ABSTRACT

BRASWELL, LEWIS RAVER. Preemergence Herbicides as Components of Resistance Management Systems in Cotton (*Gossypium hirsutum* L.) (Under the direction of Drs. Alan C. York and David L. Jordan).

Prior to glyphosate-resistance, weed control in cotton was simple, with multiple glyphosate applications effectively controlling weeds. Glyphosate-resistant Palmer amaranth has altered weed management plans. Palmer amaranth has become the most troublesome weed and is highly competitive, reducing yields if not adequately controlled. Herbicide programs are focused on residual herbicides and multiple mechanisms of action. Increasing the number of herbicides available and understanding how those herbicides fit into a weed control system will be critical for continued effective weed management and maximum crop production.

Fluridone is an herbicide that was first researched for cotton weed control during the 1970's. It inhibits carotenoid biosynthesis at the phytoene desaturase step, which is not a currently used mechanism of action in row crops in North Carolina. An experiment was implemented to understand how fluridone can be used for weed control alone or in combination with other herbicides currently used in North Carolina Fluridone effectively controlled Palmer amaranth alone and in combination with other common residual herbicides and provided equivalent control to currently used grower standards. Fluridone also controlled annual grasses better than other herbicides and grower standard herbicide combinations. Cotton yields were not reduced by fluridone or by any herbicide program. Fluridone can be an effective herbicide when used as part of a weed management system.

Flumioxazin and fomesafen are both protoporphyrinogen oxidase (PPO) inhibitors that are commonly used in cotton and other crops in North Carolina. PPO-resistance has been

found in other *Amaranthus* species and research suggests it is possible in Palmer amaranth. Research was implemented to understand if fluridone could be used to replace flumioxazin as a preplant herbicide and acetochlor could be used to replace fomesafen to reduce the pressure on selecting for weeds resistant to PPO-inhibiting herbicides. Fluridone alone controlled Palmer amaranth as well as flumioxazin. Acetochlor was effective at controlling Palmer amaranth when used in combination with other herbicides and would help reduce selection pressure on weeds resistant to PPO-inhibitors. Both fluridone and acetochlor, when used in combination with POST herbicides, provided equivalent cotton yields to grower standard herbicide programs.

Use of residual PRE herbicides presents issues should a cotton stand fail too late in the year to replant cotton. Grain sorghum and soybean are the two replacement crop options in North Carolina. Researchers understand how most residual cotton herbicides interact with grain sorghum and soybean. Diuron and fluometuron are two herbicides that have unknown effects on grain sorghum and soybean planted in the same season after their application. Previous research in the Mid-South suggests both crops offer potential to replant following those herbicides. Research was implemented to determine how those herbicides impact grain sorghum and soybean replanting and how tillage and replant delay interval impacts crop response and yield in North Carolina. Fluometuron impacted soybean more than diuron and both herbicides impacted soybean more than grain sorghum. Even though both herbicides injured soybean, replanting both crops earlier following cotton stand failure resulted in higher yields due to a longer growing season when planted earlier in the year.

Preemergence Herbicides as Components of Resistance Management Systems in Cotton (*Gossypium hirsutum* L.)

by
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A thesis submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the degree of
Master of Science

Crop Science

Raleigh, North Carolina

2015

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DEDICATION

I would like to dedicate this thesis to all of my family and friends. Without the constant love, support and encouragement, this dream would have never happened. It would have been easy to falter during the low points along the way without your support.

BIOGRAPHY

Lewis Braswell was born January 15, 1991 to Charles and Diane Braswell. Lewis spent all of his life before college living in Johnston County near Clayton, North Carolina. He did not grow up directly tied to agriculture. While attending high school at West Johnston, Lewis became involved in FFA and Envirothon. Through various competitions, the field of soil science became an interest of his, which led to enrolling in the soil science program at North Carolina State University.

The soil science program at NC State was important for directing Lewis' career goals. However, he was fortunate enough to participate in summer internships each year that directed it even further. While working for the Cooperative Extension Service following his freshman year, Lewis was first exposed to row crop field research. This was enlightening and helped him to look for future opportunities. The following summer, an opportunity was presented him working for Syngenta conducting various types of field research. During this summer and a class the following fall taught by Dr. York, Lewis became interested specifically in a graduate degree and future career dealing with weed science. Dr. York was then gracious enough to hire Lewis as an hourly employee and then to present this opportunity to work on a Master's Degree with his project.

ACKNOWLEDGMENTS

I would first like to thank my family for supporting me throughout this opportunity. This experience was filled with ups and downs and without their unwavering support I would have never been able to complete this goal of mine. I know that their support will continue with whatever opportunities I am presented with moving forward.

I would also like to thank Dr. York, Charlie and Rick for their help and leadership throughout my work on this degree. Not having grown up on a farm, I am sure there were plenty of times they all would have been happy to not have had to explain how to do some simple task. My knowledge would not be anywhere near where it is, not only in research, but general everyday tasks around agriculture.

Lastly, I would like to thank my wife, Izah, for all she has done for me over the last five and half years, and more specifically during this degree program. Between countless late nights and early mornings, as well as continuous grumpy moods and attitudes during the more difficult times, her love and support has been tremendous.

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Chapter I

Literature Review

Lewis R. Braswell, Alan C. York, David L. Jordan, Travis W. Gannon, Charles W. Cahoon Jr., Richard W. Seagroves

Palmer amaranth (*Amaranthus palmeri* S. Watts) is the most troublesome weed in cotton (*Gossypium hirsutum* L.) production in the southeastern United States (Culpepper et al. 2010; Webster 2013). Growth and physiology of Palmer amaranth make it very competitive with crops. Palmer amaranth has a large upright growth habit and can readily reach 2 m or more in height and it has faster growth rate than other *Amaranthus* species (Keely et al. 1987; Sellers et al. 2003). Palmer amaranth utilizes the C_4 photosynthetic pathway, and has efficient CO_2 and water use, even under under drought conditions, which allow it to increase photosynthesis up to air temperatures of 42°C (Ehleringer 1983). Palmer amaranth can also adapt to shading (Jha et al. 2008), allowing it to emerge through established crop canopies. Season-long control of Palmer amaranth may not be necessary to maintain crop yields, but late emerging Palmer amaranth, after 17-leaf cotton, can still produce seed to replenish the soil seed bank (MacRae et al. 2013).

It has been shown that Palmer amaranth can reduce yield in crops including cotton, corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] (Klingaman and Oliver 1994; Massinga et al. 2001; Morgan et al. 2001). In cotton, Palmer amaranth reduced yields up to 92% with 8 plants m^{-1} of row (MacRae et al. 2013; Morgan et al. 2001; Rowland et al. 1999). Harvesting efficiency in cotton was reduced by Palmer amaranth (Smith et al. 2000). Mechanical harvest at densities of six Palmer amaranth plants per 9.1 m^{-1} of row has been shown to be impractical due to potential damage to the picker and reduced yields (Morgan et al. 2001).

Prior to commercialization of glyphosate-resistant (GR) cotton, growers relied on multiple applications of residual herbicides. Applications consisted of preplant incorporated (PPI), preemergence (PRE) and post emergence (POST)-directed herbicides in order to effectively control weeds (Wilcut et al. 1995). These programs were effective if rainfall occurred shortly after application of residual herbicides and weeds were small during POST-directed applications (Culpepper and York 1997). Pyrithiobac, an acetolactate synthase (ALS)-inhibiting herbicide applied PRE or POST, controls small Palmer amaranth with minimal injury to cotton (Branson et al. 2005; Corbett et al. 2004; Jordan et al. 1993a,b). However, ALS-resistant Palmer amaranth is now common throughout the southern United States, thus reducing the utility of pyrithiobac as a POST control option (Bond et al. 2006; Heap 2015; Nandual et al. 2012; Porrier et al. 2014; Sosnoskie et al. 2011).

Cotton resistant to glyphosate was commercialized in 1997 and was quickly adopted by growers (Gianessi 2005). Weed control programs using only glyphosate were effective and allowed more flexibility in application timing, as well consistent weed control with no cotton injury or need for activating rainfall (Culpepper and York 1998, 1999; Faircloth et al. 2001). Traditionally, glyphosate effectively controlled Palmer amaranth (Bond et al. 2006; Corbett et al. 2004). Repeated use of glyphosate resulted in selection for resistant biotypes (Duke and Powles 2008). Glyphosate resistance has been confirmed in 32 weed species worldwide, including Palmer amaranth (Heap 2015). The first confirmation of any *Amaranthus* spp. being resistant to glyphosate was Palmer amaranth in Georgia in 2005 (Culpepper et al.

2006). Since that time, resistance has been confirmed in 24 states (Heap 2015). Palmer amaranth populations in several states express resistance to both ALS-inhibiting herbicides and glyphosate (Heap 2015; Nandual et al. 2012; Porrier et al. 2014; Sosnoskie et al. 2011).

Residual herbicides commonly used prior to GR cotton have again become necessary to control GR Palmer amaranth (Culpepper 2015; Whitaker et al. 2011; York 2015). Current Cooperative Extension Service recommendations (Culepper 2015; York 2015) for controlling GR Palmer amaranth in no-till cotton include a residual preplant herbicide, followed by additional residual herbicides applied PRE. These herbicides are followed by timely POST applications of glufosinate or glyphosate, in many cases with acetochlor or *S*-metolachlor and a POST-directed layby application of another residual herbicide such as diuron. Use of residual herbicides is an effective herbicide resistance management strategy because of the ability to overlap residual herbicides to minimize emergence of weeds throughout the growing season and thus the selection pressure on POST herbicides (Duke and Powles 2008; York 2015).

Protoporphyrinogen oxidase inhibitors (PPO) work by inhibiting the production of protoporphyrin IX, used in photosynthesis and heme production and ultimately results in rapid accumulation and production of toxic singlet oxygen (Beale and Weinstein 1990; Cobb and Reade 2010). Recommendations in no-till cotton have focused on two protoporphyrinogen oxidase inhibitors flumioxazin preplant followed by fomesafen PRE, which has been the most effective program for control of GR Palmer amaranth (Culpepper 2015; Whitaker et al. 2011). Fomesafen effectively controls Palmer amaranth if timely rainfall is received for activation (Cahoon et al. 2014; Everman et al. 2009; Norsworthy et al.

2010; Whitaker et al. 2010, 2011). Flumioxazin will control Palmer amaranth for up to a month into the growing season when applied 2 to 3 weeks prior to cotton planting (Cahoon et al. 2014; Price et al. 2002). Prior to GR Palmer amaranth, use of these PPO inhibitors was limited. A survey of Georgia cotton producers showed that before 2006, flumioxazin-treated and fomesafen-treated acres were only 3% and 12% of cotton acres, respectively (Sosnoskie and Culpepper 2014). After GR developed, use of flumioxazin increased almost 10-fold to 27% and fomesafen use increased to 81% of cotton grown in Georgia by 2010. Flumioxazin was also applied POST-directed to 23% of the planted acres after resistance developed. Use of PPO inhibitors in North Carolina experienced a similar upward trend after GR Palmer amaranth evolved. Extensive PPO-inhibitor use in most crops in North Carolina include soybean, peanut (*Arachis hypogaea* L.), tobacco (*Nicotiana tabacum* L.), and sweetpotato [*Ipomea batatus* (L.) Lam.]. Some of these crops often receive multiple PPO-inhibitor applications during a growing season, putting increased selection pressure on these weeds for resistance to the PPO-inhibiting herbicides (Cahoon et al. 2014).

PPO-inhibitor resistance in Palmer amaranth has not been documented, but resistance in other *Amaranthus* species has occurred. PPO-inhibitor resistant common waterhemp [*Amaranthus tuberculatus* (Moq.) Sauer var. *rudis*] was first documented in Kansas in 2000 (Shoup et al. 2003) and other resistant biotypes have been reported in Indiana, Illinois, Iowa and Missouri (Heap 2015). Multiple resistance to glyphosate, PPO inhibitors and other modes of action have also been reported in waterhemp (Heap 2015; Legleiter and Bradley 2008; Patzoldt et al. 2005). Similar genetics between Palmer amaranth and common waterhemp indicate that continued use of PPO inhibitors will result in herbicide resistance in Palmer amaranth (Riggins and Tranel 2012; Wetzel et al. 1999).

Integrating different modes of action will be required to prevent PPO resistance in Palmer amaranth; however, those options are limited (Price et al. 2011; Vencill et al. 2012). New options are now available in North Carolina in acetochlor and fluridone. Acetochlor registered for cotton is an encapsulated formulation that can be used PRE or POST in cotton (Anonymous 2015i). Understanding how these two herbicides can best be used to reduce PPO-inhibitor application will be critical in preventing resistance from evolving in Palmer amaranth.

Fluridone controls weeds by inhibiting carotenoid biosynthesis at the phytoene desaturase step (Bartels and Watson 1978; Chamovitz et al. 1993; Kowalczyk-Schroder and Sandmann 1992; Mayer et al. 1989). Fluridone was first investigated for possible use in cotton in the late 1970's (Banks and Merkle 1979a; Waldrep and Taylor 1976). Berard et al. (1978) reported that ^{14}C-labeled fluridone did not translocate from the roots to the shoots in cotton but did in other crops such as corn, soybean, and rice (*Oryza sativa* L.) and concluded this was the basis for tolerance in cotton. Banks and Merkle (1979a) and Waldrep and Taylor (1976) reported good control of *Amaranthus* species by fluridone. However, carry over of residues to subsequent crops was found to be an issue (Banks et al. 1979; Banks and Merkle 1979a; Schroeder and Banks 1986a).

Fluridone was more persistent in a fine sandy loam soil compared to a clay soil with higher organic matter (Banks et al. 1979). When compared across soil types, soils adsorbed between 2% and 68% of the fluridone that was added (Weber et al. 1986). This was attributed to organic matter and montmorillonite clay content. Banks et al. (1979) also found that fluridone is more persistent in sterilized soil than field soils, indicating microbial degradation is a factor in dissipation. Studies also suggest that repeated applications of fluridone result in more rapid microbial degradation due to increases in populations of microbial organisms which target fluridone as a carbon source (Schroeder and Banks 1986a, 1986b). Movement of fluridone through soils varied between a loamy sand, sandy loam, and clay depending on amount of water applied (Banks and Merkle 1979b). Fluridone was evenly distributed through 16 cm of soil when 10 cm of water was applied to the loamy sand soil. If 5 cm of water was applied, fluridone was restricted to the top 12 cm of the loamy sand. Fluridone was retained in the top 1 cm of both the sandy loam and clay soil regardless of amount of water application.

Research with fluridone during the 1970's and 1980's was conducted with rates of 300 to 900 g ai ha^{-1} (Banks and Merkle 1979a; Waldrep and Taylor 1976). More recently, research with fluridone for control of GR Palmer amaranth has focused on lower use rates to reduce carryover to sensitive crops and to decrease production costs. Fluridone at 200 to 224 g ha^{-1} controlled of Palmer amaranth greater than 90% (Crow et al. 2014; Hill et al. 2013, 2014a). No more than 12% visible injury to corn, soybean, rice, grain sorghum [*Sorghum bicolor* (L.) Moench], and sunflower (*Hellianthus sp.* L.) was noted following fluridone applied up to 896 g ha^{-1} (Hill et al. 2014b). Research in North Carolina has shown no carryover to soybean, grain sorghum, peanut or corn at rates anticipated for labeling (C.W. Cahoon, unpublished data).

