 0.05x; p = 0.04; r^2 = 0.13 \); diuron plus pendimethalin fb glyphosate, \( y = 8.1 + 0.093x; p = 0.009; r^2 = 0.21 \); diuron plus pendimethalin fb glyphosate plus dicamba, \( y = 4.29 - 0.037x; p = 0.135; r^2 = 0.07 \).
Figure 3. Frequency of glyphosate resistance in greenhouse Palmer amaranth populations based on actual counts. Regression expressions: glyphosate, $y=9.41+1.91x; p<0.0001; r^2=0.67$; glyphosate plus dicamba, $y=5.92-1.99x+0.106x^2; p=0.0003; r^2=0.68$; diuron plus pendimethalin fb glyphosate, $y=5.48+1.38x; p<0.0001; r^2=0.43$; diuron plus pendimethalin fb glyphosate plus dicamba, $y=4.21-1.31x-0.085x^2; p=0.0022; r^2=0.66$. 
CHAPTER TWO

Long-Term Management of Palmer Amaranth with Herbicides and Cultural Practices in Cotton and Sweetpotato

M.D. Inman, D.L. Jordan, K. M. Jennings, A. C. York, and D. W. Monks*

*First, second, and fourth authors: Graduate Research Assistant, William Neal Reynolds Professor, William Neal Reynolds Professor Emeritus, Department of Crop Science, North Carolina State University, Raleigh, NC 27695-7620; Third and fifth author: Assistant Professor and Professor, Department of Horticultural Science, North Carolina State University, Raleigh, NC 27695-7609.
ABSTRACT

Glyphosate-resistant (GR) Palmer amaranth has become one of the most problematic weeds in cotton and sweetpotato production systems throughout southern United States. Evolved resistance of this weed to glyphosate has resulted in the need to integrate alternative control methods including deep tillage and prevention of weed-seed production in some fields to manage this weed. These practices can be expensive, but they can be effective in situations where GR weed species are present at high populations. Deep tillage can also have negative impacts on conservation programs in highly erodible production areas. Research was conducted from 2012-2014 to determine the influence of a single deep tillage operation and hand removal of Palmer amaranth prior to seed production on weed populations and economic returns in continuous cotton and continuous sweetpotato over 3 years. Treatments consisted of both moldboard plowing in fall and a no-moldboard plowing, each with and without hand removal of Palmer amaranth prior to seed production during each year. Herbicide programs with cotton included preemergence (PRE) application of diuron followed by two postemergence (POST) applications of glufosinate over the entire test area during all years. Moldboard plowing and hand removal of escaped weeds reduced Palmer amaranth population in subsequent years in some but not all instances in cotton. Differences in weed populations with deep tillage or hand removal did not always translate into increased yield and economic return. In one of two fields with cotton, cumulative economic return was higher following a single moldboard plowing operation compared with no moldboard plowing regardless of hand removal treatment. In contrast, cumulative economic return was
higher following hand removal of Palmer amaranth only when moldboard plowing. In sweetpotato, weed management programs included a pre-transplant herbicide application of flumioxazin followed by a PRE application of S-metolachlor and inter-row cultivation every two weeks after transplanting for approximately six weeks. Moldboard plowing reduced Palmer amaranth density in subsequent years and increased yield in one of two years in sweetpotato. Hand removal reduced weed populations in one of two years but had no effect on yield. Economic return was not affected by moldboard plowing or hand removal of Palmer amaranth in sweetpotato.

**NOMENCLATURE:** Diuron; flumioxazin; glufosinate; S-metolachlor; Palmer amaranth (*Amaranthus palmeri* S. Watts); cotton (*Gossypium hirsutum* L.); sweetpotato (*Ipomoea batatas* L. Lam).

