ABSTRACT

EVERMAN, WESLEY JAY. Influence of Environmental and Physiological Factors on Glufosinate and Glyphosate Weed Management. (Under the direction of Dr. Alan C. York and Dr. John W. Wilcut).

Field studies were conducted near Clayton, Lewiston, and Rocky Mount, NC in 2005 to evaluate weed control and cotton response to PRE treatments of pendimethalin alone or in a tank mixture with fomesafen, POST treatments of glufosinate applied alone or in a tank mixture with *S*-metolachlor, and LAYBY treatments of glufosinate in a tank mixture with flumioxazin or prometryn.

Field studies were conducted near Clayton, Goldsboro, Kinston, and Rocky Mount, NC in 2003 to evaluate weed control and cotton response to POST treatments of glufosinate applied alone or in tank mixtures with *S*-metolachlor, pyrithiobac, or trifloxysulfuron.

Field studies were conducted near Rocky Mount, NC in 2004, Clayton, NC, Lewiston-Woodville, NC, Florence, SC, St. Joseph, LA, and Suffolk, VA in 2005 to evaluate weed control and cotton response to postemergence treatments of glufosinate or glyphosate on glufosinate-resistant and glyphosate-resistant cotton, respectively, applied alone or in tank mixtures with *S*-metolachlor EPOST.

Greenhouse studies were conducted to evaluate phytotoxicity and corresponding physiological response to simulated rainfall following POST treatments of various formulations of glufosinate or glyphosate on goosegrass, Palmer amaranth, and pitted morningglory. Ammonia levels and shikimic acid levels were used as diagnostic markers for glufosinate and glyphosate, respectively. A rain-free period of 4 hours is needed to adequately control goosegrass and Palmer amaranth, while up to 24 hours is needed to control pitted morningglory with glyphosate. A rain-free period of 1 hour is needed to provide maximum control of goosegrass and pitted morningglory with glufosinate; however a rain-free period of at least 24 hours is needed to achieve maximum control of Palmer amaranth.

Greenhouse studies were conducted to evaluate absorption, translocation, and metabolism of ^{14}C-glufosinate in glufosinate-resistant corn, glufosinate-resistant cotton, non-transgenic cotton, goosegrass, large crabgrass, Palmer amaranth, pitted morningglory, and sicklepod. Absorption of ^{14}C-glufosinate varied by species. Significant levels of translocation were observed in glufosinate-resistant corn and Palmer amaranth. Metabolites of ^{14}C-glufosinate were detected in all crop and weed species.

Influence of Environmental and Physiological Factors on
Glufosinate and Glyphosate Weed Management

by

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DEDICATION

Dedicated to my family.

Their love and support have allowed me to explore and enjoy life to the fullest.

BIOGRAPHY

Wesley Everman grew up in rural Northeast Iowa where he developed his interest in agriculture. He attended Purdue University where he earned his B.S. degree in Agronomic Business and Marketing in 2000. In August 2000, Wesley accepted a graduate research assistantship at Purdue University under the direction of Dr. Case Medlin where his Masters' thesis research investigated the effects of preemergence and postemergence herbicides on the spectral reflectance of corn. Wesley obtained his M.S. degree in 2002. While working on his Master's degree, Wesley realized the impact on students and farmers that is possible as a professor working at a Land Grant institution.

He enjoyed making presentations and interacting with producers and students alike through various extension endeavors. In order to obtain as much knowledge in as many areas as possible, in January 2003 Wesley accepted a graduate research assistantship at North Carolina State University under the direction of John Wilcut. While a student and research associate, his responsibilities included coordinating and conducting weed management and site-specific research in corn, cotton, peanut, and soybean, as well as field, laboratory and greenhouse studies involving weed biology, weed competition, and herbicide physiology. He directly coordinated research on imidazolinone tolerant corn interference in peanut, critical period of broadleaf, grass, and total weed interference in peanut, rain-free requirements following glyphosate and glufosinate applications, absorption, translocation, and metabolism of glufosinate in 3 crop and 5 weed species, temperature and humidity effects on glufosinate efficacy; as well as weed management in corn, cotton, and peanut using various herbicide programs.

In 2006, Wesley accepted a research associate position with Dr. Wilcut as part of a six-state study where his responsibilities included establishing and maintaining 30 on-farm weed surveys in three cropping rotations across the state of North Carolina. The study involved sampling and mapping weed population dynamics over a four-year period.

Wesley has accepted a position in the Department of Crop and Soil Sciences at Michigan State University as an Assistant Professor in Weed Science.

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I would like to thank Dr. John Wilcut, for accepting a Midwesterner with no peanut or cotton experience into his program. His guidance developed me into the scientist I am today. I would also like to thank Dr. Alan York for his friendship, guidance, and support as I navigated the journey of my PhD. I credit much of my success at North Carolina State University to his patience, experience, and advice; he has provided an excellent model to follow as I begin my career. I also extend appreciation to my committee members, Dr. Randy Wells, Dr. David Jordan, and Dr. Jim Burton for their good humor, excellent discussions, and advice through the years. I want to thank Ian Burke and Walter Thomas for their friendship and support as I learned how to conduct real science in the lab. Their experience and knowledge are invaluable resources that I truly appreciate. I would also like to thank Scott Clewis, Gerald Henry, Adam Hixson, Jared Whitaker, and Whitnee Askew for their camaraderie, advice, and encouragement. I also thank Clay Cole, Davie Wilson, and Randall Nelson for their encouragement in stress relieving endeavors, without their support this would have been a very difficult journey indeed.

I am forever grateful to Astra Barnes for her love and support as I worked through my PhD. It is through her patience with the long hours, endless research, and countless projects that I have been able to realize my goals. I am grateful for the unending support, encouragement, and love provided by my family. I appreciate the values instilled in me and support to experiment in life given to me by my parents, Byron and Sandy. I appreciate all the support from my brother Anthony and sister Lexie, who have supported me in everything I have done.

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Introduction

Glufosinate is a nonselective, non-residual postemergence herbicide for genetically modified crops including corn (*Zea mays* L.), cotton, and soybean. Glufosinate inhibits glutamine synthetase, the enzyme that catalyzes the conversion of glutamic acid and ammonia into glutamine (Bellinder et al. 1985, 1987; Logusch et al. 1991; Mersey et al. 1990; Wild et al. 1987). The inhibition of glutamine synthetase leads to rapid accumulation of ammonia and glyoxylate within the plant, which causes damage to chloroplast structures and a reduction and eventual termination of photosynthetic activity, which ultimately leads to necrosis of tissue (Coetzer and Al-Khatib, 2001; Devine et al. 1993; Lacuesta et al. 1992; Pline et al.1999; Wendler et al., 1990). Although the role of ammonia in phytotoxicity is not clear (Seihl 1997), phytotoxic symptoms include membrane disruption and inhibition of photosynthesis, which is followed by plant death. Visual symptoms are apparent within 72 h.

Glufosinate is a contact herbicide providing broad spectrum grass and broadleaf weed control requiring thorough or near complete coverage to ensure good control (Corbett et al. 2004; Steckel et al. 1997b). Glufosinate has no residual activity; however, glufosinate does have a rotation restriction of 120 days to most crops and 70 days to most cereal crops (Anonymous 2007a). In a non-sterile environment, glufosinate degradation occurs rapidly with DT50 values being reported at 1-10 days in sandy loam soils (Gallina and Stephenson, 1992; Behrendt et al., 1990; Smith, 1989), 15-25 days in clay and clay loam soils (Smith, 1989; Smith and Belyk, 1989), and 4.3 days in forest soils (Faber et al. 1997). Therefore replant and rotation concerns with glufosinate are generally minimal under field conditions.

Goosegrass (*Eleusine indica*), Palmer amaranth (*Amaranthus palmeri* S. Wats), and pitted morningglory (*Ipomoea lacunosa* L.) are common and troublesome weeds in several row crops throughout the southern region (Webster 2004, 2005). Palmer amaranth was listed as the most troublesome weed in cotton in Missouri, North Carolina, South Carolina: and in the ten most troublesome weeds in soybean in Florida, Georgia, Missouri, South Carolina, and Tennessee (Webster 2005). Both Palmer amaranth and pitted morningglory are highly competitive weeds with the ability to reduce crop yields and interfere with harvest (Norsworthy and Oliver, 2002a and 2002b). Goosegrass, Palmer amaranth, and pitted morningglory reduce yields not only because they compete with the crop, but also because they emerge throughout the season and present problems at harvest (Barker et al. 1984).

Timely application and proper herbicide selection are fundamental for successful weed management in all crop production systems (Wilcut and Askew 1999). Cotton traditionally has limited options for postemergence (POST) broadleaf weed control. Glyphosate- and glufosinate-resistant cotton became commercially available in 1997 and 2005, respectively (Heering et al. 1998). Prior to the 2006 growing season, glyphosate-resistant cotton tolerance issues restricted glyphosate applications to four leaf cotton or smaller (Jones and Snipes 1999; Pline et al. 2001), however, glufosinate-resistant cotton does not have the same concerns or yield loss (Thomas et al. 2004). The development and release of enhanced glyphosate-resistant cotton varieties allow greater application flexibility without the cotton yield reduction previously observed (May et al. 2004). The registrations of glyphosate- and glufosinate-resistant cotton, pyrithiobac, and trifloxysulfuron provided cotton growers with new postemergence options that were previously lacking for broadleaf weed control.

Glyphosate, like glufosinate, is a contact herbicide that offers broad spectrum control of annual grass and broadleaf weeds (Askew and Wilcut 1999; Burke et al. 2005; Corbett et al. 2004; Culpepper and York 1999; Culpepper et al. 2000; Everman et al. 2007; Scott et al. 2002; Thomas et al. 2007) with no residual activity (Anonymous 2007a, 2007b). Glyphosate inhibits the activity of EPSPS, an enzyme in the shikimic acid pathway (Duke 1988). This specific site of action inhibits the biosynthesis of the aromatic acids of tryptophan, tyrosine, and phenylalanine (Siehl 1997). Glyphosate-resistant technology has dominated variety selection in both cotton and soybean [*Glycine max* (L.) Mann] in recent years, and the widespread acceptance has increased the selection pressure for resistance (Culpepper 2006; Culpepper et al. 2006; VanGessel 2001; Young 2006).

Trifloxysulfuron, like pyrithiobac, is an acetolactate synthase (ALS) inhibitor primarily used for broadleaf and perennial sedge control (Porterfield et al. 2002b; Troxler et al. 2003). In addition, the lack of grass activity with pyrithiobac and trifloxysulfuron is a limitation for these herbicides in cotton weed management systems (Anonymous 2005a, 2005b; Burke et al. 2002; Corbett et al. 2004; Crooks et al. 2003;). Weed resistance to the ALS family of herbicides is widespread with ninety-three cases reported worldwide (Heap 2006). The potential for resistance needs to be considered when developing weed management programs for use in all crops.

The registration of herbicide-resistant cotton, which provided cotton growers with POST options that were previously absent for broadleaf weed control, has led to the adoption of total POST weed management practices in cotton. A total POST weed management system may lead to reduced yields due to early season weed interference slowing cotton growth and development (Askew and Wilcut 1999; Buchanan and Burns 1970; Culpepper and York 1999; Everman et al. 2007). However, the limited availability of data regarding the efficacy of a total POST and residual tank-mix combinations PRE, early postemergence (EPOST), and late postemergence-directed (LAYBY) for weed management in glufosinate- and enhanced glyphosate-resistant cotton creates a need to evaluate cotton injury, weed control, and cotton lint yield as influenced by various PRE, EPOST, POST, and LAYBY herbicide options in glufosinate-resistant cotton.

Comparisons of glyphosate- and glufosinate-resistant cropping systems has shown comparable weed control levels on many weed species when glyphosate or glufosinate are used in a system approach (Corbett et al. 2004; Thomas et al. 2007). Differences in weed control have also been observed in several weed species where glyphosate often provides greater control of annual grasses and pigweed (*Amaranthus* sp.) species, and glufosinate often provides greater control of annual morningglory (*Ipomoea* sp.) species (Corbett et al. 2004; Culpepper et al. 2000; Koger et al. 2007b).

Additionally, soil-applied and postemergence (POST)-applied herbicides are often required for effective weed management in cotton (Buchanan 1992), and selection of the proper herbicides is essential for successful weed management in all crop production systems (Wilcut and Askew 1999). Soil-applied herbicides, such as pendimethalin and fluometuron have traditionally been used to provide early season control of annual broadleaf and grass weeds (Buchanan 1992; Wilcut et al. 1988, 1997). Fomesafen, a diphenylether herbicide that inhibits protoporphyrinogen oxidase, is registered in cotton for PRE and LAYBY) applications. Previous research has indicated cotton tolerance to fomesafen PRE (Baumann et al. 1998; Troxler et al. 2002). Fomesafen PRE controls many annual broadleaf and sedge species, and can be utilized as an alternative mode of action to control Palmer amaranth resistant to dinitroanaline, sulfonylurea, and glyphosate herbicides (Lundsford et al. 1998; Troxler et al. 2002; Wilcut et al. 1997).

Flumioxazin, a protoporphyrinogen oxidase inhibitor, is labeled for early season burndown applications in cotton, and has recently been labeled for use as a LAYBY treatment in cotton (Askew et al. 2002; Price et al. 2004b). Flumioxazin provides an additional mode of action at LAYBY for control of common lambsquarters, common ragweed, morningglory species, and pigweed species (Askew et al. 2002; Clewis et al. 2002).

Despite the non-selective nature of glufosinate, variable control of goosegrass, large crabgrass, and Palmer amaranth, common and troublesome weeds in southern row crops (Webster 2004, 2005), has been observed in studies investigating glufosinate efficacy (Beyers et al. 2002; Coetzer et al. 2002; Corbett et al. 2004; Culpepper et al. 2000; Culpepper and York 1999; Everman et al. 2007). Differences in various levels of tolerance to glufosinate have been attributed several factors including temperature, humidity, growth stage, application rate, application timing, species, and variations in level of absorption and translocation (Anderson et al 1993a, 1993b; Coetzer et al. 2001; Grangeot et al. 2005; Maschoff et al. 2000; Mersey et al. 1990; Neto et al. 2000; Peterson and Hurle 2001; Pline et al. 1999b; Ridley and McNally 1985; Sellers et al. 2004; Steckel et al. 1997a, 1997b).

Although low levels of glufosinate metabolism have been observed in several species, metabolism has not been regarded as a factor in differential tolerance of weed species to glufosinate (Dröge et al. 1992; Dröge-Laser et al. 1994; Haas and Muller 1987; Jansen et al.

2000; Komo a and Sandermann 1992; Mersey et al. 1990; Neto et al. 2000; Pline et al. 1999b). In transgenic glufosinate-resistant corn and oilseed rape, rapid metabolism of glufosinate to various metabolites was observed (Ruhland et al. 2004). Resistance to glufosinate is conferred by *N*-acetylation of glufosinate by the enzyme phosphinothricin *N*-acetyltransferase, ultimately inactivating glufosinate (Dröge et al. 1992).

Although glufosinate provides excellent broad spectrum control of many weed species, especially pitted morningglory; goosegrass and Palmer amaranth appear to be more tolerant to glufosinate than several other annual weed species (Beyers et al. 2002; Coetzer et al. 2002; Corbett et al. 2004; Culpepper et al. 2000; Culpepper and York 1999; Steckel et al. 1997b; Tingle et al. 1996). Similarly, glyphosate is a broad-spectrum, nonselective herbicide which provides excellent control of goosegrass, Palmer amaranth, and many other weed species; however pitted morningglory has shown some tolerance (Bond et al. 2006; Jordan et al. 1997; Norsworthy et al. 2001; Norsworthy and Oliver 2002a, 2002b).

Amaranth control was greater when glufosinate was applied to smaller plants compared to larger plants (Coetzer et al. 2002); however less than 75% of Palmer amaranth was controlled with a single glufosinate application. Differential glufosinate control has been observed in several species due to either weed height at application or glufosinate rate (Coetzer et al. 2002; Corbett et al. 2004; Steckel et al. 1997b). Glufosinate has also shown to antagonize grass control by graminicides for several goosegrass, johnsongrass, and summer annual grass populations (Burke et al. 2005; Gardner et al. 2006).

Similar size response has been observed following applications of glyphosate (Jordan et al. 1997; Koger et al. 2004; Mueller et al. 2006). Application of glyphosate to small, two- to four-leaf, morningglory provides excellent control while larger, five- to eight-leaf, morningglory show greater tolerance to applications of glyphosate (Chachalis et al. 2001), but control of larger weeds can improved by increasing the glyphosate rate (Jordan et al. 1997; Shaw and Arnold 2002). Lanie et al. (1994) found that pitted morningglory control varied from 23 to 78% after 1.12 kg/ha glyphosate was applied with differences in control attributed to weed size at application. Stephenson et al. (2007) observed no differences in control, ranging from 81 to 89%, across 38 accessions of pitted morningglory treated with glyphosate. Norsworthy et al. (2001) determined the tolerance of pitted morningglory is attributed to the lack of absorption (6%), and placement on the plant did not affect absorption (Koger and Reddy 2005).

To develop an effective management program for these troublesome weeds, it is important to understand how herbicides applied to weeds respond to environmental factors such as rainfall. Rainfastness of herbicides play an important role on efficacy, and subsequently rainfall effects on herbicide performance have been studied for nearly as long as herbicides have been in use. An herbicide that remains on the leaf surface for extended periods is more likely to be lost due to volatilization, wash off, or degradation. The factors affecting absorption and translocation of glyphosate have been studied since glyphosate was released on the market (Sprankle et al. 1975). In the corresponding time several researchers have studied the effects of glyphosate under varying environmental conditions and with various adjuvant combinations to determine the optimal combination and rain-free period after application (Bryson 1987, 1988; Bariuan et al. 1999; Coble and Brumbaugh 1993; Field and Bishop 1988; Miller et al. 1998; Molin and Hirase 2005; Reddy 2000; Reddy and Singh

1992; Sandbrink et al. 1993; Willoughby 1997). The glyphosate formulation 'Roundup WeatherMax', a potassium salt, is marketed with a 30-minute rainfast warranty. Glyphosate label statements on rain-free period, however, are ambiguous, stating that rainfall or irrigation soon after application may reduce control and subsequent applications may be needed to provide adequate control (Anonymous 2007c, 2007d, 2007e). Although not covered extensively in the literature (Anderson et al. 1993), glufosinate has a more definitive rain-free period, with a label statement that a 4 hour rain-free period is required for most weed species (Anonymous 2007a, 2007b).

Site of action inhibition has been investigated as a tool for glyphosate drift detection in various field crops (Buehring, et al. 2007; Burke et al. 2005; Henry et al. 2005; Thomas et al. 2005). Shikimic acid accumulation was found to be an effective diagnostic tool to determine yield loss, however results varied due to environment.

A better understanding of rainfall effects on herbicide efficacy and site of action inhibition could provide extension personnel and producers information needed to make re-application decisions when a rainfall event occurs soon after application. If site of action can be effectively correlated to dose response, predicted control can be established. Therefore the objectives of this study were to determine the effect of weed growth stage, rain-free period, and herbicide formulation on efficacy and target site inhibition in goosegrass, Palmer amaranth, and pitted morningglory.

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Weed Control and Yield with Fomesafen, *S*-Metolachlor, and Flumioxazin Systems for Glufosinate-Resistant Cotton (*Gossypium hirsutum*) Residual Weed Management

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Field studies were conducted near Clayton, Lewiston, and Rocky Mount, NC in 2005 to evaluate weed control and cotton response to preemergence treatments of pendimethalin alone or in a tank mixture with fomesafen, postemergence treatments of glufosinate applied alone or in a tank mixture with *S*-metolachlor, and POST-directed treatments of glufosinate in a tank mixture with flumioxazin or prometryn. Excellent weed control was observed where at least two applications were made in addition to glufosinate EPOST. Reduced control of goosegrass, large crabgrass, and Palmer amaranth was observed when residual herbicides were not included PRE or mid-POST. Cotton lint yields were greatest when additional residual herbicides were included PRE or mid-POST.

Nomenclature: Flumioxazin; fomesafen; glufosinate; pendimethalin; prometryn; *S*-metolachlor; common lambsquarters, *Chenopodium album* L. # CHEAL; common ragweed, *Ambrosia artemisiifolia* L. # AMBEL; goosegrass, *Eleusine indica* # ELEIN; large crabgrass, *Digitaria sanguinalis* L. # DIGSA; Palmer amaranth, *Amaranthus palmeri* S. Wats #

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AMAPA; pitted morningglory, *Ipomoea lacunosa* L. # IPOLA; cotton, *Gossypium hirsutum* L..

Key words: Cotton, herbicide injury, flumioxazin, fomesafen, glufosinate, *S*-metolachlor, weed control, yield.

The registration of herbicide-resistant cotton, which provided cotton growers with POST options that were previously absent for broadleaf weed control, has led to the adoption of total POST weed management practices in cotton. A total POST weed management system may lead to reduced yields due to early season weed interference slowing cotton growth and development (Askew and Wilcut 1999; Buchanan and Burns 1970; Culpepper and York 1999; Everman et al. 2007). Glyphosate-resistant technology has dominated variety selection in both cotton and soybean [*Glycine max* (L.) Mann] in recent years, and the widespread acceptance has increased the selection pressure for resistance (Culpepper 2006; Culpepper et al. 2006; VanGessel 2001; Young 2006).

The introduction of glufosinate-resistant cotton has provided another POST weed management tool for cotton producers. Glufosinate inhibits glutamine synthetase, which leads to rapid accumulation of ammonia within the plant. Subsequent damage to chloroplast structures and an eventual termination of photosynthetic activity ultimately results in necrosis of tissue (Coetzer and Al-Khatib 2001; Devine et al. 1993; Lacuesta et al. 1992; Pline et al.1999; Wendler et al. 1990). Glufosinate is a non-selective, contact herbicide that requires thorough coverage to ensure good broad spectrum grass and broadleaf weed control (Corbett et al. 2004; Steckel et al. 1997). Like glyphosate, glufosinate has no residual activity (Anonymous 2007a).

Soil-applied and postemergence (POST)-applied herbicides are often required for effective weed management in cotton (Buchanan 1992), and selection of the proper herbicides is essential for successful weed management in all crop production systems (Wilcut and Askew 1999). Soil-applied herbicides, such as pendimethalin and fluometuron have traditionally been used to provide early season control of annual broadleaf and grass weeds (Buchanan 1992; Wilcut et al. 1988, 1997). Fomesafen, a diphenylether herbicide that inhibits protoporphyrinogen oxidase, is registered in cotton for PRE and POST-directed applications. Previous research has indicated cotton tolerance to fomesafen PRE (Baumann et al. 1998; Troxler et al. 2002). Fomesafen PRE controls many annual broadleaf and sedge species, and can be utilized as an alternative mode of action to control Palmer amaranth resistant to dinitroanaline, sulfonylurea, and glyphosate herbicides (Lundsford et al. 1998; Troxler et al. 2002; Wilcut et al. 1997).

Flumioxazin, a protoporphyrinogen oxidase inhibitor, is labeled for early season burndown applications in cotton, and has recently been labeled for use as a POST- directed treatment in cotton (Askew et al. 2002; Price et al. 2004b). Flumioxazin provides an additional mode of action POST- directed for control of common lambsquarters, common ragweed, morningglory species, and pigweed species (Askew et al. 2002; Clewis et al. 2002).

Due to the limited availability of data regarding the efficacy of residual herbicides applied PRE, POST, POST- directed in a glufosinate-resistant cotton weed management system, our objectives were to evaluate cotton injury, weed control, and cotton lint yield as influenced by various PRE, POST, and POST- directed herbicide options in glufosinate-resistant cotton.

Additionally, multiple herbicides with multiple modes of action were evaluated at each application timing.

Materials and Methods

Trials were conducted at Central Crops Research Station near Clayton, Peanut Belt Research Station near Lewiston, and the Upper Coastal Plain Research Station near Rocky Mount, NC in 2005. Soils included Norfolk sandy loam soil (fine-loamy, kaolinitic, thermic Typic Kandiudults) with 2.4% organic matter and pH 6.1 at Clayton, Norfolk sandy loam and Rains sandy loam (fine-loamy, siliceous, thermic Typic Paleaquults) soils with 2.1% organic matter and pH 6.1 at Lewiston, and Norfolk sandy loam and Aycock very fine sandy loam (fine-silty, siliceous, thermic Typic Paleudults) soils with 1.7% organic matter and 5.8 pH at Rocky Mount. Each location was infested with common lambsquarters, common ragweed, goosegrass, large crabgrass, Palmer amaranth, and pitted morningglory. Conventional tillage was performed at all locations with raised beds at Clayton and Lewiston. Cotton cultivar 'FM 958LL' was planted 2 cm deep at a rate of 12 seed/m of row on May 9 at Clayton, April 27 at Lewistion, and May 2, 2005 at Rocky Mount. Aldicarb insecticide was applied in the seed furrow at 1.18 kg ai/ha for early season insect control. Plots were four 97-cm rows 6.1 m in length at Clayton, and four 91-cm rows 6.1 m in length at Lewiston and Rocky Mount.

