ABSTRACT

GARDNER, ANDREW PERRY. Weed Management in Glufosinate-Tolerant Cotton (*Gossypium hirsutum* L.). (Under the direction of Alan C. York).

Glufosinate controls a broad spectrum of weeds. Control of grassy weeds, however, can sometimes be inadequate, especially when grasses are large or under dry conditions. In situations where less than adequate control of grasses by glufosinate alone might be anticipated, growers may consider mixing a postemergence graminicide with glufosinate. Most herbicides mixed with graminicides antagonize grass control. Research was conducted in North Carolina to determine the potential for antagonism with mixtures of glufosinate and four postemergence graminicides and to determine if antagonism could be alleviated by increasing the rate of graminicide in mixtures, by adding ammonium sulfate to mixtures, or by applying glufosinate and graminicides sequentially.

Antagonism was noted on johnsongrass [Sorghum halepense (L.) Pers.] and mixtures of the annual grasses broadleaf signalgrass [Brachiaria platyphylla (Griseb.) Nash], fall panicum (Panicum dichotomiflorum Michx.), goosegrass [Eleusine indica (L.) Gaertn.], and large crabgrass [Digitaria sanguinalis (L.) Scop.] when glufosinate was mixed with clethodim, fluazifop-P, quizalofop-P, or sethoxydim. Antagonism was not alleviated by increasing the graminicide rate in the mixture by 50% or by including ammonium sulfate in the mixture. Antagonism was not observed when graminicides were applied 3 or more days before glufosinate or 5 or more days after glufosinate.

Amaranthus spp. can also be difficult to control in glufosinate-resistant (GR) cotton (*Gossypium hirsutum* L.). A field experiment was conducted at six locations to determine the effect of residual herbicides and timing of the initial glufosinate application on control of annual grasses, Palmer amaranth (*Amaranthus palmeri* S.Wats.), and redroot pigweed (*Amaranthus retroflexus* L.) in GR cotton. Annual grasses included mixtures of large crabgrass [*Digitaria sanguinalis* (L.) Scop.], goosegrass [*Eleusine indica* (L.) Gaertn.], broadleaf signalgrass [*Brachiaria platyphylla* (Griseb.) Nash], and fall panicum (*Panicum dichotomiflorum* Michx.). Common lambsquarters (*Chenopodium album* L.) and mixtures of entireleaf morningglory (*Ipomoea hederacea* var. *integriuscula* Gray), pitted morningglory (*Ipomoea lacunosa* L.), and tall morningglory [*Ipomoea purpurea* (L.) Roth] were also present. Initial glufosinate application timings were early postemergence (EPOST) to 1- to 2-leaf cotton or mid-postemergence (MPOST) to 3- to 4-leaf cotton. Residual herbicides included fluometuron, fomesafen, pendimethalin, and pyrithiobac applied preemergence (PRE) and pyrithiobac mixed with glufosinate applied EPOST or MPOST. All treatments included glufosinate applied late postemergence (LPOST) to 6- to 7-leaf cotton followed by prometryn plus MSMA postemergence-directed. Weed control and cotton yield were generally greater with glufosinate applied EPOST. Preemergence herbicides increased control of annual grasses and *Amaranthus* spp. after glufosinate EPOST or MPOST at all locations and at most locations after LPOST application. Greater late-season annual grass and *Amaranthus* spp. control was noted at four and two locations, respectively, in systems with PRE herbicides. Differences among PRE herbicides were minor except that pyrithiobac was less effective on annual grasses. Pyrithiobac applied postemergence

(POST) was less effective than PRE herbicides. *Ipomoea* spp. and common lambsquarters were controlled well by all herbicide systems regardless of PRE herbicides or pyrithiobac POST. The PRE herbicides increased cotton yield at four of six locations while pyrithiobac POST increased yield at only one location. The results indicate good control of annual grasses, *Amaranthus* spp., *Ipomoea* spp., and common lambsquarters can be obtained in GR cotton with herbicide systems that include PRE herbicides and well-timed glufosinate applications.

WEED MANAGEMENT IN GLUFOSINATE-TOLERANT 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

2006

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DEDICATION

This thesis is dedicated to the memory of John Drue Morgan (July 13, 1944 – July 29, 2003). Without your encouragement and example I wouldn't be where I am today. Thank you for making a difference my life. Only God knows how much I miss your friendship.

BIOGRAPHY

Andrew Gardner was born on August 24, 1981 in Locust, North Carolina to Perry and Kathy Gardner. He grew up on a small horse farm where his family raised Paso Fino and Tennessee Walking Horses. His interest in agriculture came early and was nurtured by the many summers spent behind his grandpa in the garden. He joined the Boy Scouts of America and received the rank of Eagle Scout at age 15. Upon entering West Stanly High School he became active in his high school FFA. He was soon employed on his high school agriculture teacher's farm, Mr. Drue Morgan. He started working on this farm during his sophomore year in the afternoons and continued there throughout his high school career, time at Stanly Community College and the summers during his junior and senior years at NC State University and continues today when possible. It was through this experience of working on Mr. Morgan's farm that his agriculture interest was further cultivated. Mr. Morgan was instrumental in educating Andrew on the intricacies of the farming enterprise from the basic equipment and planting to harvesting and marketing. This education also served to further his interest in no-till and conservation farming.

Andrew attended Stanly Community College and received an associate of arts degree in May of 2001. He transferred to North Carolina State University in August of 2001. In May 2004 he graduated Summa Cum Laude with a Bachelor of Science in Agronomy with a minor in Agribusiness Management. Upon graduation with his B. S. degree he immediately started work on a Masters of Science under the direction of Dr. Alan C. York. Andrew completed all requirements for a Master's of Science degree in March, 2006.

ACKNOWLEDGEMENTS

First and foremost I want to thank my Lord, Jesus Christ for his ever present comfort and sustaining grace. His guidance has been evident in every path He has guided me down. Secondly, I want to thank my parents, Alva Perry and Kathy Kluttz Gardner. They have stood behind me and supported me in my life and decisions and always placed my comfort and well being above that of their own. I want to thank them for presenting a Godly example to follow and for being the greatest parents a son could have.

Next, I would like to thank my grandpa and grandma, Lewis Felix and Shirley Barbee Kluttz. My grandpa has been the best friend a boy could have dreamed of. The times in the garden and hunting and fishing will never be forgotten and will remain among my most cherished memories. My grandmother kept me every Monday during the summer and those times in the back porch swing are among my fondest memories, and I’m glad she cleared up the deer stand question too. These two people have provided support and guidance that I have truly been blessed to have and for that I am forever grateful.

Special thanks are due to Mr. John Drue Morgan. Drue Morgan was my teacher, employer and most of all, my friend. He allowed me the opportunity to work on his farm and learn more than I could have ever asked. He taught me the value of family, land, education, friendship, integrity of character, and being a careful steward of our natural resources. It was through Mr. Morgan’s encouragement that I truly considered pursuing a Bachelor and Master’s of Science.

Next, I would like to thank Dr. Alan York for his guidance, patience, support, and direction during my graduate education. Dr. York’s patience and understanding are appreciated more than he will ever know. No matter how busy he was, he always took time to help in any way possible. I also want to thank Rick Seagroves. Rick has been an invaluable asset and without his assistance I couldn't have gotten to this point. Thanks are due to Jamie Hinton also for his assistance in conducting the many trials. I would also like to thank Robbie Parker, Davie Wilson, James Lanier, Josh Beam, Gary Hamm, Kyle Scott, and Guy Collins for all of their technical assistance. Without their help I couldn't have gotten where I am now. Davie if it weren't for your statistical assistance, I would still be staring blankly at a SAS editor screen. I especially want to thank Guy Collins for his friendship during our undergraduate and graduate school careers. Thanks for putting up with my griping and for all the assistance.

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CHAPTER 1

Literature Review

Liberty Link cotton (*Gossypium hirsutum* L.) is genetically modified cotton, commercialized in 2004. It provides a grower the flexibility to apply glufosinate postemergence overtop to control a broad spectrum of weeds from cotton emergence to the early bloom stage without injuring the cotton (York and Culpepper, 2005). Glufosinate applied to Liberty Link cotton did not cause any injury, reduction in plant height or lint yield, or any adverse effects on fiber, micronaire, length, or strength with single or sequential applications regardless of rate. (Blair-Kerth et al., 2001).

Glufosinate was first introduced in Japan in 1984 and received U. S. registration in 1993 for use in orchards, row crop fields, vineyards and non-cropland areas (Lyon, 1991; Singh and Tucker, 1987). Glufosinate controls many annual weeds when applied in a timely manner, otherwise its control can be marginal. This is especially true with annual grasses and pigweed species in less than ideal growing conditions (Beyers et al., 2002; Corbett et al., 2004; Steckel et al. 1997; York and Culpepper, 2004, 2005).

Glufosinate is an amino acid synthesis inhibitor that works by inhibiting glutamine synthetase (EC 6.3.1.2). This inhibition leads to a rapid accumulation of ammonia within the plant, damage to the chloroplast structures, a decrease and eventual termination of photosynthetic activity, and ultimately necrosis of tissue (Coetzer and Al-Khatib, 2001; Devine et al., 1993b). Glutamine synthetase is the first enzyme in the process plants use to convert inorganic nitrogen into organic compounds. Glutamine synthetase also plays a critical role in metabolizing nitrogen, assimilating ammonia, and recycling the ammonia that is produced as a result of other processes occurring within the plant (Devine et al., 1993b).

Glufosinate-resistant crops are created by gene insertion. A gene from the fungi *Streptomyces hygroscopicus* or the related fungi *Streptomycyes viridochromogenes* is inserted into a crop plant using varying methods. These genes encode for the phosphinothricin acetyl transferase (PAT) enzyme (EC 2.3.1-). The PAT enzyme converts the herbicidal molecule phosphinothricin into a nontoxic acetylated form. The end result is the production of a glufosinate-resistant crop that has the ability to complete its life cycle in the same manner as a nontransgenic plant and produce equal amounts of viable seeds as a non-transgenic crop (Devine et al., 1993b; Tsaftaris, 1996).

Glufosinate is a broad-spectrum herbicide; however, it has some limitations in control (Corbett et al., 2004; Culpepper and York, 1999; York and Culpepper, 2004, 2005). The two major weaknesses are control of annual grasses and pigweed species. Applications made to pigweed species (*Amaranthus spp.*) and large crabgrass (*Digitaria sanguinalis* L.) the plant height should not exceed 7.6 cm. Applications to goosegrass (*Eleusine indica* L.) should be made before the plant exceeds 5 cm and a second application may be necessary to attain complete control (Anonymous, 2006). These maximum sizes should be adjusted downward if the growing conditions are stressful (York and Culpepper, 2005).

Corbett et al. (2004) reported that glufosinate was less effective on goosegrass than on other annual grasses. Control was decreased in smooth (*Amaranthus hybridus* L.) and redroot pigweed (*Amaranthus retroflexus* L.) as well as in Palmer amaranth (*Amaranthus palmeri* L.) when the plants were 8- to 10-cm tall. Control was also decreased when broadleaf signalgrass (*Brachiaria platyphylla* Griseb.), large crabgrass, and goosegrass were 8- to 10-cm tall when compared to 2- to 5-cm tall. In a study conducted by Culpepper and York (1999), two applications of ametryn were required to effectively control fall panicum (*Panicum dichotomiflorum* Michx.), goosegrass and smooth pigweed in glufosinate-resistant corn, (*Zea mays* L.). The data obtained from these tests reveals a potential weakness in Liberty Link cotton systems if proper management techniques aren't employed.

Grass Control

It is imperative that glufosinate be applied to annual grasses in a very timely manner to achieve adequate control (Corbett et al., 2004; York and Culpepper, 2005). The weather conditions during the growing season in the Southeast are quite variable and will inevitably interfere with the proper application window for effective control as well as growers becoming preoccupied with other aspects of their farming operations. If a grower is unable to make a timely application, he will have grasses that are larger than optimum for effective control. Many cotton growers have seen the value of postemergence graminicides for grass control and will inevitably ask if one can add a graminicide to their glufosinate mixture to supplement grass control. Previous research conducted on postemergence graminicides and other herbicides would suggest that this is a poor idea as antagonistic interactions have often occurred (Burke et al. 2002, 2004; Corkern et al., 1998; Crooks et al., 2003; Jordan et al., 1993b; Lanclos et al., 2002).

Two families of graminicides, aryloxyphenoxypropanoates and cyclohexanediones, disrupt the acetyl-CoA carboxylase (ACCase) enzyme (EC 6.4.1.2), an enzyme involved in the synthesis of fatty acids. These herbicides are translocated through the phloem and act by killing the growing point of the grasses but not dicot species due to the grasses' high sensitivity at the site of action (Devine et al., 1993a). Herbicides in these families have proven to be very effective against many grass species (Burke et al., 2005; Culpepper et al., 1998; Holshouser and Coble, 1990; Jordan et al., 1993b; Myers and Coble, 1992; Palmer et al., 1999).

