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WEED SCIENCE

Control of Volunteer Glyphosate-resistant Soybean in Cotton

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ABSTRACT

Volunteer glyphosate-resistant (GR) soybean [*Glycine max* (L.) Merr.] can be a problem in GR cotton (*Gossypium hirsutum* L.) grown in rotation with soybean, especially when hurricanes destroy the preceding soybean crop and leave unharvested beans in the field. No-till cotton planting and lack of fluometuron applied preemergence in GR cotton have intensified the problem. A field experiment was conducted to determine GR soybean response to pyrithiobac, trifloxysulfuron, MSMA, and combinations of pyrithiobac or trifloxysulfuron plus MSMA applied postemergence. Trifloxysulfuron at 2.6 and 5.2 g a.i. ha^{-1} controlled GR soybean 98 and 100%, respectively, compared with 60 and 77% control by pyrithiobac at 36 and 72 g a.i. ha^{-1}, respectively. MSMA at 925 g a.i. ha^{-1} controlled soybean only 30%. Soybean control by pyrithiobac or trifloxysulfuron was reduced when either herbicide was mixed with MSMA. A second experiment evaluated control of soybean with traits for both glyphosate resistance and sulfonylurea herbicide tolerance (GR/ST). The GR/ST soybean was controlled 1, 13, and 36% by pyrithiobac at 36, 72, and 108 g ha^{-1}, respectively, compared with 79, 98, and 100% control by trifloxysulfuron at 2.6, 5.3, and 7.9 g ha^{-1}, respectively. These results demonstrate that volunteer GR or GR/ST soybean can be controlled in cotton by trifloxysulfuron applied postemergence at normal use rates.

Volunteer plants of one crop growing in another crop can be a significant concern. Volunteer crop plants are considered to be weeds because they can reduce crop yield and quality and reduce harvesting efficiency (Boydston and Seymour, 2002; Tingle and Beach, 2003; Young and Hart, 1997). Volunteer crops may harbor pathogens, insects, and nematodes, thereby diminishing the positive effects of crop rotation on pest management (Porter et al., 1982; Wright and Bishop, 1981; York et al., 1994). Volunteer crop plants may also jeopardize the success of insect eradication efforts (York et al., 2004).

Volunteer soybean in cotton became a problem with the commercialization of glyphosate-resistant (GR) soybean and cotton in 1996 and 1997, respectively. This technology has been readily adopted because it offers growers a number of benefits (Culpepper and York, 1999b). In North Carolina, 85% of the soybean crop and 95% of the cotton crop is planted to GR cultivars (NCDACS, 2004; USDA-AMS, 2003).

Two consequences of the widespread adoption of GR cotton have been an increase in no-till production and a reduction or elimination in the use of the herbicide fluometuron. In North Carolina, 9% of the cotton crop was planted in a conservation tillage system in 1996 compared with 41% in 2004 (CTIC, 2004). No-till production, and the subsequent elimination of cultivation, contributes to greater problems with volunteer crops (Derksen et al., 1993; Wicks, 1985; Young and Hart, 1997). Fluometuron applied preemergence, an essential component of a weed management system in non-GR cotton production (York and Culpepper, 2004), will severely injure or kill soybean (Jackson et al., 1978). With timely glyphosate application, fluometuron is not required in a GR-cotton production system (Culpepper and York, 1999a), and use of fluometuron has greatly decreased since introduction of GR cultivars. Only 16% of the cotton crop in North Carolina in 2003 received fluometuron (USDA-NASS, 2004).

Volunteer soybean in cotton is normally not a major concern, but in years following hurricanes that damage the preceding soybean crop, volunteer plants from unharvested soybean seed can be a problem. Glyphosate-resistant soybean that have emerged at cotton planting can be controlled by paraquat or combinations containing paraquat (Montgomery et al., 2002; Murdock et al., 2002). Glyphosate-resis-

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tant soybean that have emerged after cotton planting require postemergence control, since most growers no longer use fluometuron or other preemergence herbicides that will control soybean. Some of the commonly used postemergence-directed herbicides may control soybean, but results have been erratic (Alford et al., 2002; Montgomery et al., 2002; Murdock et al., 2002). Without suppression of soybean prior to the cotton reaching a growth stage suitable for postemergence-directed herbicide application, soybean will be too large for effective spray coverage and control by directed herbicides.

The primary postemergence (over-the-top) candidates for GR soybean control in GR cotton are pyrithiobac and trifloxysulfuron. Both of these herbicides are effective on a number of broadleaf weeds (Jordan et al., 1993; Porterfield et al., 2002). Pyrithiobac can be mixed with glyphosate and applied postemergence through the four-leaf stage of cotton (Anonymous, 2004c). Combinations of glyphosate plus pyrithiobac may be more effective on certain weeds than glyphosate alone (Miller et al., 1999; Shaw and Arnold, 2002). Similarly, improved control of some species has been noted when trifloxysulfuron was mixed with glyphosate (Richardson et al., 2004). Cotton growth stage restrictions preclude postemergence application of mixtures of glyphosate and trifloxysulfuron (Anonymous, 2004a; 2004b). Trifloxysulfuron can be applied post-emergence to cotton with five or more leaves (Anonymous, 2004a).

MSMA at reduced rates (0.8 to 1.0 kg ha^{-1}) was at one time commonly applied postemergence to cotton to control susceptible broadleaf weeds, such as common cocklebur (*Xanthium strumarium* L.) (McWhorter and Bryson, 1992). Greater control of sicklepod [*Senna obtusifolia* (L.) Irwin & Barneby] and other weeds has also been observed with mixtures of MSMA plus pyrithiobac compared with pyrithiobac alone (Bridges et al., 2002; Culpepper and York, 2000; Monks et al. 1999). MSMA applied postemergence can be injurious to cotton (Byrd and York, 1987; Snipes and Byrd, 1994), and use of MSMA applied in this manner ceased with the widespread adoption of GR cultivars. MSMA at 1.7 to 2.2 kg ha^{-1} in combination with other herbicides, such as prometryn or diuron, is commonly applied as a postemergence-directed spray in GR cotton to control annual broadleaf weeds, sedges, and small annual grasses (Culpepper and York, 1999a, 1999b; Faircloth et al., 2001; Porterfield et al., 2002).

The objectives of this research were to determine control of GR and GR/ST soybean by pyrithiobac and trifloxysulfuron applied post-emergence and to evaluate the effect of mixing MSMA with pyrithiobac or trifloxysulfuron on control of GR soybean.

MATERIALS AND METHODS

Experiment 1 focused on control of GR soybean and was conducted on the Cherry Farm Unit near Goldsboro, NC in 2000 and 2001, and on the Upper Coastal Plain Research Station near Rocky Mount, NC in 2001. Experiment 2 focused on control of GR/ST soybean and was conducted on the Fountain Research Farm near Rocky Mount and on the Upper Coastal Plain Research Station in 2004. Soil types for each site are described in Table 1.

Methods common to both experiments. Soybean was planted at 10 to 12 seeds m^{-1} of row on 76-cm rows in conventionally prepared seedbeds. The experimental design for both experiments was a randomized complete block, and treatments were replicated four times. Individual plots were five rows by 4 m (experiment 1) or 7 m (experiment 2). Herbi-

Table 1. Description of soils at sites for experiments 1 and 2

Experiment	Locations[y]	Soil series[z]	Soil texture	Soil pH	Soil organic matter (%)
1	Cherry Farm, 2000	Wickham	Sandy loam	6.1	1.8
1	Cherry Farm, 2001	Goldsboro	Sandy loam	5.9	2.0
1	UCPRS, 2001	Norfolk	Sandy loam	6.2	2.2
2	Fountain Farm, 2004	Norfolk	Sandy loam	6.1	1.8
2	UCPRS, 2004	Marlboro	Sandy loam	5.8	2.0

[y] UCPRS, Upper Coastal Plain Research Station.