A Section 18 Emergency Use Exemption for fluridone applied PRE was first granted in Arkansas and South Carolina during the 2012 growing season and in South Carolina in 2013 for fluridone alone (Anonymous 2015a). During 2014, a Section 18 label for Brake® F2, a premix of fluridone and fomesafen, was granted in North Carolina, South Carolina, Georgia, and Tennessee (Anonymous 2015a). A new premix of fluridone and fomesafen has received a Section 18 label in Georgia, North Carolina, and South Carolina in 2015 along with Brake® F2 again in Arkansas, Missouri, and Tennessee (Anonymous 2015a). The new premix product, labeled Brake® F16, combines a lower rate of fluridone, (168 g ha^{-1}) with a higher rate of fomesafen, (210 g ha^{-1}).

Use of residual herbicides at planting in cotton raises concerns over stand failure and replant options. Cotton planting in North Carolina is typically done between late April and late May. Cotton requires a relatively long growing season, and planting after late May typically results in reduced yields in North Carolina (Guthrie 1991; Nuti et al. 2006). A cotton stand can be lost due to hail or other adverse weather conditions or seedling diseases. If the stand failure occurs after the acceptable planting date for cotton, the grower must decide on a replacement crop. The most likely replacement crops in the southeastern United States are grain sorghum and soybean. Although grain sorghum and soybean typically produce greater yields when planted in May, both crops can be expected to mature when planted up to mid-July in North Carolina (Anonymous 2011; Wiatrek et al. 2009). When replanting to another crop following a failed cotton stand, one must consider the potential impact of previously applied cotton herbicides on the replacement crop.

Eight soil-applied residual herbicides are currently recommended for use on cotton in North Carolina (York 2015). Of those eight which are registered for cotton, Acetochlor, flumioxazin, fomesafen, pendimethalin, and trifluralin are registered for use in soybean and therefore soybean could be replanted without concern (Anonymous 2015d, 2015e, 2015g, 2015h, 2015i) and would not be expected to impact soybean planted as a replacement crop after cotton receiving these herbicides. Neither acetochlor nor flumioxazin would be expected to injure grain sorghum. Acetochlor is registered for PRE application to grain sorghum (Anonymous 2015i). Flumioxazin is registered for application 30 days ahead of grain sorghum planting (Anonymous 2015h), and research in Texas has shown that flumioxazin can safely be applied PRE to grain sorghum (Grichar 2006). Grain sorghum would not be a suitable replacement crop following cotton treated with pendimethalin, trifluralin, or fomesafen. Labels for the dinitroaniline herbicides, pendimethalin and trifluralin, have 10- and 12-month rotational restrictions, respectively, for grain sorghum (Anonymous 2015d, 2015g), and research has shown potential injury to grain sorghum planted the season after dinitroaniline herbicide application (Fink 1972). Fomesafen has relatively long persistence in soil (Mueller et al. 2014; Rauch et al. 2007), and grain sorghum is very sensitive to fomesafen (Cobacci et al. 1998). The label for fomesafen specifies a 10-month restriction when planting grain sorghum (Anonymous 2015e). Neither grain sorghum nor soybean would be replant options following cotton treated with pyrithiobac. The pyrithiobac label has a 10-month rotational restriction for both crops (Anonymous 2015f). Johnson et al. (1993b) reported injury to soybean and grain sorghum planted 8 and 16 week, respectively, following pyrithiobac application, and Jordan et al. (1993c) reported carryover to grain sorghum planted the season following application to cotton.

The potential to replant to grain sorghum or soybean following application of diuron or fluometuron is less well understood. The label for fluometuron (Anonymous 2015b) specifies a 9-month rotational restriction for both grain sorghum and soybean. The label for diuron (Anonymous 2015c) simply states that grain sorghum and soybean can be planted the next spring following a broadcast application. It is known that some growers in North Carolina have successfully planted soybean following failed stands of cotton treated with fluometuron. Published research concerning this practice is very limited. Jackson et al. (1978), working on loam and silt loam soils in Tennessee, broadcast fluometuron at 1700 g ha^{-1} and then planted grain sorghum and soybean 3, 6, and 9 week after fluometuron application. The soil was disked prior to replacement crop planting. On the silt loam soil, soybean stand was reduced in 2 of 3 years and yield was reduced each year when soybean was planted 6 week after fluometuron application. Stand was not reduced when soybean was planted at 9 week, but significant injury was noted in 2 of 3 year and yield was reduced in 1 of 3 year. Less impact on soybean was observed on the loam soil. This was at least partially attributed to more organic matter in the loam soil and greater adsorption of the fluometuron. Soybean yield was reduced in 1 of 2 year on the loam soil when soybean was planted 3 week after fluometuron application, but there was no impact on yield when soybean was planted 6 or 9 week after application. Fluometuron had no effect on grain sorghum stand on the silt loam soil, but yield was reduced in 2 of 2 year when grain sorghum was planted 3 week after herbicide application. No yield impact was noted with the 6- or 9-week planting delays.

Similar to results with soybean, less grain sorghum injury was also noted on the loam soil. Grain sorghum stand and yield were not reduced when grain sorghum was planted 3 week following fluometuron application.

Sharp et al. (1982) conducted similar studies on silt loam and silty clay soils in Arkansas and reported a greater soybean response to fluometuron residues on the silt loam soil. On the silt loam, soybean yield was reduced in 2 of 3 year when planted 29 to 30 days after application of 1700 g ha^{-1} of fluometuron. Greater injury to soybean was noted when soil was disked prior to soybean planting compared with no-till planting.

No research is available on the impact of fluometuron on soybean or grain sorghum as replacements crops behind cotton on coarse-textured soils. And, the only data available on diuron is that of Prostko et al. (2013) who found surprisingly better tolerance of soybean than expected. Prostko et al. (2013) applied diuron at 70 to 2240 g ha^{-1} immediately after planting soybean on a sand soil with 0.4% organic matter. Diuron at 2240 g ha^{-1} reduced soybean stand in 1 of 2 year, and soybean yield was reduced 23 and 41% by diuron at 1120 and 2240 g ha^{-1} in 1 of 2 year. Diuron at 560 g ha^{-1} had no effect on stand or yield in either year.

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CHAPTER II

Palmer Amaranth Control in Cotton with Fluridone and Fluridone Mixtures

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ABSTRACT

Glyphosate-resistant (GR) Palmer amaranth (*Amaranthus palmeri* S Wats.) has increased the need for effective preemergence (PRE) residual herbicides in cotton (*Gossypium hirsutum* L.). Fluridone, a carotenoid biosynthesis inhibitor with residual activity, has a mechanism of action that is not currently used in cotton or other agronomic crops and will increase mechanisms of action available for controlling GR Palmer amaranth and other weeds. Field research was conducted at eight locations to determine Palmer amaranth control by fluridone (224 g ai ha^{-1}) alone and in combination with the following tank-mix options applied PRE: acetochlor, diuron, half and full rates of fomesafen, and pendimethalin (1260, 560, 140, 280, and 1063 g ai ha^{-1}, respectively). Also evaluated were lower rates of fluridone (112 and 168 g ha^{-1}) plus fomesafen (140 g ha^{-1}) compared with grower standards of diuron plus fomesafen (140 g ha^{-1}) and acetochlor (1260 g ha^{-1}) plus fomesafen (140 g ha^{-1}). All PRE herbicides were followed by two POST applications of glufosinate and a layby application of diuron plus MSMA. Fluridone injured cotton 3% or less and generally did not increase injury when combined with other herbicides. Palmer amaranth was controlled 97% by fluridone at 224 g ha^{-1} prior to the first glufosinate application compared with 87 to 95% control by acetochlor, diuron, fomesafen, or pendimethalin. Fluridone alone controlled Palmer amaranth as well as the grower standard of acetochlor plus fomesafen and better than diuron plus fomesafen.

Similar control was obtained with fluridone at 112, 168, and 224 g ha^{-1}, acetochlor, or diuron when applied in combination with fomesafen at 140 g $ha^{-1.}$ Good Palmer amaranth control was obtained with timely applications of glufosinate and only minor increases in Palmer amaranth control and no increase in cotton yield were attributable to PRE herbicides. This research demonstrated that fluridone, due to its unique mode of action, could be effectively used in a glufosinate-based management system for proactive resistance management.

Nomenclature: Acetochlor; diuron; fluridone; fomesafen; glufosinate; MSMA; pendimethalin; Palmer amaranth, *Amaranthus palmeri* S. Wats.; cotton, *Gossypium hirsutum* L.

Key Words: Herbicide resistance management, herbicide-resistant weeds, preemergence herbicides

INTRODUCTION

Palmer amaranth is the most troublesome weed in cotton production in the southeastern United States (Culpepper et al. 2010; Webster 2013). It grows rapidly and can reach 2 m or more in height (Horak and Loughin 2000; Sellers et al. 2003). It has a high photosynthetic capacity and utilizes the C4 photosynthetic pathway (Ehleringer 1983). Along with rapid growth, Palmer amaranth has effective drought tolerance mechanisms that allow it to survive and grow during dry conditions (Ehleringer 1983; Place et al. 2008; Wright et al. 1999). It has an extensive root system which allows it to be very competitive with crops for moisture (Wiese 1968). It readily adapts to shading (Jha et al. 2008), which allows it to compete under light-limited environments such as dense crop canopies. These characteristics allow Palmer amaranth to establish a competitive dominance for light and space with crops (Monks and Oliver 1988).

Palmer amaranth can dramatically reduce yield of cotton, corn (*Zea mays* L.), and soybean [*Glycine max* (L.) Merr.] (Klingaman and Oliver 1994; Massinga et al. 2001; Morgan et al. 2001). Cotton yield reductions up to 92% can occur with eight weeds m^{-1} of row (MacRae et al. 2013; Morgan et al. 2001; Rowland et al. 1999). It can also interfere with mechanical harvest (Smith et al. 2000).

Prior to commercialization of glyphosate-resistant (GR) cotton, growers relied on multiple applications of residual herbicides. Applications consisted of PPI, PRE and POST-directed herbicides in order to effectively control weeds (Wilcut et al. 1995). These programs were effective if rainfall occurred soon after residual herbicide application and weeds were small at POST-directed application (Culpepper and York 1997). Pyrithiobac, an acetolactate synthase (ALS)-inhibiting herbicide applied PRE or POST, controls small Palmer amaranth with minimal cotton injury (Branson et al. 2005; Corbett et al. 2004; Jordan et al. 1993a,b). However, ALS-resistant Palmer amaranth is now common throughout the southern United States, thus reducing the utility of pyrithiobac as a POST control option (Bond et al. 2006; Heap 2015; Nandual et al. 2012; Porrier et al. 2014; Sosnoskie et al. 2011).

Cotton resistant to glyphosate was commercialized in 1997 and was quickly adopted by growers (Gianessi 2005). Weed control programs using only glyphosate were effective at controlling many troublesome weeds, reduced potential herbicide carryover, and allowed more flexibility in application timing (Culpepper and York 1998, 1999; Faircloth et al. 2001). Traditionally, glyphosate effectively controlled Palmer amaranth (Bond et al. 2006; Corbett et al. 2004); however, repeated use of glyphosate resulted in selection for resistant biotypes (Duke and Powles 2008). Glyphosate resistance has been confirmed in 32 weed species worldwide, including Palmer amaranth (Heap 2015). The first confirmation of Palmer amaranth resistant to glyphosate was in Georgia in 2005 (Culpepper et al. 2006). Since that time, resistance has been confirmed in 25 states (Heap 2015). Palmer amaranth populations in several states express resistance to both ALS-inhibiting herbicides and glyphosate (Heap 2015; Nandual et al. 2012; Porrier et al. 2014; Sosnoskie et al. 2011).

Residual herbicides commonly used prior to GR cotton have again become necessary to control GR Palmer amaranth (Culpepper 2015; Whitaker et al. 2011; York 2015). Current Cooperative Extension Service recommendations for controlling GR Palmer amaranth in no-till cotton include a residual preplant herbicide, followed by additional residual herbicides applied PRE. These herbicides are followed by timely POST applications of glufosinate, in many cases mixed with acetochlor or *S*-metolachlor, and a POST-directed layby application of another residual herbicide such as diuron (York 2015). Use of residual herbicides is an effective herbicide resistance management strategy because of the ability to overlap residual herbicides to minimize emergence of weeds throughout the growing season and thus the selection pressure on POST herbicides (Duke and Powles 2008; York 2015).

Among the most effective and most widely used residual herbicides for controlling GR Palmer amaranth are flumioxazin and fomesafen (Cahoon et al. 2014; Whitaker et al. 2011), both of which inhibit protoporphyrinogen oxidase (PPO) in sensitive plants (Beale and Weinstein 1990; Cobb and Reade 2010). However, widespread use of these herbicides in cotton, along with extensive use in other crops, has increased concern over potential to select for PPO-resistant biotypes (Culpepper 2015; Riggins and Tranel 2012; York 2015).

Fluridone controls weeds by inhibiting carotenoid biosynthesis at the phytoene desaturase step (Bartels and Watson 1978; Chamovitz et al. 1993; Kowalczyk-Schroder and Sandmann 1992; Mayer et al. 1989). Fluridone was first investigated for possible use in cotton in the late 1970's (Banks and Merkle 1979; Thompson and Hammond 1978; Waldrep and Taylor 1976). Berard et al. (1978) reported that ^{14}C-labeled fluridone did not translocate from the roots to the shoots in cotton but did translocate in other crops such as corn, soybean, and rice (*Oryza sativa* L.) which was the basis for excellent tolerance in cotton. Banks and Merkle (1979) and Waldrep and Taylor (1976) reported good control of *Amaranthus* species by fluridone; however, potential carryover of fluridone to subsequent crops was a concern (Banks et al. 1979; Banks and Merkle 1979; Schroeder and Banks 1986).

Research with fluridone during the 1970's and 1980's was conducted with rates of 300 to 900 g ha^{-1} (Banks and Merkle 1979; Waldrep and Taylor 1976). More recently, research with fluridone for control of GR Palmer amaranth has focused on lower use rates to reduce carryover to sensitive crops. Fluridone at 200 to 224 g ha^{-1} controlled Palmer amaranth greater than 90% (Crow et al. 2014; Hill et al. 2013, 2014a). No more than 12% visible injury to corn, soybean, rice, grain sorghum [*Sorghum bicolor* (L.) Moench], and sunflower (*Hellianthus sp.* L.) was noted following fluridone (Hill et al. 2014b). Research in North Carolina has shown no carryover to soybean, grain sorghum, peanut (*Arachis hypogaea* L.) or corn at rates anticipated for labeling (C.W. Cahoon, unpublished data).