**KEYWORDS:** seedbank, integrated weed management.
INTRODUCTION

The existence of glyphosate-resistant Palmer amaranth has been well documented over the past decade throughout southern United States. (Heap 2015, Poirier et al. 2014). Since the introduction of herbicide-tolerant (HT) crops in the late 1990’s, the adoption of this technology has increased exponentially. As of 2014, HT corn (Zea Mays L.), cotton, and soybean [Glycine max (L.) Merr] accounted for at least 90% of planted ha in the U.S. (Fernandez-Cornejo et al. 2014). Use of HT cotton increased efficacy and ease of use while reducing input costs including cultivation, hand labor, and the decreased use of traditional herbicides (Culpepper and York 1998). Simplification of weed management programs in cotton further enabled adoption of conservation tillage and POST only herbicide programs (Givens et al. 2009a 2009b; Shaner 2000; Sosnoskie and Culpepper 2014; Young 2006).

With significant changes in management practices since the adoption of GR cotton, dependency on glyphosate to be a stand-alone herbicide has created a shift in weed populations and diversity that have a higher tolerance or express evolved resistance to glyphosate (Culpepper 2006; Duke and Powles 2008; Vencill et al. 2012). Palmer amaranth is the primary focus of weed management strategies in many cotton fields and has required growers to increase weed management costs to be successful, either through increased use of residual herbicide or through hand-removal. Beckie (2011) reported that GR Palmer amaranth has been one of the most economically damaging weed species. For example, increased cost of managing GR Palmer amaranth in Georgia and North Carolina cotton
production has been estimated at ranging from $15\text{-}247 \text{ ha}^{-1}$ compared with weed control costs in absence of GR Palmer amaranth (Culpepper 2010; York 2010).

Implementing multiple tactics is essential in preventing and managing herbicide resistance (Norsworthy et al. 2012). Weed management programs using herbicides exclusively can be ineffective and result in increased contributions of seed to the soil seedbank (Jones and Medd 2000). Historically, weed management programs have focused on preventing weed seed establishment and growth compared to carrying out management practices that eliminate weed seed from the soil seedbank (Anderson 2007; Cardina et al. 1999; Gallandt 2006; Sosnoskie et al. 2013). Menges (1987) reported that 6 years of hand-weeding and herbicides reduced the Palmer amaranth seedbank by 98%. However, 18 million seeds ha$^{-1}$ still remained in the soil seedbank. Burnside et al. (1986) observed that just 1 year without weed control following 5 years of weed-free management was sufficient to replenish the soil weed seedbank to 90% of initial levels. These data support the practice of preventing weed-seed production because even the most effective weed management programs currently used can still have weed problems in subsequent years (Norsworthy et al. 2014). Neve et al. (2011) suggested that the Palmer amaranth seedbank was the most important factor in governing occurrence of glyphosate resistance.

Culpepper et al. (2009a) reported that moldboard plowing and burying of weed seed can decrease subsequent populations of Palmer amaranth, giving growers a “re-start” in fields with unmanageable populations of this weed. Deep tillage reduced Palmer amaranth emergence up to 60% by burying weed seed and bringing soil with fewer weed seed to the
surface where germination occurs (Culpepper et al. 2009a). DeVore et al. (2013) reported an 81% reduction in Palmer amaranth emergence over two years from deep tillage alone in a soybean production system in Arkansas. In a cotton production system, DeVore et al. (2012) observed a season-long reduction of 63% in Palmer amaranth emergence one year after a deep tillage operation. Although this practice may be undesirable in certain production systems, it can be effective management in extreme cases of high infestations of GR Palmer amaranth (Price et al. 2011). Because of the potential of returning weed seed from subsequent deep tillage events, it is advised that a one-time deep tillage operation will be most effective in burying weed seed. After 36 months of weed seed burial, Sosnoskie et al. (2013) reported that 78% of seed were no longer viable at a depth of 40 cm. Their results suggest that Palmer amaranth seed buried at depths below their optimal germination zone can further reduce seed from the soil seedbank if left buried for more than 36 months.

Prevention of seed production by hand-removal of escaped weeds in late season has been suggested to minimize the long-term impact of herbicide resistance (Sosnoskie and Culpepper 2014). Removing escaped weeds can decrease the contribution of weed seed to the soil seedbank. Successfully preventing seed production will require multiple tactics (Norsworthy et al. 2012). Hand-weeding has increased since GR Palmer amaranth has become more widespread (Sosnoskie and Culpepper 2014). They reported 50-60% increase in hand-weeding operations in Georgia cotton production during 2006-2010 at an estimated cost of $57 ha$^{-1}$. When other control measures fail to manage Palmer amaranth, physically removing the plant before seed maturity can effectively decrease contributions of weed seed
to the soil seedbank. Sosnoskie et al. (2014) demonstrated that Palmer amaranth can reproduce even after being severed; still contributing to the soil weed seedbank.