[z] Wickham is a fine-loamy, mixed, semiactive, thermic Typic Hapludults; Goldsboro is a fine-loamy, siliceous, subactive, thermic Aquic Paleudults; Norfolk is a fine-loamy, kaolinitic, thermic Typic Kandiudults; Marlboro is a fine, kaolinitic, thermic Typic Paleudults.

cides were applied with a CO_2-pressurized backpack sprayer equipped with flat-fan nozzles (TeeJet XR 11002 nozzles; Spraying Systems Co.; Wheaton, IL) calibrated to deliver 140 L ha^{-1} at 166 kPa.

Soybean control was determined 30 d after the three-trifoliate application and 30 d after the five-trifoliate application in experiment 1 or 30 d after the second herbicide application in experiment 2. Control was estimated visually using a scale of 0 = no control to 100 = death of all soybean plants (Frans et al., 1986).

Experiment 1: response of GR soybean. Glyphosate-resistant soybean cultivars AG5901 in 2000 and AG5353 in 2001 (Monsanto Co.; St. Louis, MO) were planted on the dates listed in Table 2. Treatments included a factorial arrangement of four rates of pyrithiobac or trifloxysulfuron and an untreated control by two rates of MSMA by application at two soybean growth stages. Pyrithiobac (Staple; E. I. du Pont de Nemours and Co.; Wilmington, DE) was applied at 36 and 72 g ha^{-1}, and trifloxysulfuron (Envoke; Syngenta Crop Protection; Greensboro, NC) was applied at 2.6 and 5.3 g ha^{-1}. MSMA (MSMA 6.6; Drexel Chemical Co.; Memphis, TN) was applied at 925 g ha^{-1} or not applied. These herbicides were applied to soybean in the three- or five-trifoliate leaf stage on the dates listed in Table 2. Glyphosate isopropylamine salt (Roundup Ultra in 2000 or Roundup UltraMax in 2001; Monsanto Co.; St. Louis, MO) at 840 g a.e. (acid equivalent) ha^{-1} was applied to all plots at the three- and five-trifoliate leaf stages of soybean and was mixed with pyrithiobac, trifloxysulfuron, or MSMA in treatments scheduled to receive those herbicides. A nonionic surfactant (Induce; Helena Chemical Co.; Memphis, TN) at 0.25% (v/v) was included in all herbicide applications.

Data were subjected to analysis of variance using the general linear models procedure of the Statistical Analysis System (version 7.0; SAS Institute Inc.; Cary, NC), with treatment sums of squares partitioned to reflect the factorial treatment arrangement. Locations were considered as random effects (McIntosh, 1983). Visual ratings were arcsine square-root transformed prior to analysis of variance; non-transformed data are presented with statistical interpretation based on 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 herbicides applied in mixtures were examined using the method described by Colby (1967). The expected control by mixtures 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 mixtures were compared by Fisher's Protected LSD at $P = 0.05$. Mixtures were considered antagonistic when the observed value was significantly less than the expected value.

Experiment 2: response of GR/ST soybean. The GR/ST soybean cultivar AG5603 (Monsanto Co.; St. Louis, MO) was planted on the dates listed in Table 2. Treatments included pyrithiobac at 36, 72, and 108 g ha^{-1} or trifloxysulfuron at 2.6, 5.3, and 7.9 g ha^{-1} applied to three-trifoliate soybean on the dates listed in Table 2. Additional treatments included pyrithiobac at 36 and 72 g ha^{-1} and trifloxysulfuron at 2.6 and 5.3 g ha^{-1} applied twice. The first application was made to soybean in the three-trifoliate stage, and the second application was 10 (Fountain Farm) or 14 days (Upper Coastal Plain Research Station)

Table 2. Planting and herbicide application dates and rainfall preceding herbicide application for experiments 1 and 2