Control of large crabgrass, fall panicum, broadleaf signalgrass, and goosegrass by glufosinate has been found to be poor in some instances (Corbett et al., 2004; Culpepper and York, 1999; Culpepper et al., 2000; Norris et al., 2002). Due to the potential for poor control, growers may want to apply a postemergence graminicide with glufosinate to increase the spectrum of control. Lanclos et al. (2002) found that bensulfuron, halosulfuron, propanil, quinclorac or triclopyr were applied with glufosinate it could result in decreased control of barnyardgrass *(Echinochloa crus-galli* L.*)*, broadleaf signalgrass, spreading dayflower *(Commelina diffusa* Burm.*)* and rice flatsedge *(Cyperus iria* L.*)*. The only interaction between graminicides and glufosinate that has been investigated to date has been with clethodim (Burke et al., 2005).

The four graminicides that will be investigated are fluazifop-P, quizalofop-P, clethodim, and sethoxydim. Fluazifop-P and quizalofop-P are often less effective in controlling annual grasses than clethodim or sethoxydim (Crooks et al., 2003; Culpepper et al., 1998; Jordan et al., 1993b; Myers and Coble, 1992; York et al., 1993). Control by each of these four graminicides was decreased substantially when applied in combination with broadleaf herbicides. Meyers and Coble (1992) found control of large crabgrass by graminicides was decreased when the graminicides were tank mixed with imazethapyr.

Culpepper et al. (1998) also found control of large crabgrass was decreased when clethodim, sethoxydim, fluazifop-P plus fenoxaprop-P, fluazifop-P, or quizalofop-P were tank mixed with bromoxynil. Other examples of broadleaf herbicides resulting in antagonistic interactions with graminicides include the following: 2,4-DB, CGA-277476, bentazon, acifluorfen, imazaquin, chlorimuron, pyrithiobac, pyridate, CGA-362622, glufosinate, bromoxynil and imazapic (Burke et al. 2004, 2005; Burke and Wilcut, 2003; Corkern et al., 1998; Culpepper et al., 1999a; Grichar, 1991; Holshouser and Coble, 1990; Jordan et al., 1993a; Palmer et al., 1999; Snipes and Allen, 1996; York et al., 1993).

Aryloxyphenoxypropanoates are more prone to antagonistic interactions than cyclohexanediones. Tank- mixes containing aryloxyphenoxypropanoates often result in larger interactions than the corresponding mixes containing cyclohexanediones (Crooks et al., 2003; Culpepper et al., 1998, 1999a; Grichar et al., 2003; Myers and Coble, 1992, York et al., 1993). This antagonism of graminicides can be caused by reduced graminicide absorption, reduced graminicide translocation, reduction of photosynthetic and growth rates, or interference with the site of action (Burke and Wilcut, 2003; Holshouser and Coble, 1990; Jordan, 1995; Penner, 1989; Rhodes and Coble, 1984; Wanamarta et al., 1993). Green (1989) divides the antagonistic interaction mechanisms into four categories: biochemical, competitive, physiological, and chemical. A biochemical antagonistic interaction occurs when the herbicides interact in a manner that one herbicide reduces the amount of the other herbicide reaching the site of action either by reduced penetration, transport interference, or enhanced inactivation or sequestration. Competitive antagonism would occur when the herbicide responsible for the antagonism binds to the necessary site for activity and thereby prevents action of the herbicide being antagonized. Physiological antagonism results when two herbicides counteract one another through opposing modes of action. Finally, chemical antagonism occurs when the herbicide chemically interacts with another (Green 1989).

Many methods have been employed to overcome antagonism. They include increasing the graminicide rate, adding ammonium sulfate or making sequential herbicide applications (Grichar et al., 2003; Hart and Wax, 1996; Mueller et al., 1989). In many instances increasing the graminicide rate results in alleviating or substantially decreasing the antagonistic interaction. Ferreira et al. (1995) found that antagonism of fluazifop-P by pyrithiobac was overcome by increasing the fluazifop-P rate. Increasing the graminicide rate to overcome or decrease the antagonism has been documented with sethoxydim, clethodim, fluazifop-P, and quizalofop-P (Culpepper et al., 1998; Palmer et al., 1999; York et al., 1990).

Ammonium sulfate has been found to improve glufosinate efficacy on common lambsquarters (*Chenopodium album* L.), velvetleaf (*Abutilon theophrasti* Medic.), and common milkweed (*Asclepias syriaca* L.) when applied with glufosinate when compared to glufosinate alone (Maschhoff et al., 2000; Pline et al., 2000). Also, adding ammonium sulfate to sethoxydim and clethodim resulted in improved control of grasses when compared to the graminicides applied alone (Burke et al., 2004; Chow and MacGregor, 1983; York et al., 1990). In addition to improving herbicide efficacy, ammonium sulfate in the herbicide mixture is often effective in overcoming antagonistic interactions herbicides (Burke et al., 2004; Gerwick et al., 1990; Hart and Wax, 1996; Jordan et al.,1989). The mechanisms for these improvements in control are mainly attributed to improved herbicidal uptake. In many instances, the antagonistic interactions are attributed to decreased absorption or translocation of the herbicide (Gerwick et al., 1990; Hart and Wax, 1996; Rhodes and Coble, 1984). Ammonium sulfate applied with the mixture often results in more rapid uptake or maintenance of the normal uptake level of the herbicide which allows more to be translocated (Hart and Wax, 1996; Young et al., 2003). This is especially beneficial due to the rapid photodegradation that occurs when graminicides ,such as sethoxydim, are exposed to light. (Culpepper et al., 1999b). Jordan et al. (1989) found that ammonium sulfate applied with ^{14}C-sethoxydim plus bentazon increased the amount of sethoxydim that was absorbed but had no effect on sethoxydim translocation. Hart and Wax (1996) and Wanamarta et al. (1993) determined that ammonium sulfate prevented antagonism when a sodium salt formulation of an herbicide was used by out competing the sodium ions that interfere with herbicide uptake.

Another method which can alleviate antagonism is sequential herbicide applications. Previous research has shown that applying the graminicide either earlier than or after the other herbicide completely eliminated any negative interactions that were occurring from the herbicides 2,4-DB, imazethapyr, pyrithiobac, CGA-362622, bromoxynil, bentazon, dicamba, and primisulfuron. The antagonistic interaction was overcome when the interval between applications was from 1 to 7 days before to 30 minutes to 7 days after (Burke et al., 2002; Byrd and York, 1988; Corkern et al., 1998; Crooks et al., 2003; Culpepper et al., 1999a; Ferriera et al., 1995; Jordan and York, 1989; Myers and Coble, 1992; York et al., 1993). Jordan and York (1989) reported no antagonism when bentazon was applied 30 minutes to 1 hour after sethoxydim. This is an exceptionally small interval between applications and would be difficult to implement in field situations, however it serves to demonstrate that the interval need not be incredibly large. On the other hand, Burke et al. (2005) found it was necessary to apply clethodim at least 7 days prior to glufosinate to avoid antagonism.

Pigweed Control

Amaranthus species are some of the most troublesome weeds in southeastern U. S. cotton production. They have traditionally been among the most troublesome weeds ranking sixth in 1974 and fourth in 1995. In 2001, Palmer amaranth was ranked number as the most troublesome weed in Missouri, North Carolina and South Carolina cotton production (Webster, 2005; Webster and Coble, 1997). Control of *Amaranthus* species is often poor with glufosinate applied alone (Coetzer et al., 2002; Corbett et al., 2004; Culpepper and York, 1999; Culpepper et al., 2000; Hill et al., 1997). This is especially true of larger Palmer amaranth (Coetzer et al., 2002; Corbett et al., 2004).

Coetzer et al. (2002) applied glufosinate to 2- to 5-, 7- to 10-, and 15- to 18-cm Palmer amaranth. Amaranthus was controlled 81, 71 and 74 %, respectively. Redroot pigweed also followed a similar trend, where control decreased as plant size increased. These data indicate the importance of applying glufosinate to smaller plants. Corbett et al. (2004) also reported reduced smooth pigweed control with increased plant size.

One effective method for controlling *Amarathus* species with glufosinate is to make multiple applications (Beyers et al., 2002; Coetzer et al., 2002; Tharp and Kells, 2002; Wiesbrook et al., 2001). Culpepper and York (1999) found greater control of smooth pigweed with two sequential applications of glufosinate. Coetzer et al. (2002) reported less than 75% control of Palmer amaranth and redroot pigweed with a single application of glufosinate when evaluated 4 weeks after application. They attributed this partially to the regrowth and recovery of those weeds treated as well as a second flush of germination 2 weeks after treatment. Less than 80% of the Palmer amaranth and redroot pigweed were controlled 8 weeks after a single application. The sequential treatments provided greater than 90% of both Palmer amaranth and redroot pigweed.

Use of preemergence herbicides has also proven to be an effective strategy for controlling *Amaranthus* species (Beyers et al., 2002; Culpepper and York, 1997, 1998, 2000; Reddy, 2001; Taylor-Lovell and Wax, 2001; Toler et al., 2002). Beyers et al. (2002) reported that pendimethalin, sulfentrazone, cloransulam or flumioxin applied preemergence followed by glufosinate applied postemergence was more effective than glufosinate alone. Fomesafen is an effective preemergence herbicide for many broadleaf weed species, especially Palmer amaranth (Culpepper et al., 2000; Hill et al., 1997, Murdock and Keeton, 1998). Glufosinate applied alone in a 1996 soybean test only controlled Palmer amaranth 78% 9 weeks after planting in contrast to greater than 97% control by fomesafen applied premergence followed by glufosinate (Hill et al., 1997). Bauman et al. (1998) reported greater than 90% control of Palmer amaranth when fomesafen was applied preemergence and less than 10% crop injury. Data from these trials indicate a fit for fomesafen in glufosinate-tolerant cotton due to its high efficacy on Palmer amaranth and glufosinate's low efficacy.

Other preemergence herbicides commonly used in cotton include pendimethalin, pyrithiobac, and fluometuron (Culpepper and York 1997, 2000; Jordan et al., 1993b; Reddy, 2001, Toler et al., 2002; Troxler et al., 2002). Culpepper and York (1997) reported that pendimethalin controlled smooth pigweed and Palmer amaranth 95 and 88%, respectively.

They also reported that pyrithiobac postemergence over the top and fluometuron plus MSMA postemergence-directed controlled these two species similarly. Previous research indicates the best management practice includes a preemergence herbicide followed by an early postemergence treatment when weed densities are high (Culpepper et al., 2000; Reddy et al., 2001; Toler et al., 2002; Troxler et al., 2002).

Pyrithiobac is also effective at controlling *Amaranthus* species. Pyrithiobac applied either preemergence or postemergence has been reported to effectively control *Amaranthus* species, including smooth pigweed and Palmer amaranth, if applied early POST (Bailey et al., 2003; Culpepper and York, 1997, 1998, 2000; Jordan et al., 1993c). York and Culpepper (2004) reported pyrithiobac when added to glufosinate increased control of Palmer amaranth 11 to 12%.

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Chapter 2

Glufosinate Antagonizes Postemergence Graminicides Applied to Annual Grasses and Johnsongrass

Andrew P. Gardner and Alan C. York[1]

ABSTRACT

Glufosinate controls a broad spectrum of weeds. Control of grassy weeds, however, can sometimes be inadequate, especially when grasses are large or under dry conditions. In situations where less than adequate control of grasses by glufosinate alone might be anticipated, growers may consider mixing a postemergence graminicide with glufosinate. Most herbicides mixed with graminicides antagonize grass control. Research was conducted in North Carolina during 2004 and 2005, to determine the potential for antagonism with mixtures of glufosinate and four postemergence graminicides and to determine if antagonism could be alleviated by increasing the rate of graminicide in mixtures, by adding ammonium sulfate to mixtures, or by applying glufosinate and graminicides sequentially. Antagonism was noted on johnsongrass [Sorghum halepense (L.) Pers.] and mixtures of the annual grasses broadleaf signalgrass [Brachiaria platyphylla (Griseb.) Nash], fall panicum (Panicum dichotomiflorum Michx.), goosegrass [Eleusine indica (L.) Gaertn.], and large crabgrass [Digitaria sanguinalis (L.) Scop.] when glufosinate was mixed with clethodim, fluazifop-P, quizalofop-P, or sethoxydim. Antagonism was not alleviated by increasing

the graminicide rate in the mixture by 50% or by including ammonium sulfate in the mixture. However, antagonism was not observed when graminicides were applied 3 or more days before glufosinate or 5 or more days after glufosinate.