A Section 18 Emergency Use Exemption for fluridone applied PRE was first granted in Arkansas and South Carolina during the 2012 growing season (Anonymous 2015a). During 2013, a Section 18 Exemption for Brake® F2, a premix of fluridone and fomesafen, was granted in South Carolina and Brake® F2 was again granted a Section 18 Exemption for 2014 in North Carolina, South Carolina, Georgia, and Tennessee (Anonymous 2015a). A new premix of fluridone and fomesafen was granted a Section 18 Exemption for use in North Carolina, South Carolina, and Georgia 2015 (Anonymous 2015b). This product, Brake® F16, combines a lower rate of fluridone, (168 g ha^{-1}) with a higher rate of fomesafen (210 g ha^{-1}). The need for new mechanisms of action for control of GR Palmer amaranth and reduction of selection pressure on other PRE and postemergence (POST) herbicides facilitated research with fluridone in order to move forward with Section 18 Exemptions and possibly full labels for the herbicide. The objective of our research was to determine the effectiveness of fluridone in cotton applied alone or mixed with other commonly used residual herbicides to control GR Palmer amaranth. The research also aimed to understand the effect of those herbicide mixtures on cotton growth and yield on coarse-textured soils typical of cotton production in the southeastern United States.

MATERIALS AND METHODS

The experiment was conducted at four locations in North Carolina during 2013 and 2014. During both years, the experiment was on the Upper Coastal Plain Research Station at Rocky Mount, in two fields on the Central Crops Research Station at Clayton (referred to as Clayton-1 and Clayton-2), and on a private farm in Mount Olive. Adjacent areas within the same fields were used during the second year. Soil at Rocky Mount was an Aycock sandy loam (fine-silty, siliceous, subactive, thermic Typic Paleudults) with humic matter of 0.3% and pH of 5.9. Soil in both fields at Clayton was Norfolk loamy sand (fine-loamy, kaolinitic, thermic Typic Kandiudults) with humic matter of 0.2% in field 1 and 0.51% in field 2 and pH of 5.5. Soil at Mount Olive was a Wagram loamy sand (loamy, kaolinitic, thermic Arenic Kandiudults) with humic matter of 0.4% and a pH of 5.1 Soil humic matter content was determined by the North Carolina Department of Agriculture and Consumer Services, Agronomic Section, according to Mehlich (1984). Palmer amaranth densities were naturally occurring at greater than 100 plants m^{-2} at all locations.

Stoneville® variety 'ST 4946GLB2' (Bayer CropScience, Research Triangle Park, NC) was planted at each site, except for Clayton-1 in 2013, where Fibermax® 'FM 1944GLB2' (Bayer CropScience) was planted. Planting dates are listed in Table 1. At the Rocky Mount and Mount Olive locations, cotton was planted in a strip-tillage system (Meijer and Edmisten 2015). Cotton was planted no-till at Clayton-1 and into a conventionally-tilled seedbed at Clayton-2 in 2013. In 2014, cotton at Clayton-1 was planted into a conventionally-tilled seedbed and no-till at Clayton-2. Plot size was 4 rows by 9 m. Row width was 91 cm at Rocky Mount and 97 cm at Clayton and Mount Olive.

Herbicide application dates are listed in Table 1; sources of herbicides are listed in Table 2. All plots at strip-tilled and no-till locations received a burndown application of 2,4-D dimethylamine salt at 766 g ae ha^{-1} plus glyphosate potassium salt at 866 g ae ha^{-1} approximately 3 wk prior to planting and paraquat dichloride at 840 g ae ha^{-1} a few hours ahead of planting. Treatments consisted of a factorial arrangement of fluridone at two rates (0 and 224 g ha^{-1}) and the following six tank-mix options: none, acetochlor (1260 g ha^{-1}), diuron (560 g ha^{-1}), fomesafen (140 and 280 g ha^{-1}) (hereafter referred to as fomesafen-low and fomesafen-high, respectively), and pendimethalin (1063 g ha^{-1}). Fluridone and the tank-mix options were applied as broadcast sprays within 2 hr after planting. Four additional treatments in 2013 and 2014 represented grower standards and included diuron (560 g ha^{-1}) plus fomesafen-low or fomesafen-high and acetochlor (1260 g ha^{-1}) plus fomesafen-low or fomesafen-high. In 2014 only, two additional treatments included fluridone (112 and 168 g ha^{-1}) mixed with fomesafen-low. All plots except the non-treated checks received glufosinate-ammonium (594 g ha^{-1}) applied POST to 1- to 2-leaf cotton (EPOST) and again 14 to 19 d later to 6- to 8-leaf cotton (MPOST). A POST-directed layby application of diuron at (1120 g ha^{-1}) plus MSMA (2240 g ai ha^{-1}) was applied 14 to 26 d after MPOST when cotton was approximately 40 to 50 cm in height. All POST and layby applications were targeted at 5- to 10-cm Palmer amaranth. Preplant burndown herbicides and paraquat were applied with a tractor-mounted sprayer equipped with flat-fan nozzles nozzles (DG11002 TeeJet® Drift Guard flat-spray nozzles, TeeJet Technologies, Wheaton, IL) delivering 140 L ha^{-1}. The PRE and POST herbicides were applied using a CO_2-pressurized backpack sprayer equipped with flat-fan nozzles (AIXR 11002 TeeJet® Air induction flat-spray nozzles, TeeJet Technologies) delivering 140 L ha^{-1} at 165 kPa. Layby herbicides were applied with a single flood nozzle (TK-VS2 FloodJet® wide angle flat spray nozzles, TeeJet Technologies) per row middle delivering 140 L ha^{-1} at 210 kPa.

In each year, weed control and crop injury were visually estimated using a scale of 0 to 100% with 0 equal to no control or injury and 100 equal to complete control or crop death (Frans et al. 1986). Weed control and crop injury were estimated just prior to EPOST and

MPOST applications, 14 d after layby application, and in mid-September. Above-ground fresh weight of Palmer amaranth and annual grasses were determined in mid-September from three row middles (25 to 26 m^2) in treated plots and from 1 m^2 in non-treated checks. Plots were mechanically harvested in October or November. Non-treated checks were not harvested due to severe weed infestations, and yields were assumed to be zero.

The experimental design was a randomized complete block with treatments replicated four times. Data, excluding non-treated checks, were subjected to ANOVA appropriate for the factorial treatment arrangement. A fluridone by tank-mix option interaction was observed at most evaluations; hence, a second ANOVA was conducted comparing all treatments common in both years. A third ANOVA compared Palmer amaranth control in 2014 by the combinations of the three rates of fluridone plus fomesafen-low, diuron plus fomesafen-low, and acetochlor plus fomesafen-low. The PROC GLIMMIX procedure of SAS (Version 9.3; SAS Institute Inc., Cary, NC) was used. Means were separated using Fisher's Protected LSD Test ($P = 0.05$). Fresh weights of Palmer amaranth in herbicide treatments were compared to the weight in the non-treated checks using Dunnett's procedure (Dunnett 1955).

RESULTS AND DISCUSSION

Palmer Amaranth Control. Treatments responded similarly across locations for Palmer amaranth control; hence data were pooled across years and locations. Adequate rainfall for PRE herbicide activation was received with at least 1.5 cm of rainfall at 6 of 8 locations within 10 d of planting (Table 1). The remaining two locations received at least 4.9 cm during the 11- to 15-d period after planting.

In the analysis for the fluridone by tank-mix options factorial arrangement, an interaction for Palmer amaranth control was noted for evaluations taken at time of EPOST and MPOST applications, and 14 d after layby application. In light of the interaction, a second analysis was conducted comparing all treatments. Among the tank-mix partners applied alone, greatest Palmer amaranth control at time of EPOST application was obtained with acetochlor and fomesafen-high (Table 3). These two herbicides were 7 to 8% more effective than diuron or fomesafen-low. Pendimethalin was least effective and controlled Palmer amaranth 82% compared with 87% control by diuron and fomesafen-low and 94 to 95% control by acetochlor and fomesafen-high. Fluridone alone controlled Palmer amaranth 97%. Control by fluridone alone was similar to that by fluridone plus any of the tank-mix options. Fluridone alone and acetochlor alone were similarly effective whereas fluridone alone was more effective than diuron, pendimethalin, or fomesafen applied alone. Crow et al. (2014) and Hill et al. (2013) reported at least 95% control of Palmer amaranth by fluridone at 200 to 224 g ha^{-1}.

Among the four grower standards, diuron plus fomesafen-low and diuron plus fomesafen-high were similarly effective at time of EPOST application with 95 to 96% control (Table 3). Applied alone, fomesafen-high was more effective than fomesafen-low, but fomesafen-high and diuron plus fomesafen-low were similarly effective. Acetochlor plus fomesafen-low was more effective than fomesafen-high. Fomesafen often causes cotton injury (Culpepper 2015; Main et al. 2012; York 2015). Our results indicate a reduced rate of fomesafen can be applied in combination with diuron or acetochlor without sacrificing Palmer amaranth control. By reducing the rate of fomesafen, one may avoid some crop injury. Fluridone alone and combinations containing fluridone were somewhat more effective than combinations of diuron plus fomesafen, but mixtures of acetochlor plus fomesafen were as effective as mixtures containing fluridone. This included the mixture of fluridone 224 g ha^{-1} plus fomesafen 140 g ha^{-1}, which was sold as Brake® F2 under a Section 18 Emergency Exemption in 2014 in North Carolina (Anonymous 2015b).

In the absence of PRE herbicides, glufosinate applied EPOST controlled Palmer amaranth 88% at time of MPOST application (Table 3). The glufosinate was applied to small Palmer amaranth and controlled emerged weeds at application well (Everman et al. 2007; Gardner et al. 2006). The weeds present at the time of MPOST application had emerged after the EPOST glufosinate application. Residual control from the PRE herbicides was evident as all PRE herbicides and herbicide combinations increased control at least 6%. The same trends observed among the PRE herbicides prior to POST application were still evident following the EPOST application of glufosinate. After two POST applications of glufosinate and the layby application of diuron plus MSMA, Palmer amaranth was controlled 98% in the absence of PRE herbicides and 99 to 100% when PRE herbicides were included. Similar control also was noted late in the season. Palmer amaranth fresh weight late in the season correlated well with the late-season visual estimation of control. All treatments reduced Palmer amaranth fresh weight at least 99% compared with the non-treated control (Table 4).

In 2014 only, fluridone at reduced rates was applied in combination with fomesafen-low. Fluridone, diuron, and acetochlor mixed with fomesafen-low were 10 to 17% more effective than fomesafen-low alone (Table 5). No difference in Palmer amaranth control was noted among the three rates of fluridone plus fomesafen-low. Fluridone plus fomesafen-low, regardless of fomesafen rate, was somewhat more effective than diuron plus fomesafen-low but no more effective than acetochlor plus fomesafen-low at time of EPOST or MPOST applications. At 14 d after layby application and late in the season, all of these treatments controlled Palmer amaranth at least 98%. No differences in seed cotton yield were observed among these treatments.

Cotton Response. A treatment by location interaction occurred for cotton injury at time of EPOST application, with injury observed only at Clayton-1 and Clayton-2 in 2013 and Clayton-2 in 2014 (Table 6). All the tank-mix options gave essentially no injury at Clayton-2 in 2014. At Clayton-2 in 2013, 6 and 7% injury was noted with fomesafen-high and pendimethalin, respectively. Other tank-mix options at this location injured cotton 2% or less. No injury by tank-mix options was increased when fluridone was added. For grower standard treatments, both acetochlor and diuron caused more injury when combined with fomesafen-high compared to fomesafen-low. Acetochlor stunted cotton 11% at Clayton-1 in 2013 while pendimethalin injured cotton 28%. The pendimethalin injury was expressed as greatly enlarged cotyledons and malformation of the true leaves. The other tank-mix options injured cotton 3% or less at this location.

Minimal cotton injury was noted with fluridone alone, 3% or less at any location. This is similar to previous research showing excellent cotton tolerance of fluridone (Berard et al. 1978; Thompson and Hammond 1978). With only two exceptions, injury by tank-mix options alone and combined with fluridone was similar. Injury was transient; no injury was observed at time of MPOST application or later (data not shown). No differences among herbicide treatments were noted for seed cotton yield (Table 4). Lack of a yield response is consistent with the transient nature of the injury and the high level of weed control obtained (Table 3).

Control of Palmer amaranth is critical to protect cotton lint yields and to reduce herbicide-resistant weed seed banks. Glufosinate applied POST is widely used to control this weed and, while no resistance to glufosinate in dicot weeds has been observed (Heap 2015), weed scientists strongly recommend residual herbicides as part of an overall management program (Burgos et al. 2006; Culpepper 2015; Norsworthy et al. 2012; York 2015). Residual PRE herbicides reduce selection pressure on POST herbicides and can also give growers greater flexibility in the timing of POST herbicide application. In our experiment, PRE herbicides gave only minor increase in Palmer amaranth control and did not impact yield. However, the POST and POST-directed herbicides were applied very timely and good control was achieved. A benefit from PRE herbicides would have been expected if POST application had been less timely.

This research demonstrated excellent cotton tolerance to fluridone and excellent Palmer amaranth control. Palmer amaranth control by fluridone alone or in combination with other herbicides was as good as or better than with other commonly used PRE herbicides and herbicide combinations. Fluridone’s mode of action is unique in the row crop herbicide market. Use of fluridone in cotton could reduce selection pressure on other modes of action, especially protoporphyrinogen oxidase (PPO) inhibitors which are currently widely used in cotton and several other crops. Although resistance to PPO inhibitors has not been reported for Palmer amaranth, PPO resistance is found in other *Amaranthus* species (Legleiter and Bradley 2008; Patzoldt e al. 2005; Shoup et al. 2013), and this has led to concern over potential to select for resistance in Palmer amaranth (Cahoon et al. 2014; Riggins and Tranel 2012). To date, fluridone has been available under a Section 18 Emergency Use Exemption as a pre-mixed formulation containing fluridone and fomesafen, a PPO inhibitor. Use of a mixture of fluridone plus fomesafen would reduce selection pressure on fomesafen (Beckie and Reboud 2009). However, our research shows that combinations of fluridone plus diuron or fluridone plus acetochlor are as effective as fluridone plus fomesafen and thus might be better options in terms of preventing resistance to PPO inhibitors.

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Table 1. Planting dates, herbicide application dates, and rainfall in first 15 d following planting.