The experimental design was a randomized complete block (RCBD) with treatments replicated three times. Treatments consisted of a factorial treatment arrangement of three PRE options, three mid-POST options, and three POST-directed options. A non-treated check also was included. The PRE herbicide options included no PRE herbicide, pendimethalin[1] at 1120 g ai/ha, or pendimethalin plus fomesafen[2] at 280 g ai/ha. The mid-POST herbicide options included: no mid-POST herbicide, glufosinate at 470 g ai/ha, or glufosinate plus *S*-metolachlor at 1120 g ai/ha. The POST-directed herbicide options included: no POST-directed herbicide, glufosinate plus prometryn at 1120 g ai/ha, or glufosinate plus flumioxazin at 70 g ai/ha. All treatments, excluding the non-treated check, received an early POST application of glufosinate at 470 g/ha.

Weed stage and density as well as cotton size were recorded at each application (Table 1). Visual estimates of cotton injury and control of common lambsquarters, common ragweed, goosegrass, large crabgrass, Palmer amaranth, and pitted morningglory were recorded 30 days after the PRE, early POST, and POST-directed applications. Visual estimates of weed control and cotton injury were based on a scale of 0 (no control or no injury symptoms) to 100% (death of all plants) (Frans et al. 1986). Cotton yield was determined by mechanical harvest with a spindle picker modified for small-plot harvesting and were converted to lint yield for analysis using a conversion factor of 33%.

Data were subjected to ANOVA using the general linear models procedure of SAS (SAS 1998), and sums of squares were partitioned to evaluate location and herbicide treatments (McIntosh 1983). Data for weed control and crop injury were converted to square roots of the arcsine to stabilize variance (Gomez and Gomez 1984). Non-transformed data are presented with statistical interpretation based upon transformed data. Data were averaged over locations when appropriate.

Results and Discussion

Crop Injury. There was a significant location interaction for cotton injury 30 days after PRE treatments containing fomesafen with 14% injury observed only at the Rocky Mount location, with injury at all other locations less than 5% (Table 2). Fomesafen injury has been previously observed, however no negative yield effects were documented (Baumann et al. 1998). Weather data for the date of application and the days after application were examined at each location, but no apparent variations that would contribute to the observed differences in injury could be determined. Mid-season cotton injury was minimal ($\leq$5%) with the addition of *S*-metolachlor to glufosinate and was consistent with injury observed previously with the *S*-metolachlor solvent system (York and Culpepper 2007) (data not shown). This injury is characterized by transient necrotic speckling on exposed leaves. No late season cotton injury was observed with any treatment. Flumioxazin has the potential to injure cotton when applied to chlorophyllous tissue (Price et al. 2004a); however applications were directed to mature woody stems of cotton in these studies.

Weed Control. Only late-season evaluations of weed control are presented, as harvesting efficiency and therefore yield are influenced by weed presence late in the season (Wilcut et al. 1995). There were no significant location interactions for control of common ragweed and Palmer amaranth, therefore data are averaged over location. Significant location effects were observed for control of common lambsquarters, goosegrass, large crabgrass, and pitted morningglory with significant treatment interactions.

Significant PRE and mid-POST main treatment effects were observed for large crabgrass at Lewiston with no differences in treatments at Clayton or Rocky Mount. Large crabgrass control with pendimethalin, with or without fomesafen PRE averaged over mid-POST and POST-directed herbicides, was 98%, compared to 94% where no PRE was applied at Lewiston (Table 3). Control of large crabgrass was 98% or greater with glufosinate alone and in combination with *S*-metolachlor mid-POST and 93% when no mid-POST was applied at Lewiston averaged over PRE and POST-directed herbicides (Table 4).

PRE by mid-POST interactions were observed for large crabgrass at Clayton, therefore data were averaged over POST-directed herbicides. Large crabgrass control was greater than 95% when pendimethalin alone or in combination with fomesafen was applied PRE, regardless of mid-POST herbicide, however control was less than 90% when only a mid-POST application was made (Table 5). The benefit of a residual herbicide applied mid-POST is evident for large crabgrass as there was no difference in control between pendimethalin applied PRE fb no mid-POST and no PRE fb glufosinate plus *S*-metolachlor mid-POST at Clayton averaged over POST-directed herbicides (Table 5). Significant PRE by POST-directed herbicide interactions were also observed for large crabgrass control when averaged over mid-POST herbicides. Control of large crabgrass at Clayton was 95% or greater where a PRE herbicide was applied, however control was less than 85% where no PRE was applied, regardless of POST-directed application (Table 6). A POST by POST-directed interaction was observed at Rocky Mount for large crabgrass control, averaged over PRE herbicides. Glufosinate plus *S*-metolachlor mid-POST fb any POST-directed application provided greater than 95% control of large crabgrass at Rocky Mount (Table 7).

Control of large crabgrass was variable when no mid-POST was applied; however greatest control was observed when prometryn was applied with glufosinate at POST-directed (Table 7).

Significant PRE by mid-POST treatment interactions were observed for Palmer amaranth with no location effects, therefore data were averaged over locations and POST-directed herbicides. Palmer amaranth control with pendimethalin plus fomesafen PRE was at least 95% with all mid-POST treatment options (Table 5). Control of Palmer amaranth with pendimethalin PRE was greater than 95% when followed by glufosinate alone or in combination with *S*-metolachlor mid-POST; however control was reduced to 74% when pendimethalin was applied alone with no mid-POST. A benefit was seen from the addition of *S*-metolachlor mid-POST when no PRE was applied, with an increase in control of 6 percentage points on Palmer amaranth when averaged over locations and POST-directed applications (Table 5).

A significant PRE by POST-directed herbicide treatment interaction was observed for Palmer amaranth when averaged over mid-POST treatments and location. Pendimethalin plus fomesafen PRE fb any POST-directed treatment resulted in greater than 95% control of Palmer amaranth (Table 6). Similar control was observed when a POST-directed application of glufosinate plus flumioxazin followed pendimethalin PRE; however control was reduced to 91 and 80% with glufosinate plus prometryn and no POST-directed treatments, respectively. The high level of Palmer amaranth control with fomesafen PRE and flumioxazin POST-directed shows the importance of protoporphyrinogen oxidase inhibitors to cotton growers for resistance management. When no PRE was applied, Palmer amaranth control with either flumioxazin or prometryn added to glufosinate or no POST-directed herbicide was 85% or less, showing the importance of early season Palmer amaranth control in glufosinate-resistant cotton. A significant mid-POST by POST-directed treatment interaction averaged over location and PRE herbicide was also observed for Palmer amaranth. Control of Palmer amaranth when either a mid-POST or POST-directed application was made provided excellent of 99 to 100% (Table 7). Control was significantly reduced when a single POST application was made, dropping below 90%.

Significant PRE by mid-POST, PRE by POST-directed, or mid-POST by POST-directed treatment interactions were observed by location for common lambsquarters. Significant PRE by mid-POST treatment interactions were observed for common lambsquarters at Clayton with no differences in treatments observed at the other locations. Control of common lambsquarters was greater than 95% when a residual herbicide was used PRE or mid-POST, with reduced control of 92 and 73% when no PRE was followed by glufosinate and no POST, respectively, averaged over POST-directed treatment (Table 5). Similarly, PRE by POST-directed treatment interactions were observed at Clayton averaged over mid-POST treatments with no differences in treatment observed at Rocky Mount or Lewiston. Common lambsquarters control was greater than 95% when a PRE was applied regardless of POST-directed treatment when averaged over POST treatments, while control was less than 90% when no PRE was applied followed by glufosinate plus prometryn or no POST-directed herbicide when averaged over POST treatments (Table 6). A significant mid-POST by POST-directed treatment interaction was observed at Lewiston for common lambsquarters control with no differences in control at Clayton or Rocky Mount. Common lambsquarters control was greater than 98% when both a mid-POST and POST-directed herbicide treatment was applied (Table 7). Control was reduced to 88% when only a PRE treatment was applied (Table 7). Common lambsquarters germinates early in the season (until early July at the latest) with few or no flushes of germination as the season progresses in the Southeastern U. S. (J. W. Wilcut, personal observation). Excellent common lambsquarters control was observed in this study; however inconsistent common lambsquarters control with glufosinate has been reported (Steckel et al. 1997).

PRE by mid-POST interactions were observed for goosegrass at Clayton, therefore data were averaged over POST-directed herbicides. Goosegrass control was greater than 95% when pendimethalin alone or in combination with fomesafen was applied PRE, regardless of mid-POST herbicide, however control was less than 90% when only a mid-POST application was made (Table 5). The benefit of a residual herbicide applied mid-POST is evident for goosegrass as there was no difference in control between pendimethalin applied PRE fb no mid-POST and no PRE fb glufosinate plus *S*-metolachlor mid-POST at Clayton averaged over POST-directed herbicides (Table 5). Significant PRE by POST-directed herbicide interactions were also observed for goosegrass control when averaged over mid-POST herbicides at Clayton with no differences observed at Lewiston and Rocky Mount. Control of goosegrass at Clayton was 95% or greater where a PRE herbicide was applied, however control was less than 85% where no PRE was applied, regardless of POST-directed application (Table 6). A POST by POST-directed interaction was observed at Lewiston and Rocky Mount for goosegrass control averaged over PRE herbicides with no differences observed at Clayton. Glufosinate plus *S*-metolachlor mid-POST fb any POST-directed application provided 99% or greater control of goosegrass at Lewsiton (Table 7). Control at Rocky Mount was reduced compared to control at Lewiston when no POST-directed application was made following either glufosinate alone or combined with *S*-metolachlor. Control of goosegrass was 90% or less at both Lewiston and Rocky Mount when no mid-POST was applied.

Significant PRE by mid-POST interactions averaged over POST-directed herbicides were observed at Lewiston with no differences in treatments observed at other locations. Pitted morningglory control as influenced by PRE and mid-POST herbicides was 94% or greater when *S*-metolachlor was added to glufosinate mid-POST, regardless of PRE application (Table 5). Reduced pitted morningglory control, 64 to 80%, occurred when no POST herbicide was applied. Significant mid-POST by POST-directed treatment interactions averaged over PRE treatments were observed at Lewiston and Rocky Mount with no differences observed at Clayton. Control of pitted morningglory with mid-POST and POST-directed herbicides was generally high with control 94% or greater (Table 7). Pitted morningglory control was reduced below 90% at Rocky Mount only when no mid-POST and no POST-directed herbicides were applied, however at Lewiston pitted morningglory control was 90% or less when no POST-directed application was made.

A significant PRE by mid-POST by POST-directed interaction was observed for common ragweed, with no location effects. Control of common ragweed was greater than 90% for all treatments except pendimethalin applied alone with only an EPOST application and the untreated control (Table 8). The combination of pendimethalin plus fomesafen PRE (95%) provided better season-long control than pendimethalin alone (80%), and all treatments receiving at least two herbicide applications, excluding pendimethalin PRE fb glufosinate plus flumioxazin, controlled common ragweed 98% or greater.

Yield. Cotton lint yields as affected by PRE, POST, and POST-directed herbicide applications varied by location. Yields were generally greater where a PRE and a mid-POST application were made at Clayton and Lewiston (Table 8). The lack of a PRE herbicide resulted in significant yield losses in 22 out of 27 observations at all three locations. These lint yields show the importance of a PRE or mid-POST herbicide treatment to avoid early-season weed interference and preserve yield potential. Although yield differences were not as great between cotton with or without S-metolachlor added to the mid-POST herbicide treatment, mid-POST herbicide application timing was critical to avoid a cotton lint yield loss of 320 kg/ha or more at Clayton and Rocky Mount. Cotton lint yields varied very little when two or more applications were made, showing the importance of timely herbicide applications to ensure cotton lint yield potential is maintained.

Reduction in weed control has been reported previously for several weed species with glufosinate plus MSMA (Everman et al. 2007; Koger et al. 2007), however no weed control reduction was observed with glufosinate combined with flumioxazin or prometryn in this study, and the high level of control observed with these treatments make them viable POST-directed options in glufosinate-resistant cotton.

Although there were observed benefits to the addition of fomesafen PRE and *S*-metolachlor mid-POST for weed control, no appreciable benefit was seen with regard to cotton lint yield. The inclusion of fomesafen broadens the spectrum of weeds controlled

PRE and like *S*-metolachlor, provides flexibility in subsequent POST application timings by controlling problematic grasses and pigweeds. The addition of fomesafen or *S*-metolachlor also provides alternate modes of action in a proactive resistance management program, reducing the reliance on a single mode of action (Mallory-Smith and Retzinger 2003). To obtain season long control of problematic grass and broadleaf weeds in glufosinate-resistant cotton, fomesafen PRE should be followed by timely POST applications throughout a significant part of the early growing season, which is also the case in other herbicide-resistant weed management systems (Stephenson et al. 2004; Troxler et al. 2002).

The addition of POST tank mixture herbicides such as *S*-metolachlor may broaden the application window while providing additional control on problematic weeds. Flumioxazin added to glufosinate improved control of common lambsquarters and Palmer amaranth compared to prometryn plus glufosinate, however control of annual grasses and common ragweed with flumioxazin plus glufosinate was reduced when compared to prometryn plus glufosinate. Askew et al. (2002) reported excellent control of common lambsquarters, common ragweed, and Palmer amaranth with POST-directed applications of flumioxazin. Differences in observations may be due to weed size at time of application, as this was a factorial arrangement. Mixtures of glufosinate plus flumioxazin should be used in glufosinate-resistant cotton as an alternative POST-directed herbicide application, however use of fomesafen and flumioxazin in the same production year should be avoided as a proactive resistance management practice.

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Table 1. Weed stage and density and cotton size at herbicide application timings [a,b].

Plant Species	Application Timing					
	Early POST		Mid-POST		POST-Directed	
	Stage	Density	Stage	Density	Stage	Density
	Leaf #	m^2	Leaf #	m^2	Leaf #	m^2
Common lambsquarters	C - 16	12	2 - 10	8	3 - 8	2
Common ragweed	C - 8	16	C - 8	8	2 - 48	3
Goosegrass	1 - 4	9	2 L - 3 tiller	13	2 - 4 tiller	8
Large crabgrass	1L - 4 tiller	9	1 L - 3 tiller	8	1 L - 4 tiller	11
Palmer amaranth	2 - 10	20	4 - 20	13	2 - 20	10
Pitted morningglory	C - 3	6	C - 3	19	C - 7	9
Cotton	2 - 3 L	10 (cm tall)	6 - 7 L	20 - 23 (cm tall)	10 - 11 L	36 – 46 (cm tall)

Table 1. (continued).

[a] Abbreviations: C, cotyledon; L, number of leaves; POST-Directed, late POST-Directed; POST, postemergence.

[b] Stages and densities are averaged over locations.

Table 2. Effect of PRE herbicides on early-season cotton injury. [a-c]

PRE	Injury [c]
	Rocky Mount
	——%——
Pendimethalin	2 b
Pendimethalin + fomesafen	14 a
No PRE	1 b

[a] Abbreviations: PRE, preemergence.

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

[c] Injury ratings were taken 33 d after treatment.

Table 3. Effect of PRE herbicides on late season large crabgrass control at Lewiston averaged over early POST, mid-POST, and POST-Directed herbicides. [a,b]

PRE	Control
	Lewiston
	———%———
Pendimethalin	98 a
Pendimethalin + fomesafen	98 a
No PRE	94 b

[a] Abbreviations: PRE, preemergence and POST, postemergence.

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

Table 4. Effect of POST herbicides on late season large crabgrass control at Lewiston averaged over PRE, early POST, and POST-Directed herbicides.[a,b]

Mid-POST	Control
	Lewiston
	——%——
Glufosinate	98 a
Glufosinate + *S*-metolachlor	99 a
No POST	93 b

[a] Abbreviations: PRE, preemergence, and POST, postemergence.

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

Table 5. Late season weed control as affected by PRE and POST herbicide treatments. Location was not significant for Palmer amaranth, therefore data are pooled over location, early POST, and POST-Directed herbicides, other weeds are pooled over early POST and POST-Directed herbicides. [a,b]

PRE	Mid-POST	AMAPA	CHEAL	DIGSA	ELEIN	IPOLA
			Clayton	Clayton	Clayton	Lewiston
		%				
Pendimethalin + fomesafen	Glufosinate	100 a	100 a	100 a	100 a	91 b
Pendimethalin + fomesafen	Glufosinate + *S*-metolachlor	100 a	100 a	100 a	100 a	97 ab
Pendimethalin + fomesafen	No mid-POST	95 ab	99 a	99 a	99 a	80 cd
Pendimethalin	Glufosinate	97 ab	100 a	100 a	100 a	92 ab
Pendimethalin	Glufosinate + *S*-metolachlor	98 a	100 a	100 a	100 a	94 ab
Pendimethalin	No mid-POST	74 d	97 ab	96 ab	93 ab	75 d
No PRE	Glufosinate	84 c	92 b	82 c	80 c	82 c
No PRE	Glufosinate + *S*-metolachlor	90 bc	96 ab	88 bc	86 bc	98 a
No PRE	No mid-POST	34 e	73 c	59 d	52 d	64 e

Table 5. (continued)

[a] Abbreviations: POST, postemergence; PRE, preemergence; AMAPA, Palmer amaranth; CHEAL, common lambsquarters; DIGSA, large crabgrass; ELEIN, goosegrass; IPOLA, pitted morningglory.

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

Table 6. Late season weed control as affected by PRE and POST-Directed herbicide treatments. Data for Palmer amaranth are pooled over location, early POST, and mid-POST herbicides, other weeds are pooled over early POST and mid-POST herbicides.[a,b]

PRE	POST-Directed	AMAPA	CHEAL	DIGSA	ELEIN	ELEIN
			Clayton	Clayton	Clayton	Lewiston
		%				
Pendimethalin + fomesafen	Glufosinate + flumioxazin	99 ab	100 a	100 a	100 a	96 ab
Pendimethalin + fomesafen	Glufosinate + prometryn	100 a	100 a	100 a	100 a	98 ab
Pendimethalin + fomesafen	No POST-Directed	97 ab	99 a	99 a	99 a	94 ab
Pendimethalin	Glufosinate + flumioxazin	98 ab	100 a	100 a	99 a	98 ab
Pendimethalin	Glufosinate + prometryn	91 b	100 a	99 a	99 a	100 a
Pendimethalin	No POST-	80 c	97 ab	96 a	95 a	79 c
No PRE	Glufosinate + flumioxazin	85 bc	92 b	84 b	79 b	93 ab
No PRE	Glufosinate + prometryn	81 c	84 c	83 b	81 b	90 b
No PRE	No POST-Directed	42 d	88 bc	63 c	60 c	88 b

Table 6. (continued)

[a] Abbreviations: POST, postemergence; PRE, preemergence; AMAPA, Palmer amaranth; CHEAL, common lambsquarters; DIGSA, large crabgrass; ELEIN, goosegrass; IPOLA, pitted morningglory.

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

Table 7. Late season weed control as affected by mid-POST and POST-Directed herbicide treatments. Palmer amaranth data are pooled over location, PRE, and early POST herbicides; all other weeds are pooled over PRE and early POST herbicides. [a,b]

Mid-POST	POST-Directed	AMAPA	CHEAL	DIGSA	ELEIN	ELEIN	IPOLA	IPOLA
			Lewiston	Rocky Mount	Rocky Mount	Lewiston	Rocky Mount	Lewiston
		%						
Glufosinate + *S*-metolachlor	Glufosinate + flumioxazin	99 a	100 a	99 a	99 ab	100 a	100 a	100 a
Glufosinate + *S*-metolachlor	Glufosinate + prometryn	99 a	98 a	100 a	100 a	99 ab	100 a	98 a
Glufosinate + *S*-metolachlor	No POST-Directed	89 b	100 a	96 a	87 b	99 ab	94 ab	90 b
Glufosinate	Glufosinate + flumioxazin	99 a	100 a	98 a	92 ab	99 ab	100 a	97 a
Glufosinate	Glufosinate + prometryn	100 a	99 a	100 a	99 ab	98 ab	100 a	94 ab
Glufosinate	No POST-Directed	83 b	99 a	85 b	63 c	83 b	92 b	73 c
No POST	Glufosinate + flumioxazin	83 b	98 a	83 b	74 bc	88 b	96 ab	97 a
No POST	Glufosinate + prometryn	73 c	99 a	97 a	87 ab	90 b	99 ab	97 a
No POST	No POST-Directed	47 d	88 b	68 c	48 d	74 c	63 c	39 d

Table 5. (continued)

Table 7. (continued)

[a] Abbreviations: POST, postemergence; PRE, preemergence; AMAPA, Palmer amaranth; CHEAL, common lambsquarters; DIGSA, large crabgrass; ELEIN, goosegrass; IPOLA, pitted morningglory.

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

Table 8. Late season common ragweed control and cotton lint yield as affected by PRE, mid-POST, and POST-Directed herbicide treatments. Location was not significant for common ragweed, therefore data are pooled over location and early POST, however cotton yield is presented by location averaged over early POST. [a,b]

PRE	POST	POST-Directed	AMBEL	Cotton Lint Yield		
				Clayton	Lewiston	Rocky Mount
			—%—	—	kg/ha	—
Pendimethalin + fomesafen	Glufosinate + *S*-metolachlor	Glufosinate + flumioxazin	100 a	2050 ab	1680 b	1190 b
Pendimethalin + fomesafen	Glufosinate + *S*-metolachlor	Glufosinate + prometryn	100 a	2200 a	1680 b	1170 abc
Pendimethalin + fomesafen	Glufosinate + *S*-metolachlor	No POST-Directed	100 a	2030 ab	1690 b	1090 abc
Pendimethalin + fomesafen	Glufosinate	Glufosinate + flumioxazin	100 a	2040 ab	1740 ab	1240 ab
Pendimethalin + fomesafen	Glufosinate	Glufosinate + prometryn	100 a	2160 ab	1630 bc	1140 abc
Pendimethalin + fomesafen	Glufosinate	No POST-Directed	100 a	2030 ab	1660 b	980 bc
Pendimethalin + fomesafen	No mid-POST	Glufosinate + flumioxazin	99 ab	2170 f	1740 ab	1120 abc
Pendimethalin + fomesafen	No mid-POST	Glufosinate + prometryn	100 a	2070 ab	1610 bc	1290 a

Table 8. (continued).

PRE	POST	POST-Directed	AMBEL	Cotton Lint Yield		
				Clayton	Lewiston	Rocky Mount
			——%——		kg/ha	
Pendimethalin + fomesafen	No mid-POST	No POST-Directed	95 bc	1760 c	1210 c	200 f
Pendimethalin	Glufosinate + *S*-metolachlor	Glufosinate + flumioxazin	100 a	2120 ab	1920 a	1080 bc
Pendimethalin	Glufosinate + *S*-metolachlor	Glufosinate + prometryn	100 a	2130 ab	1610 bc	1020 bc
Pendimethalin	Glufosinate + *S*-metolachlor	No POST-Directed	100 a	1750 c	1780 ab	1020 bc
Pendimethalin	Glufosinate	Glufosinate + flumioxazin	99 ab	2160 ab	1780 ab	1020 bc
Pendimethalin	Glufosinate	Glufosinate + prometryn	100 a	2070 ab	1760 ab	1230 ab
Pendimethalin	Glufosinate	No POST-Directed	100 a	2150 ab	1600 bc	820 cd
Pendimethalin	No mid-POST	Glufosinate + flumioxazin	93 c	2050 ab	1380 c	720 d
Pendimethalin	No mid-POST	Glufosinate + prometryn	100 a	1990 b	1780 ab	700 d

Table 8. (continued).

PRE	POST	POST-Directed	AMBEL	Cotton Lint Yield		
				Clayton	Lewiston	Rocky Mount
			—%—		kg/ha	
Pendimethalin	No mid-POST	No POST-Directed	80 d	1830 bc	680 d	430 e
No PRE	Glufosinate + *S*-metolachlor	Glufosinate + flumioxazin	100 a	1780 c	1700 ab	830 cd
No PRE	Glufosinate + *S*-metolachlor	Glufosinate + prometryn	99 ab	1850 b	1640 b	1110 abc
No PRE	Glufosinate + *S*-metolachlor	No POST-Directed	100 a	1470 d	1740 ab	710 cd
No PRE	Glufosinate	Glufosinate + flumioxazin	100 a	1630 cd	1750 ab	990 c
No PRE	Glufosinate	Glufosinate + prometryn	99 ab	2070 ab	1660 b	940 c
No PRE	Glufosinate	No POST-Directed	98 ab	1460 d	1410 c	540 de
No PRE	No mid-POST	Glufosinate + flumioxazin	99 ab	1140 e	1510 bc	210 f
No PRE	No mid-POST	Glufosinate + prometryn	99 ab	0 g	1540 bc	960 bc
No PRE	No mid-POST	No POST-Directed	0 e	0 g	0 e	0 g

[a] Abbreviations: POST, postemergence; PRE, preemergence; AMBEL, common ragweed.