KEY WORDS: Ammonium sulfate; antagonism; clethodim; fluazifop-P; herbicide mixtures; quizalofop-P; sequential application; sethoxydim.

ABBREVIATIONS: DAT, days after treatment; DATZ, days after 0-day treatment.

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INTRODUCTION

Glufosinate is a non-selective postemergence herbicide that was originally used to control weeds in orchards, vineyards, and noncropland sites and for control of emerged vegetation prior to planting crops in conservation tillage systems (Blackshaw, 1989; Lanie et al., 1994; Singh and Tucker, 1987; Wilson et al., 1985). Glufosinate inhibits glutamine synthetase (E.C.6.3.1.2), the enzyme involved in the conversion of glutamic acid and ammonia into glutamine (Devine et al., 1993; Hinchee et al., 1993). Inhibition of glutamine synthetase leads to a rapid accumulation of toxic levels of ammonia within cells, cessation of photosynthesis, disruption of chloroplast structure, and vesiculation of stroma, and subsequently plant death.

Technological advances in identifying genes coding for specific traits and transferring those genes from unrelated organisms into crop plants have led to development of transgenic, herbicide-resistant crops, such as cotton (*Gossypium hirsutum*) resistant to glufosinate (Wilcut et al., 1996). Glufosinate-resistant cotton, commercialized in 2004, contains a gene from *Streptomyces viridochromogenes* which encodes for phosphinothricin acetyltransferase, an enzyme that catalyzes the conversion of lethal L-phosphinothricin into nonlethal *N*-acetyl-L-phosphinothricin (Devine et al., 1993; Hinchee et al., 1993). Tolerance of glufosinate-resistant cotton to glufosinate applied postemergence is excellent (Blair-Kerth et al., 2001; Thomas et al., 2004).

Glufosinate controls a broad spectrum of weeds (Beyers et al., 2002; Corbett et al., 2004; Culpepper and York, 1999; Culpepper et al., 2000; Norris et al., 2002; Steckel et al., 1997; Wiesbrook et al., 2001; York and Culpepper, 2004). Control of grassy weeds, however, can sometimes be inadequate, especially when the grasses are large or growing under dry conditions (Corbett et al., 2004; Culpepper and York, 1999; Culpepper et al., 2000; Steckel et al., 1997).

Applying herbicide mixtures is a common way to increase the spectrum of weed control. In situations where less than adequate control of grasses by glufosinate alone might be anticipated, growers would likely consider mixing a postemergence graminicide with glufosinate. However, antagonism on grasses is commonly observed when herbicides typically applied to control broadleaf weeds are mixed with the postemergence graminicides (Burke et al., 2004; Crooks et al., 2003; Culpepper et al., 1999; Holshouser and Coble, 1990; Jordan et al., 1993; Mueller et al. 1989; Myers and Coble, 1992; Young et al., 1996). This antagonism may be due to a direct effect of the broadleaf herbicide on graminicide absorption or indirectly due to an effect of the broadleaf herbicide on plant metabolism and growth (Burke and Wilcut, 2003; Culpepper et al., 1999; Jordan et al., 1989).

Antagonism of graminicides by other herbicides can sometimes be reduced or alleviated by increasing the rate of graminicide in the mixture (Campbell and Penner, 1982; Culpepper et al., 1998, 1999; Mueller et al., 1989; Palmer et al., 1999), by adding ammonium sulfate to the mixture (Gerwick et al., 1990; Hatzios and Penner, 1985; Jordan et al., 1989, 1993; Jordan and York, 1989; Wanamarta et al., 1989), or by applying the graminicides and the broadleaf herbicide sequentially (Burke et al., 2002; Corkern et al., 1998; Jordan et al., 1993; Myers and Coble, 1992; Rhodes and Coble, 1984; York et al., 1993). Preliminary research in 2003 (A. P. Gardner and A. C. York, unpublished data) indicated antagonism on annual grasses with mixtures of graminicides and glufosinate. Subsequent research, reported herein, was conducted to further investigate this potential problem. The objectives were to determine the potential for antagonism with mixtures of glufosinate and four postemergence graminicides and to determine if antagonism could be alleviated by increasing the rate of graminicide in mixtures, by adding ammonium sulfate to mixtures, or by applying glufosinate and graminicides sequentially.

MATERIALS AND METHODS

Methods common to all experiments. Each of three experiments was conducted in fallow fields selected for heavy infestations of annual grasses or johnsongrass. Sites were tilled by disking followed by a field cultivator. Ammonium nitrate fertilizer was broadcast at the rate of 110 kg N ha^{-1}. Soils at each site are described in Table 1; weed species and densities are listed in Table 2. The experiments were conducted twice within the same field and year at some sites. In these situations, the experiments were separated in time by 2 or more weeks.

The experimental design was a randomized complete block with treatments replicated three or four times, depending upon location. Plot size was 3 by 4.6 m. Herbicides were applied with a CO_2-pressurized backpack sprayer equipped with flat-fan nozzles (TeeJet XR11002 nozzles; Spraying Systems Co.; Wheaton, IL) calibrated to deliver 140 L ha^{-1} at 160 kPa. Annual grasses were 10 to 20 cm tall and tillering while johnsongrass was 5 to 15 cm tall at time of herbicide application. Applications were intentionally delayed until grasses were larger than recommended for treatment with glufosinate (Anonymous, 2006c) to simulate situations where a grower would anticipate less than adequate control by glufosinate and thus consider use of a graminicide along with glufosinate. Control of annual grasses and johnsongrass in experiments 1 and 2 was estimated visually 14 and 28 days after treatment (DAT) using a scale of 0 = no control to 100 = complete control (Frans et al., 1986). Control in experiment 3 was estimated 14 and 28 days after the 0-day application (DATZ). No attempt was made to evaluate control by species at sites with multiple species of annual grasses.

Experiment 1. Glufosinate tank mixtures with four graminicides. The experiment was conducted seven times on annual grasses and twice on johnsongrass during 2004 and 2005 (Tables 1 and 2). Treatments included a factorial arrangement of four graminicides, two rates of graminicides, and two rates of glufosinate. Graminicides and application rates included the following: clethodim (Select 2EC Herbicide; Valent Agricultural Products; Walnut Creek, CA) at 105 and 158 g a.i. ha^{-1}; fluazifop-P (Fusilade DX Herbicide; Syngenta Crop Protection, Inc.; Greensboro, NC) at 210 and 315 g a.i. ha^{-1}; quizalofop-P (DuPont Assure II Herbicide; E. I. du Pont de Nemours and Co.; Wilmington, DE) at 62 and 92 g a.i. ha^{-1}; and sethoxydim (Poast Plus Herbicide; Micro Flo Co. LLC; Memphis, TN) at 210 and 315 g a.i. ha^{-1}. Graminicide rates represent 1.0 and 1.5 times the manufacturers' suggested use rates for annual grasses (Anonymous, 2006a, 2006b, 2006d, 2006e). Glufosinate (Ignite Herbicide; Bayer CropScience; Research Triangle Park, NC) was applied at 0 and 468 g a.i. ha^{-1}. A crop oil concentrate (Agri-Dex; Helena Chemical Co.; Memphis, TN) at 1.0% ($v\ v^{-1}$) was included with all of the above treatments. Additional treatments included glufosinate at 468 g ha^{-1} applied with and without crop oil concentrate and a non-treated check.

Experiment 2. Interaction of glufosinate with clethodim and fluazifop-P as affected

by ammonium sulfate. The experiment was conducted seven times on annual grasses during 2004 and 2005 (Tables 1 and 2). Treatments included glufosinate at two rates (0 and 468 g ha^{-1}), ammonium sulfate (Fisher Scientific Co.; Pittsburgh, PA) at two rates (0 and 3.4 kg ha^{-1}), and two graminicides each applied at four rates. Graminicides included clethodim at 0, 79, 105, and 158 g ha^{-1} and fluazifop-P at 0, 158, 210, and 315 g ha^{-1}. These graminicide rates represent 0, 0.75, 1.0, and 1.5 times the manufacturers' suggested use rates (Anonymous, 2006b, 2005e). A crop oil concentrate at 1.0% (v v^{-1}) was included with all of the above herbicide-ammonium sulfate applications. Two additional treatments included glufosinate and glufosinate plus ammonium sulfate in the absence of crop oil concentrate.

Experiment 3. Glufosinate and graminicides applied sequentially. The experiment was conducted four times on annual grasses and twice on johnsongrass during 2004 and 2005 (Tables 1 and 2). Treatments consisted of a factorial arrangement of two graminicides (clethodim at 105 g ha^{-1} and fluazifop-P at 210 g ha^{-1}), glufosinate at two rates (0 and 468 g ha^{-1}), and eight application timings for graminicides. Glufosinate was applied on day 0. Graminicides were applied 1, 3, or 5 days before glufosinate, mixed with glufosinate on day 0, or applied 1, 3, 5, or 7 days after glufosinate. Crop oil concentrate at 1.0% (v v^{-1}) was included with all graminicide applications but not with glufosinate applied alone. Additional treatments included glufosinate applied alone on day zero and a non-treated control.

Statistical analysis. Data were subjected to analysis of variance using the mixed procedure of the Statistical Analysis System (version 9.1; SAS Institute Inc.; Cary, NC) with treatment sums of squares partitioned to reflect the factorial treatment arrangements. Non-treated checks were excluded from the analysis. Locations were considered as random effects (McIntosh, 1983). Data were arcsine transformed prior to analysis. Non-transformed data are presented with statistical interpretation based upon transformed data. Means for main effects of treatment factors and their interactions were separated when appropriate using Fisher's Protected LSD at $P \leq 0.05$. Interactions between glufosinate and graminicides at 28 DAT in experiments 1 and 2 were examined using the method described by Colby (1967). The expected control by herbicide combinations was calculated as the product of the percentage of control by each herbicide applied alone, divided by 100, and subtracted from the sum of the percentage of control by each herbicide applied alone. Expected control and observed control by combinations were compared by Fisher's Protected LSD at $P \leq 0.05$. Herbicide combinations were considered antagonistic when observed values were significantly less than expected values.

A separate analysis of variance compared control by glufosinate applied with and without crop oil concentrate in the absence of graminicides in experiment 1. In experiment 2, a separate analysis of variance with partitioning for a 2 (0 and 3.4 kg ha^{-1} ammonium sulfate) by 2 (presence or absence of crop oil concentrate) factorial arrangement of ammonium sulfate and crop oil concentrate rates was conducted for treatments containing glufosinate but no graminicides.

RESULTS AND DISCUSSION

Experiment 1. Glufosinate tank mixtures with four graminicides. Annual grass control was similar with glufosinate and glufosinate plus crop oil concentrate in the absence of graminicides. Averaged over locations, glufosinate and glufosinate plus crop oil concentrate controlled annual grasses 85 and 82%, respectively, 14 DAT and 68 and 64%, respectively, 28 DAT (data not shown). Lesser control 28 DAT compared with 14 DAT was due to regrowth on plants not initially killed by glufosinate (Burke et al., 2005; Culpepper and York, 1999). Inadequate control of annual grasses by glufosinate has been reported previously (Burke et al., 2005; Corbett et al., 2004; Norris et al., 2002; Van Wychen et al., 1999; Wiesbrook et al., 2001). Similarly, crop oil concentrate did not affect johnsongrass control by glufosinate in the absence of graminicides. Averaged over locations, glufosinate and glufosinate plus crop oil concentrate controlled johnsongrass 27 and 32%, respectively, 14 DAT (data not shown). No control of johnsongrass by glufosinate or glufosinate plus crop oil concentrate was noted 28 DAT.

Analysis of variance for data from the factorial arrangement of four graminicides by two graminicide rates by two glufosinate rates showed no location by treatment interactions. Averaged over locations, the main effect of graminicide rates and the interaction of graminicides by glufosinate rates were significant for both annual grasses and johnsongrass at 14 and 28 DAT. Graminicides applied at 1.5 times the manufacturers' suggested use rates were more effective on annual grasses and johnsongrass at 14 and 28 DAT than graminicides at the suggested use rates. Averaged over graminicides and glufosinate rates, annual grasses were controlled 90 and 85% at 14 and 28 DAT, respectively, by graminicides at the 1.5X rate compared with 87 and 80% control, respectively, by graminicides at the 1.0X rate (data not shown). Johnsongrass was controlled 98 and 92% at 14 and 28 DAT, respectively, by graminicides at the 1.5X rate compared with 94 and 84% by graminicides at the 1.0X rate (data not shown).