Exp.	Locations[y]	Planting date	Herbicide application dates[z]		Rainfall (cm) during 7 days preceding herbicide application	
			First	Second	First	Second
1	Cherry Farm, 2000	21 July	14 Aug.	31 Aug.	6.0	3.5
1	Cherry Farm, 2001	5 June	27 June	5 July	1.9	1.5
1	UCPRS, 2001	25 May	22 June	2 July	6.5	1.8
2	Fountain Farm, 2004	7 July	2 Aug.	11 Aug.	1.8	1.3
2	UCPRS, 2004	7 July	4 Aug.	19 Aug.	1.7	13.2

[y] UCPRS, Upper Coastal Plain Research Station.

[z] Soybean was in the three-trifoliate leaf stage for the first application for all experiments. In 2000 and 2001, soybean was in the five-trifoliate leaf stage for the second application. For 2004, the second application was 10 days after the first application at Fountain Farm and was 14 days after the first application at UCPRS.

after the first application. Glyphosate potassium salt (Roundup Weathermax; Monsanto Co.; St. Louis, MO) at 840 g a.e. ha^{-1} was applied at both application timings and was mixed with pyrithiobac or trifloxysulfuron in treatments scheduled to receive those herbicides. A nonionic surfactant (Induce) at 0.25% (v/v) was included with all pyrithiobac and trifloxysulfuron applications.

Data were subjected to analysis of variance using the general linear models procedure of the Statistical Analysis System. Visual ratings were arcsine square-root transformed prior to analysis of variance; non-transformed data are presented with statistical interpretation based on transformed data. Means were separated using Fisher's Protected LSD at $P = 0.05$.

RESULTS AND DISCUSSION

Differences in weed control among herbicide treatments were not a factor in this experiment. The glyphosate applied to all plots at each application timing controlled all weeds completely. Soybean was not under drought stress at the time of any of the applications. Accumulated rainfall during 7 d preceding herbicide application each year was at least 1.3 cm (Table 2).

Experiment 1: response of GR soybean. For the data combined over locations, significant interactions for location by pyrithiobac or trifloxysulfuron, for location by growth stage, for location by pyrithiobac or trifloxysulfuron by growth stage, for location by MSMA rate, for location by MSMA rate by pyrithiobac or trifloxysulfuron, and for location by MSMA rate by growth stage were observed. Examination of each interaction revealed that response to the treatment variables was similar at each location and varied only in magnitude, so a focus on the main effects of pyrithiobac or trifloxysulfuron, MSMA rates, and growth stages, and the interactions of these variables was justified (Murray et al., 1999). The soybean growth stage at the time of herbicide application was not significant ($P = 0.8362$). Additionally, there were no significant interactions for growth stage by pyrithiobac or trifloxysulfuron ($P = 0.5442$), for growth stage by MSMA rate ($P = 0.4082$), or for growth stage by pyrithiobac or trifloxysulfuron by MSMA rate ($P = 0.9587$). There was, however, a signficant interaction for pyrithiobac or trifloxysulfuron by MSMA rates ($P = 0.0384$).

Averaged over both growth stages of application, pyrithiobac at 36 and 72 g ha^{-1} controlled GR soybean 60 and 77%, respectively, 30 d after treatment (Table 3). This level of control was less than control observed in other studies. When pyrithiobac was applied to four-leaf cotton, Alford et al. (2002) observed greater than 95% control of GR soybean by pyrithiobac at 36 g ha^{-1} at one location but only 56% control at another location. Soybean size at time of application was not specified, but the soybean was planted at the same time as cotton. Murdock et al. (2002) reported 92 and 78% control of GR soybean that was planted at the same time as the cotton by pyrithiobac at 36 g ha^{-1} applied to 2- and 4-leaf cotton, respectively.

