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WEED SCIENCE

Cotton (*Gossypium hirsutum* L.) Injury, Growth, and Yield Following Low-Dose Flumioxazin Postemergence Applications

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ABSTRACT

The effects of postemergence (POST) herbicides off-target movement on cotton has been evaluated, but no data is available evaluating simulated off-target movement of residual herbicides. Therefore, low-dose POST applications of flumioxazin were evaluated in cotton at the cotyledon, two- and four-leaf growth stages. