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WEED SCIENCE

Impact of Adjuvants and Nozzle Types on Cotton Injury From Flumioxazin Applied Post-Directed

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ABSTRACT

Flumioxazin {2-[7-fluoro-3,4-dihydro-3-oxo-4-(2-propynyl)-2*H*-1,4-benzoxazin-6-yl]-4,5,6,7-tetrahydro-1*H*-isoindole-1,3(2*H*)-dione}, a soil residual herbicide that is practically non-selective when applied to plant foliage, is being developed for post-directed application to cotton (*Gossypium hirsutum* L). The extent of cotton injury by flumioxazin when applied with various spray nozzles and adjuvant combinations is unknown. Therefore, field experiments were conducted to determine the effect of eight adjuvants and 10 nozzle types on cotton injury by flumioxazin post-directed at 70 g ai ha^{-1}. The adjuvants had minor impact on cotton injury by flumioxazin. None of the adjuvants caused more than 10% injury 7 days after treatment (DAT), and cotton yield was not different among adjuvants. Cotton injury 7 DAT was less than 8% for all nozzles except for flat-fan flood nozzles, which produced 19% injury. Cotton injury at 28 DAT and cotton yield were not different among nozzles. Laboratory studies were also conducted to determine the effect of adjuvants and placement of $_{14}$C-flumioxazin on the cotton stem on absorption. Adjuvants had little effect on stem absorption, but placement of flumioxazin on green stem tissue resulted in greater absorption than placement on bark tissue. Recovery of $_{14}$C-flumioxazin placed on green stem was 10 to 23%, and on bark tissue was 21 to 35%. Lower recovery of $_{14}$C-flumioxazin from the green stem indicates greater absorption by the plant. Based on these data, it was concluded that for maximum cotton safety, flumioxazin should be post-directed after bark formation, and care should be taken to avoid contact with green stem tissue.

Late-season post-directed herbicides are applied to cotton to improve harvest efficiency by eliminating or suppressing weeds through harvest. Cotton producers in Georgia have traditionally relied on cyanazine for lay-by weed control because of the wide spectrum of weeds controlled, residual activity, and lack of carryover (Vencill, 2002a), but cyanazine is no longer registered for this use.

Approximately 93% of the cotton planted in Georgia is glyphosate-resistant (USDA-NASS, 2003). Glyphosate, alone or in combination with other herbicides, is applied postemergence for early season weed control. Later in the season, glyphosate can be post-directed to cotton (Anonymous, 2003b). Although glyphosate is effective against many weed species, it may not adequately control morningglory species (*Ipomoea* spp.) (Lanie et al., 1994; Wilson and Worsham, 1988). Glyphosate also has no soil residual activity (Noruma and Hilton, 1977; Sprankle et al., 1975), which allows late-emerging weeds to become established before harvest. Georgia cotton growers commonly mix diuron with glyphosate post-directed. An herbicide that could be post-directed and provide broad-spectrum weed control with residual activity would fill a needed niche in cotton weed control in Georgia.

Flumioxazin is a *N*-phenylphthalimide herbicide that has been registered for preemergence application in peanut (*Arachis hypogea* L.) and soybean [*Glycine max* (L.) Merr.] and is being developed for post-directed application in cotton. Flumioxazin would be attractive to cotton producers because of its broad spectrum residual and postemergence control of broadleaf weeds, but the short half-life of 11 to 17 d would eliminate concerns of carryover to subsequent crops (Vencill, 2002a; Wilcut et al., 2000). Minimal cotton injury and high levels of weed control have been reported with flumioxazin post-directed to cotton (Askew et al., 2002; Vencill, 2002b). Flumioxazin can be injurious to cotton if directed onto green stem tissue (Price et al., 2001), but injury is not a problem if flumioxazin is properly directed to avoid contact with green stem tissue (Altom et al., 2000; Main et al., 2000).

Most of the research on efficacy of flumioxazin post-directed in cotton has been conducted with non-

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ionic surfactants and one type of nozzle (Askew et al., 2002; Wilcut et al. 2000). Once registered for post-directed application in cotton, growers will likely use a wide range of nozzle and adjuvant combinations. Therefore, the objectives of this study were to determine cotton tolerance and weed control of flumioxazin applied post-directed with various adjuvants and with spray nozzles that have different spray patterns and spray volumes. To further characterize flumioxazin uptake from post-directed applications in cotton, absorption of $_{14}$C-flumioxazin applied to green stem tissue and to stem tissue with bark was quantified.