Research in the United States has shown the value of deep tillage in reducing populations of GR and glyphosate-susceptible (GS) Palmer amaranth (Culpepper et al. 2009a, Kelton et al. 2013, DeVore et al. 2012 2013). However, research in North Carolina is limited with respect to managing GR Palmer amaranth with deep tillage. Although research in other states has addressed the role of deep tillage in suppression of GS and GR Palmer amaranth, these efforts did not determine the long-term economic value of a single deep tillage with respect to value of hand-removal of weeds each year. Estimated cost increases in North Carolina cotton production associated with GR Palmer amaranth range from $15 to $40 ha$^{-1}$ (York 2010).

Palmer amaranth is one of the most common and troublesome weeds in sweetpotato production in North Carolina (Webster 2014). Managing weeds in sweetpotato is challenging because of limited herbicide registrations, especially POST herbicides (Meyers et al. 2013). Research in North Carolina is limited relative to the value of deep tillage of sweetpotato production systems. Additionally, ineffective control of Palmer amaranth in sweetpotato can lead to increased difficulty in managing this weed in subsequent crops (Meyers et al. 2010). The economic value of deep tillage and prevention of weed seed production in sweetpotato production systems have not been determined.

Determining the economic value of cultural practices including deep tillage and hand-removal of weeds is needed to formulate effective management strategies for Palmer
amaranth in these crops. The objective of this study was to determine the impact of a single
deep tillage operation and prevention of weed seed production on Palmer amaranth density,
yield, and economic return over 3 years of continuous cotton and continuous sweetpotato.

MATERIALS AND METHODS

Experiments with cotton were conducted in North Carolina from 2012-2014 at the
Upper Coastal Plains Research Station near Rocky Mount. One experiment was conducted at
the main research facility referred to as Kingsboro (35.893N, -77.681W) and the other
experiment was conducted at the Fountain Farm facility (35.987N, -77.761W). A mixture of
natural infestations of GS and GR Palmer amaranth were present at both locations. Soil was a
Goldsboro fine, sandy loam (fine-loamy, silicious, subactive, thermic Aquic Paleudults) with
humic matter content of 0.5% at Kingsboro and a Roanoke loam (fine, mixed, semi-active,
thermic Typic Endoaquults) with humic matter content of 2.8% at the Fountain Farm. The
experiment was also conducted with sweetpotato at the Horticultural Crops Research Station
near Clinton (35.022N, -78.281W) during 2012-2014 with a mixture of Norfolk loamy sand
soil (fine-loamy, kaolinitic, thermic Typic Kandiudults) and humic matter content of 0.5%
and Orangeburg loamy sand soil (fine-loamy, kaolinitic, thermic Typic Kandiudult) with
humic matter content of 0.8%.

The experimental design was a split-plot with a two by two factorial treatment
arrangement replicated four times. Whole plot units included deep tillage (with or without
moldboard plowing) with hand-removal of escaped weeds serving as sub-plot units (with and
without hand-weeding prior to seed maturity). The single, deep tillage operation was performed in November of 2011 at a depth of 38 cm. Plot size varied between fields, with a size of 12 rows (91-cm spacing) by 23 m at Kingsboro, 16 rows (91-cm spacing) by 60 m at the Fountain Farm, and 7 rows (107-cm spacing) by 15 m at Clinton. The deep tillage treatment occurred only in 2011 with no additional deep tillage in subsequent years. Hand-removal treatment was maintained in the same plots during 2012, 2013, and 2014.

