The *Journal of Cotton Science 10:319–327 (2006)*
http://journal.cotton.org, © The Cotton Foundation 2006

WEED SCIENCE

Glufosinate Antagonizes Postemergence Graminicides Applied to Annual Grasses and Johnsongrass

Andrew P. Gardner, Alan C. York*, David L. Jordan, and David W. Monks

ABSTRACT

Glufosinate controls a broad spectrum of weeds in glufosinate-resistant cotton (*Gossypium hirsutum* L.). Control of grassy weeds, however, can sometimes be inadequate, especially when grasses are large or growing under dry conditions. In situations where less than adequate control of grasses by glufosinate alone is anticipated, growers may consider mixing a postemergence graminicide with glufosinate. Most herbicides mixed with graminicides antagonize grass control. Research was conducted in North Carolina to determine the potential for antagonism with mixtures of glufosinate and four postemergence graminicides and to determine if antagonism could be alleviated by increasing the rate of graminicide in mixtures, by adding ammonium sulfate to mixtures, or by applying glufosinate and graminicides sequentially. Antagonism was noted on johnsongrass [*Sorghum halepense* (L.) Pers.] and on mixtures of annual grasses, broadleaf signalgrass [*Brachiaria platyphylla* (Griseb.) Nash], fall panicum (*Panicum dichotomiflorum* Michx.), goosegrass [*Eleusine indica* (L.) Gaertn.], and large crabgrass [*Digitaria sanguinalis* (L.) Scop.], when glufosinate was mixed with clethodim, fluazifop-P, quizalofop-P, or sethoxydim. Antagonism was not alleviated by increasing the graminicide rate in the mixture by 50% or by including ammonium sulfate in the mixture. Antagonism was not observed when graminicides were applied 3 or more days before glufosinate or 5 or more days after glufosinate.

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

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

Glufosinate controls a broad spectrum of weeds (Beyers et al., 2002; Corbett et al., 2004; Culpepper and York, 1999; Culpepper et al., 2000; Norris et al., 2002; Steckel et al., 1997; York and Culpepper, 2004). Control of grassy weeds, however, can sometimes be inadequate, especially when the grasses are large or growing under dry conditions (Corbett et al., 2004; Culpepper and York, 1999; Culpepper et al., 2000; Steckel et al., 1997). Applying herbicide mixtures is a common way to increase the spectrum of weed control. In situations where less than adequate control of grasses by glufosinate alone is anticipated, growers may consider mixing a postemergence graminicide with glufosinate, but antagonism on grasses is commonly observed when herbicides typically applied to control broadleaf weeds are mixed with the postemergence graminicides (Burke et al., 2005; Crooks et al., 2003; Culpepper et al., 1999; Holshouser and Coble, 1990; Jordan

A. P. Gardner, A. C. York, D. L. Jordan, and D. W. Monks, Department of Crop Science, North Carolina State University, Box 7620, Raleigh, NC 27695-7620
*Corresponding author: alan_york@ncsu.edu

et al., 1993; Mueller et al. 1989; Myers and Coble, 1992; Young et al., 1996). This antagonism may be due to a direct effect of the broadleaf herbicide on graminicide absorption or indirectly due to an effect of the broadleaf herbicide on plant metabolism and growth (Burke and Wilcut, 2003; Culpepper et al., 1999; Jordan et al., 1989).

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

MATERIALS AND METHODS

Methods common to all experiments. Each of three experiments was conducted in fallow fields selected for heavy infestations of annual grasses or johnsongrass. Sites included the Central Crops Research Station at Clayton, NC, the Upper Coastal Plain Research Station at Rocky Mount, NC, and the Umstead Farm Unit at Butner, NC. Sites were tilled by disking followed by a field cultivator. Ammonium nitrate fertilizer was broadcast at the rate of 110 kg ha^{-1} N. Soils at each site are described in Table 1. Weed species and densities are listed in Table 2. The experiments were conducted twice within the same field and year at some sites. In these situations, the experiments were separated in time by 2 or more weeks.