Table 3. Control of glyphosate-resistant soybean 30 days after application of pyrithiobac or trifloxysulfuron alone and mixed with MSMA in experiment 1

Herbicides	Application rate (g ha^{-1})	Observed control (%)[y]	Expected control (%)[z]
MSMA	925	30 g	
Pyrithiobac	36	60 e	
Pyrithiobac	72	77 c	
Pyrithiobac + MSMA	36 + 925	34 fg	73
Pyrithiobac + MSMA	72 + 925	36 f	85
Trifloxysulfuron	2.6	98 ab	
Trifloxysulfuron	5.2	100 a	
Trifloxysulfuron + MSMA	2.6 + 925	72 d	98
Trifloxysulfuron + MSMA	5.2 + 925	95 b	100

[y] Data averaged over two soybean growth stages and three locations. Means followed by the same letter are not significantly different according to Fisher's Protected LSD test ($P = 0.05$).

[z] Expected control calculated according to method described by Colby (1967). Each herbicide combination was determined to be antagonistic.

Symptoms expressed by soybean treated with pyrithiobac were similar to those reported previously (Barrentine and Street, 1996). Young leaflets were chlorotic and cupped downward. Leaflet veins were blackened, especially on the abaxial surface, and internodes were compressed. Most plants survived treatment, especially with the lower application rate.

Trifloxysulfuron was efficacious in controlling GR soybean. Applied at 2.6 g ha^{-1}, or one-half the lowest label-recommended rate for cotton (Anonymous, 2004a), trifloxysulfuron controlled soybean 98% (Table 3). Soybean was controlled completely by trifloxysulfuron at 5.2 g ha^{-1}.

MSMA alone applied at 925 g ha^{-1} controlled GR soybean only 30% (Table 3). MSMA caused extensive necrosis on soybean foliage contacted by the spray, but leaves produced after the application were unaffected and soybean death was not observed.

Combinations of pyrithiobac plus MSMA were less effective on GR soybean than pyrithiobac alone (Table 3), and combinations of pyrithiobac plus MSMA were antagonistic according to the procedure of Colby (1967). Soybean control was reduced from 60% by pyrithiobac alone at 36 g ha^{-1} to 34% with the mixture of pyrithiobac plus MSMA. MSMA mixed with pyrithiobac at 72 g ha^{-1} reduced control from 77 to 36%. This is the first published report of reduced control of a species by pyrithiobac plus MSMA compared with pyrithiobac alone. In previous studies (Bridges et al., 2002; Culpepper and York, 2000; Monks et al. 1999), MSMA added to pyrithiobac increased control of sicklepod, common cocklebur, prickly sida (*Sida spinosa* L.), Palmer amaranth (*Amaranthus palmeri* S.Wats.), pitted morningglory (*Ipomoea lacunosa* L.), tall morningglory [*Ipomoea purpurea* (L.) Roth.], common ragweed (*Ambrosia artemisiifolia* L), purple nutsedge (*Cyperus rotundus* L.), and goosegrass [*Eleusine indica* (L.) Gaertn.]. The label for pyrithiobac warns of potentially less control of certain species when pyrithiobac is mixed with MSMA (Anonymous, 2004c).

MSMA mixed with trifloxysulfuron also reduced GR soybean control compared with trifloxysulfuron alone, and mixtures of the two herbicides were antagonistic (Table 3). The effect was somewhat less dramatic than with pyrithiobac, probably because of the greater level of activity of trifloxysulfuron on soybean. Soybean was controlled only 72% by trifloxysulfuron at 2.6 g ha^{-1} plus MSMA compared with 98% control by trifloxysulfuron alone. MSMA mixed with trifloxysulfuron at 5.2 g ha^{-1} reduced soybean control 5%.

Experiment 2: response of GR/ST soybean. Since the mode of action of pyrithiobac, a pyrimidinyl thiobenzoate herbicide, and trifloxysulfuron, a sulfonylurea herbicide, is inhibition of the enzyme acetolactate synthase (EC 4.1.3.18) (HRAC, 2002), these herbicides might be expected to be less effective on GR/ST soybean than GR soybean. Medlin et al. (1998) evaluated pyrithiobac as a potential herbicide for weed control in sulfonylurea herbicide-tolerant soybean, and they reported that pyrithiobac at 70 g ha^{-1} injured soybean 30% but did not reduce soybean yield.