Prior to planting each year fields received two passes with a disc-harrow and a field cultivator parallel to rows followed by in-row sub-soiling and bedding. Other than treatments imposed for the experiment, cotton and sweetpotato were managed according to North Carolina Cooperative Extension Service recommendations (Edmisten et al. 2013, Kemble et al. 2014). The herbicide program in cotton included diuron (Direx 4L, Makhteshim Agan of North America, Raleigh, NC) at 841 g ai ha\(^{-1}\) applied preemergence (PRE) followed by glufosinate-ammonium (Liberty 280 SL, Bayer CropScience, Research Triangle Park, NC) applied twice POST at 560 g ai ha\(^{-1}\) to the entire test area to control GS and GR Palmer amaranth during each year. In sweetpotato, flumioxazin (Valor SX, Valent USA Corp., Walnut Creek, CA) at 105 g ai ha\(^{-1}\) was applied pre-transplant and S-metolachlor (Dual Magnum, Syngenta Crop Protection, Greensboro, NC) at 1121 g ai ha\(^{-1}\) applied POST-Transplant to the entire test area each year. In sweetpotato, inter-row cultivation was performed approximately 3 times each season beginning approximately ten days after transplanting.
Palmer amaranth density was recorded each year in 3 randomly selected quadrats in cotton (3.2 m per quadrant) and in 5 randomly selected quadrats in sweetpotato (2 m per quadrant) immediately prior to the first POST herbicide application (cotton) or cultivation (sweetpotato). In mid-August of each year, the time required to remove weeds from each plot by hand was recorded. Cotton from the center four rows of each plot was harvested with a spindle picker modified for small-plot harvesting during each year. Sweetpotato was harvested from 6 m of row in the center two rows of each plot using a tractor-mounted chain digger and were hand-graded into jumbo (> 8.9 cm diam), no. 1 (> 4.4 cm but < 8.9 cm), and canner (> 2.5 cm but < 4.4 cm) categories (USDA 2005) and weighed.

Estimated economic return was calculated based on North Carolina Cooperative Extension Service budget for cotton and sweetpotato (Bullen 2013a Bullen 2013b). Total production cost excluding ginning cost was set at $1,314 ha\(^{-1}\) for cotton and $6,175 ha\(^{-1}\) for sweetpotato. Moldboard plowing cost was set at $82 ha\(^{-1}\) and was added to the production costs where appropriate for both crops. Cost of hand-removal of weeds was set at $8 hr\(^{-1}\). Ginning cost was based on seed cotton yield for each plot at a price of $0.26 kg\(^{-1}\). Economic return for cotton was calculated as the difference between the product of yield (40% lint at $1.58 kg\(^{-1}\) and 60% seed at $0.64 kg\(^{-1}\)) and total production cost. Economic return for sweetpotato was calculated as the difference between the product of yield and a price $17.60 (no. 1’s), $6.60 (jumbos), and $4.40 (canners) per 121 kg and total production cost.

Data for the common log of Palmer amaranth density, lint yield (cotton), total marketable yield (sweetpotato), economic return each year, and sum of economic returns for
all years were subjected to ANOVA using PROC GLM in SAS (Version 9.3, SAS Institute, Inc., Cary, NC) appropriate for factorial arrangements of treatments including a 2 (field) by 2 (deep tillage) by 2 (hand-removal of Palmer amaranth) in cotton and a 2 (deep tillage) by 2 (hand-removal of Palmer amaranth) in sweetpotato for each year and for cumulative economic returns. Means of significant main effects and interactions were separated using Fisher’s Protected LSD test at \( p < 0.05 \).