The experimental design was a randomized complete block with treatments replicated three or four times, depending upon location. Plot size was 3 by 4.6 m. Herbicides were applied with a CO_2-pressurized backpack sprayer equipped with flat-fan nozzles (TeeJet XR11002 nozzles; Spraying Systems Co.; Wheaton, IL) calibrated to deliver 140 L ha^{-1} at 160 kPa. Annual grasses were 10 to 20 cm tall and tillering, and johnsongrass was 5 to 15 cm tall at time of herbicide application. Applications were intentionally delayed until grasses were larger than recommended for treatment with glufosinate (Anonymous, 2006c) to simulate situations where a grower would anticipate less than adequate control by glufosinate

Table 1. Description of soils at experiment sites

Location	Field No.	Year	Experiment [y]	Soil series [z]	Soil texture	Soil pH	Soil humic matter (%)
Clayton	1	2004	1,2,2,3,3	Dothan	Loamy sand	5.8	0.76
Clayton	2	2004	1,2,3	Norfolk	Loamy sand	5.7	0.76
Clayton	3	2004	1	Gilead	Sandy loam	5.6	1.02
Clayton	4	2004	2	Gilead	Sandy loam	6.1	0.60
Rocky Mount	5	2004	1,1,2,3	Goldsboro	Fine sandy loam	5.9	0.36
Clayton	6	2005	1	Appling	Sandy loam	5.9	0.32
Clayton	7	2005	2	Dothan	Loamy sand	5.9	0.73
Rocky Mount	8	2005	1	Norfolk	Loamy sand	6.4	0.41
Rocky Mount	9	2005	2	Goldsboro	Fine sandy loam	5.9	1.25
Butner	10	2005	1,1,3,3	Vance	Loam	5.7	0.36

[y] Repeated numbers indicate the experiment conducted twice in same field, separated in time by at least 2 wk.

[z] Dothan is a fine-loamy, kaolinitic, thermic Plinthic Kandiudults. Norfolk is a fine-loamy, kaolinitic, thermic Typic Kandiudults. Gilead is a fine, kaolinitic, thermic Aquic Hapludults. Goldsboro is a fine-loamy, siliceous, subactive, thermic Aquic Paleudults. Appling is a fine, kaolinitic, thermic Kanhapludults. Vance is a fine, mixed semiactive, thermic Typic Hapludults.

alone and consider use of a graminicide along with glufosinate. Control of annual grasses and johnsongrass in Experiments 1 and 2 was estimated visually 14 and 28 d after treatment (DAT) using a scale of 0 = no control to 100 = complete control (Frans et al., 1986). Control in Experiment 3 was estimated 14 and 28 d after the 0-day application (DATZ). No attempt was made to evaluate control by species at sites with multiple species of annual grasses.

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

Experiment 2. Interaction of glufosinate with clethodim and fluazifop-P as affected by ammonium sulfate. The experiment was conducted seven times on annual grasses during 2004 and 2005 (Tables 1 and 2). Treatments included glufosinate

Table 2. Weed species and densities at experiment sites

Location	Field No.	Year	Experiment[y]	Species[z]	Weed density (plants m^{-2})
Clayton	1	2004	1,2,2,3,3	Large crabgrass	320 to 380
Clayton	2	2004	1,2,3	Large crabgrass (60)	360 to 390
				Goosegrass (30)	
				Fall panicum (10)	
Clayton	3	2004	1	Broadleaf signalgrass (20)	300 to 355
				Large crabgrass (20)	
				Goosegrass (60)	
Clayton	4	2004	2	Large crabgrass (55)	360 to 400
				Goosegrass (45)	
Rocky Mount	5	2004	1,1,2,3	Broadleaf signalgrass (10)	320 to 420
				Large crabgrass (50)	
				Goosegrass (40)	
Clayton	6	2005	1	Large crabgrass (70)	450 to 490
				Goosegrass (30)	
Clayton	7	2005	2	Large crabgrass	270 to 320
Rocky Mount	8	2005	1	Large crabgrass	200 to 270
Rocky Mount	9	2005	2	Broadleaf signalgrass (25)	370 to 400
				Large crabgrass (45)	
				Goosegrass (30)	
Butner	10	2005	1,1,3,3	Johnsongrass	270 to 380

[y]Repeated numbers indicate the experiment conducted twice in same field, separated in time by at least 2 wk.