							Rainfall		
		Planting	Herbicide application date				Days after planting		
Location	Year	date	PRE	EPOST	MPOST	Layby	0-5	6-10	11-15
							cm		
Rocky Mount	2013	May 10	May 10	June 4	June 18	July 4	0.2	1.5	3.4
Clayton-1	2013	May 13	May 13	June 4	June 20	July 16	1.0	9.3	0.2
Clayton-2	2013	May 14	May 14	June 10	June 28	July 15	2.7	7.6	0.3
Mount Olive	2013	May 8	May 8	May 31	June 17	July 2	0	0	4.9
Rocky Mount	2014	May 6	May 6	May 27	June 13	July 1	0	6.6	0
Clayton-1	2014	May 12	May 12	June 3	June 17	July 2	9.8	0	0
Clayton-2	2014	May 12	May 12	May 30	June 17	July 2	9.8	0	0
Mount Olive	2014	May 3	May 3	May 28	June 16	June 27	0	0	5.3

Table 2. Herbicides used in experiment.[a]

Herbicide	Trade name	Formulation concentration	Manufacturer
acetochlor	Warrant®	359 g ai L^{-1}	Monsanto Co., St. Louis, MO
2,4-D dimethylamine salt	Weedar® 64	456 g ae L^{-1}	Nufarm Inc., Morrisville, NC
diuron	Direx® 4L	480 g ai L^{-1}	ADAMA Agicultural Solutions Ltd., Raleigh, NC
fluridone	experimental formulation	240 g ai L^{-1}	SePRO Corp., Carmel, IN
fomesafen	Reflex®	240 g ai L^{-1}	Syngenta Crop Protection, Greensboro, NC
glufosinate-ammonium	Liberty® 280 SL	280 g ai L^{-1}	Bayer CropScience, RTP, NC
glyphosate potassium salt	Roundup PowerMAX®	540 g ae L^{-1}	Monsanto Co., St. Louis, MO
MSMA	MSMA 6	720 g ai L^{-1}	Drexel Chemical Co., Memphis, TN
paraquat dichloride	Parazone® 3SL	360 g ae L^{-1}	ADAMA Agicultural Solutions Ltd., Morrisville, NC
pendimethalin	Prowl® H_2O	455 g ai L^{-1}	BASF Ag Products, RTP, NC

a Specimen labels can be found at www.cdms.net.

Table 3. Palmer amaranth control by residual herbicides.[a, b, c]

Residual herbicides	Application rate	At EPOST	At MPOST	14 d after layby	Late-season[d]
	g ha^{-1}	%			
none		—	88 f	98 c	98 a
diuron	560	87 e	94 e	99 b	98 a
pendimethalin	1063	82 f	94 e	99 b	99 a
fomesafen-low	140	87 e	94 e	99 b	99 a
fomesafen-high	280	94 cd	96 cd	100 a	99 a
acetochlor	1260	95 bc	97 bc	99 b	99 a
fluridone	224	97 ab	98 ab	100 a	99 a
fluridone + diuron	224 + 560	98 a	98 ab	100 a	99 a
fluridone + pendimethalin	224 + 1063	98 a	98 ab	100 a	99 a
fluridone + fomesafen-low	224 + 140	97 ab	98 ab	100 a	99 a
fluridone + fomesafen-high	224 + 280	98 a	99 a	100 a	100 a
fluridone + acetochlor	224 + 1250	99 a	99 a	100 a	99 a
diuron + fomesafen-low	560 + 140	92 d	95 de	99 b	99 a
diuron + fomesafen-high	560 + 280	94 cd	96 cd	99 b	99 a
acetochlor + fomesafen-low	1260 + 140	97 ab	98 ab	100 a	99 a
acetochlor + fomesafen-high	1260 + 280	98 a	98 ab	100 a	99 a

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD Test at $P = 0.05$.
[b] Data averaged over eight locations in 2013 and 2014.
[c] Glufosinate was applied at 594 g ha^{-1} EPOST (18 to 27 days after planting) and MPOST (34 to 40 days after planting). Diuron plus MSMA were applied at 1120 plus 2240 g ha^{-1}, respectively, 51 to 64 d after planting.
[d] Late season ratings were taken in early September.

Table 4. Palmer amaranth fresh weight and seed cotton yield averaged over locations. [a, b]

Residual herbicides[c]	Application rate	Palmer amaranth fresh weight[d]	Seed cotton yield
	$g\ ha^{-1}$	$kg\ ha^{-1}$	
none		110	1930
diuron	560	110	2080
pendimethalin	1063	60	2050
fomesafen-low	140	100	2060
fomesafen-high	280	30	2060
acetochlor	1260	40	2050
fluridone	224	30	2010
Fluridone + diuron	224 + 560	30	1970
Fluridone + pendimethalin	224 + 1063	10	2010
Fluridone + fomesafen-low	224 + 140	10	2030
Fluridone + fomesafen-high	224 + 280	60	1980
Fluridone + acetochlor	224 + 1250	160	2100
Diuron + fomesafen-low	560 + 140	40	1990
Diuron + fomesafen-high	560 + 280	40	2040
Acetochlor + fomesafen-low	1260 + 140	40	2010
Acetochlor + fomesafen-high	1260 + 280	50	2020

[a] Means within a column are not significantly different according to Fisher's Protected LSD Test at $P = 0.05$.
[b] Data for Palmer amaranth fresh weight and seed cotton yield averaged over eight locations in 2013 and 2014.
[c] Residual herbicides applied preemergence. All treatments included glufosinate applied at 594 $g\ ha^{-1}$ EPOST (18 to 27 days after planting) and MPOST (34 to 40 days after planting). Diuron plus MSMA were applied at 1120 plus 2240 $g\ ha^{-1}$, respectively, 51 to 64 days after planting.
[d] Palmer amaranth above-ground fresh weight in non-treated check was 18,320 $kg\ ha^{-1}$. Fresh weight of non-treated check differed from all treatments according to Dunnett's procedure at $P = 0.05$.

Table 5. Palmer amaranth control and cotton yield with varying rates of fluridone plus fomesafen-low.[a,b]

		Palmer amaranth control				
	Application			14 d after		Seed cotton
Residual herbicides[c]	rate	At EPOST	At MPOST	layby	Late-season	yield
	g ha^{-1}	%				kg ha^{-1}
fomesafen-low	140	80 c	93 b	98 b	99 a	2150 a
fluridone + fomesafen-low	112 + 140	93 ab	98 a	100 a	99 a	2170 a
fluridone + fomesafen-low	168 + 140	96 ab	98 a	100 a	100 a	2090 a
fluridone + fomesafen-low	224 + 140	96 ab	99 a	100 a	100 a	2110 a
diuron + fomesafen-low	560 + 140	90 b	95 b	100 a	100 a	2210 a
aceotchlor + fomesafen-low	1260 + 140	97 a	99 a	100 a	100 a	2070 a

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD Test at P = 0.05.
[b] Data averaged over four locations in 2014.
[c] Residual herbicides applied preemergence. All treatments included glufosinate applied at 594 g ha^{-1} EPOST (18 to 27 days after planting) and MPOST (34 to 40 days after planting). Diuron plus MSMA were applied at 1120 plus 2240 g ha^{-1}, respectively, 51 to 64 days after planting.

Table 6. Cotton injury prior to EPOST application.[a]

Residual herbicides[b]	Application rate	Clayton-1 2013	Clayton-2 2013	Clayton-2 2014
	g ha^{-1}	——%	——	
diuron	560	3 cd	2 cd	1 bc
pendimethalin	1063	28 a	7 ab	0 c
fomesafen-low	140	3 cd	0 d	0 c
fomesafen-high	280	2 d	6 abc	1 bc
acetochlor	1260	11 bcd	2 cd	0 c
fluridone	224	2 d	2 cd	3 ab
fluridone + diuron	224 + 560	8 bcd	7 ab	2 bc
fluridone + pendimethalin	224 + 1063	20 ab	4 bcd	2 bc
fluridone + fomesafen-low	224 + 140	3 cd	4 bcd	2 bc
fluridone + fomesafen-high	224 + 280	5 cd	4 bcd	3 ab
fluridone + acetochlor	224 + 1250	11 bcd	2 cd	5 a
diuron + fomesafen-low	560 + 140	17 abc	2 cd	0 c
diuron + fomesafen-high	560 + 280	5 cd	8 ab	0 c
acetochlor + fomesafen-low	1260 + 140	21 ab	2 cd	3 ab
acetochlor + fomesafen-high	1260 + 280	20 ab	9 a	0 c

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD Test at $P = 0.05$.
[b] Residual herbicides applied preemergence. All treatments included glufosinate applied at 594 g ha^{-1} EPOST (18 to 27 days after planting) and MPOST (34 to 40 days after planting). Diuron plus MSMA were applied at 1120 plus 2240 g ha^{-1}, respectively, 51 to 64 days after planting.

CHAPTER III

Potential for Fluridone and Encapsulated Acetochlor to Reduce Protoporphyrinogen Oxidase Inhibitor Applications in Cotton

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ABSTRACT

Glyphosate-resistant (GR) Palmer amaranth (*Amaranthus palmeri* S. Wats.) has increased the need for effective residual herbicides in conservation-tillage cotton (*Gossypium hirsutum* L.). Systems with flumioxazin applied preplant and fomesafen applied preemergence (PRE) are commonly used to control GR Palmer amaranth. Both herbicides are protoporphyrinogen oxidase (PPO) inhibitors and are also commonly used in several other crops, thus increasing the potential to select for Palmer amaranth resistant to this mechanism of action. A field study was conducted at four locations to determine the potential for fluridone and acetochlor to substitute for PPO-inhibiting herbicides in Palmer amaranth-infested fields with cotton planted in no-till or strip-till systems. Treatments were no herbicide, fluridone (280 g ai ha^{-1}), or flumioxazin (70 g ai ha^{-1}) applied preplant followed by no herbicide, fomesafen plus diuron (280 plus 560 g ai ha^{-1}), respectively, or acetochlor plus diuron (1260 plus 560 g ai ha^{-1}), respectively, applied PRE. Additional treatments included no herbicide or flumioxazin preplant followed by fluridone (280 g ha^{-1}) PRE. All systems included glufosinate-ammonium at (655 g ai ha^{-1}) applied twice postemergence (POST) and diuron (1120 g ha^{-1}) plus MSMA (1800 g ai ha^{-1}) postemergence-directed. Fluridone and fomesafen applied preplant 23 to 34 d prior to planting were similarly effective on Palmer amaranth. Fluridone was more effective on a mixture of large crabgrass [*Digitaria sanguinalis* (L.) Scop.] and goosegrass [*Eleusine indica* (L.) Gaertn.] than flumioxazin at one location. Fluridone and acetochlor plus diuron applied PRE controlled Palmer amaranth and the annual grasses as well as fomesafen plus diuron PRE. All systems with preplant and PRE herbicides followed by glufosinate-ammonium POST and diuron plus MSMA at layby controlled Palmer amaranth and annual grasses well. Cotton yield did not differ among the herbicide treatments. This research demonstrates that fluridone and acetochlor can substitute for PPO-inhibiting herbicides in management systems for Palmer amaranth.

Nomenclature: Acetochlor; diuron; flumioxazin; fluridone; fomesafen; glufosinate-ammonium; MSMA; cotton, *Gossypium hirsutum* L.; goosegrass, *Eleusine indica* (L.) Gaertn.; large crabgrass, *Digitaria sanguinalis* (L.) Scop.; Palmer amaranth, *Amaranthus palmeri* S. Watts.

Key Words: Herbicide resistance management; herbicide-resistant weeds; PPO-inhibiting herbicides.

INTRODUCTION

Weed control in cotton prior to commercialization of glyphosate-resistant (GR) cultivars was dependent upon residual herbicides. Weed management systems included multiple herbicides with residual activity applied preplant incorporated, preemergence (PRE), and postemergence (POST)-directed (Wilcut et al. 1995). Those systems controlled weeds if rainfall occurred to activate herbicides and a height differential between cotton and weeds was established to allow effective directed applications (Culpepper and York 1997).

Pyrithiobac was registered for POST application to cotton in the early 1990's, giving growers their first option for an over-the-top application to control broadleaf weeds, including Palmer amaranth, without significant injury to the cotton (Branson et al. 2005; Corbett et al. 2004; Jordan et al. 1993a, 1993b). However, pyrithiobac is an acetolactate synthase (ALS) inhibitor, and biotypes of a number of weedy species are resistant to this mechanism of action (Heap, 2015). Much of the Palmer amaranth in North Carolina is resistant to ALS inhibitors (Porrier et al. 2014).

Growers quickly adopted GR cotton once it was commercialized in 1997 (Gianessi 2005). Ease of use and flexibility in application timing, lack of cotton injury and carryover to rotational crops, and similar or better weed control compared to previously used programs encouraged many growers to rely on multiple applications of glyphosate without residual herbicides (Culpepper and York 1997, 1998, 1999; Faircloth et al. 2001). However, these glyphosate-only systems increased selection pressure for GR weed biotypes. There are currently 14 and 32 weed species in the United States and globally, respectively, having populations resistant to glyphosate (Heap 2015).

Palmer amaranth has become the most troublesome weed in row crops in the southern United States (Culpepper et al. 2010; Webster 2013). Many physiological adaptations make Palmer amaranth competitive in cropping systems. The plant has a center of origin in the deserts of the southwestern United States and utilizes the C_4 pathway for photosynthesis (Ehleringer 1983). These attributes, along with a fast developing and extensive root system, allow it to not only grow rapidly but also to compete well with crops under hot, dry conditions (Davis et al. 1967; Ehleringer 1983; Guo and Al-Khatib 2003; Wiese 1968).

Palmer amaranth has an upright growth habit and readily reaches 2 m or more in height, surpassing many crop canopies (Keely et al. 1987; Sellers et al. 2003). Emergence late in the season is not uncommon and Palmer amaranth has the ability to adapt and overcome shading by crops, indicating the need for season-long weed control to suppress seed production (Jha et al. 2008; Keely et al. 1987; MacRae et al. 2013).

Palmer amaranth can be very competitive in cotton and other crops (Klingaman and Oliver 1994; Massinga et al. 2001; Morgan et al. 2001). Cotton yield has been reduced 6 to 15% with one Palmer amaranth 10 m^{-1} of row (MacRae et al. 2013; Morgan et al. 2001; Rowland et al. 1999). Palmer amaranth populations of six plants per 9.1 m^{-1} of row make it impractical to mechanically harvest cotton (Morgan et al. 2001).

Palmer amaranth was first confirmed to be resistant to glyphosate in 2005 in Georgia (Culpepper et al. 2006). Glyphosate-resistant Palmer amaranth has since been confirmed in 25 states throughout the USA (Heap 2015). Palmer amaranth biotypes with multiple resistance to glyphosate and ALS inhibitors are common (Heap 2015; Porrier et al. 2014; Sosnoskie et al. 2011).

To manage GR Palmer amaranth, weed scientists are again strongly recommending residual herbicides as part of an overall management program (Burgos et al. 2006; Culpepper 2015; York 2015). These recommendations start with a residual herbicide, often flumioxazin, as a component of the preplant burndown program applied 2 to 4 wk prior to planting, followed by one to two residual herbicides applied PRE. This is then followed with POST applications of glyphosate or glufosinate tank-mixed with residual herbicides such as *S*-metolachlor or acetochlor and then a POST-directed application including a residual herbicide such as diuron (Culpepper 2015; York 2015). This herbicide program uses multiple sites of action (SOA) and is a proactive resistance management approach that limits selection pressure on any single SOA as well as offering overlapping residual herbicides to limit weed emergence throughout the growing season (Norsworthy et al. 2012).