RESULTS AND DISCUSSIONS

**Palmer amaranth density.** Interactions of field by deep tillage and field by deep tillage by hand-removal treatment were not significant for Palmer amaranth density in cotton during 2013 and 2014 (Table 1). However, the main effect of deep tillage was significant for 2013 but not for 2014. When pooled over fields in 2013, Palmer amaranth density in cotton was lower following deep tillage with 602,260 plants ha\(^{-1}\) compared with 2,401,580 plants ha\(^{-1}\) without deep tillage (Table 2). Other researchers (Culpepper et al. 2009b; DeVore et al. 2012 2013) reported a lower density of Palmer amaranth the year following a deep tillage operation. However, Palmer amaranth density during 2014 was similar with both tillage treatments. Response during 2014 may have been influenced in part depletion of the seedbank the previous year and herbicide efficacy during 2013. Although not substantiated in this research, a reduction in infestation from deep tillage could decrease selection for herbicide-resistant biotypes (Norsworthy et al. 2012).
In contrast to reductions in Palmer amaranth density with deep tillage, removing escaped weeds prior to seed maturity and preventing contributions of seed by these plants to the seedbank did not reduce density in either year (Table 1). These data suggest that reductions in the soil seedbank in the short term are affected more by deep tillage than hand-removal of escaped weeds when effective herbicides are used in subsequent years. As observed in previous research (Menges 1987), after an effective weed management program the soil seedbank is capable of holding large amounts of potentially viable seed. In our experiment, diuron was applied PRE followed by two applications of glufosinate during 2012, 2013, and 2014. Glufosinate controls Palmer amaranth when applied in a timely manner (Culpepper et al. 2009a; Norsworthy et al. 2008).

In sweetpotato, Palmer amaranth population during 2013 was affected by the main effect of deep tillage but not by hand-removal of Palmer amaranth (Table 3). In 2014, both deep tillage and hand-removal affected Palmer amaranth density. During both years, deep tillage decreased population of Palmer amaranth compared with production in absence of deep tillage (Table 4). Although Palmer amaranth density was not affected by the hand-removal of weeds in 2013 (3,460 plants ha\(^{-1}\) versus 3,200 plants ha\(^{-1}\), data now shown), hand-removal of weeds in previous years reduced density from 6,000 plants ha\(^{-1}\) to 3,790 plants ha\(^{-1}\) in 2014 (data not shown). Similar to results in cotton, these data in sweetpotato indicate that there was no interaction of deep tillage and hand-removal.

**Crop yield.** No differences for either deep tillage or hand-removal were observed in 2012 (Table 5). The interaction of tillage and hand-removal of weeds in 2013 and the interaction of
field, tillage, and hand-removal in 2014 were significant for cotton yield (Table 5). In 2013, cotton yield was higher following deep tillage treatments with hand-removal compared to no hand-removal (Table 6). Hand-removal of escaped weeds in 2012 did not transfer to differences in 2013 yield within treatments where deep tillage was absent. Lack of differences in yield due to tillage are consistent with results reported by Culpepper et al. (2009b), where deep tillage did not impact yield when an effective herbicide program was implemented. No difference in cotton yield was observed in treatments where deep tillage was not included irrespective of hand-removal of escaped weeds (Table 6). Although a significant interaction was noted in 2014 for field by tillage treatment by hand-removal, no difference was noted for cotton yield when analyzed by field (Tables 5 and 7).

The main effect of tillage in 2013 was significant for sweetpotato yield (Table 3), with yield higher following deep tillage compared to no deep tillage (Table 8). Differences in yield are likely associated with the lack of Palmer amaranth interference in plots where deep tillage was implemented (Table 4). Palmer amaranth is more competitive in sweetpotato compared to interference with peanut (Arachis hypogaea L.), corn (Zea mays L.), and soybean [Glycine max L. (Merr)] (Burke et al. 2007, Klingaman and Oliver 1994, Massinga et al. 2001, Meyers et al. 2010). Meyers et al. (2010) reported market grade sweetpotato yield reductions of 36 to 81% for Palmer amaranth densities ranging from 0.5 to 6.5 plants m of row. In contrast, no differences in yield were noted for 2014 even though reductions of Palmer amaranth density were noted for both main effects of deep tillage and hand-removal of escaped weeds treatments (Tables 4 and 7).
Economic returns. The interaction of tillage and hand-removal of Palmer amaranth during 2013, the interaction of field by tillage by hand-removal during 2014, and the 3-year cumulative were significant for economic returns in cotton (Table 5 and 9). In 2013, economic return was higher following deep tillage with hand-removal compared to no hand-removal (Table 6). Although a significant interaction was noted in 2014 for field by tillage by hand-removal of weeds, no difference was noted for economic return when comparing within a field (Tables 5 and 7). The interaction of tillage by hand-removal of weeds was noted for cumulative economic return at the Fountain Farm (Table 7). In treatments with deep tillage and hand-removal of escaped weeds, cumulative economic returns were higher compared to deep tillage without hand-removal and for treatments without deep tillage and hand-removal (Table 10). Cumulative economic returns for treatments without deep tillage and hand-removal were higher compared to treatments with deep tillage and no hand-removal (Table 10). In sweetpotato, yearly economic return and cumulative return were not affected by main effects or interactions of tillage and hand-removal of weeds (Table 11).