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

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

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

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

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

RESULTS AND DISCUSSION

Experiment 1. Glufosinate tank mixtures with four graminicides. Annual grass control was similar with glufosinate and glufosinate plus crop oil concentrate in the absence of graminicides. Averaged over locations, glufosinate and glufosinate plus crop oil concentrate controlled annual grasses 85 and 82%, respectively, 14 DAT and 68 and 64%, respectively, 28 DAT (data not shown). Previous research has shown little effect of adjuvants on the efficacy of glufosinate (Baughman et al., 2004). Less control 28 DAT compared with 14 DAT was because of regrowth on plants not initially killed by glufosinate (Burke et al., 2005; Culpepper and York, 1999). Inadequate control of annual grasses by glufosinate has been reported previously (Burke et al., 2005; Corbett et al., 2004; Norris et al., 2002). Similarly, crop oil concentrate did not affect johnsongrass control by glufosinate in the absence of graminicides. Averaged over locations, glufosinate and glufosinate plus crop oil concentrate controlled johnsongrass 27 and 32%, respectively, 14 DAT (data not shown). No control of johnsongrass by glufosinate or glufosinate plus crop oil concentrate was noted 28 DAT. Glufosinate applied once typically does not control johnsongrass (Kelly et al., 2005).

Analysis of variance for data from the factorial arrangement of four graminicides by two graminicide rates by two glufosinate rates showed no location by treatment interactions. Averaged over locations, the main effect of graminicide rates and the interaction of graminicides by glufosinate rates were significant for both annual grasses and johnsongrass at 14 and 28 DAT. Graminicides applied at 1.5 times the manufacturers' suggested use rates were more effective on annual grasses and johnsongrass at 14 and 28 DAT

than graminicides at the suggested use rates. Averaged over graminicides and glufosinate rates, annual grasses were controlled 90 and 85% at 14 and 28 DAT, respectively, by graminicides at the 1.5X rate compared with 87 and 80% control, respectively, by graminicides at the 1.0X rate (data not shown). Johnsongrass was controlled 98 and 92% at 14 and 28 DAT, respectively, by graminicides at the 1.5X rate compared with 94 and 84% by graminicides at the 1.0X rate (data not shown).

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

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

Antagonism on grasses by various herbicides mixed with graminicides can often be alleviated by increasing the rate of graminicide (Campbell and Penner, 1982; Culpepper et al., 1998; 1999; Muel-

Table 3. Control of annual grasses and johnsongrass by graminicides applied alone and mixed with glufosinate 14 and 28 days after treatment (DAT) in Experiment 1

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

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

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

ler et al., 1989; Palmer et al., 1999). In this experiment, lack of graminicide rate by glufosinate rate or graminicide by graminicide rate by glufosinate rate interactions indicate the antagonism was independent of graminicide rate and that increasing the graminicide rate by 50% did not alleviate the antagonism.

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

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

Annual grass control by fluazifop-P plus glufosinate (90%) and clethodim plus glufosinate (91%) was greater 14 DAT than control by fluazifop-P alone (72%) and clethodim alone (84%) (Table 4). Greater control by the graminicides plus glufosinate compared with graminicides alone at 14 DAT reflects relatively slow expression of symptoms by graminicides, and the more rapid activity of glufosinate. Glufosinate applied alone controlled annual grasses 90% 14 DAT (data not shown). Similar to results in Experiment 1, control by glufosinate alone decreased with time. Because of regrowth, glufosinate applied alone controlled annual grasses only 68% 28 DAT. Annual grass control 28 DAT was similar to results observed in Experiment 1. Control by clethodim exceeded control by fluazifop-P (90 vs. 61%), and glufosinate had a greater negative impact on control when mixed with clethodim as compared with fluazifop-P (Table 4). Control by clethodim was reduced 23% by glufosinate, but control was not reduced when glufosinate was mixed with fluazifop-P. Control by clethodim plus glufosinate was very similar to control by fluazifop-P plus glufosinate. Moreover, both herbicide combinations were antagonistic according to the Colby procedure.

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

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

Glufosinate applied alone controlled annual grasses 85 and 68% and johnsongrass 28 and 0% at 14 and 28 DATZ, respectively (data not shown). Averaged over glufosinate rates and graminicide application timings, clethodim was more efficacious on

Table 4. Control of annual grasses by clethodim and fluazifop-P alone and mixed with glufosinate 14 and 28 days after treatment (DAT) in Experiment 2

Graminicides	Glufosinate	Control (%)[y]		
		14 DAT	28 DAT	
			Observed	Expected[z]
Clethodim	0	84 b	90 a	
Clethodim	468	91 a	67 b	95*
Fluazifop-P	0	72 c	61 b	
Fluazifop-P	468	90 a	68 b	85*

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

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

annual grasses than fluazifop-P. Clethodim controlled annual grasses 78 and 80% at 14 and 28 DATZ, respectively, compared with 72 and 71% control by fluazifop-P (data not shown). The two graminicides were similarly effective on johnsongrass. Clethodim controlled johnsongrass 84 and 82% at 14 and 28 DATZ, respectively, compared with 80 and 76% control by fluazifop-P (data not shown).