Clethodim, quizalofop-P, and sethoxydim were similarly effective on annual grasses 14 DAT and somewhat more efficacious than fluazifop-P (Table 3). Clethodim, quizalofop-P, and sethoxydim controlled annual grasses 89 to 91% compared with 85% control by fluazifop-P. Control by clethodim and sethoxydim increased by 28 DAT relative to 14 DAT whereas control by fluazifop-P and quizalofop-P changed little. At 28 DAT, clethodim and sethoxydim controlled annual grasses 96 to 97% compared with 85 and 90% control by fluazifop-P and quizalofop-P, respectively. These results are consistent with previous research where clethodim and sethoxydim controlled annual grasses more effectively than fluazifop-P or quizalofop-P (Culpepper et al., 1998). Annual grasses were controlled similarly 14 DAT by clethodim, quizalofop-P, and sethoxydim applied alone or mixed with glufosinate while control by fluazifop-P plus glufosinate was 6 percentage points greater than control by fluazifop-P alone. By 28 DAT, however, control of annual grasses was reduced when glufosinate was mixed with each of the graminicides. Although the magnitude of the reduction was less with fluazifop-P than with the other three graminicides, each tank mixture of graminicide plus glufosinate was antagonistic according to the Colby procedure.

Johnsongrass was controlled 98 to 100% and 95 to 98% 14 and 28 DAT, respectively, by the graminicides applied alone (Table 3). These graminicides typically control johnsongrass well (Jordan et al., 1993; Snipes and Allen, 1996). Johnsongrass control 14 DAT was unaffected by glufosinate mixed with clethodim. In contrast, glufosinate reduced johnsongrass control 3 to 4 percentage points when mixed with fluazifop-P and quizalofop-P and 15 percentage points when mixed with sethoxydim. At 28 DAT, glufosinate mixed with each graminicide reduced johnsongrass control. The magnitude of the response was least with clethodim (4 percentage points), intermediate with fluazifop-P and quizalofop-P (10 to 12 percentage points), and greatest with sethoxydim 41 percentage points). Combinations of fluazifop-P, quizalofop-P, or sethoxydim plus glufosinate, but not clethodim plus glufosinate, were antagonistic according to the Colby procedure. Corkern et al. (1998) reported less antagonism in johnsongrass with mixtures of clethodim plus bromoxynil than with mixtures of fluazifop-P or quizalofop-P plus bromoxynil.

Antagonism on grasses by various herbicides mixed with graminicides can often be alleviated by increasing the rate of graminicide (Campbell and Penner, 1982; Culpepper et al., 1998, 1999; Mueller et al., 1989; Palmer et al., 1999). In this experiment, lack of graminicide rate by glufosinate rate or graminicide by graminicide rate by glufosinate rate interactions indicate the antagonism was independent of graminicide rate and that increasing the graminicide rate by 50% did not alleviate the antagonism.

Experiment 2. Interaction of glufosinate with clethodim and fluazifop-P as affected by ammonium sulfate. Lack of location by treatment interactions allowed data to be averaged over locations. The main effect of graminicide rates and the graminicide by glufosinate rate interaction were significant at 14 and 28 DAT.

Annual grass control increased as the graminicide rate increased. Averaged over graminicides, glufosinate rates, and ammonium sulfate rates, annual grasses were controlled 83, 84, and 86% (LSD 0.05 = 1) 14 DAT and 69, 71, and 75% (LSD 0.05 = 3) 28 DAT by graminicides applied at 0.75, 1.0, and 1.5 times the manufacturers' suggested use rates (data not shown).

Annual grass control by combinations of fluazifop-P plus glufosinate or clethodim plus glufosinate was greater 14 DAT than control by the graminicides alone (Table 4). Annual grass control 28 DAT was similar to results observed in experiment 1. Control by clethodim exceeded control by fluazifop-P, and glufosinate had a greater impact on control when mixed with clethodim as compared with fluazifop-P. Control by clethodim was reduced 23 percentage points by glufosinate whereas control was not reduced when glufosinate was mixed with fluazifop-P. However, both herbicide combinations were antagonistic according to the Colby procedure.

Interactions of ammonium sulfate rates by other treatment variables were not significant, indicating that ammonium sulfate did not alleviate or reduce antagonism in mixtures of graminicides and glufosinate. The main effect of ammonium sulfate rates also was not significant. Averaged over graminicides, graminicide rates, and glufosinate rates, annual grasses were controlled 85 and 72% without ammonium sulfate 14 and 28 DAT, respectively, compared with 84 and 71% with ammonium sulfate 14 and 28 DAT, respectively. Ammonium sulfate has increased the efficacy of glufosinate on some weeds, but the response has been inconsistent (Maschhoff et al., 2000; Pline et al., 2000).

Experiment 3. Glufosinate and graminicides applied sequentially. Treatment by location interactions were not significant. Averaged over locations, the main effect of graminicides was significant for annual grasses and the interaction of graminicide application timings by glufosinate rates was significant for annual grasses and johnsongrass.

Glufosinate applied alone controlled annual grasses 85 and 68% and johnsongrass 28 and 0% at 14 and 28 DATZ, respectively (data not shown). Averaged over glufosinate rates and graminicide application timings, clethodim was more efficacious on annual grasses than fluazifop-P. Clethodim controlled annual grasses 78 and 80% at 14 and 28 DATZ, respectively, compared with 72 and 71% control by fluazifop-P (data not shown). The two graminicides were similarly effective on johnsongrass. Clethodim controlled johnsongrass 84 and 82% at 14 and 28 DATZ, respectively, compared with 80 and 76% control by fluazifop-P (data not shown).

At 14 DATZ, glufosinate increased control of annual grasses and johnsongrass when graminicides were applied 5 or 7 days after glufosinate (data not shown). This occurred because the graminicides applied 5 or 7 days after glufosinate had not had sufficient time to kill the grasses at this early evaluation. At 28 DATZ, annual grass control was reduced 9, 17, 20, and 12 percentage points when graminicides were applied 1 day before, tank mixed with, or applied 1 and 3 days after glufosinate, respectively (Table 5). Johnsongrass control was reduced 29, 28, 39, and 17 percentage points when graminicides were applied 1 day before, tank mixed with, or applied 1 and 3 days after glufosinate, respectively. Neither annual grass control nor johnsongrass control was adversely affected when graminicides were applied 3 or 5 days before glufosinate or 5 or 7 days after glufosinate. Burke et al. (2005) reported no antagonism on goosegrass in the greenhouse when clethodim was applied 7 or 14 days before glufosinate; shorter intervals between application of the two herbicides were not evaluated. In contrast to our results, Burke et al. (2005) reported poor control of goosegrass when clethodim was applied 7 or 14 days after glufosinate. Glufosinate inhibits glutamine synthase, leading to a rapid accumulation of toxic levels of ammonia in the cell which causes membrane disruption and inhibition of photosynthesis. Glufosinate typically causes tissue desiccation on grasses, but larger grasses survive and initiate new growth (Burke et al., 2005;

Culpepper and York, 1999). Graminicides applied 3 or 5 days before glufosinate apparently had time to be absorbed and translocated to meristematic areas before leaf desiccation by glufosinate. By 5 days after glufosinate application, regrowth was occurring on the grasses. There was apparently enough new leaf tissue to absorb and translocate the graminicides for effective control.

Glufosinate applied to glufosinate-resistant cotton sometimes does not adequately control annual grasses or johnsongrass (Corbett et al., 2004; Culpepper and York, 1999; Culpepper et al., 2000; Steckel et al., 1997). In situations where less than adequate control of grasses by glufosinate alone might be anticipated, growers would likely consider mixing a postemergence graminicide with glufosinate. Our research indicates that mixtures of graminicides and glufosinate are antagonistic on grasses and thus should be avoided. Antagonism with mixtures of graminicides and other herbicides can sometimes be alleviated by increasing the rate of graminicide in the mixture or adding ammonium sulfate. In our work, neither increasing graminicide rates by 50% nor adding ammonium sulfate alleviated antagonism on grasses. Antagonism could be avoided by applying glufosinate and graminicides sequentially. To avoid antagonism, our results indicate graminicides should be applied at least 3 days prior to glufosinate or at least 5 days after glufosinate.

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Table 1. Description of soils at experiment sites.

Location[s]				Soil	Soil	Soil	Soil humic
Station	Field No.	Year	Experiment	series	texture	pH	matter
							%
CCRS	1	2004	1,2,2[t],3,3[t]	Dothan[u]	Loamy sand	5.8	0.76
CCRS	2	2004	1,2,3	Norfolk[v]	Loamy sand	5.7	0.76
CCRS	3	2004	1	Gilead[w]	Sandy loam	5.6	1.02
CCRS	4	2004	2	Gilead	Sandy loam	6.1	0.60
UCPRS	5	2004	1,1[t],2,3	Goldsboro[x]	Fine sandy loam	5.9	0.36
CCRS	6	2005	1	Appling[y]	Sandy loam	5.9	0.32
CCRS	7	2005	2	Dothan	Loamy sand	5.9	0.73
UCPRS	8	2005	1	Norfolk	Loamy sand	6.4	0.41
UCPRS	9	2005	2	Goldsboro	Fine sandy loam	5.9	1.25
UFU	10	2005	1,1[t],3,3[t]	Vance[z]	Loam	5.7	0.36

[s] CCRS = Central Crops Research Station, Clayton, NC; UCPRS = Upper Coastal Plain Research Station, Rocky Mount, NC; UFU = Umstead Farm Unit, Butner, NC.

[t] Experiment conducted twice in same field, separated in time.

[u] Fine-loamy, kaolinitic, thermic Plinthic Kandiudults.

[v] Fine-loamy, kaolinitic, thermic Typic Kandiudults.

[w] Fine, kaolinitic, thermic Aquic Hapludults.

[x] Fine-loamy, siliceous, subactive, thermic Aquic Paleudults.

[y] Fine, kaolinitic, thermic Kanhapludults.

[z] Fine, mixed semiactive, thermic Typic Hapludults.

Table 2. Weed species and densities at experiment sites.

Location					Weed
Station[w]	Field No.	Year	Experiment	Species[y]	density
					plants m^{-2}
CCRS	1	2004	1,2,2[x],3,3[x]	DIGSA	320 to 380
CCRS	2	2004	1,2,3	DIGSA (60)[z], ELEIN (30), PANDI (10)	360 to 390
CCRS	3	2004	1	BRAPP (20), DIGSA (20), ELEIN (60)	300 to 355
CCRS	4	2004	2	DIGSA (55), ELEIN (45)	360 to 400
UCPRS	5	2004	1,1[x],2,3	BRAPP (10), DIGSA (50), ELEIN (40)	320 to 420
CCRS	6	2005	1	DIGSA (70), ELEIN (30)	450 to 490
CCRS	7	2005	2	DIGSA	270 to 320
UCPRS	8	2005	1	DIGSA	200 to 270
UCPRS	9	2005	2	BRAPP (25), DIGSA (45), ELEIN (30)	370 to 400
UFU	10	2005	1,1[x],3,3[x]	SORHA	270 to 380

[w] CCRS = Central Crops Research Station, Clayton, NC; UCPRS = Upper Coastal Plain Research Station, Rocky Mount, NC; URF = Umstead Farm Unit, Butner, NC.

[x] Experiment conducted twice in same field, separated in time.

[y] BRAPP, broadleaf signalgrass; DIGSA, large crabgrass; ELEIN, goosegrass; SORHA, johnsongrass.

[z] Numbers in parentheses () are percentages of each species in fields with more than one weed species.

Table 3. Control of annual grasses and johnsongrass by graminicides applied alone and mixed with glufosinate in experiment 1[x]

		Annual grasses			Johnsongrass		
	Glufosinate		28 DAT			28 DAT	
Graminicides	rate	14 DAT[y]	Observed	Expected[z]	14 DAT	Observed	Expected[z]
	g ha^{-1}	%					
Clethodim	0	91 a	97 a		100 a	98 a	
Clethodim	468	92 a	75 c	100*	99 ab	94 b	99
Fluazifop-P	0	85 c	85 b		99 a	97 a	
Fluazifop-P	468	91 a	77 c	96*	95 d	85 c	99*
Quizalofop-P	0	89 ab	90 b		99 ab	96 ab	
Quizalofop-P	468	87 bc	69 c	98*	96 cd	86 c	99*
Sethoxydim	0	89 ab	96 a		98 bc	95 ab	
Sethoxydim	468	89 ab	71 c	99*	83 e	54 d	99*

[x] Data for annual grasses averaged over two rates of graminicides and seven locations; data for johnsongrass averaged over two rates of graminicides and two locations. Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at $P \leq 0.05$.

[y] DAT, days after treatment.

[z] Expected control calculated according to the method described by Colby (1967). An asterisk (*) indicates a significant difference between observed and expected values at $P \leq 0.05$.

Table 4. Control of annual grasses by clethodim and fluazifop-P alone and mixed with glufosinate in experiment 2[y]

		Control		
			28 DAT	
Graminicides	Glufosinate	14 DAT	Observed	Expected[z]
	g ha^{-1}	%		
Clethodim	0	84 b	90 a	
Clethodim	468	91 a	67 b	95*
Fluazifop-P	0	72 c	61 b	
Fluazifop-P	468	90 a	68 b	85*

[y] Data averaged over four rates of graminicides and two rates of ammonium sulfate. Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at $P \leq 0.05$.