CONCLUSIONS

Cotton yield and yearly economic return were affected in one of three years by the inclusion of deep tillage and hand-removal. By the end of the experiment, no difference in cumulative economic returns was noted for Kingsboro. However, at the Fountain Farm cumulative returns was higher where deep tillage and hand-removal were implemented compared to no hand-removal. Yields were increased one of two years from the deep tillage,
but did not have an impact on economic return. The increase in production costs associated with deep tillage and/or hand-weeding were insignificant in the long-term as economic returns were comparable, offsetting higher input costs. Furthermore, lack of differences in some cases associated with main effects or interactions can be attributed to the influence of an effective herbicide program on GR Palmer amaranth. Kelton et al. (2013) reported that a one-time tillage operation can help reduce *Amaranthus* species, however; a highly efficient herbicide program is still needed to provide optimal control. Although the use of deep tillage should be discouraged in erodible areas and because of expenses associated with this operation, in certain circumstances this may be the only viable option to reduce weed populations to a manageable level. With the limited herbicide diversity in sweetpotato and the increased selection pressure on currently used herbicides in cotton, integration of deep tillage and hand-removal of weeds may be an effective complement to current practices for weed control.
ACKNOWLEDGMENTS

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Table 1. Analysis of variance (P>F) for early season density of Palmer amaranth during 2013, 2014, and cumulative as influenced by deep tillage and hand-removal of weeds in cotton.

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Palmer amaranth density</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2013</td>
<td>2014</td>
</tr>
<tr>
<td>Field (F)</td>
<td>&lt;.0001</td>
<td>0.0100</td>
<td>0.0002</td>
</tr>
<tr>
<td>Moldboard plow (MBP)</td>
<td>0.0380</td>
<td>0.4541</td>
<td>0.0494</td>
</tr>
<tr>
<td>F*MBP</td>
<td>0.4633</td>
<td>0.8932</td>
<td>0.5857</td>
</tr>
<tr>
<td>Hand-removal</td>
<td>0.1964</td>
<td>0.3157</td>
<td>0.0586</td>
</tr>
<tr>
<td>MBP*Hand-removal</td>
<td>0.4740</td>
<td>0.2237</td>
<td>0.2762</td>
</tr>
<tr>
<td>F*Hand-removal</td>
<td>0.0611</td>
<td>0.0566</td>
<td>0.0265</td>
</tr>
<tr>
<td>F<em>MBP</em>Hand-removal</td>
<td>0.6518</td>
<td>0.9338</td>
<td>0.8759</td>
</tr>
<tr>
<td>Coefficient of variation (%)</td>
<td>9.4</td>
<td>21.8</td>
<td>11.2</td>
</tr>
</tbody>
</table>
Table 2. Palmer amaranth density during 2013 and 2014 as influenced by main effects of deep tillage and hand-removal of weeds.

<table>
<thead>
<tr>
<th>Treatment factor</th>
<th>2013</th>
<th>2014</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No. plants ha⁻¹</td>
<td></td>
</tr>
<tr>
<td><strong>Deep tillage</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moldboard Plow (MBP)</td>
<td>602,260</td>
<td>120,200</td>
</tr>
<tr>
<td>No MBP</td>
<td>2,401,580*</td>
<td>224,420</td>
</tr>
<tr>
<td><strong>Hand-removal</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>1,391,970</td>
<td>163,170</td>
</tr>
<tr>
<td>No</td>
<td>1,611,870</td>
<td>181,470</td>
</tr>
</tbody>
</table>

*Indicates significance at P ≤ 0.05 for means within a treatment factor. Data are pooled over levels of the other treatment factor and fields.
Table 3. Analysis of variance (P>F) for early season density of Palmer amaranth and yield during 2013 and 2014 as influenced by deep tillage and hand-removal of weeds in sweetpotato.