At 14 DATZ, glufosinate increased control of annual grasses and johnsongrass when graminicides were applied 5 or 7 d after glufosinate (data not shown). This occurred because the graminicides applied 5 or 7 d after glufosinate did not have sufficient time to kill the grasses at this early evaluation. At 28 DATZ, annual grass control was reduced 9, 17, 20, and 12% when graminicides were applied 1 d before, tank mixed with, or applied 1 and 3 d after glufosinate, respectively (Table 5). Johnsongrass control was reduced 29, 28, 39, and 17% when graminicides were applied 1 d before, tank mixed with, or applied 1 and 3 d after glufosinate, respectively. Neither annual grass control nor johnsongrass control was adversely affected when graminicides were applied 3 or 5 d before glufosinate or 5 or 7 d after glufosinate. Burke et al. (2005) reported no antagonism on goosegrass in the greenhouse when clethodim was applied 7 or 14 d before glufosinate; shorter intervals between applications of the two herbicides were not evaluated. In contrast to our results, Burke et al. (2005) reported poor control of goosegrass when clethodim was applied 7 or 14 d after glufosinate. Glufosinate inhibits glutamine synthase, leading to a rapid accumulation of toxic levels of ammonia in the cell which causes membrane disruption and inhibition of photosynthesis. Glufosinate typically causes tissue desiccation on grasses, but larger grasses survive and initiate new growth (Burke et al., 2005; Culpepper and York, 1999). Graminicides applied 3 or 5 d before glufosinate apparently had time to be absorbed and translocated to meristematic areas before leaf desiccation by glufosinate. By 5 d after glufosinate application, regrowth was occurring on the grasses. There was apparently enough new leaf tissue to absorb and translocate the graminicides for effective control.

Glufosinate applied to glufosinate-resistant cotton sometimes does not adequately control annual grasses or johnsongrass (Corbett et al., 2004; Culpepper and York, 1999; Culpepper et al., 2000; Steckel et al., 1997). In situations where less than adequate control of grasses by glufosinate alone might be anticipated, growers would likely consider mixing a postemergence graminicide with glufosinate. This research indicates that mixtures of graminicides and glufosinate are antagonistic on grasses and thus should be avoided. Antagonism with mixtures of graminicides and other herbicides can sometimes be alleviated by increasing the rate of graminicide in the mixture or adding ammonium sulfate. In this research, neither increasing graminicide rates by 50%

Table 5. Control of annual grasses and johnsongrass by graminicides and glufosinate applied sequentially in Experiment 3

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

[x]Control recorded 28 d after glufosinate application. An asterisk (*) signifies significantly less control ($P \leq 0.05$) with 468 g ha^{-1} glufosinate compared with no glufosinate.

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

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

nor adding ammonium sulfate alleviated antagonism on grasses. Antagonism could be avoided by applying glufosinate and graminicides sequentially. To avoid antagonism, our results indicate graminicides should be applied at least 3 d prior to glufosinate or at least 5 d after glufosinate.

ACKNOWLEDGMENTS

Partial funding was provided by the cotton growers of North Carolina through Cotton Incorporated's state support program.

LITERATURE CITED

Anonymous. 2006a. DuPont Assure II Herbicide. E. I. du Pont de Nemours and Co., Wilmington, DE. Available online at http://cdms.net/ldat/1d742002.pdf (verified 20 Feb. 2006).

Anonymous. 2006b. Fusilade DX Herbicide. Syngenta Crop Protection, Inc., Greensboro, NC. Available online at http://cdms.net/ldat/1d5UU001.pdf (verified 20 Feb. 2006).

Anonymous. 2006c. Ignite Herbicide. Bayer CropScience, Research Triangle Park, NC. Available online at http://cdms.net/ldat/1d6ER002.pdf (verified 20 Feb. 2006).

Anonymous. 2006d. Poast Plus Herbicide. Micro Flo Co. LLC, Memphis, TN. Available online at http://cdms.net/ldat/1d5KN000.pdf (verified 20 Feb. 2006).

Anonymous. 2006e. Select 2EC Herbicide. Valent Agricultural Products, Walnut Creek, CA. Available online at http://cdms.net/ldat/1d837045.pdf (verified 20 Feb. 2006).