[z] Expected control calculated according to the method described by Colby (1967). An asterisk (*) indicates a significant difference between observed and expected values at $P \leq 0.05$.

Table 5. Control of annual grasses and johnsongrass by graminicides and glufosinate applied sequentially in experiment 3[x]

Time of graminicide application relative to glufosinate application	Annual grasses[y]		Johnsongrass[z]	
	Glufosinate rate		Glufosinate rate	
	0 g ha^{-1}	468 g ha^{-1}	0 g ha^{-1}	468 g ha^{-1}
days	%			
-5	89	90	99	94
-3	90	89	95	89
-1	87	78*	98	69*
0	86	69*	97	69*
1	85	65*	97	58*
3	85	73*	95	78*
5	84	78	95	88
7	82	80	94	94

[x] An asterisk (*) signifies significantly less control ($P \leq 005$) with 468 g ha^{-1} glufosinate compared with no glufosinate.

[y] Data averaged over two graminicides and four locations.

[z] Data averaged over two graminicides and two locations.

Chapter 3

Management of Annual Grasses and *Amaranthus* spp. in glufosinate-resistant cotton

Andrew P. Gardner and Alan C. York[1]

ABSTRACT

Annual grasses and *Amaranthus* spp. can be difficult to control in glufosinate-resistant (GR) cotton (*Gossypium hirsutum* L.). A field experiment was conducted at six locations to determine the effect of residual herbicides and timing of the initial glufosinate application on control of annual grasses, Palmer amaranth (*Amaranthus palmeri* S.Wats.), and redroot pigweed (*Amaranthus retroflexus* L.) in GR cotton. Annual grasses included mixtures of large crabgrass [*Digitaria sanguinalis* (L.) Scop.], goosegrass [*Eleusine indica* (L.) Gaertn.], broadleaf signalgrass [*Brachiaria platyphylla* (Griseb.) Nash], and fall panicum (*Panicum dichotomiflorum* Michx.). Common lambsquarters (*Chenopodium album* L.) and mixtures of entireleaf morningglory (*Ipomoea hederacea* var. *integriuscula* Gray), pitted morningglory (*Ipomoea lacunosa* L.), and tall morningglory [*Ipomoea purpurea* (L.) Roth] were also present. Initial glufosinate application timings were early postemergence (EPOST) to 1- to 2-leaf cotton or mid-postemergence (MPOST) to 3- to 4-leaf cotton. Residual herbicides included fluometuron, fomesafen, pendimethalin, and pyrithiobac applied preemergence (PRE) and pyrithiobac mixed with glufosinate applied EPOST or MPOST. All treatments included glufosinate applied late postemergence (LPOST) to 6- to 7-leaf cotton followed by prometryn plus MSMA postemergence-directed. Weed control and cotton yield

were generally greater with glufosinate applied EPOST compared with MPOST. Preemergence herbicides increased control of annual grasses and *Amaranthus* spp. after glufosinate EPOST or MPOST at all locations and at most locations after LPOST application. Greater late-season annual grass and *Amaranthus* spp. control was noted at four and two locations, respectively, in systems with PRE herbicides. Differences among PRE herbicides were minor except that pyrithiobac was less effective on annual grasses. Pyrithiobac applied postemergence (POST) was less effective than PRE herbicides. *Ipomoea* spp. and common lambsquarters were controlled well by all herbicide systems regardless of PRE herbicides or pyrithiobac POST. The PRE herbicides increased cotton yield at four of six locations while pyrithiobac POST increased yield at only one location. The results indicate good control of annual grasses, *Amaranthus* spp., *Ipomoea* spp., and common lambsquarters can be obtained in GR cotton with herbicide systems that include PRE herbicides and well-timed glufosinate applications.

KEY WORDS: *Amaranthus palmeri; Amaranthus retroflexus*; *Brachiaria platyphylla*; broadleaf signalgrass; *Chenopodium album*; common lambsquarters; *Digitaria sanguinalis*; *Eleusine indica*; entireleaf morningglory; fall panicum; fluometuron; fomesafen; goosegrass; *Ipomoea hederacea* var. *integriuscula*; *Ipomoea lacunosa*; *Ipomoea purpurea*; large

crabgrass; Palmer amaranth; *Panicum dichotomiflorum*; pendimethalin; pitted morningglory; pyrithiobac; redroot pigweed; tall morningglory; time of application.

ABBREVIATIONS: EPOST, early postemergence; GR, glufosinate-resistant; LPOST, late postemergence; MPOST, mid-postemergence; POST, postemergence; POST-DIR, postemergence-directed; PRE, preemergence

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INTRODUCTION

Glufosinate is an amino acid synthesis inhibitor that works by inhibiting glutamine synthetase (EC 6.3.1.2). Glutamine synthetase is the first enzyme in the process plants use to convert inorganic nitrogen into organic compounds. Glutamine synthetase also plays a critical role in metabolizing nitrogen, assimilating ammonia, and recycling the ammonia that is produced as a result of other processes occurring within the plant. Inhibition of glutamine synthetase leads to a rapid accumulation of ammonia within the plant, causing damage to the chloroplast structures and a decrease and eventual termination of photosynthetic activity and ultimately necrosis of tissue (Coetzer and Al-Khatib, 2001; Devine et al., 1993).

Glufosinate-resistant cotton was released commercially in 2004, allowing growers to apply glufosinate POST to control a variety of annual weeds without injuring the cotton (Blair-Kerth et al., 2001). Glufosinate can be applied from cotton emergence until the early bloom stage without visual plant injury, reduction in plant height, or adverse effects on lint yield, micronaire, fiber length, or fiber strength regardless of the number of applications or application rate (Blair-Kerth et al., 2001).

Glufosinate-resistant cotton is created through insertion of a gene from the fungi *Streptomycyes viridochromogenes.* This gene encodes for the phosphinothricine acetyl transferase enzyme**,** which converts the active portion of the herbicide molecule, L-phosphinothricine into the nontoxic acetylated form, N-acetyl-L-phosphinothricine. The end result is the production of a GR crop that has the ability to complete its life cycle in the same manner as a nontransgenic plant and produce equal amounts of viable seeds as a non-transgenic crop (Devine et al., 1993; Hinchee et al., 1993; Tsaftaris, 1996).

Glufosinate was first introduced in Japan in 1984 and received U. S. registration for use in orchards, row crop fields, vineyards, and non-cropland areas in 1993 (Lyon, 1991; Singh and Tucker, 1987). Glufosinate controls many annual weeds when applied in a timely manner. However, control of annual grasses and *Amaranthus* spp. can be marginal, especially in less than ideal growing conditions (Beyers et al., 2002; Coetzer et al., 2002; Corbett et al., 2004; Culpepper and York, 1999; Culpepper et al., 2000; Hill et al., 1997 Steckel et al., 1997; York and Culpepper, 2004, 2005). *Amaranthus* spp. are among the most troublesome weeds in cotton in the southeastern U. S., and have increased in significance in recent years (Webster, 2005; Webster and Coble, 1997). In 2005, Palmer amaranth was ranked the number one most troublesome weed in cotton in Missouri, North Carolina, and South Carolina while *Amaranthus* spp. in general ranked at least fourth in Mississippi, Louisiana, and Oklahoma (Webster, 2005).

One effective method for controlling *Amaranthus* spp. with glufosinate is to make multiple applications (Beyers et al., 2002; Coetzer et al., 2002; Tharp and Kells, 2002; Wiesbrook et al., 2001). Culpepper et al. (2000) reported greater control of *Amaranthus* spp. upon two sequential applications of glufosinate. Coetzer et al. (2002) reported less than 75% control of Palmer amaranth and redroot pigweed 4 weeks after a single glufosinate application. This low level of control was attributed to regrowth on plants not completely controlled and additional weed emergence after application. Glufosinate applied sequentially controlled both species 90%.

Timely application is critical for effective control of *Amaranthus* spp. Corbett el al. (2004) reported greater control of 2- to 5- cm Palmer amaranth than 8- to 10- cm plants.

Coetzer et al. (2002) applied glufosinate to 2- to 5-, 7- to 10-, and 15- to 18-cm Palmer amaranth. Control was 81, 71, and 74%, respectively. Redroot pigweed also followed a similar trend with reduced control as plant size increased. These data indicate the importance of timely application to *Amaranthus* spp.

Preemergence herbicides are often applied to control *Amaranthus* species (Beyers et al., 2002; Culpepper and York, 1997, 2000; Reddy, 2001; Taylor-Lovell and Wax, 2001; Toler et al., 2002). Beyers et al. (2002) reported that pendimethalin, sulfentrazone, cloransulam, or flumioxin applied PRE followed by a glufosinate applied POST controlled common waterhemp (*Amaranthus rudis* Sauer), *Ipomoea* spp., giant foxtail (*Setaria faberi* Herrm.), prickly sida (*Sida spinosa* L.), and common cocklebur (*Xanthium strumarium* L.) in soybean [*Glycine max* (L.) Merr.] more effectively than glufosinate applied alone. Fomesafen also controls *Amaranthus* spp., especially Palmer amaranth, when applied PRE to cotton (Culpepper et al., 2000; Hill et al., 1997, Murdock and Keeton, 1998). Glufosinate controlled Palmer amaranth 78% in soybean 9 weeks after planting while fomesafen applied PRE followed by glufosinate controlled Palmer amaranth 97% (Hill et al., 1997). Bauman et al. (1998) reported greater than 90% control of Palmer amaranth by fomesafen applied PRE with less than 10% cotton injury. Other preemergence herbicides commonly used in cotton include pendimethalin, pyrithiobac, and fluometuron (Culpepper and York, 1997, 2000; Reddy, 2001, Toler et al., 2002; Troxler et al., 2002). Previous research indicates a benefit from PRE herbicides followed by early POST herbicides when weed populations are great enough to compete with cotton early in the season (Culpepper et al., 2000; Reddy, 2001; Toler et al., 2002; Troxler et al., 2002).

Pyrithiobac applied either PRE or POST effectively controls *Amaranthus* spp. (Bailey et al., 2003; Culpepper and York, 1997, 2000; Jordan et al., 1993b). York and Culpepper (2004) reported increased control of Palmer amaranth with pyrithiobac mixed with glufosinate.

In an effort to develop more effective weed management systems in GR cotton, research was conducted to determine the effect of glufosinate application timing and residual herbicides, including PRE herbicides and pyrithiobac applied POST, on control of annual grasses and *Amaranthus* spp. in a glufosinate-based GR cotton weed management system.

MATERIALS AND METHODS

The experiment was conducted in North Carolina at two locations during 2004 and four locations during 2005. Soil types at experiment sites are included in Table 1. Cotton cultivar FM 958LL (Bayer CropScience; Research Triangle Park, NC) was planted on 97-cm rows in two fields on the Central Crops Research Station, near Clayton, NC on May 11, 2004 and May 9, 2005. The same cultivar was planted on 91-cm rows at the Upper Coastal Plain Research Station near Rocky Mount, NC on May 12, 2005 and at the Tidewater Research Station near Plymouth, NC on May 13, 2005. One location each year at Clayton (referred to as Clayton-2) had Palmer amaranth while the other location (Clayton-1) had redroot pigweed (Table 2). All locations had a mixture of *Ipomoea* and annual grass species. All locations except Clayton-2 in 2004 also had common lambsquarters.

The experimental design was a randomized complete block with treatments replicated four times. Individual plots were four rows wide by 9.1 m long. Treatments consisted of a factorial arrangement of six residual herbicide options by two times of initial glufosinate application. Residual herbicide options included the following: no residual herbicide; fluometuron (Cotoran-4L; Griffin LLC; Valdosta, GA) applied PRE at 1120 g ai ha^{-1}; fomesafen (Reflex; Syngenta Crop Protection, Inc.; Greensboro, NC) applied PRE at 280 g ai ha^{-1}; pendimethalin (Prowl H2O; BASF Ag Products; Research Triangle Park, NC) applied PRE at 1120 g ai ha^{-1}; pyrithiobac [Staple Herbicide; E. I. du Pont de Nemours and Co.; Wilmington, DE] applied PRE at 36 g ai ha^{-1}; and pyrithiobac at 36 g ha^{-1} mixed with glufosinate and applied POST. The PRE herbicides were applied immediately after planting. Initial glufosinate (Ignite; Bayer CropScience; Research Triangle Park, NC) application timings included EPOST to1- to 2-leaf cotton and MPOST to 3- to 4-leaf cotton. A non-treated check also was included. All treatments, except the non-treated check, included glufosinate applied LPOST to 6- to 7-leaf cotton and prometryn (Caparol 4L; Syngenta Crop Protection, Inc.; Greensboro, NC) at 1120 g a.i. ha^{-1} plus MSMA (MSMA 6.6; Platte Chemical Co.; Greeley, CO) at 2220 g a.i. ha^{-1} plus nonionic surfactant (Induce; Helena Chemical Co.; Memphis, TN) at 0.25% by volume applied postemergence-directed (POST-DIR) when cotton averaged 40 cm in height. The glufosinate rate was 470 g a.i. ha^{-1} in all applications.