In experiment 2, GR/ST soybean was more tolerant of pyrithiobac than GR soybean in experiment 1. Pyrithiobac at 36, 72, and 108 g ha^{-1} applied once controlled GR/ST soybean only 1, 13, and 36%, respectively (Table 4). Multiple applications of pyrithiobac were more effective than single applications. Pyrithiobac applied twice at 36 g ha^{-1} controlled GR/ST soybean 28% compared with 13% control by pyrithiobac applied once at 72 g ha^{-1}. Pyrithobac applied twice at 72 g ha^{-1} controlled GR/ST soybean 73%, which was similar to control of GR soybean by pyrithiobac at 72 g ha^{-1} applied once (Table 3).

Trifloxysulfuron was much more effective on GR/ST soybean than pyrithiobac, and differences in control of GR soybean in experiment 1 and GR/ST soybean in experiment 2 by trifloxysulfuron were less than differences observed with pyrithiobac. Trifloxysulfuron at 2.6 g ha^{-1} controlled GR/ST soybean 79% compared with 98% control of GR soybean (Tables 3 and 4). Trifloxysulfuron at 5.2 g ha^{-1} controlled GR/ST soybean 98% compared with 36% control by pyrithiobac at 108 g ha^{-1} (Table 4). In contrast to results with pyrithiobac, multiple applications of trifloxysulfuron did not improve control compared with the same total rate applied once. The GR/ST soybean was controlled 98% by trifloxysulfuron applied once at 5.2 g ha^{-1} and trifloxysulfuron applied twice at 2.6 g ha^{-1}.

Volunteer soybean is not very competitive with cotton. Tingle and Beach (2003) reported that soybean at densities of 0.5 to 1 plant m^{-1} of cotton row reduced cotton yield 7%. This is considerably less than the yield reductions caused by common broadleaf weeds at similar densities (Askew and Wilcut, 2001, 2002;

Table 4. Glyphosate-resistant, sulfonylurea-tolerant soybean control by pyrithiobac and trifloxysulfuron in experiment 2

Herbicides[y]	Application rate (g ha^{-1})	Control (%)[z]
Pyrithiobac	36	1 f
Pyrithiobac fb pyrithiobac	36 fb 36	28 d
Pyrithiobac	72	13 e
Pyrithiobac fb pyrithiobac	72 fb 72	73 b
Pyrithiobac	108	36 c
Trifloxysulfuron	2.6	79 b
Trifloxysulfuron fb trifloxysulfuron	2.6 fb 2.6	98 a
Trifloxysulfuron	5.2	98 a
Trifloxysulfuron fb trifloxysulfuron	5.2 fb 5.2	100 a
Trifloxysulfuron	7.9	100 a

[y] Herbicides were applied once to three-trifoliate soybean or to three-trifoliate soybean followed by (fb) a second application 10 to 14 days later.

[z] Data averaged over two locations. Soybean control determined 30 days after the second herbicide application. Means followed by the same letter are not significantly different according to Fisher's Protected LSD test ($P = 0.05$).

Morgan et al., 2001; Snipes et al., 1982; Wood et al., 1999). In situations in which volunteer soybean populations justify treatment or growers want control for aesthetic reasons, these results indicate volunteer GR/ST soybean in the 3- to 5-trifoliate leaf growth stage can be controlled by trifloxysulfuron applied post-emergence at the recommended rate of 5.2 g ha^{-1} (Anonymous, 2004a). Trifloxysulfuron at 2.6 g ha^{-1} controls GR soybean. Pyrithiobac did not control GR/ST soybean, and it was less effective on GR soybean than trifloxysulfuron. Partial control and stunting of GR soybean by pyrithiobac would help establish a height differential between cotton and soybean to allow more effective use of postemergence-directed sprays (Montgomery et al., 2002).

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