MATERIALS AND METHODS

Methods common to field experiments. Field experiments were conducted in 2001 and 2002 in Athens and Plains, Georgia. The soil at Athens was a Cecil sandy loam (fine, kaolinitic, thermic Typic Kanhapludults) with 0.9% organic matter and pH 5.9. The soil at Plains was a Greenville sandy clay loam (fine, kaolinitic, thermic Rhodic Kandiudults) with 1.0% organic matter and pH 6.5. Cotton cultivars were Deltapine (DP) 5415 BG/RR (Delta and Pine Land Co., Scott, MS) in 2001 and Sure-Grow (SG) 501BR (Delta and Pine Land Co., Scott, MS) in 2002. Cotton was planted between 14 May and 21 May at each location at a rate of 18 seeds per meter of row. Plots consisted of four 91-cm rows 6.1 m in length. Conventional tillage systems were used at each site.

The experimental design was a randomized complete block with three replications. All plots received glyphosate isopropylamine salt (Roundup UltraMax, Monsanto Company, St. Louis, MO) at 0.84 kg ai ha^{-1} applied postemergence to two-leaf cotton and post-directed to six-leaf cotton using either a tractor-mounted or a CO_2-pressurized backpack sprayer calibrated to deliver 170 L ha^{-1} at 220 kPa. The row middles were cultivated two times during the season for weed control.

Flumioxazin (Valor 51WP, Valent USA, Walnut Creek, CA), in both the nozzle and the adjuvant experiments, was applied as a 10-cm band directed to the bottom 5 cm of the crop when cotton was approximately 46 cm tall with 8 cm of bark at the base of the stem. The herbicide was directed immediately adjacent to both sides of the planted row using a single nozzle. The weeds present in both experiments were sicklepod (*Senna obtusifolia* L.), Texas panicum (*Panicum texanum* Buckl.), tall morningglory (*Ipomoea purpurea* (L.) Roth), Palmer amaranth (*Amaranthus palmeri* S. Wats.), and yellow nutsedge (*Cyperus esculentus* L.). All weed species were 5 to 10 cm tall at the time of treatment.

Weed control and cotton injury resulting from post-directed treatments were assessed visually at 7, 28, and 45 days after treatment (DAT) using a 0 to 100 scale, where 0 = no injury or control and 100 = complete weed control or crop death (Frans et al., 1986). The degree of stunting, chlorosis, and necrosis caused by herbicide application was used collectively to determine the percentage injury to cotton or weed control. All weed control and cotton injury data were subjected to arcsine transformations before analysis. Non-transformed data with statistical interpretation based on transformed data are presented. Means were separated using Fisher's Protected LSD test (P = 0.05). Since treatment by year and treatment by location interactions were not significant, data were pooled over locations and years. Each experiment contained a untreated check, but the data were excluded from the data analysis and do not appear in the data tables.

Adjuvant experiment. Several adjuvants were examined to determine their impact on cotton injury by flumioxazin post-directed at 70 g ai ha^{-1} (Table 1). Additional treatments also included ammonium sulfate alone at 9 kg ha^{-1}, and a treatment that included isopropylamine salt of glyphosate (Roundup UltraMax, Monsanto Company, St. Louis, MO) at 0.84 kg ha-1 mixed with flumioxazin. The purpose of the glyphosate treatment was to apply flumioxazin with the adjuvant included in the formulated glyphosate product. All flumioxazin applications were made using an 8003XR tapered-edge, flat-fan nozzle (Spraying Systems Co., Wheaton, IL 60189) calibrated to deliver 170 L ha^{-1} at 220 kPa.

Nozzle experiment. Flumioxazin was applied post-directed at 70 g ha^{-1} using various nozzles to determine the impact of spray pattern and volume on cotton injury from directed applications. Flumioxazin was applied with non-ionic surfactant (Induce, Helena Chemical Company, Collierville, TN) at 0.25% v v^{-1} and ammonium sulfate at 2.8 kg ha-1. Nozzles, all from Spraying Systems Company (Wheaton, IL), included the following: XR TeeJet XR8003 extended pressure range, tapered-edge, flat-fan spray tips; TeeJet TP8003EVS even-spray, flat-fan spray tips; TeeJet D25143-UB 8503 off-center, tapered-edge, flat-fan spray tips; DG TeeJet DG8003