No-till cotton growers often rely on two protoporphyrinogen oxidase (PPO) inhibitors, flumioxazin preplant followed by fomesafen PRE, as this has been an effective approach to controlling GR Palmer amaranth (Cahoon et al. 2014; Whitaker et al. 2011). Flumioxazin and fomesafen effectively control Palmer amaranth if timely rainfall is received for activation (Cahoon et al. 2014; Everman et al. 2009; Norsworthy et al. 2010; Whitaker et al. 2010, 2011). Flumioxazin will control Palmer amaranth for up to a month into the growing season when applied 2 to 3 wk prior to cotton planting (Cahoon et al. 2014; Price et al. 2002). Prior to GR Palmer amaranth, use of these PPO inhibitors was limited. A survey of Georgia cotton producers showed that before 2006, flumioxazin and fomesafen use on cotton in Georgia was only 3% and 12%, respectively, of total cotton hectares (Sosnoskie and Culpepper 2014). After glyphosate resistance developed, use of flumioxazin increased almost 10-fold to 27% and fomesafen use increased to 81% of cotton grown in Georgia by 2010. Flumioxazin was also applied POST-directed to 23% of the crop after resistance developed. Similar changes in use patterns have also occurred in North Carolina (A. C. York, personal communication). Additionally, PPO inhibitors are commonly used in other crops rotated with cotton in North Carolina, including soybean [*Glycine max* (L.) Merr.], peanut (*Arachis hypogaea* L.), tobacco (*Nicotiana tabacum* L.), and sweetpotato [*Ipomea batatus* (L.) Lam.]. Some of these crops receive multiple PPO-inhibitor applications during a growing season, putting increasing selection pressure on weeds for resistance to the PPO-inhibiting herbicides (Cahoon et al. 2014).

Resistance to PPO inhibitors has not been documented in Palmer amaranth, but resistance in common waterhemp [*Amaranthus tuberculatus* (Moq.) Sauer var. *rudis*] was first documented in Kansas (Shoup et al. 2003) and later in Indiana, Illinois, Iowa, and Missouri (Heap 2015). Multiple resistance to glyphosate, PPO inhibitors, and other SOAs has also been reported in common waterhemp (Heap 2015; Legleiter and Bradley 2008; Patzoldt et al. 2005). Wuerffel et al. (2015) recently reported that use of soil-applied PPO-inhibiting herbicides increases the frequency of resistance in common waterhemp populations resistant to POST-applied PPO-inhibiting herbicides. The mechanism of PPO-inhibitor resistance in common waterhemp involves the loss of a glycine at position 210 in the mitochondrial isoform of the PPO enzyme (Patzoldt et al. 2006). Loss of this amino acid is considered to have occurred via a slippage-like mechanism within a trinucleotide repeat of one of the two isoforms of the PPO enzyme (Patzoldt et al. 2006). Palmer amaranth possesses the same repetitive motif found in common waterhemp (Riggins and Tranel 2012), suggesting continued reliance on PPO-inhibiting herbicides will likely result in PPO-inhibitor resistance in Palmer amaranth (Riggins and Tranel 2012; Wetzel et al. 1999).

Integrating different SOAs in a management system will be required to prevent PPO resistance in Palmer amaranth (Norsworthy et al. 2012; Wuerffel et al. 2015); however, herbicide options are limited (Price et al. 2011; Vencill et al. 2012). Cotton growers have two new soil-applied herbicide options, acetochlor and fluridone, that may be alternatives to PPO-inhibiting herbicides. Acetochlor registered for cotton is a micro-encapsulated formulation that can be applied PRE or POST (Anonymous 2015). Fluridone, alone or pre-mixed with fomesafen, has received Section 18 Emergence Use Exemptions over the last 4 yr in several states. Acetochlor is a Group 15 (Mallory-Smith and Retzinger 2003) herbicide that inhibits very long chain fatty acid synthesis (Fuerst 1987). Fluridone is a Group 12 herbicide which inhibits carotenoid biosynthesis (Bartels and Watson 1978; Kowalczyk-Schroder and Sandmann 1992; Mayer et al. 1989). Group 12 herbicides are currently not being used in row crop production (York 2015). Moreover, very few weedy species have developed resistance to Group 12 or Group 15 herbicides (Heap 2015). Acetochlor applied PRE controls Palmer amaranth with little to no cotton injury (Cahoon et al. 2015). Fluridone applied PRE controls Palmer amaranth, and cotton has good tolerance (Banks and Merkle 1979; Berard et al. 1978; Crow et al. 2014; Hill et al. 2013; Thompson et al. 1978; Waldrep and Taylor 1976). Understanding how these two herbicides can best be used to reduce reliance on PPO inhibitors will be critical in formulating management strategies to prevent PPO-inhibitor resistance in Palmer amaranth. The objective of this research was to compare Palmer amaranth control and cotton response to fluridone and flumioxazin applied preplant and fluridone, acetochlor, and fomesafen applied PRE.

MATERIALS AND METHODS

The experiment was conducted at the Central Crops Research Station at Clayton, NC in 2013 and 2014, the Upper Coastal Plain Research Station at Rocky Mount, NC in 2014, and on a private farm at Mount Olive, NC in 2013. Different fields were used in each year at Clayton. Soil at Clayton was a Norfolk loamy sand (fine-loamy, kaolinitic, thermic Typic Kandiudults) with humic matter of 0.22 and 0.51% in 2013 and 2014, respectively, and pH of

5.5 both years. Soil at Rocky Mount was an Aycock sandy loam (fine-silty, siliceous, subactive, thermic Typic Paleudults) with humic matter of 0.32 and pH of 5.9. The Mount Olive location had a Wagram loamy sand (loamy, kaolinitic, thermic Arenic Kandiudults) with humic matter of 0.41% and a pH of 5.1. Soil humic matter was determined by the Agronomic Services Division of the North Carolina Department of Agriculture and Consumer Services using methods described by Mehlich (1984). Each field was naturally infested with Palmer amaranth at populations greater than 100 plants per m^{-2}. Other species included annual grasses, comprised of large crabgrass [*Digitaria sanguinalis* (L.) Scop.] and goosegrass [*Eleusine indica* (L.) Gaertn.], at populations greater than 100 plants per m^{-2} at Clayton and Rocky Mount.

Cotton planting dates and herbicide application dates are listed in Table 7. Herbicides and application rates are given in Table 8. Cotton variety ST 4946GLB2 (Bayer CropScience, Research Triangle Park, NC) was planted no-till into a wheat (*Triticum aestivum* L.) cover crop at Clayton and in a strip-tillage system (Meijer and Edmisten 2015) in cotton stalks from the previous year at Mount Olive and Rocky Mount. A preplant burndown application of glyphosate plus 2,4-D was applied on the same day but separately from the preplant herbicides described below. Paraquat plus crop oil concentrate was applied 3 hr or less ahead of planting. Plot size was four rows by 9 m with row spacing of 91 cm at Rocky Mount and 97 cm at other locations.

Nine treatments consisted of a factorial arrangement of preplant by PRE herbicides. Preplant herbicides were none, flumioxazin, and fluridone. The PRE herbicides, applied within 2 hr after planting, were none, fomesafen plus diuron, and acetochlor plus diuron.

Two additional treatments included no preplant herbicide followed by fluridone PRE and flumioxazin preplant followed by fluridone PRE. All plots except the no-herbicide check received two POST applications of glufosinate when cotton was in the 1- to 2-leaf (EPOST) and 6- to 8-leaf (MPOST) stages. These POST applications were targeted at Palmer amaranth 6 to 10 cm tall. All plots except the check also received a POST-directed layby application of diuron plus MSMA plus non-ionic surfactant when cotton was 40 to 50 cm tall. The preplant, PRE, and POST herbicides were applied using a CO_2- pressurized backpack sprayer equipped with flat-fan nozzles (DG TeeJet® Drift Guard Flat Spray Tips, TeeJet Technologies, Wheaton, IL) delivering 140 L ha^{-1} at 165 kPa. The POST-directed herbicides were applied using a CO_2-pressurized backpack sprayer with a single flood nozzle (TK-VS2 FloodJet® wide angle flat-spray nozzle, TeeJet Technologies) delivering 140 L ha^{-1} at 210 kPa.

Weed control and crop injury were estimated visually prior to EPOST and MPOST application, 14 d after layby application, and late-season (September) according to Frans et al. (1986). At three of four locations, above-ground weed fresh weight was recorded following the late-season evaluation. Fresh weights were determined from 1 m^{-2} in non-treated checks and from three row middles (25 to 26 m^{-2}) in all other plots. Large crabgrass and goosegrass were not differentiated by species in the visual estimates of control and fresh weights. Cotton was mechanically harvested in mid-October to mid-November and a composite sample of seed cotton was ginned to determine lint percentage. Data for cotton injury, weed control, and yield were initially subjected to analysis of variance appropriate for the preplant by PRE herbicide factorial treatment arrangement using the PROC GLIMMIX procedure of SAS (Version 9.3; SAS Institute Inc., Cary, NC). Herbicide treatments and locations were treated as fixed factors while replications were treated as random. Preplant by PRE herbicide interactions were noted for most variables, hence a second analysis using PROC GLIMMIX was conducted comparing the nine treatments in the factorial arrangement plus the additional two treatments. Means were separated using Fisher's Protected LSD at $P = 0.05$. Non-treated checks were not included. From a separate analysis of variance which included the non-treated checks, Dunnett's procedure (Dunnett 1955) compared weed fresh weights in non-treated checks to all other treatments.

RESULTS AND DISCUSSION

Location by treatment interactions were observed for some evaluations, hence data are presented by location. At all locations, rainfall was received to activate preplant and PRE herbicides with all locations receiving 1.2 to 5.8 cm of rainfall in the 5 d following preplant application (Table 9). The Clayton locations received 1.0 and 9.8 cm of rainfall in the first 5 d following PRE herbicide application in 2013 and 2014, respectively. The Clayton 2013 location received another 9.3 cm during the 6- to 10-d period after PRE herbicide application. Rocky Mount received 6.6 cm in the 6- to 10-d period after PRE herbicide application. The Mount Olive location received no rainfall during the first 10 d after PRE herbicide application but received 4.9 cm during the 11- to 15-d period after application.

Palmer amaranth control. *2013 experiments.* Prior to EPOST application, all treatments at Clayton controlled Palmer amaranth ≥ 99% (Table 10). At Mount Olive, all treatments except flumioxazin and fluridone preplant with no PRE herbicide controlled Palmer amaranth similarly and at least 95%. Fluridone and flumioxazin preplant, in the absence of a

PRE herbicide, controlled the weed 85 and 89%, respectively. Fluridone was 11% more effective applied PRE compared with preplant application. Acetochlor plus diuron, fomesafen plus diuron, and fluridone applied PRE each controlled Palmer amaranth 96% at Mount Olive. Palmer amaranth control by these three PRE herbicides or herbicide combinations was similar with and without a preplant herbicide.

Glufosinate-ammonium applied EPOST was very effective at Clayton. Prior to the MPOST application, glufosinate-ammonium alone controlled Palmer amaranth 98% (Table 10). With this high level of control by the EPOST application, none of the preplant or PRE herbicides increased control. At Mount Olive, glufosinate-ammonium EPOST controlled Palmer amaranth 92%. Small but significant increases in control were noted with all preplant and PRE herbicides. Fluridone and flumioxazin applied preplant, in the absence of a PRE herbicide, were similarly effective and controlled Palmer amaranth 96 and 98%, respectively. Fluridone and fomesafen plus diuron applied PRE were similarly effective whereas fluridone PRE was 3% more effective than acetochlor plus diuron. Palmer amaranth control was generally greater in systems with both preplant and PRE herbicides compared to PRE herbicides only. Control was increased 3 to 5% when either fluridone or fomesafen applied preplant was included in systems with acetochlor plus diuron or fomesafen plus diuron applied PRE. Control was similar with fluridone PRE with and without flumioxazin preplant.

Glufosinate-ammonium was applied timely in 2013 (weeds less than 10 cm tall) and controlled Palmer amaranth well. Glufosinate-ammonium applied twice, followed by diuron plus MSMA POST-directed, controlled Palmer amaranth 99 to 100% in the absence of preplant or PRE herbicides 14 d after the layby application (Table 10). Similar control was obtained late in the season (data not shown). Excellent control of Palmer amaranth by glufosinate-ammonium applied timely has been reported previously (Cahoon et al. 2014; Everman et al. 2009). Palmer amaranth fresh weight was not determined at Clayton. At Mount Olive, compared with the non-treated control, all herbicide treatments reduced late-season Palmer amaranth fresh weight by at least 99.9% (Table 11).

2014 experiments. At time of the EPOST application at Rocky Mount, all treatments controlled Palmer amaranth at least 93% (Table 12). Palmer amaranth control by fluridone applied preplant was 6% less than control by flumioxazin preplant but similar to control by fluridone PRE. Acetochlor plus diuron, fomesafen plus diuron, and fluridone applied PRE were similarly effective and controlled Palmer amaranth 96 to 99%. Except for acetochlor plus diuron, preplant herbicides included in systems with PRE herbicides did not increase control compared with PRE herbicides alone; control in systems with acetochlor plus diuron increased 4% when flumioxazin was included preplant.

Excellent Palmer amaranth control was again obtained at Rocky Mount with glufosinate-ammonium applied POST. In the absence of preplant or PRE herbicides, glufosinate-ammonium applied EPOST controlled Palmer amaranth 97% at the time of MPOST application (Table 12). Preplant and PRE herbicides did not further increase control. At 14 d after layby application, following two POST applications of glufosinate-ammonium and diuron plus MSMA POST-directed, Palmer amaranth was controlled 100% in the absence of preplant or PRE herbicides. Similar control was noted late in the season (data not shown).

Palmer amaranth fresh weight in the non-treated check was 25,630 kg ha^{-1} compared with 0 kg ha^{-1} in all herbicide-treated plots (Table 11).

At Rocky Mount in 2014 and at both locations in 2013 (Tables 10 and 12), flumioxazin preplant was at least as effective as fluridone preplant. At Clayton in 2014, at time of EPOST application, flumioxazin preplant controlled Palmer amaranth only 71% compared with 87% control by fluridone (Table 12). Residues may intercept residual herbicides and the herbicide must be washed off the residue in order to contact the soil to control weeds (Reddy et al. 1995; Reddy and Locke 1996). Larger amounts of residue from the cover crop were present at Clayton in 2014 than at other locations, and the residue likely intercepted more herbicide. No data are available on ease of fluridone washoff from residue, but Hixson (2008) reported that flumioxazin was more difficult to wash off several kinds of plant residue than other herbicides evaluated. Acetochlor plus diuron, fomesafen plus diuron, and fluridone applied PRE were similarly effective and controlled Palmer amaranth 93 to 99% (Table 12). Neither flumioxazin nor fluridone applied preplant increased control in systems with these three herbicides or herbicide combinations applied PRE.

At the time of MPOST application at Clayton, following an EPOST application of glufosinate-ammonium, Palmer amaranth was controlled at least 96% in all systems that included a PRE herbicide (Table 12). Acetochlor plus diuron, fomesafen plus diuron, and fluridone were similarly effective and there was no increase in control when a preplant herbicide was included in systems with any of these PRE herbicides. Palmer amaranth was small (5 cm) in systems with a PRE herbicide when glufosinate-ammonium was applied EPOST. In the absence of PRE herbicides, the Palmer amaranth was considerably larger (averaging 10 to 13 cm tall) at time of EPOST application, and glufosinate-ammonium controlled the weed only 48%. This demonstrates the importance of Palmer amaranth size when treating with glufosinate-ammonium and the value of PRE herbicides in management systems. The poor control by flumioxazin preplant was still evident. Palmer amaranth was controlled 82% in the system with flumioxazin preplant followed by glufosinate-ammonium EPOST compared with at least 96% control in systems with PRE herbicides and good initial weed control. The second glufosinate-ammonium application and the layby application partially compensated for the poor initial control with glufosinate-ammonium. However, control 14 d after layby application was still less in systems without residual herbicides compared with all other systems. This was also reflected in late-season Palmer amaranth fresh weights (Table 13).