Table 8. (continued).

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

Weed Control and Yield with Glufosinate-Resistant Cotton (*Gossypium hirsutum*) Weed Management Systems[1]

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Abstract. Field studies were conducted near Clayton, Goldsboro, Kinston, and Rocky Mount, NC in 2003 to evaluate weed control and cotton response to postemergence treatments of glufosinate applied alone or in tank mixtures with *s*-metolachlor, pyrithiobac, or trifloxysulfuron. Late season control of common lambsquarters, common ragweed, entireleaf morningglory, ivyleaf morningglory, jimsonweed, pitted morningglory, purple nutsedge, and sicklepod with glufosinate EPOST was $\geq$90%. The addition of *S*-metolachlor to glufosinate EPOST improved control of all weeds except sicklepod, ivyleaf morningglory, and entireleaf morningglory. When applied POST, glufosinate provided $\geq$90% late season

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control of common lambsquarters, common ragweed, entireleaf morningglory, ivyleaf morningglory, jimsonweed, large crabgrass, pitted morningglory, purple nutsedge, and sicklepod. Control of goosegrass and Palmer amaranth was 81% and 84%, respectively. When pyrithiobac or trifloxysulfuron were added in POST tank mixtures, control of Palmer amaranth improved 6 and 9%, respectively. Control of goosegrass remained near 80% regardless of herbicide treatment used. The addition of a LAYBY tank-mixture of glufosinate plus prometryn provided ≥88% late season control of all weeds. Reduced control of goosegrass and Palmer amaranth was observed with the LAYBY tank mixture of glufosinate plus MSMA when compared to other LAYBY tank mixtures. Cotton lint yields in plots receiving any herbicide application were significantly higher than plots receiving no herbicide application for all application timings. Cotton lint yields were ≥ 740 kg/ha where an EPOST was applied and ≥ 680 kg/ha when a POST herbicide was applied. Cotton lint yields were at least 200 kg/ha greater on plots receiving a LAYBY application when compared to plots where no LAYBY treatment was applied.

Nomenclature: Glufosinate; MSMA; prometryn; pyrithiobac; *S*-metolachlor; trifloxysulfuron; common lambsquarters, *Chenopodium album* L. #[3] CHEAL; common ragweed, *Ambrosia artemisiifolia* L. # AMBEL; entireleaf morningglory, *Ipomoea hederacea* var. *integriuscula* Gray # IPOHG; goosegrass, *Eleusine indica* # ELEIN; ivyleaf

[3]Letters following this symbol are a WSSA-approved computer code from *Composite List of Weeds*, Revised 1989. Available only on computer disk from WSSA, 810 East 10th Street, Lawrence, KS 66044-8897.

morningglory, *Ipomoea hederacea* Jacq. # IPOHE; jimsonweed, *Datura stramonium* L. # DATST; large crabgrass, *Digitaria sanguinalis* L. # DIGSA; Palmer amaranth, *Amaranthus palmeri* S. Wats # AMAPA; pitted morningglory, *Ipomoea lacunosa* L. # IPOLA; purple nutsedge, *Cyperus rotundus* L. # CYPRO; sicklepod, *Senna obtusifolia* L. Irwin and Barnaby # CASOB; cotton, *Gossypium hirsutum* L..

Additional index words: Cotton, herbicide injury, glufosinate, pyrithiobac, trifloxysulfuron, weed control, yield.

Abbreviations used: ALS, acetolactate synthase (EC 4.1.3.18); DAT, days after treatment; NIS, non-ionic surfactant; EPOST, early postemergence; POST, postemergence; LAYBY, late post-directed; RCBD, randomized complete block design.

Timely application and proper herbicide selection are fundamental for successful weed management in all crop production systems (Wilcut and Askew 1999). Cotton traditionally has limited options for postemergence (POST) broadleaf weed control. The registrations of glyphosate-resistant and glufosinate-resistant cotton, pyrithiobac, and trifloxysulfuron provided cotton growers with new postemergence options that were previously lacking for broadleaf weed control. Glyphosate offers broad spectrum control of annual grass and broadleaf weeds (Corbett et al. 2004; Culpepper and York 1999). Prior to the 2006 growing season, glyphosate-resistant cotton tolerance issues restricted glyphosate applications to four leaf cotton or smaller (Jones and Snipes 1999; Pline et al. 2001). Glyphosate-resistant technology has dominated variety selection in both cotton and soybean [*Glycine max* (L.) Mann] in recent years, and the widespread acceptance has increased the selection pressure for resistance (Culpepper 2006; Culpepper et al. 2006; VanGessel 2001; Young 2006).

Glufosinate, a non-selective herbicide, inhibits glutamine synthetase, the enzyme that catalyzes the conversion of glutamic acid and ammonia into glutamine. The inhibition of glutamine synthetase leads to rapid accumulation of ammonia and glyoxylate within the plant, which causes damage to chloroplast structures and a reduction and eventual termination of photosynthetic activity, which ultimately leads to necrosis of tissue (Coetzer and Al-Khatib, 2001; Devine et al. 1993; Lacuesta et al. 1992; Pline et al.1999; Wendler et al., 1990). Glufosinate is a contact herbicide providing broad spectrum grass and broadleaf weed control requiring thorough or near complete coverage to ensure good control (Corbett et al. 2004; Steckel et al. 1997). Like glyphosate, glufosinate has no residual activity (Anonymous 2005c). Glufosinate does have a rotation restriction of 120 days to most crops and 70 days to most cereal crops (Anonymous 2005c). However, in a non-sterile environment, glufosinate degradation occurs rapidly with DT50 values being reported at 1-10 days in sandy loam soils (Gallina and Stephenson, 1992; Behrendt et al., 1990; Smith, 1989), 15-25 days in clay and clay loam soils (Smith, 1989; Smith and Belyk, 1989), and 4.3 days in forest soils (Faber et al. 1997). Therefore replant and rotation concerns with glufosinate are generally minimal under field conditions.

Trifloxysulfuron, like pyrithiobac, is an acetolactate synthase (ALS) inhibitor primarily used for broadleaf and perennial sedge control (Porterfield et al. 2002b; Troxler et al. 2003). In addition, the lack of grass activity with pyrithiobac and trifloxysulfuron is a limitation for these herbicides in cotton weed management systems (Anonymous 2005a, 2005b; Burke et al. 2002; Corbett et al. 2004; Crooks et al. 2003;). Weed resistance to the ALS family of herbicides is widespread with ninety-three cases reported worldwide (Heap 2006). The potential for resistance needs to be considered when developing weed management programs for use in all crops.

Due to the limited availability of data regarding the efficacy of total POST weed management systems in glufosinate-resistant cotton, our objectives were to evaluate cotton injury, weed control, and cotton lint yield as influenced by various early postemergence (EPOST), POST, and late postemergence-directed (LAYBY) herbicide options in glufosinate-resistant cotton. Additionally, multiple herbicides with multiple modes of action were evaluated at each application timing.

Materials and Methods

Trials were conducted at Central Crops Research Station near Clayton, Cherry Research Farm near Goldsboro, Caswell Research Farm near Kinston, and the Upper Coastal Plain Research Station near Rocky Mount, NC in 2003. Cotton was planted in Norfolk loamy sand soils (fine-loamy, siliceous, thermic Typic Kandiudults) at Goldsboro and Kinston on May 21, 2003 and Norfolk sandy loam and Goldsboro sandy loam (fine-loamy, siliceous, thermic Aquic Paleudults) at Clayton on May 23, 2003 and Rocky Mount on May 15, 2003. These soils are typical for the Mid-Atlantic and Southeastern Coastal Plain cotton production regions. Soil pH ranged from 5.9 to 6.2. Pre-plant tillage was performed at all locations and consisted of strip-tillage at Clayton, conventional tillage at Goldsboro, Kinston, and Rocky Mount with raised beds at Goldsboro and Rocky Mount. Fibermax 958LL cotton was planted at all locations with aldicarb in-furrow at 1.18 kg ai/ha for early season insect control at all locations according to North Carolina Cooperative Extension Service recommendations (Bacheler 2005). Cotton was planted 3 cm deep at a rate of 12 seed/m of row. Plots were four 97-cm rows 6.1 m in length at Clayton, Goldsboro, and Kinston, and four 91-cm rows 6.1 m in length at Rocky Mount.

The experiments were arranged in a randomized complete block design (RCBD) with a factorial treatment arrangement of three EPOST treatment options, four POST treatment options, and four LAYBY treatment options, resulting in a total of 48 treatments. EPOST herbicide options included: no EPOST, glufosinate at 470 g ai/ha, or glufosinate at 470 g/ha plus *S*-metolachlor at 1120 g ai/ha; POST options included: no POST, glufosinate at 470 g/ha, glufosinate at 470 g/ha plus trifloxysulfuron at 2.7 g ai/ha, or glufosinate at 470 g /ha plus pyrithiobac at 36 g ai/ha; and LAYBY options included: no LAYBY, prometryn at 1120 g ai/ha plus MSMA at 2240 g ai/ha, glufosinate at 470 g/ha plus prometryn at 1120 g/ha, or glufosinate at 470 g/ha plus MSMA at 2240 g/ha. All treatments were replicated three times. Two additional treatments were added, one a standard comparison and the second a weed-free check with both consisting of pendimethalin at 840 g ai/ha plus fluometuron at 1120 g ai/ha PRE followed by glufosinate at 470 g/ha EPOST and POST with prometryn at 1120 g /ha plus MSMA at 2240 g/ha applied LAYBY with hand-weeding as necessary in the weed-free check.

Weed stage and density as well as cotton size were recorded at each application date (Table 1). Visual estimates of cotton injury and control of common lambsquarters, common ragweed, goosegrass, entireleaf morningglory, ivyleaf morningglory, large crabgrass, Palmer amaranth, pitted morningglory, purple nutsedge, and sicklepod were recorded early and late in the season prior to harvest. Visual estimates of weed control and cotton injury were based on a scale of 0 (no control or no injury symptoms) to 100 (death of all plants or no plants present) (Frans et al. 1986). Yield data were collected at the end of the season to determine the effect of herbicide applications and timings on cotton.

Data were subjected to an analysis of variance using the general linear models procedure of SAS (SAS 1998), and sums of squares were partitioned to evaluate location and herbicide treatments (McIntosh 1983). Data for weed control and crop injury were converted to square roots of the arcsine to stabilize variance (Gomez and Gomez 1984). All data are shown non-transformed for reader clarity. If location effects were not significant, data were pooled; otherwise data are presented by location.

Results and Discussion

Crop Injury. No late season cotton injury was observed with any EPOST or LAYBY treatment, respectively. Early-season cotton injury was minimal ($\leq$7%) with the addition of *S*-metolachlor to glufosinate and was consistent with injury observed previously with the *S*-metolachlor solvent system (York and Culpepper 2005) (data not shown). This injury is characterized by transient necrotic speckling on exposed leaves. There was a significant location interaction for cotton injury as influenced by POST treatments containing trifloxysulfuron (Table 2). Injury at Rocky Mount was not evaluated after POST treatments and is therefore not shown. Injury with glufosinate applied alone POST was $\leq$1% at all locations and injury at Clayton was $\leq$6% with all POST treatments (Table 2). Injury with treatments containing trifloxysulfuron at Goldsboro and Kinston was 17 and 35%, respectively (Table 2). The level of injury reported here is consistent with injury reported in other studies with trifloxysulfuron in North Carolina (Burke and Wilcut 2004; Porterfield et al. 2002a, 2002b). The addition of pyrithiobac to glufosinate POST resulted in injury of 9 and 7% at Goldsboro and Kinston, respectively. Pyrithiobac injury has been reported in other studies at higher levels than those observed here (Burke and Wilcut 2004; Jordan et al 1993; Paulsgrove and Wilcut 1999, 2001; Porterfield et al. 2002b). Weather data for the date of application and the days after application were examined at each location, but no apparent variations that would contribute to the observed differences in injury could be determined. Similar differences in injury across locations were also observed by Porterfield et al. (2002b) and Burke and Wilcut (2004) after trifloxysulfuron treatments. However, the magnitude of injury observed was lower (6 to 35%) when compared to injury observed by Porterfield et al. (2002b) of 62 to 67% and Burke and Wilcut (2004) of 2 to 76%.

Weed Control. Only late-season evaluations of weed control are presented, as harvesting efficiency and therefore yield are influenced by weed presence late in the season (Wilcut et al. 1995). There were significant main effects for EPOST, POST, and LAYBY treatments for control of common lambsquarters, common ragweed, entireleaf morningglory, goosegrass, ivyleaf morningglory, jimsonweed, large crabgrass, Palmer amaranth, pitted morningglory, purple nutsedge, and sicklepod, with no significant location or treatment interactions. When averaged over POST and LAYBY herbicides, glufosinate EPOST controlled late-season common lambsquarters 98% (Table 3). The high level of common lambsquarters control obtained with glufosinate alone at EPOST is due to common lambsquarters' germination pattern in the Southeast. Common lambsquarters germinates early in the season (until early July at the latest) with few or no flushes of germination as the season progresses (J. W. Wilcut, personal observation). Steckel et al. (1997) reported that common lambsquarters was not consistently controlled with glufosinate in Illinois (<80%). Height may also be a factor in common lambsquarters control. Steckel et al. (1997) reported that control was greatest when applications were made to common lambsquarters that were 10 cm tall.

Greater than 90% late-season control with glufosinate EPOST averaged over POST and LAYBY herbicide treatments was observed on common ragweed, entireleaf morningglory, ivyleaf morningglory, pitted morningglory, jimsonweed, purple nutsedge, and sicklepod while 89% control of Palmer amaranth was observed (Tables 3 and 4). Goosegrass and large crabgrass were controlled 86 and 89%, respectively. While the addition of *S*-metolachlor EPOST improved control by 1 to 2 percentage points for common lambsquarters, common ragweed, ivyleaf morningglory, pitted morningglory, jimsonweed, and purple nutsedge, the increase was of little biological significance (Table 3 and 4). Control of goosegrass, large crabgrass, and Palmer amaranth was improved 4, 5, and 3 percentage points, respectively, when *S*-metolachlor was tank-mixed with glufosinate EPOST. *S*-Metolachlor provides preemergence control of grasses and small-seeded broadleaf weed species (Anonymous 2005d). Pooled over locations, POST, and LAYBY herbicides, glufosinate alone and in combination with *S*-metolachlor EPOST improved control of goosegrass 36 to 40 percentage points when compared with no EPOST treatments. Similarly, late-season control of large crabgrass and Palmer amaranth were improved 22 to 28 percentage points when glufosinate was applied with or without *S*-metolachlor EPOST (Table 4).

An application of glufosinate applied POST averaged over EPOST and LAYBY treatments provided 98% control of common lambsquarters when evaluated late season (Table 5). Late season control of common lambsquarters where no POST was applied was 73%, which is explained as previously mentioned by the germination patterns in the southeastern United States. Glufosinate alone POST, averaged over EPOST and LAYBY options, controlled common ragweed, entireleaf morningglory, ivyleaf morningglory, pitted morningglory, jimsonweed, and purple nutsedge 92% or greater while the addition of trifloxysulfuron or pyrithiobac improved control $\geq$ 2 percentage points (Table 5 and 6). Large crabgrass and sicklepod control was 90% with glufosinate applied alone POST while the addition of trifloxysulfuron or pyrithiobac improved control $\leq$ 1% (Table 6). Control of Palmer amaranth and goosegrass was 84 and 81%, respectively with glufosinate applied alone POST (Table 6). Corbett et al. (2004) and Culpepper and York (1999) reported a similar lack of goosegrass control with glufosinate. The lack of control illustrates the need for timely applications and/or other herbicide inputs to provide season-long control of goosegrass. The addition of trifloxysulfuron or pyrithiobac to glufosinate POST improved Palmer amaranth control 6 and 11 percentage points, respectively (Table 6). Burke and Wilcut (2004) observed 86 and 94% control of Palmer amaranth with trifloxysulfuron alone and in combination with pyrithiobac, respectively. Although the use of trifloxysulfuron and pyrithiobac provide additional control of Palmer amaranth, the use of multiple modes of action and herbicide combinations should be utilized in developing a resistance management program, especially for weeds such as Palmer amaranth which has developed resistance to several classes of herbicides including ALS and amino acid inhibiting herbicides like trifloxysulfuron and pyrithiobac (Heap 2006) and glyphosate (Culpepper et al. 2006), respectively. Late season control of all weeds evaluated was improved $\geq$ 24 percentage points when a POST herbicide was applied compared to no POST treatments.

LAYBY treatments of glufosinate plus prometryn, glufosinate plus MSMA, or prometryn plus MSMA averaged over location, EPOST, and POST treatments controlled common lambsquarters 94% or greater, while control was 85% when no LAYBY was applied (Table 7). The level of common lambsquarters control demonstrates the early germination pattern for common lambsquarters in North Carolina and the control obtained by early season herbicide applications. Common ragweed, entireleaf morningglory, ivyleaf morningglory, pitted morningglory, jimsonweed, and sicklepod were controlled $\geq$93% with all herbicide applications at LAYBY when averaged over locations, EPOST, and POST treatments (Tables 7 and 8). Glufosinate plus prometryn LAYBY controlled Palmer amaranth 93% when averaged over locations, EPOST, and POST treatments, however, control of Palmer amaranth with MSMA plus prometryn or glufosinate resulted in 88 and 83% control, respectively (Table 8). The reduced control of Palmer amaranth treated with glufosinate plus MSMA was also observed by Koger et al. (2007, *In Press*), who concluded that MSMA is not a compatible tank mixture partner with glufosinate for weed control in cotton. Purple nutsedge control was 89 to 90% with all LAYBY herbicide applications (Table 8).

Glufosinate plus MSMA applied at LAYBY, averaged over locations, EPOST, and POST treatments, was the least effective treatment for large crabgrass and goosegrass, 90 and 77%, respectively (Table 8). Greater control of large crabgrass and goosegrass was obtained with prometryn plus MSMA, 91 and 85%, respectively, and further improved with glufosinate plus prometryn, 93 and 88%, respectively (Table 8). The reduction in weed control observed with glufosinate plus MSMA has been reported previously for several weed species (Koger et al. 2007, *In Press*). Control of all weed species evaluated where no LAYBY was applied was ≤71% (Tables 7 and 8), demonstrating the importance of a LAYBY herbicides to control weeds thereby avoiding late season weed competition and harvest interference.

Yield. Cotton lint yields as affected by EPOST herbicide applications, pooled over locations, POST, and LAYBY herbicide treatments, were similar where glufosinate was applied alone or in combination with *S*-metolachlor and were 740 and 770 kg/ha, respectively (Table 9). Treatments with no EPOST herbicide treatment resulted in cotton lint yields of 530 to 560 kg/ha less than treatments receiving an EPOST treatment. These lint yields show the importance of an EPOST herbicide treatment to avoid early-season weed interference and preserve yield potential. Cotton treated with glufosinate alone or in combination with trifloxysulfuron POST yielded 680 kg/ha while a treatment of glufosinate plus pyrithiobac improved cotton lint yield to 720 kg/ha when averaged over locations, EPOST, and LAYBY treatments (Table 10). Although yield differences were not as great between cotton with or without a POST herbicide treatment, POST herbicide application timing is critical to avoid a cotton lint yield loss of 200 kg/ha or more. As with the EPOST and POST herbicide timings, LAYBY herbicide treatments resulted in an increase of 200 kg/ha cotton lint yield over treatments receiving no LAYBY herbicide treatment (Table 11). Treatments of glufosinate plus prometryn, glufosinate plus MSMA, and prometryn plus MSMA resulted in yields of 690, 670, and 680 kg/ha cotton lint when averaged over location, EPOST, and POST applications. These results show the importance of timely herbicide applications to ensure cotton lint yield potential is maintained.

Although there were observed benefits to the addition of *S*-metolachlor to glufosinate EPOST for weed control, no appreciable benefit was seen with regard to cotton lint yield. The inclusion of *S*-metolachlor in a total POST weed control system is important to provide flexibility in subsequent application timings by controlling problematic grasses and pigweeds. The addition of *S*-metolachlor also provides an alternate mode of action in a proactive resistance management program, reducing the reliance on a single mode of action (Mallory-Smith and Retzinger 2003). The addition of pyrithiobac and trifloxysulfuron to glufosinate POST provided additional control of Palmer amaranth compared to glufosinate applied alone, however additional control of other weeds evaluated was minimal. Similar weed control was seen with all LAYBY herbicide treatments for all weeds excluding goosegrass and Palmer amaranth, where glufosinate plus MSMA control was at least 10 percentage points lower than treatments of glufosinate plus prometryn. Koger et al. (2007, *In press*) observed similar antagonism when glufosinate plus MSMA was applied to Palmer amaranth and other grass species. To maintain a total POST herbicide system in glufosinate-resistant cotton, timely applications must be made on small weeds throughout a significant part of the early growing season. The addition of tank mixture herbicides such as *S*-metolachlor, pyrithiobac, and trifloxysulfuron may broaden the application window while providing additional control on problematic weeds. Mixtures of glufosinate plus MSMA should not be used in glufosinate-resistant cotton due to antagonism observed on goosegrass and Palmer amaranth in this study.

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Table 1. Weed stage and density and cotton size at herbicide application timings [a,b].

Plant Species	Application Timing					
	EPOST		POST		LAYBY	
	Stage	Density	Stage	Density	Stage	Density
	Leaf #	m^2	Leaf #	m^2	Height (cm)	m^2
Cotton	2 – 5 L	10 – 15 (cm tall)	4 – 7 L	20 – 25 (cm tall)	8 – 14 L	36 – 41 (cm tall)
Common lambsquarters	C - 10	27	C - 10	8	C – 61	8
Common ragweed	C - 6	29	C - 7	20	C - 51	13
Entireleaf morningglory	C - 3	9	C - 6	14	C – 20 cm runner	9

Table 1. (continued).

Goosegrass	1 L - 2 tiller	21	1 L - 4 tiller	15	2 - 5 tiller	12
Ivyleaf morningglory	C - 3	7	C - 5	6	C – 20 cm runner	8
Jimsonweed	C - 4	12	C - 10	12	C - 51	10
Large crabgrass	1 - 6 L	12	2 - 6	10	2 L - 4 tiller	8
Palmer amaranth	2 - 10	19	C - 12	25	C - 91	18
Pitted morningglory	C - 4	6	C - 5	8	C – 23 cm runner	9
Purple nutsedge	5 - 20 cm	24	10 - 20 cm	8	10 - 25	10
Sicklepod	C - 4	9	C - 2	7	C - 10	12

Table 1. (continued).

[a] Abbreviations: C, cotyledon; EPOST, early postemergence; L, number of leaves; LAYBY, late POST-directed; POST, postemergence.

[b] Stages and densities are averaged over locations.

Table 2. Effect of POST herbicides on mid-season cotton injury.[a-c]

POST treatments	Injury[d]		
	Clayton	Goldsboro	Kinston
	%		
Glufosinate + trifloxysulfuron	6 a	35 a	17 a
Glufosinate + pyrithiobac	3 ab	9 b	7 c
Glufosinate	1 b	1 c	0 d
No EPOST	0 b	0 c	10 b

[a] Data averaged over EPOST treatment options of glufosinate at 470 g/ha, glufosinate plus *S*-metolachlor at 1120 g/ha, or no EPOST.

[b] Abbreviations: POST, postemergence; EPOST, early postemergence.

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

[d] Injury ratings were taken 4 to 7 d after treatment.

Table 3. Main treatment data for late season weed control as affected by EPOST herbicide treatments pooled over locations, POST, and LAYBY herbicides. [ab]

EPOST treatments	CHEAL	AMBEL	IPOHG	IPOHE	IPOLA	DATST
	%					
Glufosinate	98b	94b	94a	93a	93b	93b
Glufosinate + *S*-metolachlor	99a	95a	94a	94a	94a	94a
No EPOST	80c	76c	77b	76b	77c	75c

[a] Abbreviations: EPOST, early postemergence; LAYBY, late POST-directed; POST, postemergence; CHEAL, common lambsquarters; AMBEL, common ragweed; IPOHG, entireleaf morningglory; IPOHE, ivyleaf morningglory; IPOLA, pitted morningglory; DATST, jimsonweed.

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

Table 4. Main treatment data for late season weed control as affected by EPOST herbicide treatments pooled over locations, POST, and LAYBY herbicides. [ab]

EPOST treatments	ELEIN	DIGSA	CYPRO	AMAPA	CASOB
	%				
Glufosinate	86b	89b	92b	89b	90a
Glufosinate + *S*-metolachlor	90a	94a	94a	92a	90a
No EPOST	50c	68c	70c	64c	76b

[a] Abbreviations: EPOST, early postemergence; LAYBY, late POST-directed; POST, postemergence; ELEIN, goosegrass; DIGSA, large crabgrass; CYPRO, purple nutsedge; AMAPA, Palmer amaranth; CASOB, sicklepod.