Table 1. Technical information and rates of adjuvants used in the experiments

Adjuvant	Abbreviation	Adjuvant constituents	Rate (% v v^{-1})	Manufacturer
Induce	NIS	Non-ionic surfactant	0.25	Helena Chemical Co.; Collierville, TN
Exchange	COC	Crop oil concentrate	1.0	Precision Labs Inc.; Northbrook, IL
Dyne-Amic	MSO	Blend of methylated seed oil, non-ionic surfactant, and organosilicone surfactant	1.0	Helena Chemical Co.; Collierville, TN
Dyne-a-Pak	MSO + UAN	Blend of methylated seed oil, non-ionic surfactant, organosilicone surfactant, and urea ammonium nitrate	1.0	Helena Chemical Co.; Collierville, TN
Silwet L-77	OSS	Organosilicone surfactant	0.1	Helena Chemical Co.; Collierville, TN
Border Xtra DF	Poly + AMS	Dry-flowable hydroxyl propyl guar polymer adjuvant plus ammonium sulfate	18 kg ha^{-1}	Precision Labs Inc.; Northbrook, IL

low drift, tapered-edge, fan-flat spray tips; Turbo TeeJet TT11003-VP wide-angle, tapered-edge, flat-fan spray tips; Turbo FloodJet TF-VS4 wide-angle, tapered-edge, flat-fan flood spray tips; TwinJet TJ60-8003VS twin outlet, tapered-edge, flat-fan spray tips; TeeJet 80015LP low-pressure flat-fan spray tips; FullJet FL-5VS wide-angle, full-cone spray tips; and AI TeeJet AI11003-VS air induction, tapered-edge, flat-fan spray tips. All applications were made at 220 kPa resulting in an output from each nozzle of 187 L ha^{-1}, except for the full cone and the flood nozzle which were 215 and 243 L ha^{-1}, respectively.

Stem absorption of flumioxazin. A laboratory study was conducted to determine if flumioxazin applied to bark or to green stem tissue was absorbed differently. Cotton cultivar Fibermax 989BR (Bayer CropScience, Research Triangle Park, NC) was grown in a growth chamber for 6 wk (30/28C day/night; 16-h photoperiod with a light intensity of approximately 1000 µmol m^{-2} s^{-1}) until the plants developed approximately 6 cm of bark on the lower stem. Labeled ^{14}C-flumioxazin [phenyl-^{14}C, specific activity 12.9 MBq mg^{-1}] was mixed with either non-ionic surfactant (0.25% v v^{-1}), crop oil concentrate (1% v v^{-1}), glyphosate (0.84 kg ai ha^{-1}), or applied in water with no adjuvant. A 3-µl droplet, containing 17 Bq of ^{14}C-flumioxazin, was placed on either green stem tissue or bark tissue. After 24 hours the stem was washed with water and a stem segment, cut 2.5 cm above and below the placement of the ^{14}C-flumioxazin spot, was removed. The stem segment was split lengthwise in order to separate the epidermal tissue from the vascular tissue. The epidermal tissue was then combusted in a biological oxidizer (Harvey OX-500, Hillsdale, NJ), and using liquid scintillation spectroscopy (Beckman LS-500, Fullerton, CA), ^{14}C was quantified. All treatments were replicated three times and the study was conducted twice. The data were subjected to analysis of variance, and means were separated using Fisher's Protected LSD test (P = 0.05). All data were pooled because a treatment by trial interaction was not detected.

RESULTS AND DISCUSSION

Adjuvants. Weed control data presented in Table 2 are from observations made 45 DAT. These data were used, instead of 7 and 28 DAT data, to discern whether weed regrowth or additional weed emergence would occur 6 wk after treatment. The 45-DAT data would indicate whether or not flumioxazin applied post-directed will serve as an effective lay-by treatment.

Weeds were controlled >90% by all treatments at 45 DAT (Table 2). In the absence of an adjuvant, flumioxazin controlled sicklepod, tall morningglory, Texas panicum, Palmer amaranth, and yellow nutsedge by at least 94% (Table 2). None of the adjuvants, nor glyphosate, increased control compared with flumioxazin applied alone. The high levels of weed control by flumioxazin applied without adjuvant and with glyphosate are similar to that observed by Askew et al. (2002).