Herbicides were broadcast PRE and POST using a CO_2-pressurized backpack sprayer equipped with flat-fan nozzles (TeeJet XR 11002 nozzles; Spraying Systems Co.; Wheaton, IL) calibrated to deliver 140L ha^{-1} at 160 kPa. Postemergence-directed sprays were broadcast using a CO_2-pressurized backpack sprayer equipped with three flat-fan nozzles per row middle calibrated to deliver 140L ha^{-1} at 193 kPa.

Weed control and crop injury were estimated visually 3 weeks after PRE, 1 week after EPOST, MPOST, and LPOST herbicide applications and late in the season (early September) using a scale of 0 to 100, where 0 = no control or injury to 100 = death of all plants (Frans et al., 1986). The center two rows of each plot were harvested using a spindle picker modified for small-plot harvesting. A sample of mechanically harvested seed cotton was collected from each plot at all locations except Plymouth and used to determine lint percentage and fiber quality. Seed cotton was ginned on a laboratory gin without lint cleaning. Cotton grades are not presented as they would not be representative of cotton ginned commercially. However, fiber upper half mean length, fiber length uniformity index, fiber strength, and micronaire were determined by high volume instrumentation testing (Sasser, 1981).

Data were subjected to analysis of variance using the mixed model procedure of the Statistical Analysis System (version 9.1; SAS Institute Inc.; Cary, NC) with partitioning appropriate for the 6 by 2 factorial arrangement. Data are presented with statistical interpretation. Data were averaged over locations as appropriate. Means of significant main effects and interactions were separated using Fisher's protected LSD at $P \leq 0.05$.

RESULTS AND DISCUSSION

Rainfall was adequate for PRE herbicide activation at each location. Both locations at Clayton received 1.22 cm of rainfall within eight days after planting in 2004 and 3.4 cm of rainfall within 1 week after planting in 2005. Rocky Mount and Plymouth received 3.5 and 1.7 cm of rainfall, respectively, within 1 week after planting (Appendix tables 1 – 4).

Amaranthus control. Residual herbicides increased *Amaranthus* spp. control in glufosinate-based systems. All PRE herbicides controlled *Amaranthus* spp. greater than 90% 3 weeks after planting and prior to the initial glufosinate application (Table 3). Fomesafen was the most effective PRE herbicide on *Amaranthus* spp. and somewhat more effective than fluometuron or pyrithiobac. Excellent control of *Amaranthus* spp. by fomesafen applied PRE has been reported previously (Bauman et al., 1998; Kendig et al., 2000; Murdock and Keeton, 1998; Troxler et al., 2002).

Amaranthus spp. control 1 week after the initial glufosinate application and 1 week after the LPOST glufosinate application was greater when PRE herbicides were included in the system (Tables 4 and 5). Control was similar when fluometuron, fomesafen, pendimethalin, or pyrithiobac applied PRE preceded the initial glufosinate application by 10 to 15 percentage points greater than systems with no PRE herbicide. Pyrithiobac mixed with glufosinate increased *Amaranthus* spp. control 4 to 6 percentage points compared with glufosinate alone. However, control by glufosinate plus pyrithiobac was less than control by a PRE herbicide followed by glufosinate. Pyrithiobac kills susceptible plants slowly (Duke, 1990), hence a 1-week interval after application may not been sufficient for the maximum effect to be expressed.

A location by residual herbicide interaction was noted for *Amaranthus* spp. control late in the season. Following the POST-DIR application of prometryn plus MSMA, *Amaranthus* spp. at four of the six locations were controlled at least 98% by all herbicide systems (Table 6). At Clayton-2 in 2004 and at Rocky Mount in 2005, however, greater *Amaranthus* spp. control was noted in systems with residual PRE herbicides or with pyrithiobac mixed with the initial glufosinate application. All PRE herbicides were more effective than pyrithiobac POST at Rocky Mount whereas fomesafen was the only PRE herbicide more effective than pyrithiobac POST at Clayton-2 in 2004. Few *Amaranthus* spp. emerged following the POST-DIR application at any location. Poorer late-season control in the absence of residual herbicides at Clayton-2 in 2004 and Rocky Mount was due to some weeds being too large for effective spray coverage and control by prometryn plus MSMA applied POST-DIR.

A time of initial glufosinate application by location interaction was noted for control of *Amaranthus* spp. At 1 week after the initial glufosinate application, greater control was noted at five of six locations when glufosinate was initially applied EPOST compared with MPOST (Table 7). The *Amaranthus* spp. were smaller at time of EPOST, and glufosinate typically is more effective on smaller *Amaranthus* spp. (Coetzer et al., 2002; Corbett et al., 2004). Similar results were noted at four locations 1 week after the LPOST glufosinate application (data not shown). Larger *Amaranthus* spp. not killed by glufosinate initially applied at MPOST were also not controlled as well following the LPOST glufosinate application. The exception to this occurred at Rocky Mount. The density of *Amaranthus* was less at Rocky Mount (Table 2), and a greater proportion of the *Amaranthus* emerged shortly after the EPOST application relative to other locations. With the later emergence, the weeds were still small enough for excellent control by glufosinate applied MPOST (Table 7). At the time of LPOST glufosinate application, *Amaranthus* was larger in plots receiving glufosinate EPOST because of the later emergence and were controlled less effectively by glufosinate LPOST (data not shown). A response to time of initial glufosinate application was not observed following the POST-DIR application of prometryn plus MSMA.

Common lambsquarters. Prior to glufosinate application, fluometuron, pendimethalin, and pyrithiobac applied PRE controlled common lambsquarters 93 to 98% (Table 3). Each of these herbicides was more effective than fomesafen, which controlled common lambsquarters 80%. Wiesbrook et al. (2001) also reported poor control of common lambsquarters by fomesafen.

At 1 week after the initial glufosinate application, common lambsquarters was controlled 99 to 100% in systems that included fluometuron, pendimethalin, or pyrithiobac applied PRE compared with 86% control by glufosinate in the absence of residual herbicides (Table 4). Similar to observations prior to glufosinate application, control of common lambsquarters was less in systems with fomesafen applied PRE than in systems with the other PRE herbicides. Pyrithiobac mixed with glufosinate increased common lambsquarters control 5 percentage points, but control by glufosinate plus pyrithiobac was less than control by fluometuron, pendimethalin, or pyrithiobac applied PRE followed by glufosinate.

Greater control was noted in systems including a PRE when evaluated 1 week after the 6- to 7- leaf treatment applications. However all treatments controlled common lambsquarters at least 97% (Table 5.)

A time of initial glufosinate application by location interaction was noted for common lambsquarters control 1 week after the initial glufosinate application. At Clayton-2 in 2005, common lambsquarters control was 29 percentage points greater when glufosinate was applied EPOST compared with MPOST application (Table 7). An explanation for this observation is not readily apparent. The weeds at this location were generally no larger at time of MPOST glufosinate application than at other locations (Table 2). Although the response was less 1 week after LPOST glufosinate application, common lambsquarters control at Clayton-2 in 2005 was still greater when glufosinate was initially applied EPOST (100 vs. 99%, data not shown). A minor response to time of initial glufosinate application was also noted 1 week after initial glufosinate application at Plymouth (Table 7). Time of initial glufosinate application had no effect on common lambsquarters control at the remaining locations. No differences in late-season common lambsquarters control were noted among treatments, where all treatments controlled common lambsquarters at least 96% (data not shown).

Morningglory control. The PRE herbicides controlled *Ipomoea* spp. poorly, with control ranging from 35 to 54% (Table 3). Glufosinate, however, controlled *Ipomoea* spp. very well. Regardless of PRE herbicide, *Ipomoea* spp. were controlled at least 94% by all treatments 1 week after the initial glufosinate application (Table 4). A time of initial glufosinate application by location interaction was noted for *Ipomoea* spp. control 1 week after the initial glufosinate application. *Ipomoea* spp. control was 2 to 18 percentage points less with MPOST application compared with EPOST application at four of six locations (Table 7). An effect of timing of the initial glufosinate application was not observed 1 week after LPOST glufosinate application, when all treatments controlled *Ipomoea* spp. at least 97% (Table 5). All treatments controlled *Ipomoea* spp. at least 97% late in the season (data not shown). These results are consistent with previous reports of excellent *Ipomoea* spp. control by glufosinate (Corbett et al., 2004; Culpepper et al., 2000).

Annual grass control. Annual grasses were controlled 90 to 91% 3weeks after PRE application of fluometuron, fomesafen, and pendimethalin (Table 3). Pyrithiobac was less effective, controlling annual grasses 71%. This is similar to findings from Jordan et al. (1993a) where control of large crabgrass was poor with pyrithiobac alone.

Greater control of annual grasses was noted in systems with a PRE herbicide at 1 week after the initial glufosinate application (Table 4). The PRE herbicides increased control of annual grasses 7 to 13 percentage points. Only minor differences were noted among the PRE herbicides, with fluometuron being somewhat more effective than pyrithiobac. Pyrithiobac applied POST in combination with glufosinate did not impact annual grass control. Time of initial glufosinate application affected annual grass control 1 week after initial application at five of six locations (Table 7). Annual grasses were controlled 23 to 26 percentage points less by glufosinate applied MPOST compared with EPOST at both Clayton locations in 2004. At Plymouth and Rocky Mount, control was reduced 6 to 7 percentage points by delaying the initial glufosinate application. The opposite response was noted at Clayton-1 in 2005, where control by glufosinate applied MPOST was 7 percentage points greater than with the earlier application. This response appeared to be due grasses emerging shortly after the EPOST application. Annual grasses were controlled 99 to 100% at Clayton-2 in 2005 regardless of time of initial glufosinate application.

An interaction of residual herbicides by locations was noted for annual grass control 1 week after LPOST glufosinate application. All treatments controlled annual grasses 98 to 100% at both Clayton locations in 2005 (Table 8). All PRE herbicides, except fomesafen at Clayton-2 in 2004, increased annual grass control 6 to 27 percentage points at the remaining four locations. Pyrithiobac mixed with glufosinate at the initial application impacted annual grass control 1 week after LPOST glufosinate application only at Plymouth, where pyrithiobac POST increased annual grass control 5 percentage points. An interaction of residual herbicides by locations was also noted for annual grass control late in the season. Trends for annual grass control late in the season at both Clayton locations in 2004 and at Rocky Mount (Table 9) were similar to those observed 1 week after LPOST glufosinate application (Table 8). At these locations, all PRE herbicides increased late-season annual grass control 9 to 42 percentage points (Table 9). Annual grass control at both Clayton locations in 2005 was generally less late in the season than 1 week after LPOST glufosinate application. The cotton canopy never closed at Clayton in 2005 due to dry conditions from mid-season until harvest. The open row middles allowed annual grasses to emerge after the POST-DIR application of prometryn plus MSMA. The opposite response was noted at Plymouth where the cotton tended to be excessively vegetative. All treatments at Plymouth controlled annual grasses at least 97% late in the season. Greater control late in the season as compared with 1 week after LPOST glufosinate application is indicative of excellent control by prometryn plus MSMA applied POST-DIR followed by a closed cotton canopy. Pyrithiobac mixed with glufosinate increased annual grass control late in the season only at Clayton-2 in 2004.

Cotton response. Cotton injury, determined 3 weeks after planting and before EPOST application of glufosinate was similar for all PRE herbicides and ranged from 13- 16% (data not shown). Pyrithiobac mixed with glufosinate injured the cotton 6% when applied EPOST. Injury from all other treatments were 2% or less (data not shown). Injury from glufosinate alone and pyrithiobac mixed with glufosinate applied EPOST at late season was 5% for both treatments (data not shown). This is the result of cotton stunting due to poor grass control

(Table 8). Injury for all other treatments was not greater than 2% at all other rating dates (data not shown).