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

Table 5. Main treatment data for late season weed control as affected by POST herbicide treatments pooled over locations, EPOST, and LAYBY herbicides. [ab]

POST treatments	CHEAL	AMBEL	IPOHG	IPOHE	IPOLA	DATST
	%					
Glufosinate + pyrithiobac	99a	94b	96a	95a	95a	96a
Glufosinate + trifloxysulfuron	99a	96a	96a	95a	95a	94b
Glufosinate	98b	94b	94b	94b	94a	94b
No POST	73c	68c	67c	67c	68b	64c

[a] Abbreviations: EPOST, early postemergence; LAYBY, late POST-directed; POST, postemergence; CHEAL, common lambsquarters; AMBEL, common ragweed; IPOHG, entireleaf morningglory; IPOHE, ivyleaf morningglory; IPOLA, pitted morningglory; DATST, jimsonweed.

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

Table 6. Main treatment data for late season weed control as affected by POST herbicide treatments pooled over locations, EPOST, and LAYBY herbicides. [ab]

POST treatments	ELEIN	DIGSA	CYPRO	AMAPA	CASOB
	%				
Glufosinate + pyrithiobac	82a	91a	94a	95a	90a
Glufosinate + trifloxysulfuron	82a	91a	94a	90b	91a
Glufosinate	81b	90a	92a	84c	90a
No POST	57c	62b	61b	58d	69b

[a] Abbreviations: EPOST, early postemergence; LAYBY, late POST-directed; POST, postemergence; ELEIN, goosegrass; DIGSA, large crabgrass; CYPRO, purple nutsedge; AMAPA, Palmer amaranth; CASOB, sicklepod.

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

Table 7. Main treatment data for late season weed control as affected by LAYBY herbicide treatments pooled over locations, EPOST, and POST herbicides.[ab]

LAYBY treatments	CHEAL	AMBEL	IPOHG	IPOHE	IPOLA	DATST
			%			
Glufosinate + prometryn	96a	96a	95a	95a	95a	95a
Glufosinate + MSMA	94b	94b	95a	95b	95a	94b
Prometryn + MSMA	94c	94b	93a	93c	93b	93b
No LAYBY	85d	68c	71b	68d	68c	66c

[a] Abbreviations: EPOST, early postemergence; LAYBY, late POST-directed; POST, postemergence; CHEAL, common lambsquarters; AMBEL, common ragweed; IPOHG, entireleaf morningglory; IPOHE, ivyleaf morningglory; IPOLA, pitted morningglory; DATST, jimsonweed.

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

Table 8. Main treatment data for late season weed control as affected by LAYBY herbicide treatments pooled over locations, EPOST, and POST herbicides.[ab]

LAYBY treatments	ELEIN	DIGSA	CYPRO	AMAPA	CASOB
	%				
Glufosinate + prometryn	88a	93a	90a	93a	97a
Glufosinate + MSMA	77c	90c	89a	83c	95b
Prometryn + MSMA	85b	91b	89a	88b	93b
No LAYBY	51d	61d	73b	64d	56c

[a] Abbreviations: EPOST, early postemergence; LAYBY, late POST-directed; POST, postemergence; ELEIN, goosegrass; DIGSA, large crabgrass; CYPRO, purple nutsedge; AMAPA, Palmer amaranth; CASOB, sicklepod.

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

Table 9. Cotton yield main treatment as affected by EPOST treatment pooled over locations, POST, and LAYBY herbicides. [ab]

EPOST treatments	Cotton Lint Yield
	kg/ha
Glufosinate	740a
Glufosinate + *S*-metolachlor	770a
No EPOST	210b

[a] Abbreviations: EPOST, early postemergence; LAYBY, late POST-directed; POST, postemergence.

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

Table 10. Cotton yield main treatment as affected by POST treatment pooled over locations, EPOST, and LAYBY herbicides. [ab]

POST treatments	Cotton Lint Yield
	kg/ha
Glufosinate	680a
Glufosinate + pyrithiobac	720a
Glufosinate + trifloxysulfuron	680a
No POST	420b

[a] Abbreviations: EPOST, early postemergence; LAYBY, late POST-directed; POST, postemergence.

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

Table 11. Cotton yield main treatment as affected by LAYBY treatment pooled over locations, EPOST, and POST herbicides. [ab]

LAYBY treatments	Cotton Lint Yield
	kg/ha
Glufosinate + prometryn	690a
Glufosinate + MSMA	670a
prometryn + MSMA	680a
No LAYBY	470b

[a] Abbreviations: EPOST, early postemergence; LAYBY, late POST-directed; POST, postemergence.

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

Weed Control and Yields in Glufosinate- and Glyphosate-Resistant Cotton (*Gossypium hirsutum*) Weed Management Systems

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Field studies were conducted near Rocky Mount, NC in 2004, Clayton, NC, Lewiston, NC, Florence, SC, St. Joseph, LA, and Suffolk, VA in 2005 to evaluate weed control and cotton response to postemergence treatments of glufosinate or glyphosate on glufosinate-resistant and glyphosate-resistant cotton, respectively, applied alone or in tank mixtures with *S*-metolachlor EPOST. Greater than 90% late season control was observed for all weeds evaluated. No significant differences were observed for control of goosegrass, large

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crabgrass, Palmer amaranth, or yellow nutsedge. Cotton lint yield was greater in glyphosate-resistant cotton cultivars than in glufosinate-resistant cultivars, with differences in yield ranging from 410 to 700 kg/ha, depending on location.

Nomenclature: Flumioxazin; glufosinate; glyphosate; metolachlor; MSMA; prometryn; broadleaf signalgrass, *Urochloa platyphylla* (Nash) R.D. Webster # BRAPP; cotton, *Gossypium hirsutum* L.; common lambsquarters, *Chenopodium album* L. #CHEAL; common ragweed, *Ambrosia artemisiifolia* L. # AMBEL; entireleaf morningglory, *Ipomoea hederacea* var. *integriuscula* Gray # IPOHG; goosegrass, *Eleusine indica* # ELEIN; large crabgrass, *Digitaria sanguinalis* L. # DIGSA; Palmer amaranth, *Amaranthus palmeri* S. Wats # AMAPA; pitted morningglory, *Ipomoea lacunosa* L. # IPOLA; yellow nutsedge, *Cyperus esculentus* L. # CYPES.

Key words: Flex cotton, Liberty-Link cotton, residual, *S*-metolachlor, transgenic.

The introduction of glufosinate-resistant and enhanced glyphosate-resistant cotton in recent years has provided cotton growers with new postemergence (POST) options that were previously lacking for broadleaf weed control. Cotton traditionally has limited options for POST broadleaf weed control. Glyphosate and glufosinate are contact herbicides which provide broad spectrum grass and broadleaf weed control (Askew and Wilcut 1999; Burke et al. 2005; Corbett et al. 2004; Culpepper and York 1999; Culpepper et al. 2000; Everman et al. 2007; Faircloth et al. 2001; Scott et al. 2002; Thomas et al. 2007) with no residual activity (Anonymous 2007a, 2007b). Glufosinate, however, requires thorough or near complete coverage to ensure good control (Corbett et al. 2004; Steckel et al. 1997).

Glyphosate- and glufosinate-resistant cotton became commercially available in 1997 and 2005, respectively (Heering et al. 1998). Prior to the 2006 growing season, glyphosate-resistant cotton tolerance issues restricted glyphosate applications to four leaf cotton or smaller (Jones and Snipes 1999; Pline et al. 2001), however, glufosinate-resistant cotton does not have the same concerns or yield loss (Thomas et al. 2004). The development and release of enhanced glyphosate-resistant cotton varieties allow greater application flexibility without the cotton yield reduction previously observed (May et al. 2004). Glyphosate-resistant technology has dominated variety selection in both cotton and soybean [*Glycine max* (L.) Mann] in recent years, and the widespread acceptance has increased the selection pressure for resistance (Culpepper 2006; Culpepper et al. 2006; VanGessel 2001; Young 2006), creating the need for weed control alternatives.

Comparisons of glyphosate- and glufosinate-resistant cropping systems has shown comparable weed control levels on many weed species when glyphosate or glufosinate are used in a system approach (Corbett et al. 2004; Thomas et al. 2007). Differences in weed control have also been observed in several weed species where glyphosate often provides greater control of annual grasses and pigweed (*Amaranthus* sp.) species, and glufosinate often provides greater control of annual morningglory (*Ipomoea* sp.) species (Corbett et al. 2004; Culpepper et al. 2000; Koger et al. 2007b).

Due to the limited availability of data regarding the efficacy of weed management systems in glufosinate-resistant and enhanced glyphosate-resistant cotton, our objectives were to evaluate cotton injury, weed control, and cotton lint yield as influenced by various preemergence (PRE), early postemergence (EPOST), mid-postemergence (MPOST), and late postemergence (LPOST) herbicide options in glufosinate-resistant and enhanced glyphosate-resistant cotton. Additionally, residual herbicides, providing additional modes of action, were included EPOST to investigate potential weed control benefits.

Materials and Methods

Trials were conducted at the Upper Coastal Plain Research Station near Rocky Mount, NC in 2004 and the Central Crops Research Station near Clayton, NC, the Peanut Belt Research Station near Lewiston, NC, the Pee Dee Research and Education Center near Florence, SC, the Northeast Research Station near St. Joseph, LA, and the Tidewater Agricultural Research and Extension Center near Suffolk, VA in 2005. Soils are described in Table 1. Cotton was planted 2 cm at 12 seed/m of row into conventionally prepared seedbeds during the first half of May. Glufosinate-resistant cultivars included ‘FM966LL’ at Florence and ‘FM958LL’ at other locations. Glyphosate-resistant cultivars included ‘DP117BG2RF’ at Florence, ‘ST454B2RF’ at Suffolk, and a proprietary variety at Clayton, Lewiston, Rocky Mount, and St. Joseph. Aldicarb[1] was applied in-furrow at 1.18 kg ai/ha for early season insect control. Other production practices, including fertilization, growth management, late-season insect control, and defoliation were according to local practices. Plot size was four rows by 6.1 m. Row spacing was 91 cm at Lewiston, Rocky Mount, St. Joseph, and Suffolk, and 97 cm at Clayton and Florence.

The experiment was arranged in a randomized complete block design with treatments replicated three times. Treatments, listed in Table 2, consisted of PRE, EPOST, MPOST, and LPOST options applied to glufosinate- or enhanced glyphosate-resistant cotton. A non-treated check was included for each cultivar. The PRE herbicide options included no PRE, pendimethalin[2] at 1120 g ai/ha, or pendimethalin plus fluometuron[3] at 1120 g ai/ha. The EPOST options, applied topically to cotton that was 8 to 13 cm tall with 2 to 4 leaves, included glyphosate[4], glyphosate plus *S*-metolachlor[5], and pyrithiobac[6] on glyphosate-resistant cotton and glufosinate[7], glufosinate plus *S* -metolachlor, and pyrithiobac on glufosinate-resistant cotton. Options for MPOST application to cotton 15 to 30 cm tall with 4 to 8 leaves included glyphosate applied to glyphosate-resistant cotton, glufosinate applied to glufosinate-resistant cotton, and prometryn[8] plus MSMA[9] applied to both cultivars. Glyphosate and glufosinate were applied topically while prometryn plus MSMA was directed to the lower 5 cm of the cotton stalk. Options for LPOST included glyphosate, glyphosate plus prometryn, and glyphosate plus flumioxazin[10] applied to glyphosate-resistant cotton, glufosinate, glufosinate plus prometryn, and glufosinate plus flumioxazin applied to glufosinate-resistant cotton, and prometryn plus MSMA and flumioxazin plus MSMA applied to both cultivars. Glufosinate and glyphosate alone were applied topically while other LPOST options were postemergence-directed to cotton 46 to 51 cm tall with 10 to 12 leaves. Application rates were as follows: glyphosate at 840 g ae/ha; glufosinate at 470 g ai/ha; *S*-metolachlor at 1120 g ai/ha; pyrithiobac at 35 g ai/ha; prometryn at 1120 g ai/ha; flumioxazin at 70 g ai/ha; and MSMA at 2240 g ai/ha. Ammonium sulfate[11] at 1360 g/ha was included with all glyphosate, glyphosate plus prometryn, glyphosate plus flumioxazin, glufosinate, glufosinate plus prometryn, and glufosinate plus flumioxazin applications. A nonionic surfactant[12] at 0.25% (v/v) was included with pyrithiobac, prometryn plus MSMA, flumioxazin plus MSMA, glyphosate plus flumioxazin, and glufosinate plus flumioxazin applications.

Weed stage and density as well as cotton size were recorded at each application date (Table 3). Visual estimates of cotton injury and control of common lambsquarters, common ragweed, goosegrass, entireleaf morningglory, large crabgrass, Palmer amaranth, pitted morningglory, and yellow nutsedge were recorded 30 days after EPOST, MPOST, and LPOST applications. Visual estimates of weed control and cotton injury were based on a scale of 0 (no control or no injury symptoms) to 100% (complete death of all plants or no plants present) (Frans et al. 1986). Seed cotton yield was determined by mechanical harvest with spindle pickers modified for small-plot harvesting. Lint yield was determined using a conversion of 33% lint per kg of seed yield. Fiber quality was not determined.

For statistical analysis, treatments were separated into a factorial arrangement of two genetically modified (GM) cotton systems and 12 herbicide treatments (Table 2). This allowed direct comparison of the two GM cotton systems. Data were subjected to an analysis of variance using the general linear models procedure of SAS (SAS 1998), and sums of squares were partitioned to reflect location and herbicide treatments (McIntosh 1983). Yields of non-treated check plots were assumed to be zero as these plots were decimated by weeds and could not be harvested mechanically. Data for the checks were excluded from the analysis. Data for weed control and crop injury were converted to square roots of the arcsine to stabilize variance (Gomez and Gomez 1984). The transformation did not change data interpretation, therefore results are presented with statistical interpretation based upon non-transformed data.

Results and Discussion

Minimal early season cotton injury was observed (less than 15%), with no injury noted at the end of the season (data not shown). Only late-season evaluations of weed control are presented as harvesting efficiency, and therefore, yield is influenced by weed presence late in the season (Wilcut et al. 1995). There were no significant differences in control of goosegrass, large crabgrass, Palmer amaranth, or yellow nutsedge due to GM system, herbicide treatment, or location (data not shown). Reduced control of goosegrass with glufosinate compared to glyphosate has previously been observed (Corbett et al. 2004; Culpepper and York 1999, Everman et al. 2007), however no differences in control were observed in this study. Weed sizes at each application were generally small, which may contribute to the excellent control observed in this study compared to other research, illustrating the importance of timely applications to provide season-long control of goosegrass and other problematic weeds in a glufosinate-based weed management system.

There was a significant location by herbicide treatment interaction for control of broadleaf signalgrass and entireleaf morningglory in St. Joseph, LA, common lambsquarters in Lewiston, NC, and pitted morningglory in Clayton, NC with no significant effects due to GM cotton system (Table 4). Significant location, GM system, and herbicide treatment effects were observed for common ragweed and pitted morningglory control at Rocky Mount and Lewiston, respectively (Table 5).

Greater than 90% late-season control of all weeds was obtained with all herbicide treatments regardless of glyphosate or glufosinate system (Table 4 and 5). Control of broadleaf signalgrass with pyrithiobac averaged over GM system was 91% averaged over

PRE and LPOST herbicide, while greater than 92% control was observed with glyphosate or glufosinate, regardless of PRE or LPOST herbicide (Table 4). Corbett et al. (2004) observed 30 to 50% control of broadleaf signalgrass with pyrithiobac, compared to greater than 95% control with glufosinate or glyphosate.

Common lambsquarters control was greater than 95% with all herbicide treatments when averaged over GM cotton systems. The high level of control obtained on common lambsquarters is likely due to its germination pattern in the Southeast. Common lambsquarters germinates early in the season with few or no flushes of germination as the season progresses, therefore timely early season applications provide excellent control. Steckel et al. (1997) reported that common lambsquarters was not consistently controlled acceptably (less than 80%) with glufosinate.

Annual morningglory control was greater than 90% when averaged over glyphosate- or glufosinate-resistant cotton systems when observed on at three locations (Table 4 and 5). Entireleaf and pitted morningglory control was variable in St. Joseph, with consistently high control, greater than 99%, observed at Clayton. Pitted morningglory control at Lewiston was greater than 99% in glufosinate tolerant cotton systems, while a reduced level of control was observed with the pendimethalin + fluometuron PRE fb glyphosate EPOST fb glyphosate POST fb prometryn + MSMA LAYBY (Table 5). The reduced control of pitted morningglory with a LPOST application prometryn + MSMA was also observed in entireleaf and pitted morningglory control at the St. Joseph location, primarily when no PRE was applied (Table 4).

Common ragweed control at Rocky Mount ranged from 98 to 100% (Table 5). Corbett et al. (2004) observed 100% control of two to five cm common ragweed with glufosinate and glyphosate, however, control with glufosinate was reduced on larger eight to ten cm common ragweed. Similarly, when no PRE herbicide was applied in glufosinate-resistant cotton, LPOST treatments containing prometryn provided 98 and 99% control of common ragweed (Table 5).

Cotton lint yields as affected by location and GM cotton system, pooled over herbicide treatment, varied from 410 to 700 kg/ha difference at Suffolk and St. Joseph, respectively (Table 6). Glyphosate-resistant cotton cultivars provided higher lint yields than glufosinate-resistant cultivars at five of the six locations evaluated (Table 6 and 7). The yield benefits of PRE herbicides in both glufosinate- and glyphosate-resistant cotton systems were evident at Clayton, NC, Lewiston, NC, and Florence, SC (Table 7). Although there were no observed benefits to the addition of metolachlor to glufosinate or glyphosate EPOST for weed control or cotton lint yield, the inclusion of metolachlor in a total POST weed control system is important to provide flexibility in subsequent application timings. The addition of metolachlor also provides an alternate mode of action in a proactive resistance management program, reducing the reliance on a single mode of action.

Weed control on all weeds was similar with glufosinate- and glyphosate-resistant cotton systems, with greater than 90% late season control of all weeds evaluated. The lack of differences in weed control between glyphosate- and glufosinate-resistant cotton systems may be due to sequential applications of glyphosate or glufosinate providing high levels of weed control on many weed species when compared to control with a single application

(Corbett et al. 2004; Culpepper et al. 2000; Everman et al. 2007; Koger et al. 2007b). Weed control in this study may have also benefited from residual herbicides both PRE and EPOST, which provide flexibility for the first and second POST application, respectively. Glufosinate systems, in particular, require timely application to small weeds to ensure adequate control, and residual herbicides such as metolachlor broaden the application window. The substitution of glyphosate or glufosinate for MSMA at LAYBY provided comparable grass and broadleaf weed control to treatments using MSMA, and therefore should be considered a viable alternative to MSMA.

Sources of Materials

[1] Temik® insecticide, Bayer CropScience, P.O. Box 12014, 2 T.W. Alexander Drive, Research Triangle Park, NC 27709.

[2] Prowl®, BASF Corporation, 26 Davis Drive, Research Triangle Park, NC 27709.

[3] Cotoran®, Griffin LLC/Dupont Crop Protection, 2509 Rocky Ford Road, Valdosta, GA 31601.

[4] Roundup WEATHERMAX™, Monsanto Company, 800 North Lindbergh Boulevard, St. Louis, MO 63167.

[5] Dual Magnum®, Syngenta Crop Protection, P.O. Box 18300, Greensboro, NC 27419.

[6] Staple®, du Pont de Nemours and Company, Wilmington, DE 19898.

[7] Ignite® herbicide, Bayer CropScience, P.O. Box 12014, 2 T.W. Alexander Drive, Research Triangle Park, NC 27709.

[8] Caparol herbicide®, Syngenta Crop Protection, P.O. Box 18300, Greensboro, NC 27419.

[9] MSMA 6 Plus, Loveland Products, Inc., P.O. Box 1286, Greeley, CO 80632.

[10] Valor™ SX, Valent U.S.A. Corporation, P.O. Box 8025 Walnut Creek, CA 94596.

[11] Amaze Gold™, Royster Clark, Inc, 999 Waterside Drive, 8th Floor, Norfolk, VA 23510.

[12] Induce® nonionic low-foam wetter/spreader adjuvant contains 90% nonionic surfactant (alkylaryl and alcohol ethoxylate surfactants) and fatty acids and 10% water. Helena Chemical Company, Suite 500, 6075 Popular Avenue, Memphis, TN 38119.

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Table 1. Description of soils at experiment sites.

Location	Soil series	Soil texture	Soil pH	Soil organic matter
				%
Clayton, NC	Norfolk[a]	Sandy loam	6.2	2.7
Lewiston, NC	Goldsboro[b], Rains[c]	Sandy loam	6.1	2.4
Rocky Mount, NC	Rains, Norfolk	Sandy loam	6.0	1.7
St. Joseph, LA	Mhoon[d]	Silt loam	6.8	0. 5
Florence, SC	Norfolk	Loamy sand	5.8	2
Suffolk, VA	Norfolk	Loamy sand	6.3	0.9

[a] Fine-loamy, kaolinitic, thermic Typic Kandiudults

[b] Fine-loamy, siliceous, thermic Aquic Paleudults

[c] Fine-loamy, siliceous, thermic Typic Paleaquults

[d] Fine-silty, mixed nonacid, thermic Typic Fluvaquent

Table 2. Factorial arrangement of treatments into GM system and herbicide treatment. [a]

Factor 1	Factor 2			
System	PRE	EPOST	MPOST	LPOST
LL	No PRE	glufosinate + s-metolachlor	glufosinate	prometryn + MSMA
LL	No PRE	glufosinate + s-metolachlor	glufosinate	flumioxazin + MSMA
LL	No PRE	glufosinate + s-metolachlor	glufosinate	glufosinate + prometryn
LL	No PRE	glufosinate + s-metolachlor	glufosinate	glufosinate + flumioxazin
LL	pendimethalin	glufosinate + s-metolachlor	glufosinate	prometryn + MSMA
LL	pendimethalin	glufosinate + s-metolachlor	glufosinate	flumioxazin + MSMA
LL	pendimethalin	glufosinate + s-metolachlor	glufosinate	glufosinate + prometryn
LL	pendimethalin	glufosinate + s-metolachlor	glufosinate	glufosinate + flumioxazin
LL	pendimethalin + fluometuron	glufosinate	glufosinate	glufosinate (OT)
LL	pendimethalin + fluometuron	glufosinate	glufosinate	prometryn + MSMA

Table 2. (continued).

Factor 1	Factor 2			
System	PRE	EPOST	MPOST	LPOST
LL	pendimethalin + fluometuron	glufosinate	glufosinate	flumioxazin + MSMA
LL	pendimethalin + fluometuron	pyrithiobac	prometryn + MSMA	prometryn + MSMA
RR	No PRE	glyphosate + s-metolachlor	glyphosate	prometryn + MSMA
RR	No PRE	glyphosate + s-metolachlor	glyphosate	flumioxazin + MSMA
RR	No PRE	glyphosate + s-metolachlor	glyphosate	glyphosate + prometryn
RR	No PRE	glyphosate + s-metolachlor	glyphosate	glyphosate + flumioxazin
RR	pendimethalin	glyphosate + s-metolachlor	glyphosate	prometryn + MSMA
RR	pendimethalin	glyphosate + s-metolachlor	glyphosate	flumioxazin + MSMA

Table 2. (continued).

Factor 1	Factor 2			
System	PRE	EPOST	MPOST	LPOST
RR	pendimethalin	glyphosate + s-metolachlor	glyphosate	glyphosate + prometryn
RR	pendimethalin	glyphosate + s-metolachlor	glyphosate	glyphosate + flumioxazin
RR	pendimethalin + fluometuron	glyphosate	glyphosate	glyphosate (OT)
RR	pendimethalin + fluometuron	glyphosate	glyphosate	prometryn + MSMA
RR	pendimethalin + fluometuron	glyphosate	glyphosate	flumioxazin + MSMA
RR	pendimethalin + fluometuron	pyrithiobac	prometryn + MSMA	prometryn + MSMA

[a] Abbreviations: GM, genetically modified; LL, glufosinate tolerant cotton; RR, enhanced glyphosate tolerant cotton; PRE, preemergence; EPOST, early postemergence; POST, postemergence; LAYBY, late post-directed; OT, over the top.

Table 3. Weed stage and density at herbicide application timings [a].

		EPOST		MPOST		LPOST	
Location	Species	No. leaves	Density	No. leaves	Density	No. leaves	Density
			no./m^2		no./m^2		no./m^2
Clayton	AMAPA	C - 8	20	C - 8	22	C - 70	12
	CHEAL	C - 8	10	C - 10	12	--	--
	DIGSA	2 - 4	10	2L - 2T	10	2L - 4T	4
	ELEIN	1- 3	13	2 - 5	14	2L - 3T	5
Lewiston	CHEAL	C - 10	8	3 - 12	8	2 - 5	3
	CYPES	6 - 10	15	4 - 7	8	6 - 10	10
	DIGSA	1 - 3	14	1 - 4	10	2 - 4	5
	ELEIN	1 - 2	5	1 - 4	5	1 - 3	5
	IPOLA	C - 2	8	C - 4	15	C - 4	4

Table 3. (continued).