Table 2. Effect of adjuvants applied post-directed with flumioxazin at 70 g ha^{-1} on weed control, cotton injury, and seed cotton yield

Adjuvants[y]	Control (%)[z]					Cotton Injury[z]	Yield (kg ha^{-1})
	Sicklepod	Tall morningglory	Texas panicum	Palmer amaranth	Yellow nutsedge		
None	97	96	99	96	94	3	1480
NIS	99	99	99	94	99	6	1440
COC	99	99	99	92	99	8	1470
MSO	99	97	99	99	99	9	1430
MS0 + UAN	99	99	99	92	99	7	1580
OSS	97	97	99	92	99	10	1470
AMS	97	99	99	99	99	6	1330
Poly + AMS	96	96	99	90	99	4	1500
Glyphosate	99	99	99	96	99	6	1650
LSD (*P* = 0.05)	NS	NS	NS	NS	NS	5	NS

[y] NIS = nonionic surfactant, 0.25% v v^{-1}; COC = crop oil concentrate, 1.0% v v^{-1}; MSO = methylated seed oil, nonionic surfactant, and organo-silicone surfactant blend, 1.0% v v^{-1}; MSO + UAN = methylated seed oil, nonionic surfactant, organo-silicone surfactant, and urea ammonium nitrate, 1.0% v v^{-1}; OSS = organosilicone surfactant, 0.1% v v^{1}; AMS = ammonium sulfate, 9 kg ha^{-1}; Poly + AMS = polymer adjuvant + ammonium sulfate, 18 kg ha^{-1}; glyphosate and adjuvant included in the glyphosate formulated product mixed with flumioxazin.

[z] Weed control ratings were taken 45 d after treatment and cotton injury ratings taken 7 d after treatment. Weed control and cotton injury were rated using a 0 to 100 scale, where 0 = no injury or control and 100 = complete weed control or crop death (Frans et al., 1986). The degree of stunting, chlorosis, and necrosis caused by herbicide application was used collectively to determine the percentage injury or control of treated plants. These data were subjected to arcsine transformations before analysis.

Differences in cotton injury were observed 7 DAT when flumioxazin was applied with various adjuvants (Table 2). The greatest injury was observed when flumioxazin was applied with organosilicone surfactant, although injury by this treatment did not differ from that by flumioxazin plus nonionic surfactant, crop oil concentrate, methylated seed oil, methylated seed oil plus urea ammonium nitrate, ammonium sulfate, or glyphosate. The greatest injury would be expected with flumioxazin plus organosilicone surfactant since this type of adjuvant generally increases herbicide absorption and enhances field performance more than other adjuvants (Knoche, 1994). Regardless of the adjuvant used, no treatment injured cotton more than 10%. Although Wilcut et al. (2000) reported that flumioxazin with crop oil concentrate applied post-direct would be more likely to result in cotton injury at 7 DAT, cotton injury from flumioxazin with and without crop oil concentrate was not different in this experiment. Additionally, seed cotton yield was not different when flumioxazin was applied alone or with adjuvants.

Nozzles. Cotton injury 7 DAT from flumioxazin was not different among nozzles except for the flat-fan flood nozzle (Table 3). Flumioxazin applied with the flat-fan flood nozzle injured cotton 19%, while flumioxazin applied with the other nozzles injured cotton 5 to 10%. Cotton receiving flumioxazin applied with the flat-fan flood nozzle displayed yellowing leaves and reduction in plant height. By 28 DAT, the cotton had partially recovered, and no treatment injured cotton more than 8%. Injury was not observed from any treatment 45 DAT (data not shown). Based on these data, most herbicide application nozzles would be acceptable for applying flumioxazin post-directed in cotton, but it would be advisable to avoid the use of flat-fan flood nozzles which may increase injury. Although yield reduction from the use of flood nozzles was not observed in this experiment, application strategies used to minimize crop injury would be best.

Stem absorption of flumioxazin. Figure 1 describes the quantity of ^{14}C recovered from the epidermal portion of the cotton stem when ^{14}C-flumioxazin was applied to green stem tissue or bark

Table 3. Effect of flumioxazin applied at 70 g ha^{-1} applied post-directed with different spray nozzles on cotton injury 7 and 28 days after treatment (DAT) and seed cotton yield

Nozzles	Injury (%)[z]		Yield (kg ha^{-1})
	7 DAT	28 DAT	
Even-spray flat-fan	5	3	2440
Extended pressure range flat-fan	7	5	2630
Low drift flat-fan	10	5	2550
Wide-angle flat-fan	6	3	2320
Off-center flat-fan	7	3	2490
Flat-fan flood	19	8	2600
Twin outlet flat-fan	8	4	2350
Low pressure flat-fan	9	5	2420
Air induction flat-fan	8	3	2370
Full-cone	8	3	2530
LSD (P = 0.05)	6	NS	NS

[z] Cotton injury was rated using a 0 to 100 scale, where 0 = no injury and 100 = crop death (Frans et al., 1986). The degree of stunting, chlorosis, and necrosis caused by herbicide application was used collectively to determine the percentage injury of treated plants. These data were subjected to arcsine transformations before analysis.