Baughman, T. A., P. A. Dotray, K. M. McCormick, J. C. Reed, and J. W. Keeling. 2004. The effects of application timing and spray additives on glufosinate performance. p. 2894. *In* Proc. Beltwide Cotton Conf., San Antonio, TX. 5-9 Jan. 2004. Natl. Cotton Counc. Am., Memphis, TN.

Beyers, J. T., R. J. Smeda, and W. G. Johnson. 2002. Weed management programs in glufosinate-resistant soybean (*Glycine max*). Weed Technol. 16:267-273.

Blackshaw, R. E. 1989. HOE-39866 use in chemical fallow systems. Weed Technol. 3:420-428.

Blair-Kerth, L. K., P. A. Dotray, J. W. Kneeling, J. R. Gannaway, M. J. Oliver, and J. E. Quisenberry. 2001. Tolerance of transformed cotton to glufosinate. Weed Sci. 49:375-380.

Burke, I. C., S. D. Askew, J. L. Corbett, and J. W. Wilcut. 2005. Glufosinate antagonizes clethodim control of goosegrass *(Eleusine indica)*. Weed Technol. 19:664-668.

Burke, I. C., and J. W. Wilcut. 2003. Physiological basis for antagonism of clethodim by CGA 362622. Weed Sci. 51:671-677.

Burke, I. C., J. W. Wilcut, and D. Porterfield. 2002. CGA-362622 antagonizes annual grass control with clethodim. Weed Technol. 16:749-754.

Campbell, J. R., and D. Penner. 1982. Compatibility of diclofop and BAS 9052 with bentazon. Weed Sci. 30:458-462.

Colby, S. R. 1967. Calculating synergistic and antagonistic responses of herbicide combinations. Weeds 15:20-22.

Corbett, J. L., S. D. Askew, W. E. Thomas, and J. W. Wilcut. 2004. Weed efficacy evaluations for bromoxynil, glufosinate, glyphosate, pyrithiobac, and sulfosate. Weed Technol. 18:443-453.

Corkern, C. B., D. B. Reynolds, P. R. Vidrine, J. L. Griffin, and D. L. Jordan. 1998. Bromoxynil antagonizes johnsongrass (*Sorghum halepense*) control with graminicides. Weed Technol. 12:205-208.

Crooks, H. L., A.C. York, A. S. Culpepper, and C. Brownie. 2003. CGA-362622 antagonizes annual grass control by graminicides in cotton (*Gossypium hirsutum*). Weed Technol. 17:373-380.

Culpepper, A. S., and A. C. York. 1999. Weed management in glufosinate resistant corn (*Zea mays*). Weed Technol. 13:324-333.

Culpepper, A. S., A. C. York, and C. Brownie. 1999. Influence of bromoxynil on annual grass control by graminicides. Weed Sci. 47:123-128.

Culpepper, A. S., A. C. York, K. M. Jennings, and R. B. Batts. 1998. Interaction of bromoxynil and postemergence graminicides on large crabgrass (*Digitaria sanguinalis*). Weed Technol. 12:554-559.

Culpepper, A. S., A. C. York, K. M. Jennings, and R. B. Batts. 2000. Weed management in glufosinate- and glyphosate-resistant soybean (*Glycine max*). Weed Technol. 14:77-88.

Devine, M., S. O. Duke, and C. Fedtke. 1993. Inhibition of amino acid biosynthesis. p. 252-263. *In* Physiology of herbicide action. P T R Prentice Hall, Inc., Englewood Cliffs, NJ.

Frans, R. E., R. Talbert, D. Marx, and H. Crowley. 1986. Experimental design and techniques for measuring and analyzing plant responses to weed control practices. p. 29-46. *In* N. D. Camper (ed.) Research methods in weed science. South. Weed Sci. Soc., Champaign, IL.

Gerwick, B. C., L. D. Tanguay, and F. G. Burroughs. 1990. Differential effects of UAN on antagonism with bentazon. Weed Technol. 4:620-624.

Hinchee, M.A.W., S. R. Padgette, G. M. Kishore, X. Delannay, and R. T. Fraley. 1993. Herbicide-tolerant crops. p. 243-263. *In* S. Kung and R. Wu (ed.) Transgenic plants. Academic Press, Inc., San Diego, CA.

Holshouser, D. L., and H. D. Coble. 1990. Compatibility of sethoxydim with five postemergence broadleaf herbicides. Weed Technol. 4:128-133.