Location	Species	EPOST		MPOST		LPOST	
		No. leaves	Density	No. leaves	Density	No. leaves	Density
			no./m^2		no./m^2		no./m^2
Rocky Mount	AMAPA	C - 4	10	4 - 6	12	2 - 48	10
	AMBEL	C - 2	10	3 - 5	12	2 - 12	4
	BRAPP	1 - 3	7	1 - 4	10	1 - 4	5
	CHEAL	C - 5	8	2 - 10	10	2 - 20	7
	CYPES	1 - 3	6	1 - 4	10	4 - 8	6
	DIGSA	1 - 2	7	1 - 4	9	1 - 3	3
	ELEIN	1 - 2	7	1 - 3	10	2 - 6	4
	IPOHG	C - 1	5	C - 3	7	2 - 10	5
	IPOLA	C - 2	7	C - 3	8	2 - 10	4

Table 3. (continud).

		EPOST		MPOST		LPOST	
Location	Species	No. leaves	Density	No. leaves	Density	No. leaves	Density
			no./m^2		no./m^2		no./m^2
St. Joseph	BRAPP	1 - 3	--	1 - 3	--	1 - 4	--
	CYPES	1 - 3	--	1 - 3	--	4 - 8	--
	DIGSA	1 - 3	--	1 - 3	--	1 - 3	--
	ELEIN	1 - 3	--	1 - 3	--	2 - 6	--
	IPOHG	C - 1	--	C - 3	--	2 - 9	--
	IPOLA	C - 2	--	C - 3	--	2 - 8	--
Suffolk	AMBEL	6	--	14	--	--	--
	CHEAL	6	--	10	--	--	--

Table 3. (continued).

		EPOST		MPOST		LPOST	
Location	Species	No. leaves	Density	No. leaves	Density	No. leaves	Density
			no./m^2		no./m^2		no./m^2
	CYPES	5	--	4	--	3	--
	IPOHG	3	--	2	--	2	--
	IPOLA	3	--	2	--	2	--

[a] Abbreviations: C, cotyledon; EPOST, early postemergence; L, number of leaves; LPOST, late POST-directed; MPOST, mid-postemergence; T, number of tillers.

Table 4. Late season weed control as affected by location and herbicide treatments averaged over GM system. [a-c]

PRE	EPOST	POST	LAYBY	BRAPP St. Joseph		CHEAL Lewiston		IPOHG St. Joseph	
No PRE	+ s-metolachlor	system	prometryn + MSMA	93	a	96	bc	93	b
No PRE	+ s-metolachlor	system	flumioxazin + MSMA	95	a	99	a	94	ab
No PRE	+ s-metolachlor	system	system + prometryn	95	a	96	bc	92	c
No PRE	+ s-metolachlor	system	system + flumioxazin	95	a	99	a	95	a
pendimethalin	+ s-metolachlor	system	prometryn + MSMA	95	a	98	ab	94	ab
pendimethalin	+ s-metolachlor	system	flumioxazin + MSMA	95	a	100	a	95	a
pendimethalin	+ s-metolachlor	system	system + prometryn	95	a	96	bc	95	a
pendimethalin	+ s-metolachlor	system	system + flumioxazin	95	a	99	a	95	a
+ fluometuron	+ s-metolachlor	system	system (OT)	95	a	96	bc	95	a
+ fluometuron	+ s-metolachlor	system	prometryn + MSMA	95	a	95	c	94	ab
+ fluometuron	+ s-metolachlor	system	flumioxazin + MSMA	95	a	99	a	95	a

Table 4. (continued).

PRE	EPOST	POST	LAYBY	BRAPP	CHEAL	IPOHG
				St. Joseph	Lewiston	St. Joseph
+ fluometuron	pyrithiobac	prometryn + MSMA	prometryn + MSMA	91 b	100 a	95 a

[a] Data averaged over GM system options of LL or RR, with system herbicide options of glufosinate at 470 g/ha or glyphosate at 840 g/ha, respectively.

[b] Abbreviations: BRAPP, broadleaf signalgrass ; CHEAL, common lambsquarters ; GM, genetically modified; IPOHG, entireleaf morningglory, ;PRE, preemergence; EPOST, early postemergence; LPOST, late post-directed; MPOST, mid-postemergence; OT, over the top.

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

Table 5. Late season pitted morningglory control as affected by location and herbicide treatments averaged over GM system. [a-c]

PRE	EPOST	POST	LAYBY	IPOLA			
				Clayton		St. Joseph	
No PRE	+ s-metolachlor	system	prometryn + MSMA	100	a	93	b
No PRE	+ s-metolachlor	system	flumioxazin + MSMA	100	a	94	ab
No PRE	+ s-metolachlor	system	system + prometryn	100	a	92	c
No PRE	+ s-metolachlor	system	system + flumioxazin	100	a	95	a
pendimethalin	+ s-metolachlor	system	prometryn + MSMA	100	a	94	ab
pendimethalin	+ s-metolachlor	system	flumioxazin + MSMA	100	a	95	a
pendimethalin	+ s-metolachlor	system	system + prometryn	100	a	95	a
pendimethalin	+ s-metolachlor	system	system + flumioxazin	100	a	95	a
+ fluometuron	+ s-metolachlor	system	system (OT)	99	b	95	a
+ fluometuron	+ s-metolachlor	system	prometryn + MSMA	100	a	94	ab
+ fluometuron	+ s-metolachlor	system	flumioxazin + MSMA	100	a	95	a

Table 5. (continued).

PRE	EPOST	POST	LAYBY	IPOLA	
				Clayton	St. Joseph
+ fluometuron	pyrithiobac	prometryn + MSMA	prometryn + MSMA	100 a	95 a

[a] Data averaged over GM system options of LL or RR, with system herbicide options of glufosinate at 470 g/ha or glyphosate at 840 g/ha, respectively.

[b] Abbreviations: GM, genetically modified; IPOLA, pitted morningglory, ;PRE, preemergence; EPOST, early postemergence; LPOST, late post-directed; MPOST, mid-postemergence; OT, over the top.

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

Table 6. Late season weed control as affected by location, GM system, and herbicide treatment.[a,b]

System	PRE	EPOST	MPOST	LPOST	IPOLA		AMBEL	
					Lewiston		Rocky Mount	
LL	No PRE	+ s-metolachlor	glufosinate	prometryn + MSMA	99	a	99	b
LL	No PRE	+ s-metolachlor	glufosinate	flumioxazin + MSMA	100	a	100	a
LL	No PRE	+ s-metolachlor	glufosinate	glufosinate + prometryn	100	a	98	c
LL	No PRE	+ s-metolachlor	glufosinate	glufosinate + flumioxazin	100	a	100	a
LL	pendimethalin	+ s-metolachlor	glufosinate	prometryn + MSMA	100	a	100	a
LL	pendimethalin	+ s-metolachlor	glufosinate	flumioxazin + MSMA	100	a	100	a
LL	pendimethalin	+ s-metolachlor	glufosinate	glufosinate + prometryn	100	a	100	a
LL	pendimethalin	+ s-metolachlor	glufosinate	glufosinate + flumioxazin	100	a	100	a
LL	+ fluometuron	glufosinate	glufosinate	glufosinate (OT)	99	a	100	a
LL	+ fluometuron	glufosinate	glufosinate	prometryn + MSMA	100	a	100	a
LL	+ fluometuron	glufosinate	glufosinate	flumioxazin + MSMA	100	a	100	a
LL	+ fluometuron	pyrithiobac	prometryn + MSMA	prometryn + MSMA	100	a	100	a

Table 6. (continued).

System	PRE	EPOST	MPOST	LPOST	IPOLA		AMBEL	
					Lewiston		Rocky Mount	
RR	No PRE	+ s-metolachlor	glyphosate	prometryn + MSMA	99	a	100	a
RR	No PRE	+ s-metolachlor	glyphosate	flumioxazin + MSMA	100	a	100	a
RR	No PRE	+ s-metolachlor	glyphosate	glyphosate + prometryn	98	a	100	a
RR	No PRE	+ s-metolachlor	glyphosate	glyphosate + flumioxazin	100	a	100	a
RR	pendimethalin	+ s-metolachlor	glyphosate	prometryn + MSMA	100	a	99	b
RR	pendimethalin	+ s-metolachlor	glyphosate	flumioxazin + MSMA	100	a	100	a
RR	pendimethalin	+ s-metolachlor	glyphosate	glyphosate + prometryn	100	a	100	a
RR	pendimethalin	+ s-metolachlor	glyphosate	glyphosate + flumioxazin	100	a	100	a
RR	+ fluometuron	glyphosate	glyphosate	glyphosate (OT)	100	a	100	a
RR	+ fluometuron	glyphosate	glyphosate	prometryn + MSMA	95	b	100	a
RR	+ fluometuron	glyphosate	glyphosate	flumioxazin + MSMA	100	a	100	a
RR	+ fluometuron	pyrithiobac	prometryn + MSMA	prometryn + MSMA	100	a	100	a

Table 6. (continued).

[a] Abbreviations: AMBEL, common ragweed, ; EPOST, early postemergence; GM, genetically modified; IPOLA, pitted morningglory, ; LL, glufosinate tolerant cotton; RR, enhanced glyphosate tolerant cotton; PRE, preemergence; LPOST, late post-directed; MPOST, mid-postemergence; OT, over the top.

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

Table 7. Cotton lint yield as affected by location and GM system averaged over herbicide treatment.[a,b]

System	St. Joseph		Florence		Suffolk	
	---------------------------------kg/ha--------------------------					
RR	2380	a	1470	a	1780	a
LL	1680	b	940	b	1370	b

[a] Abbreviations: GM, genetically modified; LL, glufosinate tolerant cotton; RR, enhanced glyphosate tolerant cotton.

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

Table 8. Cotton lint yield as affected by location, GM system, and herbicide program. [a,b]

PRE	EPOST	MPOST	LPOST	Clayton		Lewiston		Florence	
				----------------------------	----	kg/ha	----	--------------------------	
No PRE	+ s-metolachlor	glufosinate	prometryn + MSMA	1750	j	1280	i	650	i
No PRE	+ s-metolachlor	glufosinate	flumioxazin + MSMA	1890	hij	1600	cdefg	820	gh
No PRE	+ s-metolachlor	glufosinate	glufosinate + prometryn	1920	ghij	1390	hi	450	i
No PRE	+ s-metolachlor	glufosinate	glufosinate + flumioxazin	2260	ab	1630	bcdefg	1140	cdef
pendimethalin	+ s-metolachlor	glufosinate	prometryn + MSMA	2180	abcde	1520	fgh	1120	def
pendimethalin	+ s-metolachlor	glufosinate	flumioxazin + MSMA	2010	defghi	1850	ab	680	i
pendimethalin	+ s-metolachlor	glufosinate	glufosinate + prometryn	1870	ij	1580	defgh	730	hi
pendimethalin	+ s-metolachlor	glufosinate	glufosinate + flumioxazin	1950	fghij	1810	abc	1030	efgh
+ fluometuron	system	glufosinate	glufosinate (OT)	2150	abcdef	1600	cdefgh	1020	fgh
+ fluometuron	system	glufosinate	prometryn + MSMA	2250	abc	1720	abcdef	1160	cdef
+ fluometuron	system	glufosinate	flumioxazin + MSMA	2020	defghi	1700	bcdefg	1440	abc
+ fluometuron	pyrithiobac	prometryn + MSMA	prometryn + MSMA	2120	abcdefg	1750	abcde	1040	efg
No PRE	+ s-metolachlor	glyphosate	prometryn + MSMA	2030	cdefghi	1600	cdefgh	1410	abcd
No PRE	+ s-metolachlor	glyphosate	flumioxazin + MSMA	2100	bcdefgh	1810	abc	1270	abc

Table 8. Cotton lint yield as affected by location, GM system, and herbicide program. [a,b]

PRE	EPOST	MPOST	LPOST	Clayton		Lewiston		Florence	
				-----------------------------		kg/ha		-------------------------	
No PRE	+ s-metolachlor	glyphosate	glyphosate + prometryn	1970	efghij	1820	abc	1540	ab
No PRE	+ s-metolachlor	glyphosate	glyphosate + flumioxazin	2130	abcdefg	1780	abcd	1420	i
pendimethalin	+ s-metolachlor	glyphosate	prometryn + MSMA	2020	defghi	1570	defgh	1270	bcdef
pendimethalin	+ s-metolachlor	glyphosate	flumioxazin + MSMA	2330	a	1820	abc	1330	bcde
pendimethalin	+ s-metolachlor	glyphosate	glyphosate + prometryn	2110	abcdefgh	1770	abcde	1520	ab
pendimethalin	+ s-metolachlor	glyphosate	glyphosate + flumioxazin	2220	abcd	1930	a	1520	ab
+ fluometuron	system	glyphosate	glyphosate (OT)	2110	abcdefgh	1500	ghi	1500	ab
+ fluometuron	system	glyphosate	prometryn + MSMA	2170	abcde	1560	efgh	1640	a
+ fluometuron	system	glyphosate	flumioxazin + MSMA	2270	ab	1730	abcdef	1560	ab
+ fluometuron	pyrithiobac	prometryn + MSMA	prometryn + MSMA	1950	efghij	1790	abcd	1490	ab

[a] Abbreviations: EPOST, early postemergence; GM, genetically modified; LL, glufosinate tolerant cotton; RR, enhanced glyphosate tolerant cotton; PRE, preemergence; LPOST, late post-directed; MPOST, mid-postemergence; OT, over the top.

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

Influence of Rain-free Period on Glufosinate and Glyphosate Phytotoxicity and Physiological Response in Different Weed Species at Two Growth Stages

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Greenhouse studies were conducted to evaluate phytotoxicity and corresponding physiological response to simulated rainfall following postemergence treatments of various formulations of glufosinate or glyphosate. Size effects were also investigated for goosegrass, 7.5 and 15 cm, Palmer amaranth, 7.5 and 20 cm, and pitted morningglory, one- to two-leaf and four- to six-leaf. Ammonia levels and shikimic acid levels were used to detect site of action inhibition for glufosinate and glyphosate, respectively. Weed size at time of application and herbicide formulation did not affect phytotoxicity with either herbicide, however there was a strong correlation with rain-free period. Shikimic acid accumulation and ammonia accumulation were affected by weed size at time of application, increasing as

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rain-free interval was increased. Changes in accumulation of ammonia and shikimic acid in response to the rain-free period closely resembled phytotoxicity profile for both herbicides in pitted morningglory. In Palmer amaranth, the shikimate accumulation profile was most similar to phytotoxicity at the 7.5 cm height, and not similar at 20 cm. The ammonia profile was not similar to glufosinate phytotoxicity at either height of Palmer amaranth. Shikimate profile and glyphosate phytotoxicity were not similar at either height in goosegrass. The ammonia and glufosinate profiles were similar in 7.5 cm goosegrass, but not at the 15 cm height. A rain-free period of 4 hours is needed to adequately control goosegrass and Palmer amaranth, while up to 24 hours is needed to control pitted morningglory with glyphosate. A rain-free period of 1 hour is needed to provide maximum control of goosegrass and pitted morningglory with glufosinate; however a rain-free period of at least 24 hours is needed to achieve maximum control of Palmer amaranth. Similarities between glyphosate and glufosinate phytotoxicity profiles and the profiles of their corresponding diagnostic markers were not predictable, and varied with species and weed size.

Nomenclature: Glufosinate; glyphosate; goosegrass, *Eleusine indica* # ELEIN; Palmer amaranth, *Amaranthus palmeri* S. Wats # AMAPA; pitted morningglory, *Ipomoea lacunosa* L. # IPOLA.

Key words: Ammonia accumulation, herbicide injury, rainfall, shikimic acid, target site inhibition, and weed control.

Abbreviations used: DAT, days after treatment; EPSPS, 5-enolpyruvylshikimate-3-phosphate synthase; NIS, non-ionic surfactant; RCBD, randomized complete block design.

Goosegrass (*Eleusine indica*), Palmer amaranth (*Amaranthus palmeri* S. Wats), and pitted morningglory (*Ipomoea lacunosa* L.) are common and troublesome weeds in several row crops throughout the southern region (Webster 2004, 2005). Palmer amaranth was listed as the most troublesome weed in cotton in Missouri, North Carolina, South Carolina: and in the ten most troublesome weeds in soybean in Florida, Georgia, Missouri, South Carolina, and Tennessee (Webster 2005). Both Palmer amaranth and pitted morningglory are highly competitive weeds with the ability to reduce crop yields and interfere with harvest (Norsworthy and Oliver, 2002). Goosegrass, Palmer amaranth, and pitted morningglory reduce yields not only because they compete with the crop, but also because they emerge throughout the season and present problems at harvest (Barker et al. 1984).

Glufosinate is a nonselective, non-residual postemergence herbicide for genetically modified crops including corn (*Zea mays* L.), cotton, and soybean. Glufosinate inhibits glutamine synthetase, an enzyme that catalyzes the conversion of glutamate plus ammonia to glutamine as part of nitrogen metabolism (Bellinder et al. 1985, 1987; Logusch et al. 1991; Mersey et al. 1990; Wild et al. 1987). Inhibition of glutamine synthetase leads to a rapid accumulation of ammonia to toxic levels in the cell, although the role of ammonia in phytotoxicity is not clear (Seihl, 1997). Phytotoxic symptoms include membrane disruption and inhibition of photosynthesis, which is followed by plant death. Visual symptoms are apparent within 72 h.

Glyphosate is also a nonselective, non-residual postemergence herbicide which genetically modified crops have been developed for including canola, corn, cotton, and soybean. Glyphosate inhibits the activity of EPSPS, an enzyme in the shikimic acid pathway (Duke

1988). This specific site of action inhibits the biosynthesis of the aromatic acids of tryptophan, tyrosine, and phenylalanine (Siehl 1997).

Although glufosinate provides excellent broad spectrum control of many weed species, especially pitted morningglory, goosegrass and Palmer amaranth appear to be more tolerant to glufosinate than several other annual weed species (Beyers et al. 2002; Coetzer et al. 2002; Corbett et al. 2004; Culpepper et al. 2000; Culpepper and York 1999; Steckel et al. 1997; Tingle et al. 1996). Similarly, glyphosate is a broad-spectrum, nonselective herbicide which provides excellent control of goosegrass, Palmer amaranth, and many other weed species; however pitted morningglory has shown some tolerance (Bond et al. 2006; Jordan et al. 1997; Norsworthy et al. 2001; Norsworthy and Oliver 2002a, 2002b).

Amaranth control was greater when glufosinate was applied to smaller plants compared to larger plants (Coetzer et al. 2002); however less than 75% of Palmer amaranth was controlled with a single glufosinate application. Differential glufosinate control has been observed in several species due to either weed height at application or glufosinate rate (Coetzer et al. 2002; Corbett et al. 2004; Steckel et al. 1997). Glufosinate has also shown to antagonize grass control by graminicides for several goosegrass, johnsongrass, and summer annual grass populations (Burke et al. 2005; Gardner et al. 2006).

Similar size response has been observed following applications of glyphosate (Jordan et al. 1997; Koger et al. 2004; Mueller et al. 2006). Application of glyphosate to small, two- to four-leaf, morningglory provides excellent control while larger, five- to eight-leaf, morningglory show greater tolerance to applications of glyphosate (Chachalis et al. 2001), but control of larger weeds can improved by increasing the glyphosate rate (Jordan et al.

1997; Shaw and Arnold 2002). Lanie et al. (1994) found that pitted morningglory control varied from 23 to 78% after 1.12 kg/ha glyphosate was applied with differences in control attributed to weed size at application. Stephenson et al. (2007) observed no differences in control, ranging from 81 to 89%, across 38 accessions of pitted morningglory treated with glyphosate. Norsworthy et al. (2001) determined the tolerance of pitted morningglory is attributed to the lack of absorption (6%), and placement on the plant did not affect absorption (Koger and Reddy 2005).

To develop an effective management program for these troublesome weeds, it is important to understand how weeds respond to environmental factors such as rainfall. Rainfastness of herbicides play an important role on efficacy, and subsequently rainfall effects on herbicide performance have been studied for nearly as long as herbicides have been in use. An herbicide that remains on the leaf surface for extended periods is more likely to be lost due to volatilization, wash off, or degradation. The factors affecting absorption and translocation of glyphosate have been studied since glyphosate was released on the market (Sprankle et al. 1975). In the corresponding time several researchers have studied the effects of glyphosate under varying environmental conditions and with various adjuvant combinations to determine the optimal combination and rain-free period after application (Bryson 1987, 1988; Bariuan et al. 1999; Coble and Brumbaugh 1993; Field and Bishop 1988; Miller et al. 1998; Molin and Hirase 2005; Reddy 2000; Reddy and Singh 1992; Sandbrink et al. 1993; Willoughby 1997). The glyphosate formulation ‘Roundup WeatherMax’, a potassium salt, is marketed with a 30-minute rainfast warranty. Glyphosate label statements on rain-free period, however, are ambiguous, stating that rainfall or irrigation soon after application may reduce control and subsequent applications may be needed to provide adequate control (Anonymous 2007d, 2007e, 2007f). Although not covered extensively in the literature (Anderson et al. 1993), glufosinate has a more definitive rain-free period, with a label statement that a 4 hour rain-free period is required for most weed species (Anonymous 2007a, 2007b).

Site of action inhibition has been investigated as a tool for glyphosate drift detection in various field crops (Buehring, et al. 2007; Burke et al. 2005; Henry et al. 2005; Thomas et al. 2005). Shikimic acid accumulation was found to be an effective diagnostic tool to determine yield loss, however results varied due to environment.

A better understanding of rainfall effects on herbicide efficacy and site of action inhibition could provide extension personnel and producers information needed to make re-application decisions when a rainfall event occurs soon after application. If site of action can be effectively correlated to dose response, predicted control can be established. Therefore the objectives of this study were to determine the effect of weed growth stage, rain-free period, and herbicide formulation on efficacy and target site inhibition in goosegrass, Palmer amaranth, and pitted morningglory.

Materials and Methods

The experiment was conducted in a greenhouse in Raleigh, NC. Goosegrass, Palmer amaranth, and pitted morningglory seeds were planted in excess into plastic pots (10 by 10 by 7.5 cm) and thinned to one plant per plot shortly after emergence. Plants were grown with approximate day/night temperatures of 20/10 C and were watered overtop daily. Plants were fertilized weekly with a complete fertilizer[1]. Natural light in the greenhouse was supplemented for a 12-h photoperiod by metal halide lamps (300 µmol/m-2s-1 photosynthetic photon flux).

Treatments applied to each species included a factorial arrangement of weed growth stages at application, herbicides, and rain-free intervals. Weed growth stages included 7.5- and 15-cm goosegrass (4 and 7 leaves, respectively), 7.5 and 20 cm Palmer amaranth (6 and 20 leaves, respectively), and 1-2 and 4-6 leaf pitted morningglory (5 and 12 cm, respectively). Herbicide treatment options included three commercial glyphosate products applied at 840 g ae/ha and two commercial glufosinate-ammonium products applied at 470 g ai/ha. Glyphosate products included Roundup Original® herbicide[2] (480 g/L isopropylamine salt), Roundup WEATHERMAX® herbicide[3] (660 g/L potassium salt), and Touchdown® Total herbicide[4] (600 g/L potassium salt). Glufosinate-ammonium products included Ignite® herbicide[5] (200 g/L) and Ignite® 280 herbicide[6] (280 g/L). A nonionic surfactant[7] at 0.25% v/v was included with Roundup Original. Labels for the other products do not require the use of an adjuvant Herbicides were applied using a spray chamber equipped with a single even-spray, flat-fan nozzle calibrated to deliver 252 L/ha at 165 kPa and 2.6 km/h approximately 3 hr after sunrise.

Simulated rainfall was achieved using an apparatus based upon the design by Shelton et al. (1985). Two HH-SS50WSQ nozzles[8], equidistantly spaced at 240 cm and suspended 240 cm above the plants, delivered simulated rainfall at 7.6 cm/hr at 207 kPa (Shelton et al. 1985). Simulated rainfall was applied for 10 min at 0.25, 0.5, 1, 4, and 8 h after herbicide treatment. Rainfall rate and uniformity were verified and monitored using rain gauges positioned at plant level. Treated plants with no rainfall and non-treated plants were included for comparison. All plants, including the no-rainfall treatment, received overhead irrigation 24 hr after herbicide application.

Visual estimates of goosegrass, Palmer amaranth, and pitted morningglory control were recorded at 21 d after treatment. Visual estimates of weed control were based on a scale of 0 (no control or no injury symptoms) to 100 (complete death of all plants or no plants present) (Frans et al. 1986). Above-ground plant fresh and dry weights also were recorded at 21 d.