Annual grass control. Mixed populations of large crabgrass and goosegrass were present at three of the four locations. At Clayton in 2013, all preplant and PRE herbicides controlled annual grasses at least 97% at time of EPOST application (Table 13). Glufosinate-ammonium applied EPOST controlled grasses 96% at time of MPOST application. Small, but significant, increases in control were noted with all preplant and PRE herbicides. At Clayton in 2014, all herbicides except flumioxazin preplant controlled grasses at least 89% (Table 14). Flumioxazin preplant controlled grasses only 48%. As discussed for Palmer amaranth control, the poor grass control by flumioxazin may have been due to the herbicide being tied up on cover crop residue. Glufosinate EPOST controlled grasses only 60% at time of MPOST application. All preplant and PRE herbicides except flumioxazin increased control to at least 93%. The grasses were controlled only 81% by flumioxazin preplant followed by glufosinate-ammonium EPOST. Following the MPOST application of glufosinate-ammonium and the layby application of diuron plus MSMA, grasses were controlled 86%. All preplant and PRE herbicides increased control to at least 98%. At Rocky Mount in 2014, all preplant and PRE herbicides controlled grasses 99 to 100% at time of EPOST application. Glufosinate-ammonium applied EPOST controlled grasses 97%. A small increase in control was noted when most preplant and PRE herbicides were included. Following the layby application, grasses were controlled completely in all treatments. Similar results were noted with annual grass fresh weight (Table 11).

Cotton response. Only minor cotton injury was observed, and differences among treatments were not significant. At time of EPOST application, injury averaged 3, 3, 2, and 1% at Clayton 2013, Mount Olive 2013, Rocky Mount 2014, and Clayton 2014, respectively (data not shown). Injury was transient, with little to no injury noted at later observations.

Non-treated checks were inundated with weeds and could not be harvested. No differences in cotton lint yield were noted among herbicide treatments at any location (Table 15). Lack of a yield response to preplant or PRE herbicides at both locations in 2013 and Rocky Mount in 2014 reflects the high level of control by glufosinate-ammonium plus the layby herbicides (Tables 10 and 12). Although PRE herbicides increased Palmer amaranth control at Clayton in 2014, the early weed competition was insufficient to adversely impact cotton yield.

At three of four locations in this research, little to no improvement in weed control resulted from use of preplant or PRE herbicides. Lack of response to these residual herbicides was primarily due to timely glufosinate-ammonium application and relatively small weeds at time of the layby application. However, a large improvement in Palmer amaranth control was noted at one location where the weeds were too large for effective control by glufosinate-ammonium in the absence of residual herbicides. This demonstrates that soil-applied residual herbicides can provide greater flexibility in timing of POST herbicides. Additionally, soil-applied residual herbicides are a critical component of herbicide resistance management strategies. Soil-applied residual herbicides significantly reduce selection pressure placed upon POST herbicides. Although no resistance to glufosinate-ammonium has been documented in Palmer amaranth and only a few other species have evolved resistance (Heap 2015), glufosinate-ammonium is critical in the management of GR Palmer amaranth. Soil-applied residual herbicides should be components of glufosinate-ammonium-based management programs to reduce the potential for evolution of resistance to this herbicide.

The PPO-inhibiting herbicides, flumioxazin and fomesafen, are also critical in the management of GR Palmer amaranth. Flumioxazin applied preplant in no-till systems and fomesafen alone or in combination with another herbicide applied PRE effectively control GR Palmer amaranth. However, these herbicides are being used extensively, thus increasing the risk of selecting for resistant biotypes. This research demonstrates that fluridone and acetochlor can effectively substitute for PPO-inhibiting herbicides.

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Table 7. Planting and herbicide application dates.[a]

Location	Year	Planting date	Herbicide application date: Preplant	PRE	EPOST	MPOST	Layby
Clayton	2013	May 13	April 9	May 13	June 4	June 20	July 16
Mount Olive	2013	May 8	April 15	May 8	May 31	June 17	July 2
Rocky Mount	2014	May 6	April 11	May 6	May 27	June 13	July 1
Clayton	2014	May 12	April 10	May 12	June 3	June 17	July 2

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

Table 8. Herbicide trade names, formulations, manufacturers, and application rates.

Herbicides and adjuvants	Trade name	Formulation concentration	Application rate	Manufacturer
			ha^{-1}	
acetochlor	Warrant®	360 g ai L^{-1}	1260 g ai	Monsanto Co., St. Louis, MO
crop oil concentrate	Agri-Dex®	99%	1.0% (v/v)	Helena Chemical Co., Collierville, TN
2,4-D dimethylamine salt	Weedar® 64	456 g ae L^{-1}	800 g ae	Nufarm Inc., Morrisville, NC
diuron	Direx® 4L	480 g ai L^{-1}	560 g ai[a]	ADAMA Agicultural Solutions, Raleigh,
			1120 g ai[b]	
flumioxazin	Valor® SX	51%	71 g ai	Valent U.S.A. Corp., Walnut Creek, CA
fluridone	experimental	240 g ai L^{-1}	280 g ai	SePRO Corp., Carmel, IN
fluridone + fomesafen	Brake® F2	192 + 120 g ai L^{-1}	168 + 210 g ai	SePRO Corp., Carmel, IN
fomesafen	Reflex®	240 g ai L^{-1}	280 g ai	Syngenta Crop Protection, Greensboro, NC
glufosinate-ammonium	Liberty® 280 SL	280 g ai L^{-1}	655 g ai	Bayer CropScience, RTP, NC
glyphosate potassium salt	Roundup PowerMAX®	540 g ae L^{-1}	1200 g ae	Monsanto Co., St. Louis, MO
MSMA	MSMA 6	720 g ai L^{-1}	1800 g ai	Drexel Chemical Co., Memphis, TN
non-ionic surfactant	Induce®	90%	0.25% (v/v)	Helena Chemical Co., Collierville, TN
paraquat dichloride	Parazone® 3SL	360 g ae L^{-1}	840 g ae	ADAMA Agicultural Solutions, Raleigh,

a Applied preemergence.
b Applied postemergence-directed.

Table 9. Rainfall following preplant and preemergence herbicide application.

		Days after application					
		Preplant			Preemergence		
Location	Year	0-5	6-10	11-15	0-5	6-10	11-15
		cm					
Clayton	2013	1.2	2.4	0.4	1.0	9.3	0.2
Mount Olive	2013	1.7	0.1	1.9	0	0	4.9
Rocky Mount	2014	5.8	0.9	1.7	0	6.6	0
Clayton	2014	3.5	1.8	1.9	9.8	0	0

Table 10. Palmer amaranth control by residual herbicides in 2013.[a,b]

Residual herbicides[c]		At time of EPOST[d]		At time of MPOST[d]		14 d after layby[e]	
Preplant	PRE	Clayton	Mount Olive	Clayton	Mount Olive	Clayton	Mount Olive
		%					
none	none			98 a	92 e	100 a	99 a
none	acetochlor + diuron	100 a	96 ab	100 a	95 d	100 a	100 a
none	fomesafen + diuron	100 a	96 ab	99 a	96 cd	99 a	99 a
none	fluridone	100 a	96 ab	100 a	98 abc	100 a	100 a
flumioxazin	none	100 a	89 bc	100 a	98 abc	100 a	99 a
flumioxazin	acetochlor + diuron	100 a	100 a	100 a	100 a	100 a	99 a
flumioxazin	fomesafen + diuron	100 a	99 a	100 a	99 ab	100 a	100 a
flumioxazin	fluridone	100 a	95 ab	100 a	97 bcd	100 a	100 a
fluridone	none	100 a	85 c	100 a	96 cd	100 a	100 a
fluridone	acetochlor + diuron	100 a	100 a	100 a	99 ab	100 a	100 a
fluridone	fomesafen + diuron	99 a	98 a	100 a	99 ab	100 a	100 a

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD Test at P = 0.05.

[b] Abbreviations: PRE, preemergence; EPOST, early postemergence; MPOST, mid-postemergence.

[c] Flumioxazin and fluridone applied at 71 and 280 g ha^{-1}, respectively, 23 to 34 days prior to planting. Acetochlor, diuron, fluridone, and fomesafen applied PRE at 1260, 560, 280, and 280 g ha^{-1}, respectively.

[d] Glufosinate-ammonium applied at 655 g ha^{-1} to 2-leaf (EPOST) and 8-leaf (MPOST) cotton.

[e] Diuron and MSMA applied POST-directed to 40- to 50-cm cotton at 1120 and 1800 g ha^{-1}, respectively.

Table 11. Late-season Palmer amaranth and annual grass fresh weight.[a,b]

Residual herbicides[c]		Palmer amaranth			Annual grasses[d]	
		Mount Olive	Clayton	Rocky	Clayton	Rocky Munt
Preplant	PRE	2013	2014	2014	2014	2014
		kg ha^{-1}				
none	none	20 a	1040 a	0 a	100 a	0 a
none	acetochlor + diuron	10 a	0 b	0 a	0 b	0 a
none	fomesafen + diuron	30 a	0 b	0 a	0 b	0 a
none	fluridone	10 a	0 b	0 a	0 b	0 a
flumioxazin	none	20 a	400 b	0 a	0 b	0 a
flumioxazin	acetochlor + diuron	30 a	0 b	0 a	0 b	0 a
flumioxazin	fomesafen + diuron	0 a	0 b	0 a	0 b	0 a
flumioxazin	fluridone	10 a	0 b	0 a	0 b	0 a
fluridone	none	10 a	170 b	0 a	0 b	0 a
fluridone	acetochlor + diuron	10 a	0 b	0 a	0 b	0 a
fluridone	fomesafen + diuron	20 a	0 b	0 a	0 b	0 a
Non-treated		42,070[e]	24,480[e]	25,630[e]	12,690[e]	6,470[e]

[a] Means within a column are not different according to Fisher's Protected LSD Test at P = 0.05.

[b] Abbreviations: PRE, preemergence.

[c] Flumioxazin and fluridone applied at 71 and 280 g ha^{-1}, respectively, 23 to 34 days prior to planting. Acetochlor, diuron, fluridone, and fomesafen applied at 1260, 560, 280, and 280 g ha^{-1}, respectively, PRE. Glufosinate-ammonium applied at 655 g ha^{-1} to 2-leaf (EPOST) and 8-leaf (MPOST) cotton. Diuron and MSMA applied POST-directed to 40- to 50-cm cotton at 1120 and 1800 g ha^{-1}, respectively.

[d] Annual grasses consisted of large crabgrass and goosegrass.

[e] Non-treated check different from all herbicide treatments according to Dunnett's procedure at P = 0.05.

Table 12. Palmer amaranth control by residual herbicides in 2014.[a,b]

Residual herbicides[c]		At time of EPOST[d]		At time of MPOST[d]		14 d after layby[e]	
Preplant	PRE	Clayton	Rocky Mount	Clayton	Rocky Mount	Clayton	Rocky Mount
		%					
none	none			48 c	97 a	90 b	100 a
none	acetochlor + diuron	97 a	96 bcd	98 a	100 a	100 a	100 a
none	fomesafen + diuron	93 ab	99 ab	96 a	98 a	100 a	100 a
none	fluridone	99 a	96 bcd	99 a	98 a	97 a	100 a
flumioxazin	none	71 c	99 ab	82 b	96 a	100 a	100 a
flumioxazin	acetochlor + diuron	100 a	100 a	99 a	100 a	100 a	100 a
flumioxazin	fomesafen + diuron	100 a	100 a	100 a	99 a	99 a	100 a
flumioxazin	fluridone	100 a	95 cd	100 a	98 a	100 a	100 a
fluridone	none	87 b	93 d	91 ab	99 a	100 a	99 a
fluridone	acetochlor + diuron	100 a	98 abc	100 a	100 a	100 a	100 a
fluridone	fomesafen + diuron	99 a	99 ab	99 a	100 a	100 a	100 a

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD Test at P = 0.05.

[b] Abbreviations: PRE, preemergence; EPOST, early postemergence; MPOST, mid-postemergence.

[c] Flumioxazin and fluridone applied at 71 and 280 g ha^{-1}, respectively, 23 to 34 days prior to planting. Acetochlor, diuron, fluridone, and fomesafen applied at 1260, 560, 280, and 280 g ha^{-1}, respectively, PRE.

[d] Glufosinate-ammonium applied at 655 g ha^{-1} to 2-leaf (EPOST) and 8-leaf (MPOST) cotton.

[e] Diuron and MSMA applied POST-directed to 40- to 50-cm cotton at 1120 and 1800 g ha^{-1}, respectively.

Table 13. Annual grass control by residual herbicides at Clayton in 2013.[a,b]

Residual herbicides[c]				
Preplant	PRE	At time of EPOST[d]	At time of MPOST[d]	14 d after layby[e]
		%		
none	none		96 d	95 e
none	acetochlor + diuron	100 a	99 b	96 cd
none	fomesafen + diuron	100 a	99 b	99 ab
none	fluridone	100 a	100 a	100 a
flumioxazin	none	97 a	98 d	96 cd
flumioxazin	acetochlor + diuron	98 a	100 a	97 bcd
flumioxazin	fomesafen + diuron	97 a	100 a	97 bcd
flumioxazin	fluridone	100 a	100 a	99 ab
fluridone	none	100 a	100 a	98 abc
fluridone	acetochlor + diuron	100 a	100 a	99 ab
fluridone	fomesafen + diuron	100 a	100 a	100 a

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD Test at P = 0.05.

Annual grasses consisted of large crabgrass and goosegrass.

[b] Abbreviations: PRE, preemergence; EPOST, early postemergence; MPOST, mid-postemergence.

[c] Flumioxazin and fluridone applied at 71 and 280 g ha^{-1}, respectively, 23 to 34 days prior to planting. Acetochlor, diuron, fluridone, and fomesafen applied at 1260, 560, 280, and 280 g ha^{-1}, respectively, PRE.

[d] Glufosinate-ammonium applied at 655 g ha^{-1} to 2-leaf (EPOST) and 8-leaf (MPOST) cotton.

[e] Diuron and MSMA applied POST-directed to 40- to 50-cm cotton at 1120 and 1800 g ha^{-1}, respectively.