Yields of non-treated check plots were assumed to be zero as these plots were decimated by weeds and could not be harvested mechanically. Visual estimates of yield reduction in non-treated checks exceeded 95%. Residual herbicides had no effect on seed cotton yield at Clayton-2 in 2005 and Plymouth (Table 10). At the remaining four locations, all PRE herbicides, except pyrithiobac at Clayton-1 in 2005, increased seed cotton yield. Yields were similar with the four PRE herbicides at Clayton-2 in 2004, Clayton-1 in 2005, and Rocky Mount. At Clayton-1 in 2004, yields were greatest with fluometuron, intermediate with fomesafen and pendimethalin, and lowest with pyrithiobac. Averaged over herbicides, yields were increased 57, 32, 19, and 36% by PRE herbicides at Clayton-1 in 2004, Clayton-2 in 2004, Clayton-1 in 2005, and Rocky Mount, respectively. Pyrithiobac applied POST increased yield at Clayton-2 in 2004 27% but had no effect at the remaining locations. Time of initial glufosinate application affected seed cotton yield at four of the six locations (Table 11). Seed cotton yields were 6 to 13% greater when glufosinate was initially applied EPOST compared with MPOST application.

Percent lint and selected fiber quality parameters were determined at five of the six locations. No differences among herbicide treatments were noted for percent lint, fiber length, fiber length uniformity, fiber strength, or micronaire. Averaged over herbicide treatments and locations, percent lint, upper half mean fiber length, fiber length uniformity index, fiber strength, and micronaire were 43%. 1.14 mm, 83%, 32 kN m kg^{-1}, and 4.5, respectively (data not shown).

This research, along with previously reported work (Burns et al., 2003; Murdock et al., 2003; York and Culpepper, 2004), demonstrates that good weed control can be achieved in glufosinate-resistant cotton. Of the commonly encountered weeds, annual grasses and *Amaranthus* spp. are among the most difficult to control with glufosinate (Coetzer et al., 2002; Corbett et al., 2004, Culpepper et al., 2000). Our research indicates that annual grasses and *Amaranthus* spp. can be controlled in glufosinate-based management systems that integrate PRE herbicides and timely applied glufosinate.

Currently available glufosinate-resistant cultivars have not performed well in North Carolina's official cultivar trials (Bowman, 2006). However, efforts are being made to transfer the glufosinate-resistance trait into cultivars that are better adapted to the southeastern United States (Klingenberg, 2005). Once such cultivars are commercialized, a glufosinate-based weed management system may be a viable alternative to glyphosate-based systems and offer growers an additional tool to manage herbicide-resistant weeds (Henniger et al., 2005).

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Table 1. Description of soils at experiment sites

Location	Year	Soil series	Soil texture	Soil pH	Soil organic matter
					%
Clayton-1	2004	Norfolk[w]	Loamy sand	6.3	0.7
Clayton-2	2004	Gilead[x]	Sandy loam	5.6	1.0
Clayton-1	2005	Dothan[y]	Loamy sand	5.7	0.9
Clayton-2	2005	Gilead	Sandy loam	5.5	0.7
Rocky Mount	2005	Norfolk	Loamy sand	5.5	0.5
Plymouth	2005	Cape Fear[z]	Loam	5.7	5.4

[w] Fine-loamy, kaolinitic, thermic Typic Kandiudults.

[x] Fine, kaolinitic, thermic Aquic Hapludults.

[y] Fine-loamy, kaolinitic, thermic Plinthic Kandiudults.

[z] Cape Fear, fine, mixed, semiactive, thermic Typic Umbraquults.

Table 2. Weed species and densities at experiment sites and weed size at initial glufosinate application

				Height at initial glufosinate application[u]	
Location	**Year**	**Species**	**Density[v]**	**EPOST[w]**	**MPOST[x]**
			no. m^{-2}	**cm**	
Clayton-1	**2004**	**Redroot pigweed**	**50**	**5**	**9**
		***Ipomoea* spp.[y]**	**25**	**4**	**18**
		Common lambsquarters	**4**	**10**	**15**
		Annual grasses[z]	**22**	**8**	**15**
Clayton-2	**2004**	**Palmer amaranth**	**40**	**3**	**18**
		***Ipomoea* spp.[y]**	**3**	**3**	**6**
		Annual grasses[z]	**30**	**3**	**13**
Clayton-1	**2005**	**Redroot pigweed**	**16**	**5**	**9**
		***Ipomoea* spp.[y]**	**10**	**3**	**8**
		Common lambsquarters	**5**	**3**	**13**
		Annual grasses[z]	**17**	**5**	**13**
Clayton-2	**2005**	**Palmer amaranth**	**55**	**5**	**20**
		***Ipomoea* spp.[y]**	**4**	**3**	**8**
		Common lambsquarters	**12**	**4**	**10**
		Annual grasses[z]	**38**	**5**	**9**
Plymouth	**2005**	**Redroot pigweed**	**13**	**8**	**10**
		***Ipomoea* spp.[y]**	**9**	**4**	**10**
		Common lambsquarters	**5**	**5**	**9**
		Annual grasses[z]	**49**	**8**	**15**
Rocky Mount	**2005**	**Redroot pigweed**	**6**	**6**	**11**
		***Ipomoea* spp.[y]**	**25**	**13**	**18**
		Common lambsquarters	**18**	**6**	**19**
		Annual grasses[z]	**33**	**8**	**13**

[u] Weed height recorded in plots not receiving preemergence herbicides.

[v] Weed densities recorded in non-treated checks 1 week after MPOST application.

[w] **EPOST, early postemergence application to 1- to 2-leaf cotton.**

[x] **MPOST, mid-postemergence application to 3- to 4-leaf cotton.**

[y] ***Ipomoea* spp. distribution consisted of the following: Clayton-1 in 2004, 65% entireleaf morningglory (*Ipomoea hederacea* var. *integriuscula* Gray) and 35% pitted morningglory (*Ipomoea lacunosa* L.); Clayton-2 in 2004, tall morningglory [*Ipomoea purpurea* (L.) Roth]; Clayton-1 in 2005, 40% entireleaf morningglory, 35% tall morningglory, and 25% pitted morningglory; Clayton-2 in 2005, 75% tall morningglory and 25% entireleaf morningglory; Rocky Mount, 75% tall morningglory and 25% entireleaf morningglory; and Plymouth, 65% tall morningglory, 20% entireleaf morningglory, and 15% pitted morningglory.**

[z] **Annual grass species distribution consisted of the following: Clayton-1 in 2004, 50% large crabgrass [*Digitaria sanguinalis* (L.) Scop.], 30% goosegrass [*Eleusine indica* (L.) Gaertn.], and 20% broadleaf signalgrass [*Brachiaria platyphylla* (Griseb.) Nash]; Clayton-2 in 2004, 95% goosegrass and 5% large crabgrass; Clayton-1 in 2005, 45% goosegrass, 40% large crabgrass, and 15% fall panicum (*Panicum dichotomiflorum* Michx.); Clayton-2 in 2005, 60% goosegrass and 40% large crabgrass; Rocky Mount, 55% goosegrass and 45% large crabgrass; and Plymouth, 50% goosegrass, 40% fall panicum, and 10% large crabgrass.**

Table 3. Weed control by herbicides applied preemergence[v]

Herbicide[w]	***Amaranthus* spp.[x]**	**Common lambsquarters**	***Ipomoea* spp.[y]**	**Annual grasses[z]**
	%			
Fluometuron	**93 b**	**98 a**	**50 a**	**91 a**
Fomesafen	**98 a**	**80 b**	**48 a**	**90 a**
Pendimethalin	**95 ab**	**98 a**	**35 a**	**90 a**
Pyrithiobac	**91 b**	**93 a**	**54 a**	**71 b**

[v] **Data recorded prior to early postemergence application of glufosinate (3 weeks after planting) and averaged over five locations for common lambsquarters or six locations for other species. Means within a column followed by the same letter are not different according to Fisher's Protected LSD at *P* $\leq$ 0.05.**

[w] **Fluometuron, fomesafen, pendimethalin, and pyrithiobac applied preemergence at 1120, 280, 1120, and 36 g ha^{-1}, respectively.**

[x] ***Amaranthus* spp. consisted of redroot pigweed and Palmer amaranth.**

[y] ***Ipomoea* spp. consisted of mixtures of entireleaf morningglory, pitted morningglory, and tall morningglory.**

[z] **Annual grasses consisted of mixtures of two or more of the following: large crabgrass, goosegrass, broadleaf signalgrass, and fall panicum.**

Table 4. Weed control 1 week after initial glufosinate application as affected by residual herbicides[v]

Residual herbicides[w]		Control			
Preemergence	Postemergence	*Amaranthus* spp.[x]	Common lambsquarters	*Ipomoea* spp.[y]	Annual grasses[z]
		%			
Fluometuron	Glufosinate	97 a	100 a	97 ab	96 a
Fomesafen	Glufosinate	98 a	92 b	96 b	94 ab
Pendimethalin	Glufosinate	96 a	100 a	94 b	94 ab
Pyrithiobac	Glufosinate	96 a	99 a	99 a	90 b
None	Glufosinate	83 c	86 c	96 b	83 c
None	Glufosinate + pyrithiobac	87 b	91 b	98 ab	82 c

[v] Data recorded 1 week after EPOST application (early postemergence, 1- to 2-leaf cotton) or 1 week after MPOST application (mid-postemergence, 3- to 4-leaf cotton). Data averaged over EPOST and MPOST glufosinate applications and five locations for common lambsquarters or six locations for other species. Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at $P \leq 0.05$.

[w] Fluometuron, fomesafen, pendimethalin, and pyrithiobac applied preemergence at 1120, 280, 1120, and 36 g ha^{-1}, respectively. Glufosinate and pyrithiobac applied postemergence at 470 and 36 g ha^{-1}, respectively.

[x] *Amaranthus* spp. consisted of redroot pigweed and Palmer amaranth.

[y] *Ipomoea* spp. consisted of mixtures of entireleaf morningglory, pitted morningglory, and tall morningglory.

[z] Annual grasses consisted of mixtures of two or more of the following: large crabgrass, goosegrass, broadleaf signalgrass, and fall panicum.

Table 5. Weed control 1 week after late-postemergence glufosinate application as affected by residual herbicides[w]

Residual herbicides[x]		Control		
Preemergence	Postemergence	*Amaranthus* spp.[y]	Common lambsquarters	*Ipomoea* spp.[z]
		%		
Fluometuron	Glufosinate	98 a	100 a	98 ab
Fomesafen	Glufosinate	100 a	100 a	98 ab
Pendimethalin	Glufosinate	98 a	100 a	98 ab
Pyrithiobac	Glufosinate	98 a	100 a	98 ab
None	Glufosinate	88 c	97 c	97 b
None	Glufosinate + pyrithiobac	94 b	99 b	99 a

[w] Data averaged over EPOST (early postemergence, 1- to 2-leaf cotton) and MPOST (mid-postemergence, 3- to 4-leaf cotton) glufosinate applications and five locations for common lambsquarters or six locations for other species. Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at $P \leq 0.05$.

[x] Fluometuron, fomesafen, pendimethalin, and pyrithiobac applied preemergence at 1120, 280, 1120, and 36 g ha^{-1}, respectively. Glufosinate and pyrithiobac applied postemergence at 470 and 36 g ha^{-1}, respectively.

[y] *Amaranthus* spp consisted of redroot pigweed and Palmer amaranth.

[z] *Ipomoea* spp. consisted of mixtures of entireleaf morningglory, pitted morningglory, and tall morningglory.

Table 6. Late-season control of *Amaranthus* spp. as affected by residual herbicides[y]

Residual herbicides[z]		Control					
		2004		2005			
Preemergence	Postemergence	Clay-ton-1	Clay-ton-2	Clay-ton-1	Clay-ton-2	Ply-mouth	Rocky Mount
		%					
Fluometuron	Glufosinate	100 a	96 ab	100 a	99 a	100 a	99 a
Fomesafen	Glufosinate	100 a	98 a	100 a	100 a	100 a	100 a
Pendimethalin	Glufosinate	100 a	92 ab	100 a	99 a	100 a	97 a
Pyrithiobac	Glufosinate	100a	86 b	100 a	100 a	100 a	99 a
None	Glufosinate	99 a	71 c	98 a	99 a	100 a	74 c
None	Glufosinate + pyrithiobac	99 a	85 b	98 a	100 a	100 a	80 b

[y] **Data averaged over six locations and two times of initial glufosinate application (1- to 2-leaf or 3- to 4-leaf cotton). All systems included a late-postemergence (6- to 7-leaf cotton) application of glufosinate and a lay-by application of prometryn plus MSMA. *Amaranthus* spp. consisted of redroot pigweed at four locations and Palmer amaranth at two locations. Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at $P \leq 0.05$.**

[z] **Fluometuron, fomesafen, pendimethalin, and pyrithiobac applied preemergence at 1120, 280, 1120, and 36 g ha^{-1}, respectively. Glufosinate and pyrithiobac applied postemergence at 470 and 36 g ha^{-1}, respectively.**

Table 7. Effect of glufosinate application timing on weed control 1 week after initial glufosinate application[v]

Location	Year	Time of initial glufosinate application	Control			
			Amaranthus spp.[w]	Common lambsquarters	*Ipomoea* spp.[x]	Annual grasses[y]
			%			
Clayton-1	2004	EPOST[z]	100	100	100	93
		MPOST[z]	91*	96	90*	70*
Clayton-2	2004	EPOST	97	----	100	95
		MPOST	60*	----	82*	69*
Clayton-1	2005	EPOST	100	100	99	92
		MPOST	93*	100	97*	99*
Clayton-2	2005	EPOST	100	94	99	100
		MPOST	94*	65*	100	99
Plymouth	2005	EPOST	96	100	98	96
		MPOST	94*	98*	100*	90*
Rocky Mount	2005	EPOST	93	95	98	91
		MPOST	99*	98	97	84*

[v] Data recorded 1 week after EPOST application or 1 week after MPOST application and averaged over residual herbicides. An asterisk (*) denotes a significant difference between EPOST and MPOST means.