Shikimic Acid Accumulation. A modified spectrophotometric method for detection of shikimic acid was used due to the relative simplicity of the laboratory procedures compared to high-pressure liquid chromatographic detection methods (Pline et al. 2002; Singh and Shaner 1998). The spectrophotometric method has been shown to become less efficient at higher shikimic acid concentrations, but plants exhibiting these high accumulation values resulting from high rates of glyphosate are most often killed (Pline et al. 2002). Ten leaf discs were removed from the newest fully-expanded leaf of glyphosate treated plants using a 7 mm hole punch 5 days after glyphosate application (Buehring et al. 2007; Henry et al. 2005; Pline et al. 2002). The ten discs were placed in microcentrifuge tubes containing 0.5 mL of 0.01 M H_2SO4 and placed on ice while transported back to the laboratory. Once in the laboratory, the samples were ground using sea sand and 0.25 mL of 0.4 M NaH_2CO_3 was added to each sample. Solutions remained in –20° C freezer storage until assay. Samples were allowed to thaw for one hour and then centrifuged at 10,000 x *g* for 5 min. After centrifuging, 20 μL of the non-diluted sample was analyzed according to the methods of Singh and Shaner (1998) using a spectrometer at 380 nm. A standard curve was developed using pure shikimic acid standards with known concentrations (Pline et al. 2002a). The total μg shikimic acid/g plant tissue from all plants was determined by comparison with the standard curve, and background levels obtained from the non-treated plants were subtracted from the spectrophotometric readings of sample values prior to statistical analysis.

Ammonia Accumulation. A modified spectrophotometric method for detection of ammonium (NH_4-N) content was determined as described by Frantz et al (1982) and Coetzer and Al-Khatib (2001). Fresh leaf tissue (0.6 to 1.3 g) was collected 1 d after glufosinate application and frozen in –20° C freezer storage until assay. Leaf tissue was homogenized with mortar and pestle in 5 ml of a 12:5:3 (v/v/v) mixture of methanol:chloroform:water, centrifuged at 20,000 × *g* for 15 min, and the supernatant containing ammonium removed. Prior to centrifugation, 15 ml distilled water was added to the extract. Absorbance of the blue-green color, formed by the salicylic acid analog of indophenol blue, was measured at 660 nm. A standard curve was developed using ammonium nitrate and ammonium sulfate with known concentrations. The total μg ammonia/g plant tissue from all plants was determined by comparison with the standard curve, and ammonia background levels obtained from the non-treated plants were subtracted from the spectrophotometric readings of each sample prior to statistical analysis.

Statistical Analysis. The experimental design was a randomized complete block with a factorial treatment arrangement consisting of five herbicides or formulations, six rain-free period options, and two growth stage options. Treatments were replicated three times, and the experiment was repeated once.

Data were subjected to an analysis of variance using the general linear models procedure of SAS (SAS 1998), and sums of squares were partitioned to evaluate run and treatment effects (McIntosh 1983). Log, arcsine, and square root transformations were conducted individually in an attempt to stabilize variance (Gomez and Gomez 1984); however, the transformations did not improve homogeneity, therefore data are presented with statistical interpretation based upon non-transformed data. A modified rectangular hyperbolic function was used to conduct regression analysis on site of action inhibition and control (Table 1).

Results and Discussion

Weed Control. Visual control ratings, fresh weight reduction, and dry weight reduction showed similar trends statistically; therefore only visual control ratings are presented. Significant size effects of growth stage at time of herbicide application were observed for control of all species, therefore data are presented by species and size. Data are averaged over formulation and rain-free intervals where appropriate. Significant herbicide by rain-free period interactions were detected for 7.5- and 20- cm Palmer amaranth, 7.5- cm goosegrass, and 1- to 2- and 4- to 6- lf pitted morningglory.

In general, glyphosate provides good control of Palmer amaranth (Anonymous 2007d, 2007e, 2007f). No differences in Palmer amaranth control were noted among the three glyphosate formulations. Averaged over growth stages and rain-free intervals, Roundup Original, Roundup WEATHERMAX, and Touchdown Total controlled Palmer amaranth 75, 85, and 80%, respectively (data not shown). Control of 7.5 cm Palmer amaranth 21 days after application with glyphosate was >90% at all rain-free periods (Figure 1a), and when averaged over rain-free period (Table 2). However, one hour or less of a rain-free period resulted in less than 50% control with 20 cm Palmer amaranth (Figure 1b).

Glufosinate is often used for Palmer amaranth control (label info). A rain-free period of greater than 1 to 4 hours was needed for adequate control of Palmer amaranth at both heights with glufosinate (Figure 2a and 2b). Glufosinate formulation also affected control, the Ignite 280 formulation of glufosinate provided greater control of 7.5 cm Palmer amaranth when compared to the Ignite formulation when averaged over rain-free period (Table 3). Variability in control of Palmer amaranth has also been observed in field efficacy trials, with control ranging from 71 to 99% (Coetzer et al. 2002; Gardner et al. 2006).

A significant glufosinate formulation by rain-free period interaction was also observed for 7.5 cm Palmer amaranth, with greater control at all rain-free periods obtained with Ignite 280 (data not shown). Differences in control between 20 cm Palmer amaranth treated with glyphosate and glufosinate were not as evident, however greater control was observed with glyphosate when a rainfall event occurred at four hrs after application (Figure 1b and 2b). In field studies, Palmer amaranth control following glyphosate applications was 100% in ultra narrow row cotton (Culpepper and York 2000), 86 to 100% in cotton (Scott et al. 2002), and at least 99% across 47 Palmer amaranth accessions (Bond et al. 2006).

Goosegrass control 21 days after application was also dependent on weed size, herbicide formulation, and rain-free period. Goosegrass was generally sensitive to glyphosate, but needed a rain-free period of at least 0.5 hr for 100% control at 7.5 cm, but the rain-free period needed at 20 cm increased to 4 hr (Figure 3a and b). Goosegrass at 7.5 cm was relatively tolerant to glufosinate, with greatest control of 58% with 24 hr rain-free treatment

(Figure 4a), however glufosinate provided 90% control of goosegrass at 15 cm with a rain-free period of 8 hr or more (Figure 4b). Steckel et al. (1997) observed greater control with glufosinate when applied to 10 cm giant foxtail, common lambsquarters, common cocklebur, and Pennsylvania smartweed when compared to applications made to 5 or 15 cm growth stages. Herbicide formulation significantly affected phytotoxicity for both glyphosate and glufosinate applied to 7.5 cm goosegrass. Roundup Original and Touchdown Total provided greater control than Roundup WEATHERMAX when simulated rainfall occurred within four hrs of application; however all glyphosate formulations provided 100% goosegrass control with a rain-free period of 4 hrs or greater (Figure 3a). Goosegrass control was greater at all rain-free periods following an Ignite 280 application when compared to Ignite, with maximum control reaching 63% (data not shown), and when averaged over rain-free period, Ignite 280 and Ignite controlled goosegrass 36 and 17%, respectively (Table 3). Although no differences in formulation were observed in 15 cm goosegrass; glyphosate consistently provided greater control than glufosinate at all rain-free periods (Figures 3b and 4b). Culpepper et al. (2000) observed 99% goosegrass control with glyphosate applied alone and 96% control when glufosinate was applied alone while Burke et al. (2006) observed glufosinate control from 9 to 43% depending on goosegrass growth stage at time of application.

Though no differences in pitted morningglory control were observed within either glyphosate or glufosinate herbicide formulations, control of pitted morningglory was greater with glufosinate than glyphosate when averaged over rain-free period (Table 2). Control of 1- to 2- lf pitted morningglory reached 100% when rainfall was delayed eight hrs following a glufosinate application; however no rain-free period resulted in equal control with glyphosate (Figures 5a and 6a). Glufosinate provided greater control of 4- to 6- lf pitted morningglory than glyphosate at all rain-free periods (Figures 5b and 6b). In field studies, pitted morningglory control ranged from 60 to 90% when glyphosate was applied late POST and early POST, respectively (Jordan et al. 1997).

Glyphosate and glufosinate control of each weed species was similar to previous research which demonstrated significant differences due to size and herbicide type (Burke et al. 2005; Culpepper et al. 2000; Everman et al. 2007; Jordan et al. 1997). Glyphosate controlled small goosegrass, Palmer and pitted morningglory 89, 98, and 64%, respectively, while glufosinate controlled them 27, 78, and 78%, respectively (Table 2). Pitted morningglory control in cotton was 94% when glufosinate was applied POST, while goosegrass and Palmer amaranth control was 81 and 84%, respectively following a POST glufosinate application (Everman et al. 2007). No differences in control were observed for large Palmer amaranth; however glyphosate and glufosinate control of goosegrass was 95 and 56%, respectively, and 49 and 59%, respectively, on pitted morningglory (Table 2).

Similarity between glyphosate phytotoxicity and Shikimic Acid Accumulation. A commonly used chemical indicator of glyphosate phytotoxicity is increased content of shikimic acid which accumulates due to inhibition of EPSP synthase. Therefore, it was expected that the profile of shikimic acid content would be similar to the phytotoxicity levels. It was thus unexpected to find the similarity between shikimic acid and phytotoxicity profiles varied between species and plant height.

Shikimic acid accumulation did not show close similarities to control in Palmer amaranth (Figures 1a and 1b). Shikimic acid increased slowly in 7.5 cm Palmer amaranth, rising to a maximum when rainfall was delayed 24 hr, however control did not follow the same trend, with maximum control achieved when a rainfall event occurred as early as 1 hr after glyphosate application. Control and shikimic acid accumulation followed a closer trend in 20 cm Palmer amaranth, with a sizeable lag in shikimic acid accumulation (Figure 1b). Control increased as rainfall was delayed, with maximum control occurring when rainfall occurred 4 hr after application or later. Shikimic acid accumulated in 20 cm Palmer amaranth slowly when rainfall was delayed from 0.25 to 4 hr, with a rapid increase when a rainfall event occurred 8 and 24 hr after application (Figure 1b).

Similar results were observed between control and shikimic acid accumulation in goosegrass. A rapid increase in control of 7.5 cm goosegrass when rainfall was delayed from 0.25 to 1 hr after application did not result in a corresponding increase in shikimic acid (Figure 3a). Accumulation progressed slowly when rainfall occurred from 0.25 to 4 hr, with a gradual increase from 4 to 24 hr. Significant differences were observed in formulation for both control and site of action inhibition. Goosegrass control with Roundup WEATHERMAX was less than control observed with Touchdown Total or Roundup Original when rainfall occurred within 1 hr of application (Figure 3a). Shikimic acid accumulation was significantly higher in both 7.5 and 15 cm goosegrass treated with Touchdown Total compared to those treated with either Roundup formulation, but was not influenced by timing in 15 cm goosegrass (Table 4). Shikimic acid accumulation in 15 cm goosegrass resembled accumulation in 20 cm Palmer amaranth, with a gradual increase when rainfall occurred from 0.25 to 4 hr after application, and a rapid increase when rainfall occurred at 8 or 24 hr, although maximum control was achieved with a rain-free period of 4 hrs (Figure 3b).

The shikimic acid profile most closely resembled the phytotoxicity profile in both 1- to 2-, and 4- to 6- lf pitted morningglory. Glyphosate phytotoxicity (control) ranged from 50% with a 0.25 hr rain-free period to near 90% phytotoxicity with a 24 hr rain-free period, and the shikimic acid profile similarly increased, from about 200 to 1800 μg/g fresh wt (Figure 5a). Glyphosate phytotoxicity in 4- to 6- lf morningglory was lower, and varied between 30% with a 0.25 hr rain-free period to a maximum of 70% with a 24 hr rain-free period (Figure 5b). The shikimic acid profile showed similarities to the phytotoxicity in that it increased from the 0.25 to the 24 hr rain free period, but the increase was from 0.25 to 0.5 hr, and as the rain-free period increased, there was no increase in shikimate levels (Figure 5b).

Shikimic acid accumulation was less responsive in susceptible species, goosegrass and Palmer amaranth, than in more tolerant pitted morningglory. High variability in shikimic acid accumulation between sizes and species of weeds indicates shikimic acid accumulation is not a reliable indicator of control for all species.

Ammonia Accumulation. No significant differences were observed between glufosinate formulation in 15 cm goosegrass and pitted morningglory; therefore data were pooled over glufosinate formulation. Ammonia accumulation was affected by glufosinate formulation applied to 7.5 cm Palmer amaranth, with greater accumulation observed following Ignite application when averaged over rain-free period (Table 5).

Palmer amaranth did not show similarities in ammonia accumulation and control at both weed sizes (Figures 2a and b), and ammonia accumulated slowly with a total accumulation of approximately 30 μg/g fresh weight. Ammonia accumulation in 20 cm Palmer amaranth showed did increase steadily as control increased when rainfall was delayed from 0.25 to 24 hr after glufosinate application, with an increase from 15 μg/g fresh weight to 25 μg/g fresh weight, respectively (Figure 2b).

Goosegrass, like Palmer amaranth, did not show similarities between control and ammonia accumulation. Control increased as rain-free period increased for both sizes, however ammonia did not increase after 1 hr for 7.5 cm goosegrass, and showed no increase for 15 cm goosegrass(Figures 4a and b). Although control was not as great for the 7.5 cm goosegrass, there was a greater increase in ammonia accumulation when rainfall occurred 24 hr after application than any other rainfall time (Figure 4a).

Ammonia accumulation in 1- to 2- and 4- to 6- lf pitted morningglory showed a steady increase as rain-free period was increased, which was very similar to the increased control as rain-free period was increased with glufosinate formulations (Figure 6a and b). Control and ammonia accumulation increased for 1- to 2-lf pitted morningglory from 65 to 100% and 40 to 120 μg/g fresh weight when rainfall was delayed from 0.25 to 24 hr, respectively (Figure 6a). Although the same level of control was not achieved with 4- to 6-lf pitted morningglory, both control and ammonia accumulation increased from 25 to 90% and 20 to 150 mg/g fresh weight when rainfall was delayed from 0.25 to 24 hr, respectively (Figure 6b).

Ammonia accumulation, as with shikimic acid accumulation, was not similar to control for all species. Ammonia accumulation in pitted morningglory, Palmer amaranth, and 7.5 cm goosegrass increased as rain-free period increased. Coetzer and Al-Khatib observed 58 times higher ammonia accumulation in treated Palmer amaranth than in control plants. Target site inhibition may be an excellent indicator of herbicide absorption for various crop and weed species, showing similar results to radiological studies (Coetzer and Al-Khatib 2001; Kumaratilake and Preston 2005; Kumaratilake et al. 2002; Mersey et al. 1990; Neto et al. 2000; Steckel et al. 1997), however, this study shows there may be differences in accumulation due to growth stage and species that need to be considered. Target site inhibition following glyphosate and glufosinate applications did not responded similarly to control in all species, and we observed that greater accumulation of shikimic acid or ammonia does not equate to greater control. Ridley and McNally (1985) observed a 70-fold difference in the susceptibility of seven plant species, and various sizes within species, to glufosinate. The differences in control were not attributed to the degree to which glutamine synthetase was inhibited, but rather another undiscovered variable.

The results of this study indicate rain-free period is species and herbicide specific. Therefore, when making decisions concerning the need for reapplication, species, growth stage, and rain-free period should be considered. Repeat glyphosate applications should be made if a rainfall event occurs within one or eight h of the initial application to goosegrass, depending on formulation, one and four h for 7.5 and 20 cm Palmer amaranth, respectively, and within 4 or 24 h for 1 - 2 and 4 - 6 lf pitted morningglory, respectively, to ensure adequate control. Similarly, if a rainfall event occurs within four or 24 h of a glufosinate application to 7.5 and 15 cm goosegrass, respectively, 8 hrs to Palmer amaranth, or within 8 h of an application to pitted morningglory, a repeat glufosinate application should be made.

Our results also indicate an inherent inconsistency in target site inhibition of weed species according to growth stage. Target site inhibition showed similarity to control in pitted morningglory treated with glufosinate or glyphosate, however there was great variability in target site inhibition in relation to control for Palmer amaranth and goosegrass. Direct comparisons of target site inhibition to control could not be made, and further investigation into the mechanisms involved in differential control may be necessary.

Sources of Materials

[1] Peter's 20-20-20 Professional Plant Food. Spectrum Group, Division of United Industries Corporation, P.O. Box 15842, St. Louis, MO 63114-0842.

[2] Roundup Original®, Monsanto Company, 800 North Lindbergh Boulevard, St. Louis, MO 63167.

[3] Roundup WEATHERMAX™, Monsanto Company, 800 North Lindbergh Boulevard, St. Louis, MO 63167.

[4] Touchdown® Total, Syngenta Crop Protection, P.O. Box 18300, Greensboro, NC 27419.

[5] Ignite® herbicide, Bayer CropScience, P.O. Box 12014, 2 T.W. Alexander Drive, Research Triangle Park, NC 27709.Roundup WEATHERMAX™, Monsanto Company, 800 North Lindbergh Boulevard, St. Louis, MO 63167.

[6] Ignite® 280 herbicide, Bayer CropScience, P.O. Box 12014, 2 T.W. Alexander Drive, Research Triangle Park, NC 27709.

[7] Induce® nonionic low-foam wetter/spreader adjuvant contains 90% nonionic surfactant (alkylaryl and alcohol ethoxylate surfactants) and fatty acids and 10% water. Helena Chemical Company, Suite 500, 6075 Popular Avenue, Memphis, TN 38119.

[8] Nozzles.

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Anonymous. 2007b. Ignite 280 label. Research Triangle Park, NC: Bayer CropScience LP. 14 p.

Anonymous. 2007c. Roundup Original label. St. Louis, MO: Monsanto Company. 21 p.

Anonymous. 2007d. Roundup WEATHERMAX label. St. Louis, MO: Monsanto Company. 23 p.

Anonymous. 2007e. Touchdown Total label. Greensboro, NC: Syngenta Crop Protection, Inc. 48 p.

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Table 1. Parameters for regression analysis [$y=a-(b/(1+cx)^{1/d})$] on the change in shikimic acid, ammonia, and control in response to various simulated rainfall timings.

Species	Size	Parameters				
		a	b	c	d	R^2
AMAPA	7.5 cm SA	5223	1957	0.00000157	0.0000168	53.8
	20 cm SA	3851	3740	0.0000013	0.0002	88.3
	7.5 cm AA	67	42	0.000000028	0.0000099	14.5
	20 cm AA	58	90	6121	16.6	84.1
ELEIN	wmax SA	205	191.7	0.0000016	0.000012	99.1
	orig SA	67857	67851	2.49	3376	68.8
	TD SA	5137190	5136843	0.31	22874	96.3
	15 cm SA	1408	1281	0.000002	0.000097	98.6
	7.5 cm AA	46.5	76	0.0000257	0.0000053	69.1
	15 cm AA	2662	2613	-1.8	0.0067	33.84
IPOLA	1-2 lf SA	4630	4955	12.8	10.5	94.8
	4-6 lf SA	1261	25996646658	285	0.24	70.2
	1-2 lf AA	5363	5460	15490	315	90.3
	4-6 lf AA	146424	146463	64.9	5909	93.8

Table 1. (continued).

Species	Size	Parameters				
		a	b	c	d	R^2
AMAPA	7.5 cm gly	100	17.9	0.0000083	0.0000031	99.2
	20 cm gly	94	96	-0.041	-0.046	99.2
	7.5 cm glu	116	1043	364784	4	93.4
	20 cm glu	119.7	126	5.3	2.96	88.6
ELEIN	7.5 cm wmax gly	99.9	75.2	0.000003	0.000002	99.9
	7.5 cm orig gly	100	409	1.04	0.09	100
	7.5 cm td gly	100	111.8	2	0.29	100
	big gly	94	96	-0.04	-0.05	99.2
	7.5 cm glu	111.7	513	898456.6	7.96	90.9
	15 cm glu	119.7	126	5.4	3	88.6
IPOLA	1-2 lf gly	82.6	40.2	-0.04	-0.14	97.9
	4-6 lf gly	415003	414970	0.65	29108	88.98

Table 1. (continued).

Species	Size	Parameters				
		a	b	c	d	R^2
	1-2 lf glu	97.7	34	-0.04	-0.27	92.7
	4-6 lf glu	1239	1379	1533027	95.9	90.9

[a] Abbreviations: AMAPA, Palmer amaranth; ELEIN, goosegrass; IPOLA, pitted morningglory; SA, shikimic acid; AA, ammonia accumulation; gly, glyphosate (averaged over formulations; glu, glufosinate averaged over formulations; wmax, Roundup WEATHERMAX; orig, Roundup Original; and td, Touchdown Total.

Table 2. Control of Palmer amaranth, goosegrass, and pitted morningglory by glufosinate-ammonium and glyphosate. Data averaged over herbicide formulations and rain-free intervals.

	Palmer amaranth		Goosegrass		Pitted morningglory	
Herbicide	7.5 cm	20 cm	7.5 cm	15 cm	1- to 2-leaf	4- to 6-leaf
	%					
Glufosinate-ammonium	78	62	27	56	78	59
Glyphosate	98	65	89	95	64	49
LSD[a]	5.3	5.9	6.5	6.2	6.7	6.4
LSD[b]	7.0		8.2		6.8	
LSD[c]	4.9		4.2		6.0	

[a] LSD to compare herbicides within a species and growth stage.

[b] LSD to compare growth stages within a species treated with glufosinate-ammonium.

[c] LSD to compare growth stages within a species treated with glyphosate.

Table 3. Control of 7.5 cm Palmer amaranth and goosegrass with glufosinate averaged over rain-free period [a].

	Palmer amaranth		Goosegrass	
	Ignite 280	Ignite	Ignite 280	Ignite
	----------------------------%--------------------------			
Control	85 a	70 b	36 a	17 b

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

Table 4. Shikimic acid accumulation in goosegrass averaged over rain-free period[a].

Herbicide	Shikimic Acid Accumulation	
	μg/g fresh wt.	
	7.5 cm	15 cm
Touchdown Total	520 a	630 a
Roundup WeatherMAX	85 b	95 b
Roundup Original	50 b	85 b

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

Table 5. Ammonia accumulation in 7.5 cm Palmer amaranth averaged over rain-free period [a].

Herbicide	Ammonia Accumulation
	μg/g fresh wt.
Ignite 280	22 b
Ignite	30 a

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

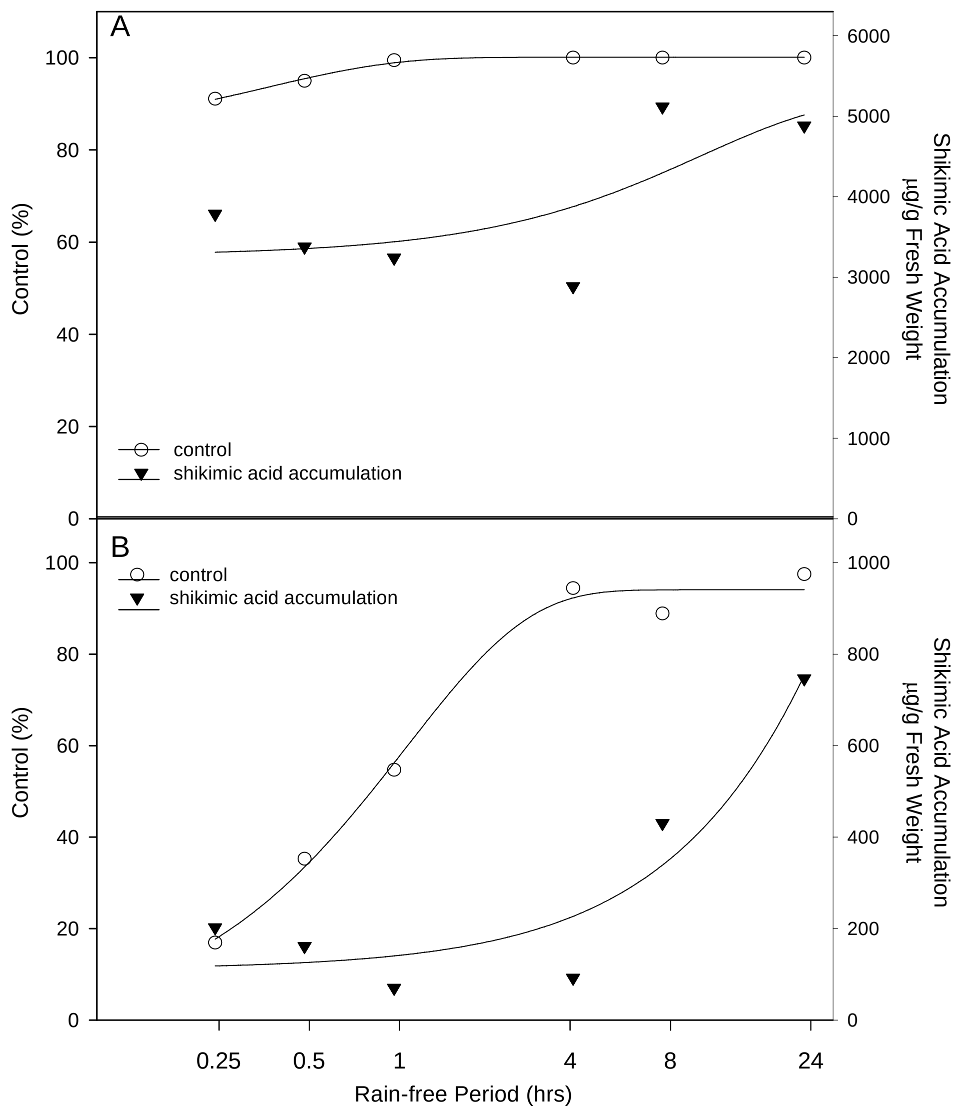

Figure 1. A) Control and shikimic acid accumulation in 7.5 cm Palmer amaranth with glyphosate as affected by rain-free period shown on a log scale pooled over glyphosate formulation. B) Control and shikimic acid accumulation in 20 cm Palmer amaranth with

glyphosate as affected by rain-free period shown on a log scale pooled over glyphosate formulation.