Table 14. Annual grass control by residual herbicides in 2014.[a,b]

Residual herbicides[c]		At time of EPOST[d]		At time of MPOST[d]		14 d after layby[e]	
Preplant	PRE	Clayton	Rocky Mount	Clayton	Rocky Mount	Clayton	Rocky Mount
		%					
none	none			60 c	97 c	86 b	100 a
none	acetochlor + diuron	99 a	100 a	100 a	100 a	100 a	100 a
none	fomesafen + diuron	93 a	99 a	95 a	98 bc	100 a	100 a
none	fluridone	96 a	100 a	98 a	100 a	100 a	100 a
flumioxazin	none	48 b	99 a	81 b	99 ab	98 a	100 a
flumioxazin	acetochlor + diuron	99 a	100 a	100 a	100 a	100 a	100 a
flumioxazin	fomesafen + diuron	97 a	99 a	96 a	100 a	100 a	100 a
flumioxazin	fluridone	97 a	100 a	99 a	99 ab	100 a	100 a
fluridone	none	89 a	99 a	93 a	99 ab	100 a	100 a
fluridone	acetochlor + diuron	98 a	100 a	100 a	100 a	100 a	100 a
fluridone	fomesafen + diuron	97 a	100 a	98 a	100 a	100 a	100 a

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD Test at P = 0.05. Annual grasses consisted of large crabgrass and goosegrass.

[b] Abbreviations: PRE, preemergence; EPOST, early postemergence; MPOST, mid-postemergence.

[c] Flumioxazin and fluridone applied at 71 and 280 g ha^{-1}, respectively, 25 to 32 days prior to planting. Acetochlor, diuron, fluridone, and fomesafen applied PRE at 1260, 560, 280, and 280 g ha^{-1}, respectively.

[d] Glufosinate-ammonium applied at 655 g ha^{-1} to 2-leaf (EPOST) and 8-leaf (MPOST) cotton.

[e] Diuron and MSMA applied POST-directed to 40- to 50-cm cotton at 1120 and 1800 g ha^{-1}, respectively.

Table 15. Cotton lint yield as affected by residual herbicides.[a,b]

Residual herbicides[c]			Mount		Rocky
Preplant	PRE	Clayton	Olive	Clayton	Mount
		kg ha^{-1}			
none	none	790 a	1410 a	1600 a	2560 a
none	acetochlor + diuron	810 a	1440 a	1450 a	2440 a
none	fomesafen + diuron	1020 a	1390 a	1640 a	2570 a
none	fluridone	840 a	1270 a	1710 a	2600 a
flumioxazin	none	1060 a	1450 a	1590 a	2560 a
flumioxazin	acetochlor + diuron	820 a	1380 a	1500 a	2520 a
flumioxazin	fomesafen + diuron	940 a	1490 a	1330 a	2610 a
flumioxazin	fluridone	1020 a	1520 a	1630 a	2590 a
fluridone	none	820 a	1570 a	1810 a	2510 a
fluridone	acetochlor + diuron	920 a	1450 a	1560 a	2610 a
fluridone	fomesafen + diuron	1080 a	1360 a	1650 a	2630 a

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD Test at P = 0.05.

[b] Abbreviations: PRE, preemergence.

[c] Flumioxazin and fluridone applied at 71 and 280 g ha^{-1}, respectively, 25 to 32 days prior to planting. Acetochlor, diuron, fluridone, and fomesafen applied PRE at 1260, 560, 280, and 280 g ha^{-1}, respectively. Glufosinate-ammonium applied at 655 g ha^{-1} to 2-leaf (EPOST) and 8-leaf (MPOST) cotton. Diuron and MSMA applied POST-directed to 40- to 50-cm cotton at 1120 and 1800 g ha^{-1}, respectively.

CHAPTER IV

Effect of Diuron and Fluometuron on Grain Sorghum and Soybean as Replacement Crops Following a Cotton Stand Failure

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ABSTRACT

Preemergence herbicides are widely used in cotton (*Gossypium hirsutum* L.) to control glyphosate-resistant weeds. If a stand failure occurs after the acceptable replanting date for cotton, the most likely replacement crops are grain sorghum [*Sorghum bicolor* (L.) Moench.] and soybean [*Glycine max* (L.) Merr.]. When replanting to another crop, one must consider the potential impact of previously applied cotton herbicides on the replacement crop. The goal of this study was to determine the potential for sorghum and soybean as replacement crops following diuron- and fluometuron-treated cotton on coarse-textured, low organic matter soils. Specific objectives were to determine effects of tillage and time between herbicide application and replacement crop planting. Treatments consisted of a factorial arrangement of no herbicide, 1120 g ai ha^{-1} of fluometuron, or 840 g ai ha^{-1} of diuron, replant delays of 3, 6 or 9 wks after cotton herbicide application, and no tillage or disking prior to replacement crop planting. Soybean response to cotton herbicides was noted primarily with the 3-wk replant delay, and a greater response was noted with fluometuron. Soybean planted

3 wk after diuron application was injured 15% and stand reduced 17% at one location while injury was 2% or less and stand reduction 5% or less at two other locations. Soybean planted 3 wk following fluometuron application was injured 33% at one location and 6% at other locations while stand was reduced 14 to 21% at each location. Disking prior to soybean planting generally increased injury. Regardless of replant delay, diuron did not reduce soybean yield. Soybean yield was reduced at 2 of 3 locations by fluometuron in a 3-wk replant delay but not with 6- or 9-wk replant delays. No visible injury was noted on grain sorghum and yield was not reduced at any of four locations regardless of replant delay or cotton herbicide.

Nomenclature: Diuron; fluometuron; cotton, *Gossypium hirsutum* L.; grain sorghum [*Sorghum bicolor* (L.) Moench.]; soybean [*Glycine max* (L.) Merr.]

INTRODUCTION

Glyphosate-resistant (GR) cotton cultivars, commercially released in 1997, offered a number of benefits to growers (Culpepper and York 1998,1999; Gianessi 2008), and the technology was quickly adopted in the U.S. (Gianessi 2005). Nearly all the cotton now grown in the Southeast and Mid-South regions of the U.S. Cotton Belt is resistant to glyphosate or glyphosate and glufosinate (USDA-AMS 2014). Glyphosate-resistant cotton allowed growers to obtain good weed control while reducing or eliminating use of soil-applied residual herbicides (Culpepper and York 1998, 1999; Scott et al. 2002). This alleviated concerns over crop injury from soil-applied herbicides and potential carryover to rotational crops (Bradley et al. 2001; York 1993). Unfortunately, extensive reliance on glyphosate in the absence of other herbicide modes of action led to selection for GR weed biotypes. Resistance to glyphosate has now been confirmed in 32 and 14 weed species globally and in the U.S., respectively (Heap 2015). The first confirmation of resistance to glyphosate in an *Amaranthus* species occurred with Palmer amaranth in Georgia in 2004 (Culpepper et al. 2006). By the end of 2014, GR Palmer amaranth had been confirmed in 24 states in the U.S. (Heap 2015). Multiple resistance to glyphosate and acetolactate synthase (ALS)-inhibiting herbicides is also common (Heap 2015; Nandula et al. 2012; Poirier et al. 2014; Sosnoskie et al. 2011). Cotton growers are once again integrating herbicides with other modes of action into their management systems in an attempt to control glyphosate- and ALS-resistant Palmer amaranth (Sosnoskie and Culpepper 2014).

Cotton planting in North Carolina is typically done between late April and late May. Cotton requires a relatively long growing season, and planting after late May typically results in reduced yields in North Carolina (Guthrie 1991; Nuti et al. 2006). A cotton stand can be lost due to hail or other adverse weather conditions or seedling diseases. If the stand failure occurs after the acceptable planting date for cotton, the grower must decide on a replacement crop. The most likely replacement crops in the southeastern United States are grain sorghum and soybean. Although grain sorghum and soybean typically produce greater yields when planted in May, both crops can be expected to mature when planted up to mid-July in North Carolina (Anonymous 2011; Wiatrek et al. 2009). When replanting to another crop following a failed cotton stand, one must consider the potential impact of previously applied cotton herbicides on the replacement crop.

Eight soil-applied residual herbicides are currently recommended for use on cotton in North Carolina (York 2015). Flumioxazin is commonly applied about 3 wk ahead of planting as part of a preplant burndown program in conservation tillage cotton. Although no longer commonly used, trifluralin can be applied preplant incorporated (PPI). Pendimethalin can be applied PPI or PRE. Acetochlor, diuron, fluometuron, and fomesafen are commonly applied PRE. Pyrithiobac can also be applied PRE. Acetochlor, flumioxazin, fomesafen, pendimethalin, and trifluralin are registered for use in soybean (Anonymous 2015c, 2015d, 2015f, 2015g, 2015h) and would not be expected to impact soybean planted as a replacement crop after cotton receiving these herbicides. Neither acetochlor nor flumioxazin would be expected to injure grain sorghum. Acetochlor is registered for PRE application to grain sorghum (Anonymous 2015h). Flumioxazin is registered for application 30 d ahead of grain sorghum planting (Anonymous 2015g), and research in Texas has shown that flumioxazin can safely be applied PRE to grain sorghum (Grichar 2006). Grain sorghum would not be a suitable replacement crop following cotton treated with pendimethalin, trifluralin, or fomesafen. Labels for the dinitroaniline herbicides, pendimethalin and trifluralin, have 10- and 12-mo rotational restrictions, respectively, for grain sorghum (Anonymous 2015c, 2015f), and research has shown potential injury to grain sorghum planted the season after dinitroaniline herbicide application (Fink 1972). Fomesafen has relatively long persistence in soil (Mueller et al. 2014; Rauch et al. 2007), and grain sorghum is very sensitive to fomesafen (Cobacci et al. 1998). The label for fomesafen specifies a 10-mo restriction when planting grain sorghum (Anonymous 2015d). Neither grain sorghum nor soybean would be replant options following cotton treated with pyrithiobac. The pyrithiobac label has a 10-mo rotational restriction for both crops (Anonymous 2015e). Johnson et al. (1993) reported injury to soybean and grain sorghum planted 8 and 16 wk, respectively, following pyrithiobac application, and Jordan et al. (1993) reported carryover to grain sorghum planted the season following application to cotton.

The potential to replant to grain sorghum or soybean following application of diuron or fluometuron is less well understood. The label for fluometuron (Anonymous 2015a) specifies a 9-mo rotational restriction for both grain sorghum and soybean. The label for diuron (Anonymous 2015b) simply states that grain sorghum and soybean can be planted the next spring following a broadcast application. It is known that some growers in North Carolina have successfully planted soybean following failed stands of cotton treated with fluometuron. Published research concerning this practice is very limited. Jackson et al. (1978), working on loam and silt loam soils in Tennessee, broadcast fluometuron at 1700 g ha^{-1} and then planted grain sorghum and soybean 3, 6, and 9 wk after fluometuron application. The soil was disked prior to replacement crop planting. On the silt loam soil, soybean stand was reduced in 2 of 3 years and yield was reduced each year when soybean was planted 6 wk after fluometuron application. Stand was not reduced when soybean was planted at 9 wk, but significant injury was noted in 2 of 3 yr and yield was reduced in 1 of 3 yr. Less impact on soybean was observed on the loam soil. This was at least partially attributed to more organic matter in the loam soil and greater adsorption of the fluometuron. Soybean yield was reduced in 1 of 2 yr on the loam soil when soybean was planted 3 wk after fluometuron application, but there was no impact on yield when soybean was planted 6 or 9 wk after application. Fluometuron had no effect on grain sorghum stand on the silt loam soil, but yield was reduced in 2 of 2 yr when grain sorghum was planted 3 wk after herbicide application. No yield impact was noted with the 6- or 9-wk planting delays. Similar to results with soybean, less grain sorghum injury was also noted on the loam soil. Grain sorghum stand and yield were not reduced when grain sorghum was planted 3 wk following fluometuron application.

Sharp et al. (1982) conducted similar studies on silt loam and silty clay soils in Arkansas and reported a greater soybean response to fluometuron residues on the silt loam soil. On the silt loam, soybean yield was reduced in 2 of 3 yr when planted 29 to 30 d after application of 1700 g ha^{-1} of fluometuron. Greater injury to soybean was noted when soil was disked prior to soybean planting compared with no-till planting.

No research is available on the impact of fluometuron on soybean or grain sorghum as replacements crops behind cotton on coarse-textured soils. And, the only data available on diuron is that of Prostko et al. (2013) who found surprisingly better tolerance of soybean than expected. Prostko et al. (2013) applied diuron at 70 to 2240 g ha^{-1} immediately after planting soybean on a sand soil with 0.4% organic matter. Diuron at 2240 g ha^{-1} reduced soybean stand in 1 of 2 yr, and soybean yield was reduced 23 and 41% by diuron at 1120 and 2240 g ha^{-1} in 1 of 2 yr. Diuron at 560 g ha^{-1} had no effect on stand or yield in either year.

Questions continue to arise concerning the planting of an alternative crop behind cotton when stand failures occur (Prostko et al. 2013). In light of the very limited information available, we conducted experiments to determine the potential for grain sorghum and soybean as replacement crops following diuron- and fluometuron-treated cotton on coarse-textured, low organic matter soils typical of cotton production in the southeastern U.S.

Specific objectives were to determine the effects of tillage and time between application of the herbicides and replacement crop planting.

MATERIALS AND METHODS

Separate experiments for grain sorghum and soybean were conducted in North Carolina during 2013 and 2014 at the sites described in Table 16. Fields were disked at the initiation of the experiments. Treatments consisted of a factorial arrangement of three cotton herbicide options, three replant crop planting delays, and two tillage systems for the replacement crops in a split-strip-strip design with treatments replicated four times. Cotton herbicides were the split plot, replant crop planting delays were the first strip, and tillage was the second strip. Replacement crop row spacing and plot dimensions are in Table 17.

Cotton herbicides included fluometuron (Cotoran® 4L, ADAMA USA, Raleigh, NC) at 1120 g ha^{-1}, diuron (Direx® 4L, ADAMA USA) at 840 g ha^{-1}, and no herbicide. Cotton herbicides were applied on the dates listed in Table 17 using a tractor-mounted sprayer equipped with flat-fan nozzles (DG11002 TeeJet® Drift Guard flat-spray nozzles, TeeJet Technologies, Wheaton, IL) calibrated to deliver 140 L ha^{-1} at 193 kPa. A cotton crop was not planted; fields remained fallow until the replacement crops were planted. Replacement crops, grain sorghum or soybean, were planted either no-till or following disking at 3, 6, and 9 wk (20 to 23, 40 to 42, and 61 to 64 d, respectively) after cotton herbicide application (Table 17). Grain sorghum hybrids included 83P17 (Pioneer Hi-Bred International, Johnston, IA) in 2013 and DKS28-05 (Monsanto Company, St. Louis, MO) in 2014. Grain sorghum seed were treated with fluxofenim (Concep® III, Syngenta Crop Protection, Greensboro, NC) seed protectant to protect against chloroacetamide herbicide damage.

Soybean cultivars included AG6732 (Monsanto Company, St. Louis, MO) at Rocky Mount in 2014 and AG5831 (Monsanto Company) at other locations. Atrazine at 1389 g ai ha^{-1} plus *S*-metolachlor at 1075 g ai ha^{-1} (Bicep II Magnum®, Syngenta Crop Protection) were applied PRE to grain sorghum. The sodium salt of fomesafen at 266 g a.e. ha^{-1} plus *S*-metolachlor at 1215 g ai ha^{-1} (Prefix® Herbicide, Syngenta Crop Protection) was applied PRE to soybean. In no-till treatments, paraquat dichloride (Parazone® 3SL, ADAMA USA) at 1260 g ai ha^{-1} plus crop oil concentrate was included with PRE soybean and grain sorghum herbicides. Soybean and grain sorghum herbicides were applied using a CO_2-pressurized backpack sprayer equipped with flat-fan nozzles (DG11002, TeeJet Technologies) delivering 140 L ha^{-1} at 165 kPa. Escaped weeds were removed by hand. Rainfall was recorded onsite (Table 18).