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Palmer amaranth</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2013</td>
<td>2014</td>
</tr>
<tr>
<td>Moldboard plow (MBP)</td>
<td>0.0226*</td>
<td>0.0024*</td>
</tr>
<tr>
<td>Hand-removal</td>
<td>0.9531</td>
<td>0.0044*</td>
</tr>
<tr>
<td>MBP*Hand-removal</td>
<td>0.9531</td>
<td>0.3990</td>
</tr>
<tr>
<td>Coefficient of variation (%)</td>
<td>153.7</td>
<td>13.5</td>
</tr>
</tbody>
</table>
Table 4. Palmer amaranth density during 2013 and 2014 as influenced by tillage in sweetpotato.

<table>
<thead>
<tr>
<th>Palmer amaranth density</th>
<th>2013</th>
<th>2014</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. ha⁻¹</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moldboard plow</td>
<td>3</td>
<td>2,050</td>
</tr>
<tr>
<td>No moldboard plow</td>
<td>6,700*</td>
<td>7,740*</td>
</tr>
</tbody>
</table>

*Indicates significance at p ≤ 0.05 for means within a year. Data are pooled over hand-removal treatments.
Table 5. Analysis of variance (P>F) for cotton lint and economic return within each year combined locations as influenced by deep tillage and hand-removal of weeds in cotton.

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Cotton lint yield</th>
<th>Economic return</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2012</td>
<td>2013</td>
</tr>
<tr>
<td>Field (F)</td>
<td>0.0014</td>
<td>0.0126</td>
</tr>
<tr>
<td>Moldboard plow (MBP)</td>
<td>0.8397</td>
<td>0.9449</td>
</tr>
<tr>
<td>F*MBP</td>
<td>0.9722</td>
<td>0.9362</td>
</tr>
<tr>
<td>Hand-removal</td>
<td>0.4759</td>
<td>0.1424</td>
</tr>
<tr>
<td>MBP*Hand-removal</td>
<td>0.3141</td>
<td>0.0329</td>
</tr>
<tr>
<td>F*Hand-removal</td>
<td>0.3920</td>
<td>0.9611</td>
</tr>
<tr>
<td>F<em>MBP</em>Hand-removal</td>
<td>0.3048</td>
<td>0.2140</td>
</tr>
<tr>
<td>Coefficient of variation (%)</td>
<td>10.4</td>
<td>15</td>
</tr>
</tbody>
</table>
Table 6. Cotton lint yield and economic return during 2013 as influenced by the interaction of deep tillage and hand-removal of weeds. Data are pooled over fields.\textsuperscript{a,b}

<table>
<thead>
<tr>
<th>Hand-removal</th>
<th>Moldboard plow</th>
<th>2013</th>
<th>Economic return</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Lint yield</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>1030 aA</td>
<td>920 aA</td>
<td>518 aA</td>
</tr>
<tr>
<td>No</td>
<td>830 bA</td>
<td>960 aA</td>
<td>162 bA</td>
</tr>
</tbody>
</table>

\textsuperscript{a}Means within a tillage treatment followed by the same lowercase letter are not significantly different at \( p < 0.05 \).

\textsuperscript{b}Means within hand-removal of weeds followed by the same uppercase letter are not significantly different at \( p < 0.05 \).
Table 7. Analysis of variance (P>F) for lint yield 2014, economic return 2014, and 3-year cumulative return by location as influenced by deep tillage and hand-removal of weeds in cotton.