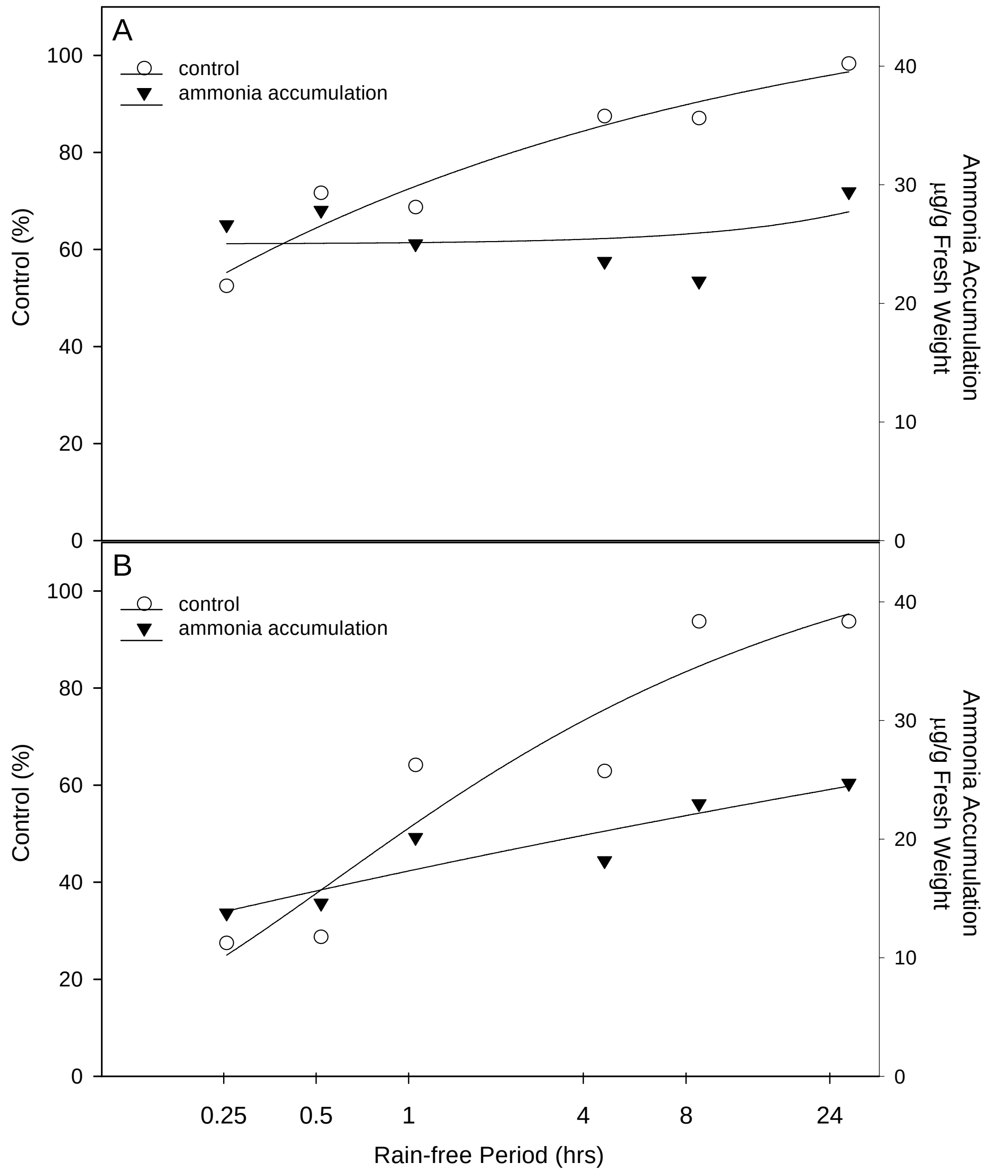

Figure 2. A) Control and ammonia accumulation in 7.5 cm Palmer amaranth with glufosinate-ammonium as affected by rain-free period shown on a log scale pooled over glufosinate-ammonium formulation. B) Control and ammonia accumulation in 20 cm Palmer

amaranth with glufosinate-ammonium as affected by rain-free period shown on a log scale pooled over glufosinate-ammonium formulation.

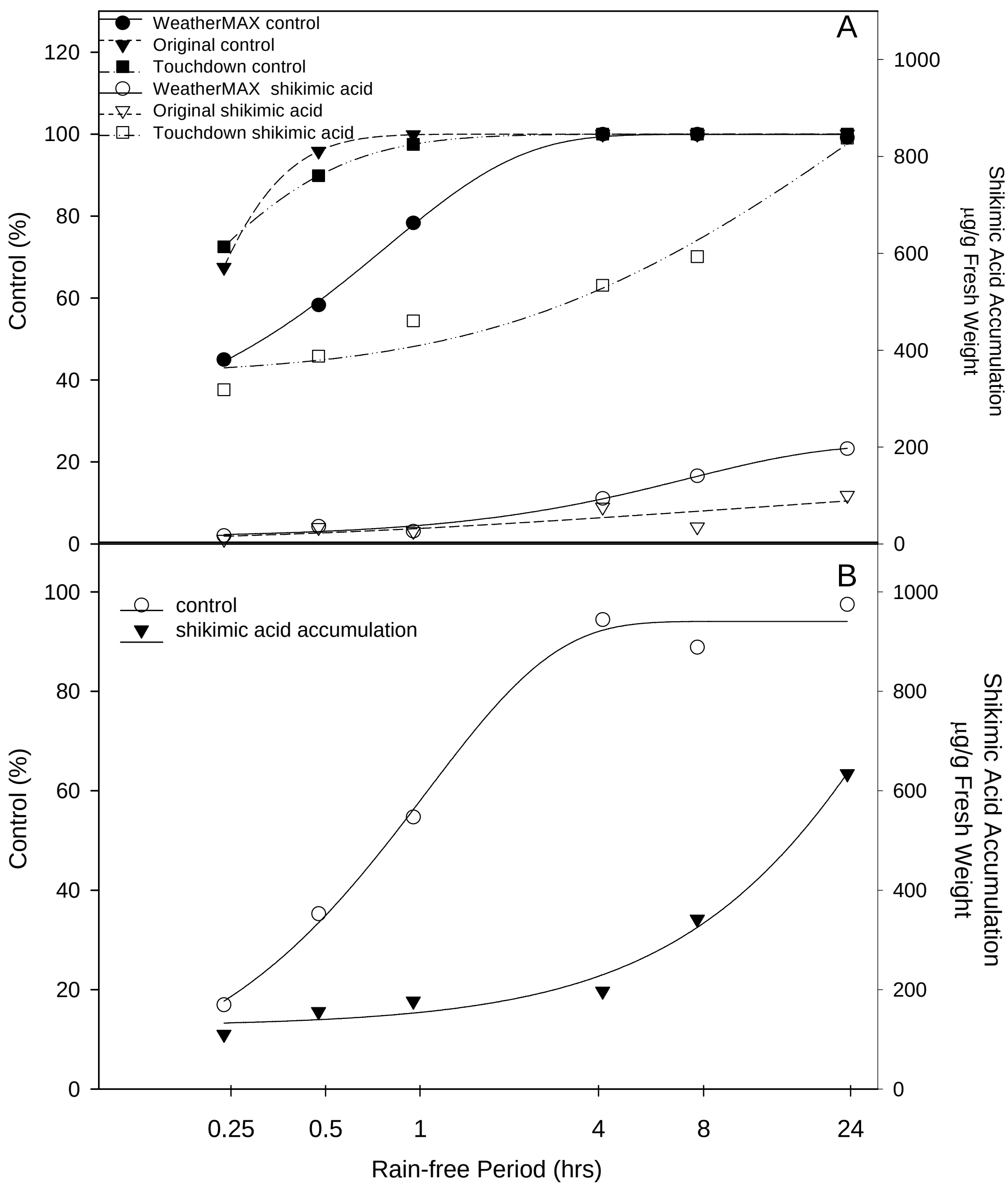

Figure 3. A) Control and shikimic acid accumulation in 7.5 cm goosegrass with glyphosate as affected by glyphosate formulation and rain-free period shown on a log scale. B) Control

and shikimic acid accumulation in 15 cm goosegrass with glyphosate as affected by rain-free period shown on a log scale pooled over glyphosate formulation.

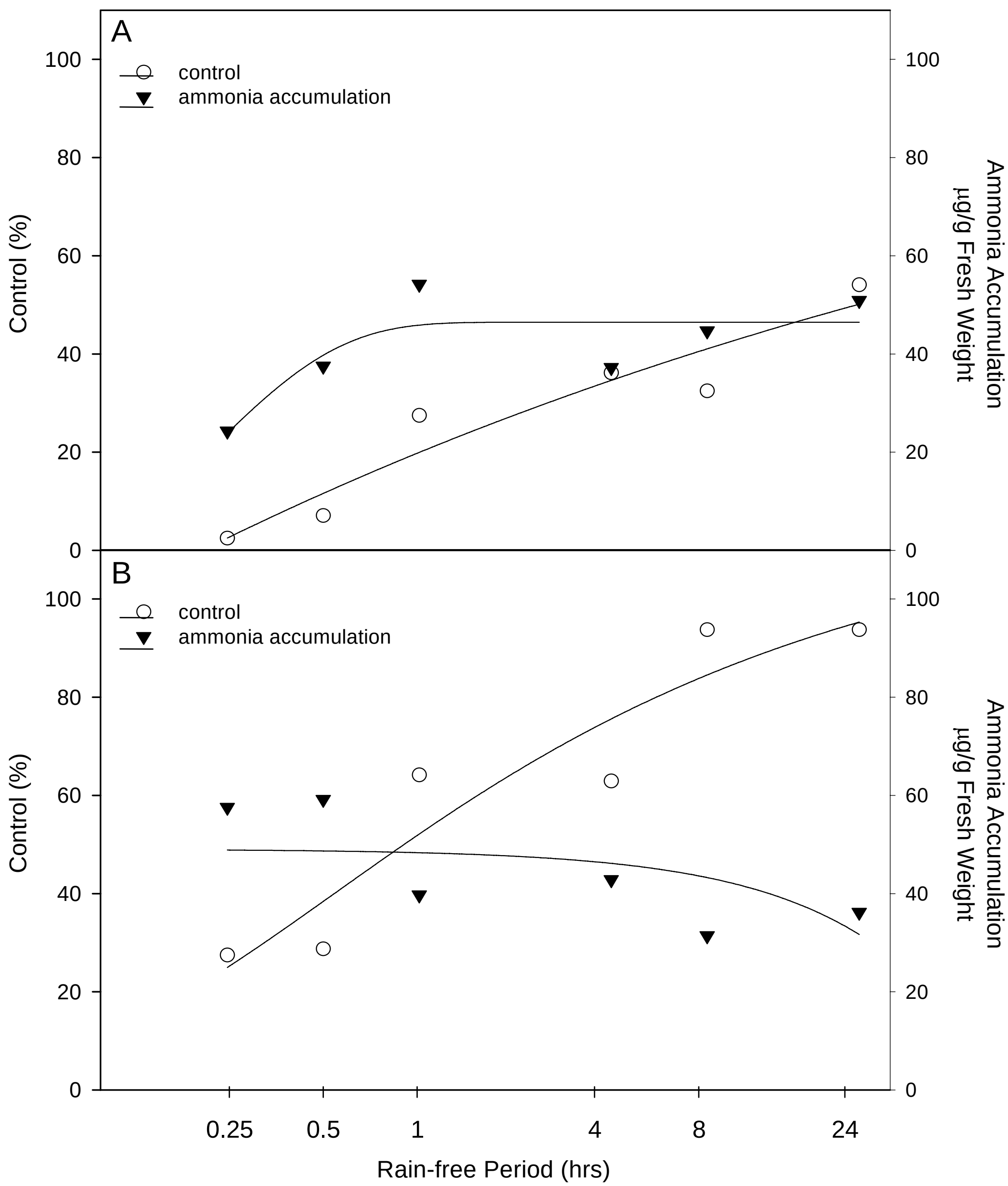

Figure 4. A) Control and ammonia accumulation in 7.5 cm goosegrass with glufosinate-ammonium as affected by rain-free period shown on a log scale pooled over glufosinate-

ammonium formulation. B) Control and ammonia accumulation in 15 cm goosegrass with glufosinate-ammonium as affected by rain-free period shown on a log scale pooled over glufosinate-ammonium formulation.

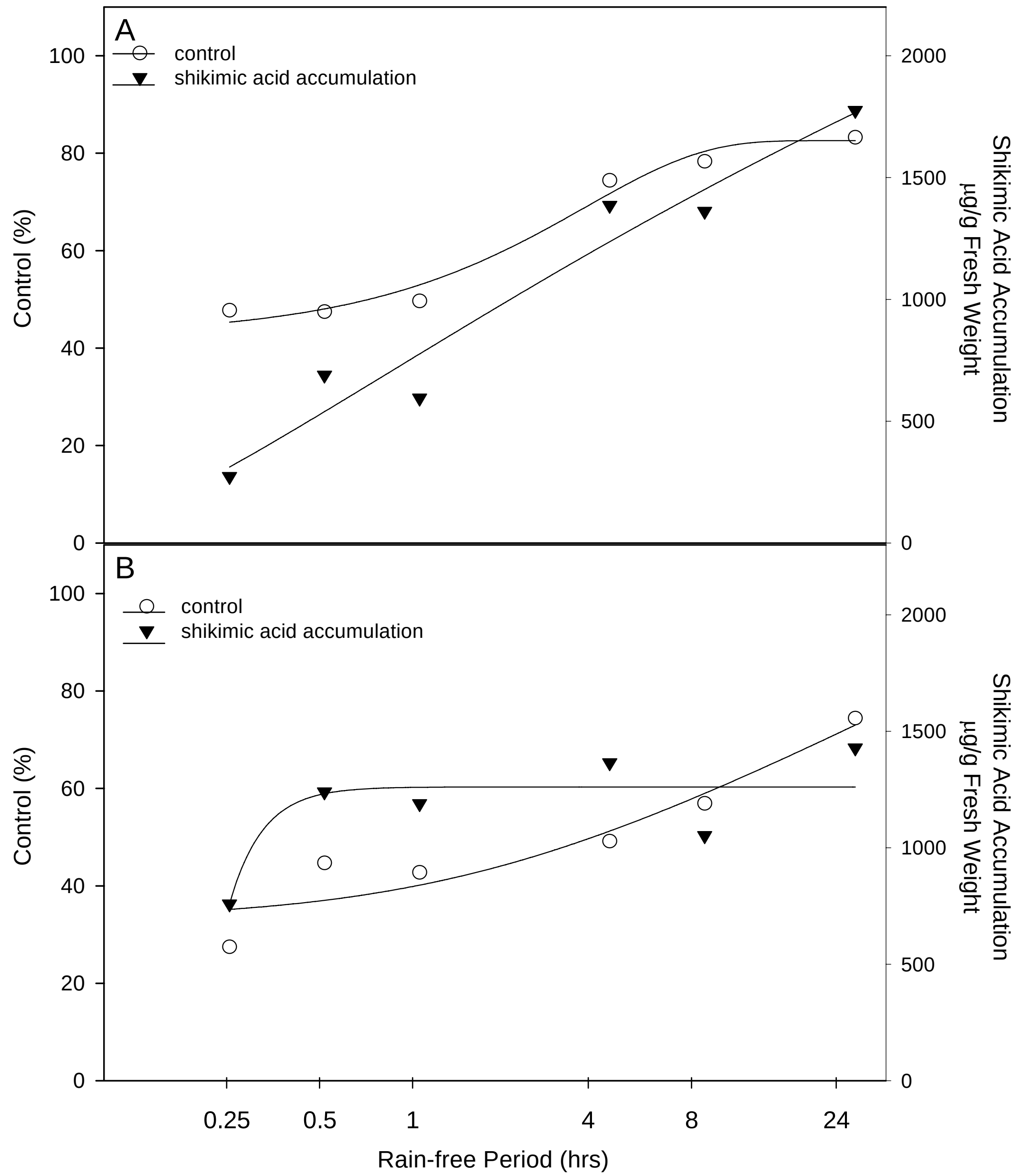

Figure 5. A) Control and shikimic acid accumulation in 1- to 2-lf pitted morningglory with glyphosate as affected by rain-free period shown on a log scale pooled over glyphosate

formulation. B) Control and shikimic acid accumulation in 4- to 6-lf pitted morningglory with glyphosate as affected by rain-free period shown on a log scale pooled over glyphosate formulation.

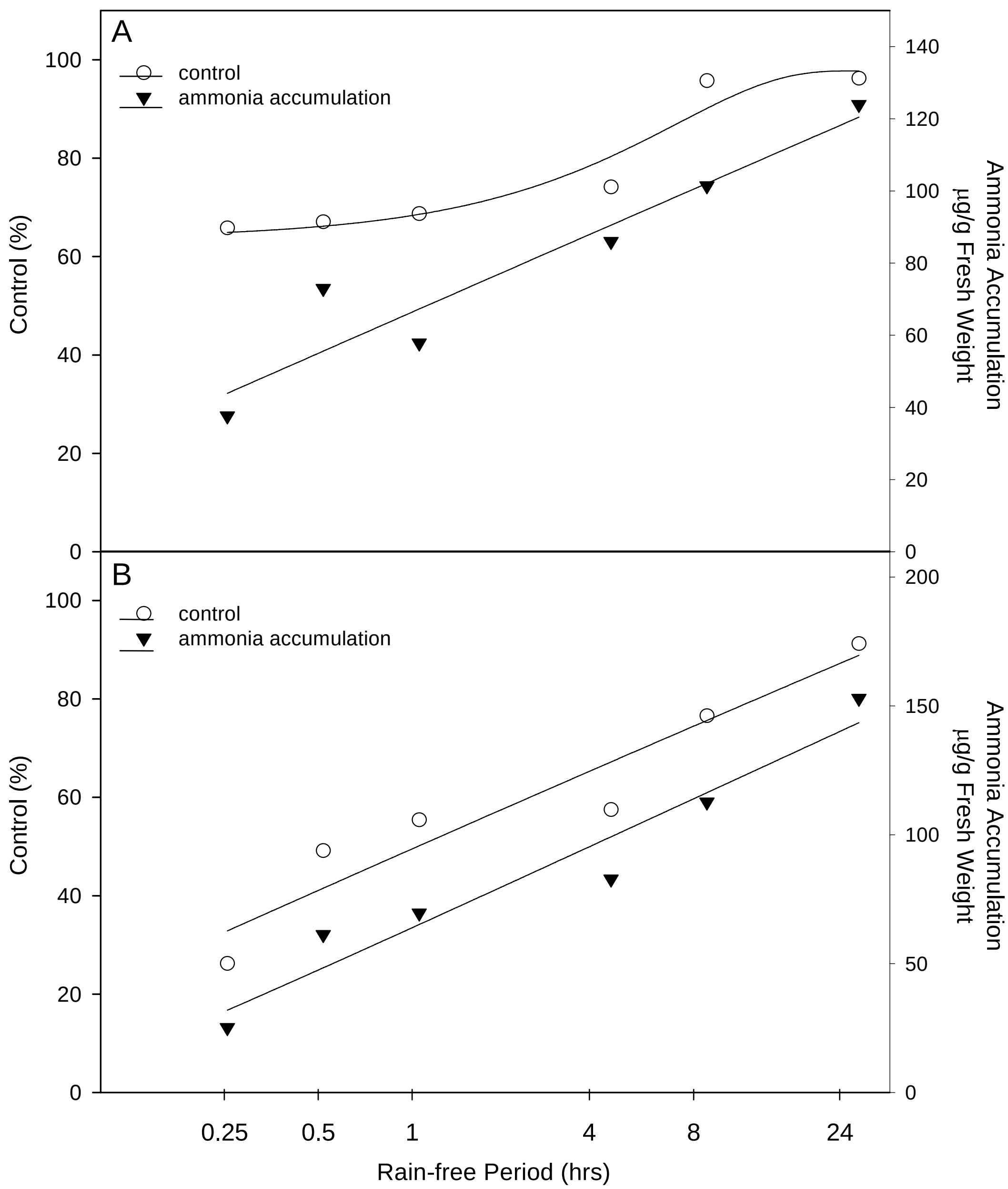

Figure 6. A) Control and ammonia accumulation in 1- to 2-lf pitted morningglory with glufosinate-ammonium as affected by rain-free period shown on a log scale pooled over

glufosinate-ammonium formulation. B) Control and ammonia accumulation in 4- to 6-lf pitted morningglory with glufosinate-ammonium as affected by rain-free period shown on a log scale pooled over glufosinate-ammonium formulation.

Absorption, Translocation, and Metabolism of Glufosinate in Glufosinate-Resistant Corn, Non-Transgenic and Glufosinate-Resistant Cotton, and Five Weed Species

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Greenhouse studies were conducted to evaluate absorption, translocation, and metabolism of ^{14}C-glufosinate in glufosinate-resistant corn, glufosinate-resistant cotton, non-transgenic cotton, goosegrass, large crabgrass, Palmer amaranth, pitted morningglory, and sicklepod. Corn and cotton plants were treated at the 4 leaf stage; whereas goosegrass, large crabgrass, Palmer amaranth, pitted morningglory, and sicklepod were treated at 5, 7.5, 7.5, 10, and 10 cm, respectively. All plants were harvested at 1, 6, 24, 48, and 72 h after treatment (HAT). Absorption of ^{14}C-glufosinate was $\geq$87% 24 hours after treatment in Palmer amaranth and sicklepod. Absorption was <30% at all harvest intervals for glufosinate-resistant cotton and corn, non-transgenic cotton, and pitted morningglory. Significant levels of translocation were observed in glufosinate-resistant corn and Palmer amaranth. ^{14}C-glufosinate was translocated to the region above the treated leaf and the roots up to 41 and 27%, respectively, and up to 49 and 15% to regions above and below the treated leaf, respectively, in Palmer amaranth. Metabolites of ^{14}C-glufosinate were detected in all crop and weed species. Metabolism of ^{14}C-glufosinate was < 20% in non-transgenic cotton and pitted morningglory,

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however metabolism rates were >70% in glufosinate-resistant cotton and large crabgrass 72 hours after treatment. Intermediate rates of metabolism were observed for Palmer amaranth, sicklepod, goosegrass, and glufosinate-resistant corn, with metabolites comprising >30% of detectable radioactivity.

Nomenclature: Cotton, *Gossypium hirsutum* L.; corn, *Zea mays* L.; glufosinate; goosegrass, *Eleusine indica* # ELEIN; large crabgrass, *Digitaria sanguinalis* L. # DIGSA; Palmer amaranth, *Amaranthus palmeri* S. Wats # AMAPA; pitted morningglory, *Ipomoea lacunosa* L. # IPOLA; sicklepod, *Senna obtusifolia* (L.) H.S. Irwin & Barneby.

Key words: Absorption, cotton, corn, glufosinate, metabolism, translocation.

Glufosinate, a postemergence herbicide, acts by inhibiting the glutamine synthetase enzyme (Coetzer and Al-Khatib, 2001; Devine et al. 1993; Wendler et al., 1990). Although glufosinate is considered a non-selective herbicide, weed species show various degrees of sensitivity and control (Mersey et al. 1990; Neto et al. 2000; Ridley and McNally 1985; Steckel et al. 1997a, 1997b). Variable control of goosegrass, large crabgrass, and Palmer amaranth, which are common and troublesome weeds in southern row crops (Webster 2004, 2005), has been observed in studies investigating glufosinate efficacy (Beyers et al. 2002; Coetzer et al. 2002; Corbett et al. 2004; Culpepper et al. 2000; Culpepper and York 1999; Everman et al. 2007).

Differences in various levels of tolerance to glufosinate have been attributed several factors including temperature, humidity, growth stage, application rate, application timing, species, and variations in level of absorption and translocation (Anderson et al 1993a, 1993b; Coetzer et al. 2001; Grangeot et al. 2005; Maschoff et al. 2000; Mersey et al. 1990; Neto et al. 2000;

Peterson and Hurle 2001; Pline et al. 1999b; Ridley and McNally 1985; Sellers et al. 2004; Steckel et al. 1997a, 1997b).