Grain sorghum and soybean injury were estimated visually 3 and 6 wk after planting (WAP) according to Frans et al. (1986) and crop stand was determined at the time of the 6-wk injury rating. Plots were mechanically harvested with separate harvest dates for the three planting dates. Data were subjected to analysis of variance, with partitioning to reflect the factorial treatment arrangement, using the PROC GLM procedure of SAS (version 9.3; SAS Institute Inc., Cary, NC) and means separated using Fisher's Protected LSD Test at $P = 0.05$ where appropriate.

RESULTS AND DISCUSSION

Diuron and fluometuron are degraded primarily by soil microorganisms. Soil moisture would, therefore, be expected to impact the rate of dissipation, with more rapid dissipation occurring with good moisture conditions (El Sebar et al. 2010, Mueller et al. 1992; Rogers et al. 1986). Rainfall at experiment sites varied by year and location (Table 18). Overall, 2013 was a wetter than normal season. Rainfall between cotton herbicide application and the 9-wk planting date was 115, 14, and 47% above normal at Jackson Springs, Lewiston, and Rocky Mount in 2013. Rainfall at Jackson Springs was above normal during each 3-wk segment of the 9-wk period between cotton herbicide application and the 9-wk planting delay. Rainfall at Lewiston was below normal in the first 3-wk period, above normal in the second period, and about normal during the third period. Rainfall at Rocky Mount in 2013 was below normal during the first 3-wk period, normal during the second period and above normal during the third period. In contrast, 2014 was generally drier than normal. Rainfall during the 9-wk period from cotton herbicide application until the 9-wk planting date was 28 to 29% below normal in 2014. However, rainfall during the first 3 wk after cotton herbicide application was well above normal at both locations while rainfall during the second 3-wk period was well below normal.

Soybean Response. Data are presented by location as treatment by location interactions were often noted. Tillage by herbicide or tillage by replant delay interactions were not observed for soybean injury, soybean stand, or soybean yield. A cotton herbicide by replant delay interaction was noted for soybean injury. Greater injury was noted with fluometuron than with diuron, although this injury was primarily observed with the 3-wk replant delay (Table 19). Evaluated at 3 WAP, soybean planted 3 wk after cotton herbicide application was injured 6, 11, and 33% by fluometuron at Lewiston, Rocky Mount in 2014, and Rocky Mount in 2013, respectively, while diuron injured soybean 2, 1, and 15% at the same locations. At 6 WAP, injury to soybean planted 3 wk after fluometuron and diuron application was 6% or less and 1% or less, respectively. Injury appeared primarily as foliar chlorosis.

Soybean stands varied by planting dates, probably due to differing soil moisture conditions at the time of planting and shortly after. Because of variation by planting date, stand data are presented as percent reduction relative to the no-herbicide check within a replant delay and tillage system. A cotton herbicide by replant delay interaction was noted for soybean stand at Lewiston in 2013 and Rocky Mount in 2014. Regardless of replant delay, diuron reduced stands 6% or less (Table 20). In contrast, stand of soybean planted 3 wk after fluometuron application was reduced 16 to 21% at each location and 12% at Lewiston when soybean was planted 6 wk after fluometuron application. A cotton herbicide by replant delay interaction was not observed with stand at Rocky Mount in 2013 and differences between diuron and fluometuron were not observed. Averaged over herbicides, soybean stand at Rocky Mount in 2013 was reduced 15% when soybean was planted 3 wk after cotton herbicide application but only 2 to 4% with planting 6 or 9 wk after diuron or fluometuron application.

The tillage system for soybean had no effect on soybean injury 6 WAP or soybean stand (data not shown). Averaged over herbicides and replant delays, somewhat greater injury was observed 3 WAP when the land was disked prior to soybean planting. At that time, soybean planted following tillage at Lewiston, Rocky Mount in 2013, and Rocky Mount in 2014 was injured 2, 11, and 4%, respectively, while soybean planted no-till was injured 1, 6, and 3%, respectively (data not shown).

Tillage by herbicide or tillage by replant delay interactions were not observed for soybean yield at any location. Averaged over herbicides and replant delays, yield of soybean planted no-till was 12 and 16% greater at Lewiston and Rocky Mount in 2013 but 4% less at Rocky Mount in 2014 (data not shown). A herbicide by replant delay interaction was noted at Lewiston and Rocky Mount in 2013, although the interaction was only significant at $p = 0.10$ at Rocky Mount (Table 21). Compared to the no-herbicide check within a replant delay, diuron did not reduce yield with any replant delay. Yield of soybean planted 3 wk after fluometuron application was reduced 13 to 16% at Lewiston and Rocky Mount in 2013, but no yield reduction occurred when soybean was planted 6 or 9 wk after fluometuron application. However, in spite of the injury and stand reduction (Tables 4 and 5), yield was still greater with soybean planted 3 wk after fluometuron application compared with the 6-wk replant delay (Table 21). This reflects a strong effect of planting date on overall yield at those locations. Averaged over tillage, yields of the no-herbicide checks at Lewiston and Rocky Mount in 2013 were reduced 23 to 24% and 44 to 46% with 6- and 9-wk replant delays, respectively, compared with the 3-wk replant delay. Later planted soybean often yields less than an earlier planted crop (Beatty et al. 1982; Egli and Cornelius 2009). Neither herbicides nor replant delays impacted soybean yield at Rocky Mount in 2014. Lack of an effect of planting date on yield at Rocky Mount in 2014 was likely due to excellent growing conditions. Row spacing or planting date may have little impact on soybean yield if the crop canopy reaches 1 m or more in height and closes the row middles by the early bloom stage (E. J. Dunphy, Extension Soybean Specialist, North Carolina State University, personal communication). Those parameters were met at Rocky Mount in 2014, in part because of above-normal rainfall in the 6- to 9-wk period after cotton herbicide application and the following 60 d (Table 18).

Grain Sorghum Response. No grain sorghum response (visible injury, stand reduction, yield) to previously applied cotton herbicides was noted at Jackson Springs in 2013 or 2014 or at Rocky Mount in 2014. Averaged over all treatments, grain sorghum yields were 2450, 3590, and 3670 kg ha^{-1} at Jackson Springs in 2013, Jackson Springs in 2014, and Rocky Mount in 2014, respectively (data not shown). The only response at Lewiston in 2013 was a significant main effect of replant delays on yield. At that location, yield was similar with replant delays of 3 and 6 wk (5050 and 4580 kg ha^{-1}, respectively) but less (2440 kg ha^{-1}) with the 9-wk replant delay (data not shown). Grain sorghum planted 9 wk after cotton herbicide application at Lewiston failed to fully mature.

Our results are similar to those of Jackson et al. (1978) in that soybean was more sensitive to fluometuron than diuron residues and that grain sorghum was less sensitive than soybean to fluometuron residues. Similar to results of Sharp et al. (1982), we found no benefit from tillage prior to planting replacement crops. And, similar to results of Prostko et al. (2013), soybean tolerance of diuron was surprisingly good. Our results indicate grain sorghum can be planted no-till 3 wk after a failed stand of diuron- or fluometuron-treated cotton, and soybean can be planted no-till 3 wk after diuron-treated cotton. Yield of soybean was reduced at 2 or 3 locations when planted 3 wk after fluometuron but not if planting was delayed 6 wk. However, because earlier planted soybean yielded more, yield of soybean planted 3 wk after fluometuron still exceeded yield of soybean planted 6 wk after fluometuron.

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Table 16. Description of soils at experiment sites.

Site and GPS coordinates	Replacement crop	Year	Soil series[a]	Soil texture	Soil pH[b]	Soil humic Matter[b]
Jackson Springs 35.19° N, -79.69° W	Sorghum	2013	Candor	Sand	6.8	0.6
Jackson Springs 35.18° N, -79.68° W	Sorghum	2014	Candor	Sand	6.5	0.5
Lewiston 36.13° N, -77.18° W	Sorghum	2013	Goldsboro	Sandy loam	6.6	0.9
Rocky Mount 35.87° N, -77.69° W	Sorghum	2014	Johns	Fine sandy loam	6.1	0.5
Lewiston 36.13° N, -77.18° W	Soybean	2013	Goldsboro	Sandy loam	6.6	0.9
Rocky Mount 35.90° N, -77.68° W	Soybean	2013	Norfolk	Loamy sand	6.2	0.5
Rocky Mount 35.89° N, -77.67° W	Soybean	2014	Goldsboro	Fine sandy loam	5.7	0.3

[a] Candor: sandy, kaolinitic, thermic Grossarenic Kandiudult; Goldsboro: fine-loamy, siliceous, subactive, thermic Aquic Paleudult; Johns: fine-loamy over sandy, silicious, semiactive, thermic Aquic Hapludult; Norfolk: fine-loamy, kaolinitic, thermic Typic Kandiudult.

[b] Soils characterized by the Agronomic Services Division of the North Carolina Department of Agriculture and Consumer Services. Soil humic matter determined according to Mehlich (1984).

Table 17. Cotton herbicide application dates, replacement crop planting dates and row spacing, and plot dimensions.

Site	Crop	Year	Cotton herbicide application dates	Replacement crop planting dates			Row spacing	Plot width	Plot length
				3 wk	6 wk	9 wk			
							cm	rows	m
Jackson Springs	Sorghum	2013	25 April	17 May	5 June	25 June	38	16	25
Jackson Springs	Sorghum	2014	29 April	19 May	9 June	30 June	97	8	22
Lewiston	Sorghum	2013	26 April	16 May	6 June	26 June	91	4	25
Rocky Mount	Sorghum	2014	28 April	21 May	11 June	1 July	91	8	22
Lewiston	Soybean	2013	26 April	16 May	6 June	26 June	91	4	25
Rocky Mount	Soybean	2013	26 April	16 May	5 June	26 June	38	12	18
Rocky Mount	Soybean	2014	28 April	21 May	11 June	1 July	91	8	22

Table 18. Rainfall at experiment sites.[a]

Location	Year	Application to 3-wk planting	3-wk planting to 6-wk planting	6-wk planting to 9-wk planting	0 to 30 d after 9-wk planting	31-60 d after 9-wk planting
		cm				
Jackson Springs	2013	10.3 (5.7)	13.1 (5.1)	14.6 (6.9)	30.3 (12.0)	13.5 (12.9)
Lewiston	2013	2.5 (5.5)	12.0 (6.6)	7.0 (6.8)	19.8 (10.9)	8.5 (11.6)
Rocky Mount	2013	3.9 (5.3)	6.2 (6.2)	17.0 (6.9)	19.3 (11.0)	11.6 (12.6)
Jackson Springs	2014	10.2 (5.7)	0.8 (5.1)	1.7 (6.9)	7.1 (12.0)	9.3 (12.9)
Rocky Mount	2014	12.0 (6.1)	2.7 (7.0)	10.4 (6.4)	16.9 (11.6)	22.4 (12.3)

[a] Values in parentheses are 30-yr averages, recorded from 1981 to 2010.

Table 19. Soybean injury as affected by cotton herbicides and replant delays.[a]

Cotton Herbicides[b]	Replant Delay[c]	Lewiston, 2013		Rocky Mount, 2013		Rocky Mount, 2014	
		3 WAP[d]	6 WAP	3 WAP	6 WAP	3 WAP	6 WAP
	wk	%					
diuron	3	2 b	1 a	15 b	1 b	1 d	0 b
diuron	6	0 c	0 c	0 c	0 b	2 c	0 b
diuron	9	0 c	0 c	0 c	0 b	0 e	0 b
fluometuron	3	6 a	3 b	33 a	6 a	11 a	2 a
fluometuron	6	0 c	0 c	2 c	0 b	5 b	0 b
fluometuron	9	0 c	0 c	0 c	0 b	1 d	0 b

[a] Data averaged over tillage and no tillage prior to planting soybean. Means within a column followed by the same letter are not different according to Fisher's Protected LSD Test at $p = 0.05$.

[b] Diuron and fluometuron applied at 860 and 1120 g ha^{-1}, respectively.

[c] Weeks after cotton herbicide application.

[d] WAP, weeks after soybean planting.

Table 20. Soybean stand reduction as affected by cotton herbicides and replant delays.[a]

Cotton Herbicides[b]	Replant Delay[c]	Lewiston 2013	Rocky Mount 2013	Rocky Mount 2014
	wk	% reduction[d]		
diuron	3	5 c	17	3 b
diuron	6	2 c	4	6 b
diuron	9	3 c	2	4 b
fluometuron	3	21 a	14	16 a
fluometuron	6	12 b	4	4 b
fluometuron	9	2 c	2	5 b
Main effect of herbicides				
diuron			7 A	
fluometuron			9 A	
Main effect of replant delays				
3 wk			15 A	
6 wk			4 B	
9 wk			2 B	

[a] Data averaged over tillage and no tillage prior to planting soybean. Means within a column for herbicide by replant delay combinations followed by the same lower case letter are not different according to Fisher's Protected LSD Test at p = 0.05. Means within a column and main effect followed by the same upper case letter are not different at p = 0.05.

[b] Diuron and fluometuron applied at 860 and 1120 g ha^{-1}, respectively.

[c] Weeks after cotton herbicide application.

[d] Expressed as percentage of no-herbicide check within a cotton herbicide and replant delay.

Table 21. Soybean yield as affected by cotton herbicides and replant delays.[a]

Cotton Herbicides[b]	Replant Delay[c]	Lewiston 2013	Rocky Mount 2013	Rocky 2014
	wk	kg ha^{-1}		
no herbicide	3	2890 a	4230 a	3980
no herbicide	6	2200 bc	3240 cd	3790
no herbicide	9	1630 e	2270 e	3880
diuron	3	2780 ab	4080 ab	4000
diuron	6	2070 c	2870 d	3880
diuron	9	1410 e	2020 e	3940
fluometuron	3	2440 b	3690 bc	3760
fluometuron	6	2050 cd	2850 d	3570
fluometuron	9	1710 de	1800 e	3600
Main effect of herbicides				
no herbicide				3880 A
diuron				3940 A
fluometuron				3640 A
Main effect of replant delays				
3 wk				3910 A
6 wk				3750 A
9 wk				3810 A

[a] Data averaged over tillage and no tillage prior to planting soybean. Means within a column for herbicide by replant delay combinations at Lewiston and Rocky Mount in 2013 followed by the same lower case letter are not different according to Fisher's Protected LSD Test at p = 0.05 and p = 0.10, respectively. Means within a main effect at Rocky Mount in 2014 followed by the same upper case letter are not different at p = 0.05.

[b] Diuron and fluometuron applied at 860 and 1120 g ha^{-1}, respectively.

[c] Weeks after cotton herbicide application.