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Kingsboro</th>
<th></th>
<th></th>
<th>Fountain Farm</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lint yield 2014</td>
<td>Economic return 2014</td>
<td>Cumulative return</td>
<td>Lint yield 2014</td>
<td>Economic return 2014</td>
<td>Cumulative return</td>
</tr>
<tr>
<td>Moldboard plow (MBP)</td>
<td>0.3405</td>
<td>0.3376</td>
<td>0.8157</td>
<td>0.1680</td>
<td>0.1695</td>
<td>0.9456</td>
</tr>
<tr>
<td>Hand-removal</td>
<td>0.4385</td>
<td>0.7876</td>
<td>0.7627</td>
<td>0.1131</td>
<td>0.1275</td>
<td>0.1536</td>
</tr>
<tr>
<td>MBP*Hand-removal</td>
<td>0.2817</td>
<td>0.2281</td>
<td>0.7656</td>
<td>0.0785</td>
<td>0.0822</td>
<td>0.0457</td>
</tr>
<tr>
<td>Coefficient of variation (%)</td>
<td>14.1</td>
<td>58</td>
<td>34.9</td>
<td>12.6</td>
<td>35.1</td>
<td>21.5</td>
</tr>
</tbody>
</table>
Table 8. Sweetpotato yield as influenced by main effects of deep tillage and hand-removal of weeds during 2013 and 2014.

<table>
<thead>
<tr>
<th>Treatment factor</th>
<th>2013</th>
<th>2014</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moldboard plow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>18,415</td>
<td>28,275</td>
</tr>
<tr>
<td>No</td>
<td>10,708*</td>
<td>29,600</td>
</tr>
<tr>
<td>Hand-removal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>15,726</td>
<td>30,372</td>
</tr>
<tr>
<td>No</td>
<td>13,397</td>
<td>27,503</td>
</tr>
</tbody>
</table>

*Indicates significance at $p \leq 0.05$ for means within a treatment factor. Data are pooled over levels of the other treatment factor.
Table 9. Analysis of variance (P>F) for cumulative economic return combined locations as influenced by deep tillage and hand-removal of weeds in cotton.

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Economic return</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field (F)</td>
<td>0.0037</td>
</tr>
<tr>
<td>Moldboard plow (MBP)</td>
<td>0.8849</td>
</tr>
<tr>
<td>F*MBP</td>
<td>0.9783</td>
</tr>
<tr>
<td>Hand-removal</td>
<td>0.1495</td>
</tr>
<tr>
<td>MBP*Hand-removal</td>
<td>0.0728</td>
</tr>
<tr>
<td>F*Hand-removal</td>
<td>0.2737</td>
</tr>
<tr>
<td>F<em>MBP</em>Hand-removal</td>
<td>0.0376</td>
</tr>
<tr>
<td>Coefficient of variation (%)</td>
<td>27</td>
</tr>
</tbody>
</table>
Table 10. Cumulative economic return as influenced by the interaction of deep tillage and hand-removal of weeds for Fountain Farm in cotton.$^{a,b}$

<table>
<thead>
<tr>
<th>Hand-removal</th>
<th>Moldboard plow</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Yes</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>______________________</td>
<td>$\text{ha}^{-1}$</td>
<td>$\text{ha}^{-1}$</td>
<td>$\text{ha}^{-1}$</td>
</tr>
<tr>
<td>Yes</td>
<td>3,352 aA</td>
<td>2,386 aB</td>
<td></td>
</tr>
<tr>
<td>No</td>
<td>1,865 bB</td>
<td>2742 aA</td>
<td></td>
</tr>
</tbody>
</table>

$^a$Means within a tillage treatment followed by the same lowercase letter are not significantly different at $p \leq 0.05$.

$^b$Means within hand-removal of weeds followed by the same uppercase letter are not significantly different at $p \leq 0.05$. 
Table 11. Analysis of variance (P>F) for economic return during 2013, 2014, and cumulative as influenced by deep tillage and hand-removal of weeds in sweetpotato.

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>2013</th>
<th>2014</th>
<th>Cumulative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moldboard plow (MBP)</td>
<td>0.0592</td>
<td>0.8531</td>
<td>0.5240</td>
</tr>
<tr>
<td>Hand-removal</td>
<td>0.3709</td>
<td>0.7807</td>
<td>0.5906</td>
</tr>
<tr>
<td>MBP*Hand-removal</td>
<td>0.5590</td>
<td>0.7748</td>
<td>0.9750</td>
</tr>
<tr>
<td>Coefficient of variation (%)</td>
<td>50.7</td>
<td>492.1</td>
<td>199.9</td>
</tr>
</tbody>
</table>