Although low levels of glufosinate metabolism have been observed in several species, metabolism has not been regarded as a factor in differential tolerance of weed species to glufosinate (Dröge et al. 1992; Dröge-Laser et al. 1994; Haas and Muller 1987; Jansen et al. 2000; Komo a and Sandermann 1992; Mersey et al. 1990; Neto et al. 2000; Pline et al. 1999b). In transgenic glufosinate-resistant corn and oilseed rape, rapid metabolism of glufosinate to various metabolites was observed (Ruhland et al. 2004). Resistance to glufosinate is conferred by *N*-acetylation of glufosinate by the enzyme phosphinothricin *N*-acetyltransferase, ultimately inactivating glufosinate (Dröge et al. 1992).

Due to the observed variability in control with glufosinate in southern row crops, the objectives of this study were to determine the basis of observed goosegrass, large crabgrass, and Palmer amaranth tolerance to glufosinate through comparisons to glufosinate-resistant cotton and corn and the highly susceptible weed species pitted morningglory and sicklepod.

Materials and Methods

Plant material. Pioneer ‘34A55 LL’ corn, Fibermax ‘958’ and ‘958 LL', goosegrass, large crabgrass, Palmer amaranth, pitted morningglory, and sicklepod, collected near Clayton, NC, were planted in 10-cm pots containing a commercial potting medium[1] and thinned to one plant pot^{-1} upon emergence. Plants were watered daily. Plants were grown in a plastic greenhouse maintained at 25 ± 2 C constant temperature where natural sunlight was supplemented 4 h daily with metal halide lighting with an average midday photosynthetic photon flux of 700 μmol m^{-2} s^{-1}, providing a 16-h day length. Studies were conducted from January to March 2006.

Absorption and Translocation. For all studies, corn and cotton plants were treated at the 4-lf stage, goosegrass was treated at 5 cm, large crabgrass and Palmer amaranth were treated at 7.5 cm, and pitted morningglory and sicklepod were treated at 10 cm. Glufosinate[2] at 470 g ai/ha was applied POST at each growth stage near mid-day to avoid time of day effects (Sellers et al 2003, 2004). Immediately after spraying, five or 10 1 μl drops containing a total of 5 kBq of ^{14}C-glufosinate[3] were applied to the adaxial surface of the first fully expanded leaf of each weed and crop species, respectively. The radiolabeled spotting solution contained the ^{14}C-glufosinate, formulation blank, and water to simulate a spray solution at 15 GPA.

Plants were harvested at 1, 6, 24, 48, and 72 HAT. Absorption was determined by rinsing the treated leaf portion with 10 ml of distilled water containing 0.05% (v/v) oxysorbic (20 POE) (polyoxyethelene sorbitan monolaurate)[4] (Devine et al. 1984; Mersey et al. 1990). A 1.0-ml aliquot was taken from the leaf rinsate, diluted in 25 ml scintillation fluid[5] and radioactivity was quantified with liquid scintillation spectrometry (LSS)[6]. All plants were divided into four regions: 1) treated leaf, 2) above treated leaf, 3) below treated leaf, and 4) roots. The treated leaf was removed at the point of attachment to the stem. This point of attachment determined the division for above and below the treated leaf sections. Plant parts were dried for 48 h at 40 C, weighed, and combusted with a biological sample oxidizer[7]. Radioactivity in the oxidized samples was quantified by LSS.

Absorption and translocation studies were arranged as a two level factorial with 8 species and 5 harvest timings. The study was arranged in a randomized completed block with three replications of treatments and repeated in time. Data were subjected to analysis of variance (ANOVA) with sums of squares partitioned (SAS 1998). Treatments were separated by Fisher's Protected LSD test at P = 0.05.

Glufosinate Metabolism. Plants were grown and treated as in the translocation study, however at plant harvest, partitioned plant parts were immediately stored at -20 C until further analysis. Only the treated leaf area and other leaves were used for the analysis of metabolites. Glufosinate metabolism was determined using a method adapted from Mersey et al. (1990) and Pline et al. (1999b). Plant tissues of each species were pulverized in liquid nitrogen. The ground tissue was transferred to 10-ml test tubes containing 3 ml g^{-1} fresh wt. of 4:1 Water:Methanol (v/v) to extract 14C-glufosinate and labeled metabolites. Tubes were vortexed and then centrifuged at 15,000 rpm for 5 min., after which the supernatant was transferred to another 10-ml test tube, and the process was repeated. The tissue pellet remaining after centrifugation was oxidized and radioactivity in the oxidized samples was quantified by LSS. The aqueous extracts were extracted twice with ethyl acetate (1:1, v/v) and extractions were followed by centrifugation at 15,000 rpm for 5 min. The ethyl acetate portion was transferred to a 10-ml test tube, and the process was repeated. The water and ethyl acetate extracts were then separately dried by evaporation, resuspended with 0.25 ml 80% methanol and transferred into 1.5-ml microfuge tubes.

^{14}C-Glufosinate and metabolites were separated by thin-layer chromatography (TLC), utilizing a silica-gel solid phase TLC plates[8]. Aliquots of the labeled extracts and standard

^{14}C-glufosinate were applied on separate 0.75-cm-wide lanes on TLC plates. The TLC plates were then developed in a solvent system containing isopropyl alcohol, glacial acetic acid, water (2:1:1, v/v/v). After development plates were air-dried, and radioactivity in each lane was quantified with a radiochromatogram scanner[9], which determined radioactive positions, quantities, and corresponding *Rf* values. Radioactive peaks were integrated using the Win-Scan software[10]. The parent herbicide was identified by comparing the *Rf* value from the corresponding standard. Data consisted of the percentage parent herbicide, the percentage of metabolites that were more polar than the parent herbicide, and the percentage of metabolites that were less polar than the parent herbicide. Statistical procedures were similar to the uptake and translocation study.

Results and Discussion

Glufosinate Absorption. According to ANOVA, ^{14}C–glufosinate absorption (based on leaf wash recovery and total ^{14}C recovered from plant parts) was not different between experimental runs: thus, data were pooled over runs. Glufosinate absorption within species was not different over time, except for goosegrass and pitted morningglory (Table 1). In general, the weed species studied could be divided into three groups based on glufosinate absorption: high (Palmer and Sicklepod), intermediate (crabgrass and goosegrass) and low (both conventional and resistant cotton, morningglory, and corn) (Table 1). Exceptions to this grouping occurred at 1 HAT, wherein there were only two groupings; 6 HAT when conventional cotton and morningglory absorbed an intermediate level; and at 72 HAT when crabgrass absorbed a high level. Palmer amaranth and sicklepod absorbed the highest amount of glufosinate, and this was evident at 1 HAT. Absorption was greater than 65% at all harvest timings for Palmer amaranth and sicklepod and absorption was < 22% for all other species 1 HAT, and <30% at all harvest timings for glufosinate-resistant corn and cotton, non-transgenic cotton, and pitted morningglory (Table 1). Crabgrass and goosegrass absorbed an intermediate level of glufosinate 6 HAT, and this ranking remained through 72 HAT, with the exception noted above.

Coetzer et al. (2001) observed 59 and 83% absorption of ^{14}C-glufosinate in amaranth species at 6 and 24 HAT, respectively. However, Pline et al. (1999b) reported less than 50% absorption of ^{14}C-glufosinate in sicklepod at all harvest intervals. Differences in absorption may be due to factors such as glufosinate rate or formulation. A formulation blank and a field rate of glufosinate was used in this study, while a non-ionic surfactant and a reduced rate was used by Pline et al. (1999b). Environment could also be a factor in differences observed between studies. Differential absorption was also observed between studies investigating absorption of common lambsquarters and giant foxtail (Maschoff et al. 2000; Pline et al. 1999b; Steckel et al. 1997a).

Tall morningglory absorbed less than 8% ^{14}C-glufosinate 96 HAT compared to up to 27% absorption 72 HAT in pitted morningglory in this study (Neto et al. 2000). Absorption of ^{14}C-glufosinate in goosegrass and large crabgrass ranged from 39% at 24 HAT up to 76% 72 HAT, greater than all low absorbing species (Table 1). Elevated levels of ^{14}C-glufosinate absorption in difficult to control grass species has been observed for barley and rigid ryegrass, as well as susceptible grass species such as green foxtail and sterile oat (Mersey et al. 1990 and Kumaratilake et al. 2002). Absorption of ^{14}C-glufosinate in glufosinate-resistant crops ranged from 48% in soybean at 48 HAT to 83% in *Brassica napus* (Pline et al. 1999a and Beriault et al. 1999).

Glufosinate Translocation. In general, glufosinate did not show evidence of translocation and only in two species was movement out of the treated leaf significant. From 1 through 72 HAT, greater than 90% of ^{14}C-glufosinate remained in the treated leaf of goosegrass, large crabgrass, pitted morningglory, and sicklepod; and greater than 85% in non-transgenic and glufosinate-resistant cotton (Table 2). The greatest levels of translocation were observed in Palmer amaranth and glufosinate-resistant corn. Translocation of ^{14}C-glufosinate above the treated leaf ranged from 23 to 49% over the study period, and translocation below treated leaf portions ranged from 6 to 16 % (Table 2). Translocation in corn was evidenced by ^{14}C accumulation above the treated leaf and in the roots. From 24 to 72 HAT, accumulation above the treated leaf ranged from 25 to 41% and from 22 to 27% in the roots (Table 2).

Translocation observed in sicklepod in this study, 3% 72 HAT, is lower than translocation observed in previous studies conducted with sub-lethal rates (Pline et al. 1999b). Approximately 9% of absorbed ^{14}C-glufosinate was translocated out of the treated leaf in pitted morningglory, which is similar to the 5% previously reported in tall morningglory (Neto et al. 2000). Minimal translocation was observed in difficult to control grass species barley, barnyardgrass, and rigid ryegrass when compared to sensitive species (Kumaratilake et al. 2002; Mersey et al. 1990; Steckel et al. 1997a). The pattern of reduced translocation in tolerant grass species is also observed in goosegrass and large crabgrass in this study (Table 2).

Coetzer et al. (2001) observed greater translocation of ^{14}C-glufosinate in amaranth species treated at 90% relative humidity when compared to those grown at 35% relative humidity. Higher translocation was also observed in Palmer amaranth at 26/31 and 21/26 C night/day temperatures compared to 16/21 C temperatures (Coetzer et al. 2001). The results obtained in this study were similar to those observed at 90% relative humidity and higher temperature regimes (Coetzer et al. 2001), which are close to the conditions maintained in the plastic greenhouse where our plants were grown and treated.

A higher proportion of labeled glufosinate translocated to the above treated leaf and root of glufosinate-resistant corn than any other species, reaching 33 and 23% at 72 HAT, however, translocation in glufosinate-resistant and non-transgenic cotton reached 10 and 15%, respectively, at 72 HAT (Table 2). Translocation of ^{14}C-glufosinate in glufosinate-resistant soybean was 29% at 25 C, and slightly less, 22% at 15 C (Pline et al. 1999a). The portion of the soybean plant accumulating the greatest amount of glufosinate were the shoots below the treated leaf, which is similar to results observed in glufosinate-resistant cotton but not glufosinate-resistant corn. No significant differences in translocation were observed between glufosinate-resistant and non-transgenic cotton in this study, however Beriault et al. (1999) observed significantly more translocation via phloem mobility in transgenic canola compared to a non-transgenic variety.

Glufosinate Metabolism. Significant levels of metabolic alteration of glufosinate were found in six of the eight species studied, with evidence of two separate metabolites in 5 species. The principle metabolite found utilizing this extraction and separation system was more **(?)** polar than glufosinate, and accounted for up to 72% of the radioactivity (Table 3).

The lower levels of the second metabolite, found in fewer species, was less polar than glufosinate, and accounted for up to 12 %. Higher levels of metabolism were observed in goosegrass, large crabgrass, Palmer amaranth, and sicklepod than previously reported for any weed species (Table 3) (Haas and Muller 1987; Mersey et al. 1990; Neto et al. 2000; Pline et al. 1999b; Steckel et al. 1997a). Two distinct metabolites were observed in goosegrass, large crabgrass, and sicklepod. Metabolism increased rapidly in goosegrass, Palmer amaranth, and sicklepod, leveling at approximately 30%, however metabolism increased to 70% 72 HAT in large crabgrass (Table 3). Metabolism of ^{14}C-glufosinate in pitted morningglory was less than 10% at all harvest timings (Table 3), which is similar to metabolism in tall morningglory observed by Neto et al. (2000).

Glufosinate-resistant cotton showed the highest level of ^{14}C-glufosinate metabolism with 72% metabolism 72 HAT, while non-transgenic cotton metabolism was less than 16% 72 HAT (Table 3). Similarly, transgenic canola metabolized ^{14}C-glufosinate readily into acetyl-^{14}C-glufosinate (Beriault et al. 1999), however no metabolism was observed in non-transgenic canola. Glufosinate-resistant corn metabolism of ^{14}C-glufosinate increased to 42% 72 HAT, which is similar to previous observations of rapid accumulation of acetyl-^{14}C-glufosinate in glufosinate-resistant corn and oilseed rape, 85 and 77% respectively (Ruhland et al. 2004).

Results from this study and previous research indicate tolerance to glufosinate, and mechanism of tolerance, is highly species dependent. Palmer amaranth was unique, because high levels of absorption (Table 1), translocation (Table 2) and metabolism (Table 3) were evident. Sicklepod absorbed high levels of glufosinate, and there were high levels of metabolism, but there was little movement out of the treated leaf. Crabgrass and goosegrass were similar with intermediate levels of absorption, little translocation, and significant metabolism. Transgenic, glufosinate-resistant corn absorbed relatively little of the applied glufosinate, but what entered the plant was relatively mobile, and there was significant metabolism. Transgenic, glufosinate-resistant cotton absorbed and translocated very little glufosinate, but glufosinate metabolism was very high. Non-transgenic cotton and pitted morningglory were similar, showing little absorption, translocation, and metabolism.

Palmer amaranth, a relatively tolerant species, had greater absorption and translocation, each approximately 3-fold greater than the highly susceptible pitted morningglory (Tables 1 and 2). However, in this study, less than 10% of ^{14}C-glufosinate was metabolized in pitted morningglory while up to 30% was metabolized in Palmer amaranth. Pline et al. (1999b) hypothesized that high absorption and translocation of foliar-applied glufosinate by horsenettle could explain low phytotoxicity observed in greenhouse studies. A similar situation may occur in Palmer amaranth, which also has high absorption and translocation that mah may be occurring in concert with metabolism to provide an enhanced level of tolerance. Sicklepod, a highly susceptible species, absorbed greater than 90% of ^{14}C-glufosinate, translocated less than 4% 72 HAT, but had greater than 50% metabolism within 1 hr of application. The rapid absorption, combined with the lack of translocation likely overwhelms the metabolic processes in the plant, leading to high levels of glufosinate phytotoxicity in sicklepod.

For tolerant grass species such as goosegrass and large crabgrass, the lack of translocation, as was the case in barley, barnyardgrass, and rigid ryegrass (Kumaratilake et al. 2002;

Mersey et al. 1990; Steckel et al. 1997), coupled with elevated metabolism may contribute to tolerance. Very little absorption, translocation, and metabolism was observed in either non-transgenic cotton or pitted morningglory, however both are highly susceptible species, indicating a lack of translocation is a factor in control of these species. No differences were observed in absorption or translocation between glufosinate-resistant and non-transgenic cotton, however translocation patterns in glufosinate-resistant and –susceptible canola differed (Beriault et al. 1999). The absorption, translocation, and metabolism of ^{14}C-glufosinate in glufosinate-resistant corn were similar to results observed previously for including glufosinate-resistant corn (Ruhland et al. 2004). The results of this study indicate metabolism may play a greater role in tolerance of certain weed species to glufosinate than previously considered.

Sources of Materials

[1] MetroMix 200, Sun Gro Horticulture, 15831 N.E. 8th Street, Suite 100, Bellevue, WA 98008.

[2] Ignite® herbicide, Bayer CropScience, P.O. Box 12014, 2 T.W. Alexander Drive, Research Triangle Park, NC 27709.

[3] ^{14}C-glufosinate, Bayer CropScience, P.O. Box 12014, 2 T.W. Alexander Drive, Research Triangle Park, NC 27709.

[4] Tween® 20. Sigma Chemical Co., P.O. Box 14508, St. Louis, MO 63178.

[5] Ultima Flo Gold, Packard Bioscience, 800 Research Parkway, Meriden, CT

[6] Packard TRI-CARB 2100TR Liquid Scintillation Spectrometer,

Packard Instrument Company, 2200 Warrenville Road, Downers Grove, IL 60515.

[7] Model OX-500 Biological Material Oxidizer, R. J. Harvey Instrument Corp., 123 Patterson Street, Hillsdale, NJ 07642.

[8] Whatman Thin Layer Chromatography plates, Maidstone, England.

[9] BioScan System 200 Imaging Scanner, Bioscan, 4590 Mac-Arthur Boulevard NW, Washington, DC 20007..

[10] LabLogic® Win-Scan Radio TLC Version 2.2(5) 32-bit, BioScan, 4590 MacArthur Boulevard NW, Washington, DC 20007.

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Table 1. Absorption of ^{14}C-glufosinate expressed as percent of total ^{14}C-glufosinate applied.

Species [a]	Timing [b]				
	1	6	24	48	72
	%				
Glufosinate-resistant corn	7 b	5 e	16 c	13 d	10 e
Glufosinate-resistant cotton	7 b	6 de	11 c	11 d	11 e
Goosegrass	21 b	46 b	39 b	43 c	50 c
Large crabgrass	18 b	18 c	49 b	52 c	76 b
Non-transgenic cotton	5 b	9 cde	10 c	13 d	7 e
Palmer amaranth	66 a	73 a	87 a	72 a	71 b
Pitted morningglory	6 b	18 c	21 c	13 d	27 d
Sicklepod	80 a	84 a	96 a	95 b	94 a

[a] Species: glufosinate-resistant corn, *Zea mays*; glufosinate-resistant cotton, *Gossypium hirsutum*; goosegrass, *Eleusine indica* L. Gaertn.; large crabgrass, *Digitaria sanguinalis* (L.) Scop.; non-transgenic cotton, *Gossypium hirsutum*; Palmer amaranth, *Amaranthus palmeri* S. Wats.; pitted morningglory, *Ipomoea lacunosa* L.; sicklepod, *Senna obtusifolia* (L.) H.S. Irwin & Barneby.

Table 1. (continued).

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

Table 2. Translocation of ^{14}C-glufosinate expressed as percent of total ^{14}C-glufosinate absorbed.

Species [a]	Part [b]	Timing [c]									
		1		6		24		48		72	
		%									
Glufosinate-resistant corn	TL	87	b	68	cd	49	de	32	ef	42	e
	ATL	4	gh	13	gh	25	fg	41	ef	33	ef
	BTL	2	h	5	gh	4	h	1	h	2	h
	R	7	gh	14	gh	22	fg	27	f	23	fg
Glufosinate-resistant cotton	TL	98	a	96	ab	93	ab	85	b	90	ab
	ATL	1	h	2	h	3	h	42	gh	5	gh
	BTL	1	h	3	h	4	gh	11	gh	5	gh
	R	1	h	1	h	2	h	4	gh	4	h

Table 2. (continued).

Species [a]	Part [b]	Timing [c]				
		1	6	24	48	72
		—% —				
Goosegrass	TL	97 ab	89 ab	90 ab	87 ab	93 ab
	ATL	1 h	4 gh	4 h	5 gh	3 h
	BTL	2 h	5 gh	3 h	4 h	1 h
	R	1 h	2 h	3 h	4 h	2 h
Large crabgrass	TL	97 ab	90 ab	95 ab	92 ab	92 ab
	ATL	2 h	5 gh	2 h	3 h	2 h
	BTL	2 h	5 gh	2 h	3 h	5 gh
	R	0.4 h	0.8 h	1 h	2 h	1 h

Table 2. Translocation of ^{14}C-glufosinate expressed as percent of total ^{14}C-glufosinate absorbed.

Species [a]	Part [b]	Timing [c]									
		1		6		24		48		72	
		%									
Non-transgenic cotton	TL	98	a	95	ab	95	ab	89	ab	85	b
	ATL	2	h	4	gh	3	h	4	h	10	gh
	BTL	0.5	h	1	h	2	h	7	gh	3	h
	R	0	h	1	h	0.7	h	2	h	4	gh
Palmer amaranth	TL	49	de	64	cd	40	ef	58	d	69	cd
	ATL	37	ef	30	f	49	de	28	f	23	fg
	BTL	15	gh	5	gh	12	gh	13	gh	8	gh
	R	0.4	h	0.5	h	0.5	h	0.7	h	0.1	h

Table 2. (continued).

Species [a]	Part [b]	Timing [c]									
		1		6		24		48		72	
		%									
Pitted morningglory	TL	97	ab	90	ab	86	b	92	ab	93	ab
	ATL	1	h	5	gh	4	gh	2	h	3	h
	BTL	2	h	5	gh	10	gh	6	gh	5	gh
	R	1	h	0.6	h	1	h	1	h	1	h
Sicklepod	TL	92	ab	97	ab	98	a	97	ab	97	ab
	ATL	3	h	1	h	1	h	2	h	2	h
	BTL	5	gh	1	h	1	h	1	h	1	h
	R	1	h	1	h	1	h	1	h	1	h

[a] Species: glufosinate-resistant corn, *Zea mays*; glufosinate-resistant cotton, *Gossypium hirsutum*; goosegrass, *Eleusine indica* L. Gaertn.; large crabgrass, *Digitaria sanguinalis* (L.) Scop.; non-transgenic cotton, *Gossypium hirsutum*; Palmer amaranth, *Amaranthus palmeri* S.

Table 2. (continued).

Wats.; pitted morningglory, *Ipomoea lacunosa* L.; sicklepod, *Senna obtusifolia* (L.) H.S. Irwin & Barneby.

[b] Abbreviations: ATL, above treated leaf; BTL, below treated leaf; R, roots; TL, treated leaf.

[c] Means followed by the same letter are not different according to Fisher's Protected LSD at $P = 0.05$.

Table 3. Metabolism of ^{14}C-glufosinate expressed as percent of total ^{14}C detected.

Species [a]	Timing	Glufosinate [b]		Metabolite 1		Metabolite 2	
		———		%		———	
Glufosinate-resistant corn	1	83	ab	0	f	0.0	d
	6	66	bc	23	de	0.0	d
	24	79	ab	15	e	0.0	d
	48	61	bc	33	cd	0.0	d
	72	52	cd	42	c	0.0	d
Glufosinate-resistant cotton	1	34	de	38	cd	7.8	bc
	6	27	e	49	bc	7.6	bc
	24	35	de	56	b	2.6	cd
	48	32	de	59	b	1.0	d
	72	15	f	72	a	1.8	d
Goosegrass	1	31	de	35	cd	6.9	bc
	6	33	de	36	cd	7.0	bc

Table 3. (continued).

Species [a]	Timing	Glufosinate [b]		Metabolite 1		Metabolite 2	
		——————————		%		——————————	
	24	40	d	35	cd	8.2	bc
	48	40	d	32	cd	8.0	bc
	72	44	cd	36	cd	8.2	bc
Large crabgrass	1	53	cd	0	f	0.0	d
	6	39	de	31	cd	7.5	bc
	24	32	de	41	c	5.6	c
	48	43	cd	38	cd	2.2	d
	72	5	f	70	ab	1.2	d
Non-transgenic cotton	1	66	bc	4	ef	5.3	c
	6	68	b	13	ef	2.0	d
	24	78	ab	7	ef	2.0	d
	48	84	ab	0	f	0.0	d
	72	73	ab	16	de	0.0	d

Table 3. (continued).

Species [a]	Timing	Glufosinate [b]		Metabolite 1		Metabolite 2	
		%					
Pitted morningglory	1	41	d	2	f	0.0	d
	6	60	bc	4	ef	0.0	d
	24	69	b	0	f	0.0	d
	48	75	ab	1	f	0.0	d
	72	75	ab	10	ef	0.0	d
Palmer amaranth	1	71	b	3	ef	0.0	d
	6	54	c	22	de	0.0	d
	24	60	bc	23	de	0.0	d
	48	48	cd	31	cd	0.0	d
	72	63	bc	20	de	1.1	d

Table 3. (continued).

Species[a]	Timing	Glufosinate[b]		Metabolite 1		Metabolite 2	
		——— % ———					
Sicklepod	1	41	d	25	de	7.4	bc
	6	40	d	31	cd	12.6	a
	24	48	cd	34	cd	8.9	b
	48	51	cd	28	d	6.0	bc
	72	47	cd	34	cd	8.0	bc

[a] Species: glufosinate-resistant corn, *Zea mays*; glufosinate-resistant cotton, *Gossypium hirsutum*; goosegrass, *Eleusine indica* L. Gaertn.; large crabgrass, *Digitaria sanguinalis* (L.) Scop.; non-transgenic cotton, *Gossypium hirsutum*; Palmer amaranth, *Amaranthus palmeri* S. Wats.; pitted morningglory, *Ipomoea lacunosa* L.; sicklepod, *Senna obtusifolia* (L.) H.S. Irwin & Barneby.

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