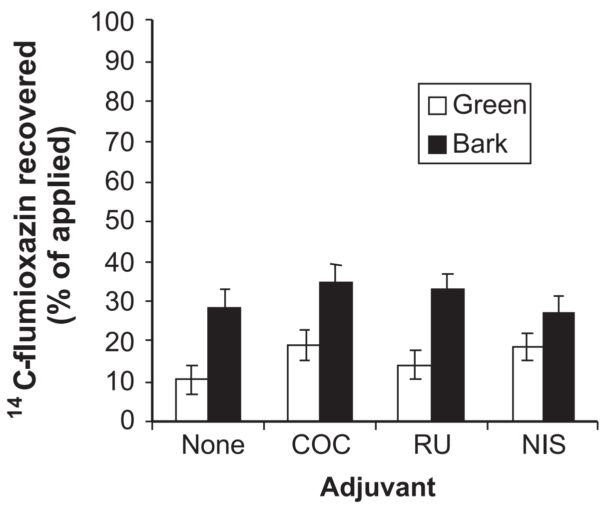

Figure 1. Effect of placement on green stem tissue or bark and by the adjuvants crop oil concentrate (COC, 1% v v^{-1}), non-ionic surfactant (NIS, 0.25% v v^{-1}) or glyphosate (RU, 0.84 kg ha^{-1}) on the percentage recovery of 14C-flumioxazin from epidermal stem tissue. Error bars represent Fisher's Protected LSD (P = 0.05).

tissue. Percentage recovery and percentage absorption would be inversely proportional because analysis of the water used to rinse the stems prior to harvest did not reveal detectable amounts of ^{14}C. Therefore, all flumioxazin applied to the stem was considered to have been absorbed by the stem. The lower recovery from the outer portion of the stem with application to green stem tissue indicates that more flumioxazin was absorbed and translocated away from the point of application.

Adjuvants had little effect on absorption of stem-applied flumioxazin (Figure 1). This was expected considering that few differences were detected among various adjuvants when flumioxazin was applied in field studies (Table 2). Placement on the stem (ie. the bark or green stem tissue) did influence flumioxazin uptake. Flumioxazin recovery was between 10 and 23% when applied to the green stem as opposed to 21 to 35% when applied to bark. The stem bark provided a protective barrier and prevented flumioxazin from being absorbed into the stem. Approximately 80 to 90% of applied flumioxazin applied to green stem tissue was not recovered from the point of application. This indicates that flumioxazin was absorbed into the stem and translocated away from the point of application. This occurrence of absorption and translocation could result in crop injury if sufficient flumioxazin was accumulated at sites of action. Contrarily, if flumioxazin is inhibited from entering the plant, due to exclusion by the bark layer, then critical concentrations of herbicide would be less likely to reach the site of action and less crop injury would be expected.

To determine if flumioxazin was accumulating in other plant tissues, the apical meristem was oxidized in an attempt to detect the presence of flumioxazin, but flumioxazin was not detected. It is possible that 17 Bq of ^{14}C-flumioxazin was an insufficient quantity to examine long-distance transport.

These data demonstrate that flumioxazin is a highly effective herbicide for post-directed weed control in cotton. Excellent crop safety was observed when flumioxazin was combined with various spray adjuvants or applied with different spray nozzles. Although 19% crop injury was observed when flumioxazin was applied with flat-fan flood nozzles, this injury had dissipated by 45 DAT and cotton lint yield was not affected. Flumioxazin penetration of cotton stems was greater when applied to green stem tissue as opposed to bark stem tissue. Therefore, for ultimate crop safety, flumioxazin application should be postponed until bark formation, and applications must be made with care to avoid treatment of green stem tissue. This policy would most likely lead to high levels of weed control and minimize crop injury. Careless flumioxazin applications, or applications made to small cotton that has not developed sufficient bark, could result in severe cotton injury.

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DISCLAIMER

Mention of a trademark, warranty, proprietary product or vendor does not constitute a guarantee by the University of Georgia and does not imply approval or recommendation of the product to the exclusion of others that may be suitable.

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