[w] *Amaranthus* spp. consisted of redroot pigweed and Palmer amaranth.

[x] *Ipomoea* spp. consisted of mixtures of entireleaf morningglory, pitted morningglory, and tall morningglory.

[y] Annual grasses consisted of mixtures of two or more of the following: large crabgrass, goosegrass, broadleaf signalgrass, and fall panicum.

[z] EPOST, early postemergence application to 1- to 2-leaf cotton; MPOST, mid-postemergence application to 3- to 4-leaf cotton.

Table 8. Annual grass control 1 week after late-postemergence glufosinate application as affected by residual herbicides[y]

Residual herbicides[z]		Control					
		2004		2005			
Preemergence	Postemergence	Clay-ton-1	Clay-ton-2	Clay-ton-1	Clay-ton-2	Ply-mouth	Rocky Mount
		%					
Fluometuron	Glufosinate	90 a	97 a	100 a	100 a	92 ab	90 a
Fomesafen	Glufosinate	91 a	90 ab	100 a	100 a	92 ab	90 a
Pendimethalin	Glufosinate	88 a	96 a	100 a	100 a	94 a	93 a
Pyrithiobac	Glufosinate	77 b	94 a	100 a	100 a	89 b	80 b
None	Glufosinate	66 c	80 b	100 a	100 a	83 c	66 c
None	Glufosinate + pyrithiobac	67 c	83 b	98 a	100 a	88 b	65 c

[y] Data averaged over six locations and two times of initial glufosinate application (1- to 2-leaf or 3- to 4-leaf cotton). All systems included a late-postemergence (6- to 7-leaf cotton) application of glufosinate. Annual grasses consisted of a mixture of two or more of the following: large crabgrass, goosegrass, broadleaf signalgrass, and fall panicum. Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at $P \leq 0.05$.

[z] Fluometuron, fomesafen, pendimethalin, and pyrithiobac applied preemergence at 1120, 280, 1120, and 36 g ha^{-1}, respectively. Glufosinate and pyrithiobac applied postemergence at 470 and 36 g ha^{-1}, respectively.

Table 9. Late-season control of annual grasses as affected by residual herbicides[y]

Residual herbicides[z]		Control					
		2004		2005			
Preemergence	Postemergence	Clay-ton-1	Clay-ton-2	Clay-ton-1	Clay-ton-2	Ply-mouth	Rocky Mount
		%					
Fluometuron	Glufosinate	98 a	94 a	93 a	94 ab	99 a	99 a
Fomesafen	Glufosinate	97 a	87 ab	90 a	95 ab	99 a	98 a
Pendimethalin	Glufosinate	97 a	94 a	91 a	97 a	100 a	98 a
Pyrithiobac	Glufosinate	92 ab	85 ab	86 ab	94 ab	100 a	89 a
None	Glufosinate	83 c	66 c	80 b	90 b	100 a	56 b
None	Glufosinate + pyrithiobac	89 bc	79 b	78 b	94 ab	97 a	49 b

[y] Data averaged over six locations and two times of initial glufosinate application (1- to 2-leaf or 3- to 4-leaf cotton). All systems included a late-postemergence (6- to 7-leaf cotton) application of glufosinate and a postemergence-directed application of prometryn plus MSMA. Annual grasses consisted of a mixture of two or more of the following: large crabgrass, goosegrass, broadleaf signalgrass, and fall panicum. Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at $P \leq 0.05$.

[z] Fluometuron, fomesafen, pendimethalin, and pyrithiobac applied preemergence at 1120, 280, 1120, and 36 g ha^{-1}, respectively. Glufosinate and pyrithiobac applied postemergence at 470 and 36 g ha^{-1}, respectively.

Table 10. Seed cotton yield as affected by residual herbicides in a glufosinate-based weed management system[y]

Residual herbicides[z]		Yield					
		2004		2005			
Preemergence	Postemergence	Clay-ton-1	Clay-ton-2	Clay-ton-1	Clay-ton-2	Ply-mouth	Rocky Mount
		kg ha^{-1}					
Fluometuron	Glufosinate	3170 a	2900 a	2580 a	3290 a	3220 a	2960 a
Fomesafen	Glufosinate	2930 b	2750 a	2580 a	3310 a	3320 a	2870 a
Pendimethalin	Glufosinate	2890 b	2920 a	2530 a	3240 a	3420 a	3000 a
Pyrithiobac	Glufosinate	2410 c	2950 a	2390 ab	3480 a	3530 a	2970 a
None	Glufosinate	1810 d	2180 b	2120 b	3450 a	3280 a	2170 b
None	Glufosinate + pyrithiobac	1970 d	2760 a	1810 b	3230 a	3180 a	2200 b

[y] Data averaged over early postemergence (1- to 2-leaf cotton) and mid-postemergence (3- to 4-leaf cotton) glufosinate applications. All systems included a late-postemergence (6- to 7-leaf cotton) application of glufosinate and a postemergence-directed (40-cm cotton) application of prometryn plus MSMA. Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at $P \leq 0.05$.

[z] Fluometuron, fomesafen, pendimethalin, and pyrithiobac applied preemergence at 1120, 280, 1120, and 36 g ha^{-1}, respectively. Glufosinate and pyrithiobac applied postemergence at 470 and 36 g ha^{-1}, respectively.

Table 11. Seed cotton yield as affected by time of initial glufosinate application in a glufosinate-based weed management system[y]

Time of initial glufosinate application[z]	Yield					
	2004		2005			
	Clayton-1	Clayton-2	Clayton-1	Clayton-2	Plymouth	Rocky Mount
	kg ha^{-1}					
EPOST	2600	2910	2460	3310	3380	2820
MPOST	2460*	2580*	2220*	3360	3270	2570*

[y] Data averaged over residual herbicides. An asterisk (*) denotes a significant difference between EPOST and MPOST means at $P \leq 0.05$.

[z] EPOST, early postemergence to 1- to 2-leaf cotton; MPOST, mid-postemergence to 3- to 4-leaf cotton.

APPENDICES

Appendix Table 1 **Daily Precipitation at Central Crops Research Station, Clayton, NC 2004**

Day	May	June	July	August	September
			---------------cm---------------		
1	0.56				0.18
		(EPOST)[c]			
2	3.0	(POST)[d]		1.09	
3	2.34			0.08	
4		1.27			
5			0.05	1.98	
6				0.38	1.42
7					0.10
8					2.31
9			(P-DIR)[i]		1.02
10			0.51		
		4.06			
		(POST)[e]			
11	(PRE)[a]	(LPOST)[f]			
12	0.94		1.63	1.22	
13				0.56	
14			0.30	2.44	0.99
15				9.50	0.10
16		0.58		0.05	
17			0.05		1.40
18		1.04	0.30		0.28
19	0.28				
20					

Appendix Table 1 **continued**

21		**(LPOST)[g]**		**1.14**	
22	**2.08**		**0.56**		
23		**2.51**	**1.68**		
24	**(EPOST)[b]**				
25		**2.77**			
26	**0.43**	**0.20**			
27					**0.33**
28		**0.81**			**0.28**
29			**5.26**	**1.73**	
30	**0.18**	**1.35 (P-DIR)[h]**	**1.27**	**3.07**	
31			**0.18**	**4.62**	
Totals	**9.81**	**14.59**	**11.79**	**27.86**	**8.41**

[a] Preemergence applications at both locations

[b] 1- to 2- leaf application made to CCRS-2

[c] 1- to 2- leaf application made to CCRS-1

[d] 3- to 4- leaf application made to CCRS-2

[e] 3- to 4- leaf application made to CCRS-1

[f] 6- to 7- leaf application made to CCRS-2

[g] 6- to 7- leaf application made to CCRS-1

[h] Postemergence Directed application made to CCRS-1

[i] Postemergence Directed application made to CCRS-2

Appendix Table 2 **Daily Precipitation at Central Crops Research Station, Clayton, NC, 2005**

Day	May	June	July	August	September
			---------------cm---------------		
1	0.53	0.30			
2		1.57			
3		0.66			
4					
5			0.05		
6	3.28			0.48	
7		1.68 (POST)[d]		0.03	
8		0.05			
9	(PRE)[a]			4.14	
10	(PRE)[b]	0.08			
11					
12	0.66		0.25 (P-DIR)[h]		
13			0.43		
		(POST)[e]			
14		(LPOST)[f]	0.23		0.48
15	2.72		0.13		
16	0.03			0.53	0.13
17				1.47	0.18
18			0.84		0.03
19		0.30	3.76		
20	1.04		0.36		2.40
21	0.03	(LPOST)[g]			
22			0.46		

Appendix Table 2 **continued**

23				**0.25**	
24					
25					
26		**0.91**			**0.05**
27					**0.03**
28		**1.37**	**3.61**		
		0.69			
29		**(LPOST)[g]**	**1.40**		**0.03**
30			**0.69**	**0.79**	
31	**(EPOST)[c]**		**0.20**		
Totals	**8.29**	**7.61**	**12.41**	**7.69**	**3.33**

[a] **Preemergence applications at CCRS-2**

[b] **Preemergence applications at CCRS-2**

[c] **1- to 2- leaf application made at both locations**

[d] **3- to 4- leaf application made to CCRS-2**

[e] **3- to 4- leaf application made to CCRS-1**

[f] **6- to 7- leaf application made to CCRS-2**

[g] **6- to 7- leaf application made to CCRS-1**

[h] **Postemergence Directed application made at both locations**

Appendix Table 3 **Daily Precipitation at Tidewater Research Station, Plymouth, NC 2005**

Day	May	June	July	August	September
			---------------cm---------------		
1		0.48			
2	0.10	3.81			
3		0.20	0.30		
4		0.03			
5					
6	8.94	3.99 (EPOST) [b]			
7			(P-DIR) [e]	2.77	0.66
8				0.41	
9		0.76		8.92	
10					
11					
12					
13	(PRE) [a]				0.84
14					0.10
15	0.05	(POST) [c]		0.56	3.10
16	0.03			3.25	0.08
17			0.48	0.48	
18			0.05		0.48
19	0.43				
20	1.14				0.30
21	0.03			1.09	0.15
22			1.57		
23		(LPOST) [d]		0.08	

Appendix Table 3 **continued**

24	**0.76**			**0.03**	
25					
26		**0.30**			**0.30**
27		**0.91**			**0.36**
28					
29				**2.18**	
30					
31					
Totals	**11.79**	**10.49**	**2.41**	**17.58**	**6.37**

[a] **Preemergence applications**

[b] **1- to 2- leaf application**

[c] **3- to 4- leaf application**

[d] **6- to 7- leaf application**

[e] **Postemergence Directed application**

Appendix Table 4 **Daily Precipitation at Upper Coastal Plains Research Station, Rocky Mt., NC 2005**

Day	May	June	July	August	September
			---------------cm---------------		
1	0.25	0.15		0.05	
2		1.22	0.41		0.28
3		0.18			
4					
5					
6	7.04				
7		3.68		0.71	
8		0.03	0.38		
9		(EPOST) [b]		0.08	
10		2.29		0.99	
11					
12	0.64 (PRE)[a]		0.03		
13	0.05		0.23		1.73
14			0.71 (P-DIR) [e]		0.30
15	0.33		0.13	0.38	
16	0.94			3.33	
17				0.10	
18			0.76		
19	1.57		0.33	0.81	
20	0.48		0.03		1.88
21		(POST) [c]	0.84		0.05
22			0.30		
23			0.86	0.28	

Appendix Table 4 **continued**

24	**0.23**			**0.03**	
25					
26					**0.13**
27		**0.38**	**0.23**		
28		**5.08 (LPOST)[d]**			
29		**0.58**	**1.19**		**0.05**
30			**0.08**		
31			**0.08**		
Total	**11.53**	**13.59**	**6.59**	**6.76**	**4.42**

[a] **Preemergence application**

[b] **1- to 2- leaf application**

[c] **3- to 4- leaf application**

[d] **6- to 7- leaf application**

[e] **6- to 7- leaf application made to CCRS-1**