Jordan, D. L., R. E. Frans, and M. R. McClelland. 1993. Interactions of DPX-PE350 with fluazifop-P, sethoxydim, clethodim, and quizalofop-P. Weed Technol. 7:605-610.

Jordan, D. L., and A. C. York. 1989. Effects of ammonium fertilizers and BCH 81508 S on antagonism with sethoxydim plus bentazon mixtures. Weed Technol. 3:450-454.

Jordan, D. L., A.C. York, and F. T. Corbin. 1989. Effect of ammonium sulfate and bentazon on sethoxydim absorption. Weed Technol. 3:674-677.

Kelly, S. T., D. K. Miller, and A. M. Stewart. 2005. Ignite weed control systems in Liberty Link cotton. p. 2926-2927. *In* Proc. Beltwide Cotton Conf., New Orleans, LA. 4-7 Jan. 2005. Natl. Cotton Counc. Am., Memphis, TN.

Lanie, A. J., J. L. Griffin, P. R. Vidrine, and D. B. Reynolds. 1994. Weed control with non-selective herbicides in soybean (*Glycine max*) stale seedbed culture. Weed Technol. 8:159-164.

McIntosh, M. S. 1983. Analysis of combined experiments. Agron. J. 75:153-155.

Maschoff, J. R., S. E. Hart, and J. L. Baldwin. 2000. Effect of ammonium sulfate on the efficacy, absorption, and translocation of glufosinate. Weed Sci. 48:2-6.

Mueller, T. C., W. W. Witt, and M. Barrett. 1989. Antagonism of johnsongrass (*Sorghum halepense*) control with fenoxaprop, haloxyfop, and sethoxydim by 2, 4-D. Weed Technol. 3:86-89.

Myers, P. F., and H. D. Coble. 1992. Antagonism of graminicide activity on annual grass species by imazethapyr. Weed Technol. 6:333-338.

Norris, J. L., D. R. Shaw, and C. E. Snipes. 2002. Influence of row spacing and residual herbicides on weed control in glufosinate-resistant soybean (*Glycine max*). Weed Technol. 16:319-325.

Palmer, E. W., D. R. Shaw, and J. C. Holloway, Jr. 1999. Influence of CGA-277476 on efficacy of postemergence graminicides. Weed Technol. 13:48-53.

Pline, W. A., K. K. Hatzios, and E. S. Hagood. 2000. Weed and herbicide-resistant soybean (*Glycine max*) response to glufosinate and glyphosate plus ammonium sulfate and pelargonic acid. Weed Technol. 14:667-674.

Rhodes, G. N., Jr., and H. D. Coble. 1984. Influence of application variables on antagonism between sethoxydim and bentazon. Weed Sci. 32:436-441.

Singh, M. And D.P.H. Tucker. 1987. Glufosinate (Ignite): a new promising postemergence herbicide for citrus. p. 58-61. *In* Proc. Florida State Hort. Soc., 100th, Orlando, FL. 2-5 Feb. Florida State Hort. Soc., Lake Alfred, FL.

Steckel, G. J., L. M. Wax, F. W. Simmons, and W. H. Phillips II. 1997. Glufosinate efficacy on annual weeds is influenced by rate and growth stage. Weed Technol. 11:484-488.

Wilcut, J. W., H. D. Coble, A. C. York, and D. W. Monks. 1996. The niche for herbicide-resistant crops in U. S. agriculture. p. 213-230. *In* S. O. Duke (ed.) Herbicide-resistant crops: agricultural, environmental, economic, regulatory, and technical aspects. CRC Press, Inc., Boca Raton, FL.

Wilson, H. P., T. E. Hines, R. R. Bellinder, and J. A. Grande. 1985. Comparisons of HOE-39866, SC-0224, paraquat, and glyphosate in no-till corn (*Zea mays*). Weed Sci. 33:531-536.

York, A. C., and A. S. Culpepper. 2004. Weed management in Liberty Link and Roundup Ready Flex cotton. p. 2932. *In* Proc. Beltwide Cotton Conf., San Antonio, TX. 5-9 Jan. Natl. Cotton Counc. Am., Memphis, TN.

York, A. C., J. W. Wilcut, and W. J. Grichar. 1993. Interaction of 2,4-DB with postemergence graminicides. Peanut Sci. 20:57-61.

Young, B. G., S. E. Hart, and L. M. Wax. 1996. Interactions of sethoxydim and corn (*Zea mays*) postemergence broadleaf herbicides on three annual grasses. Weed Technol. 10:914-922.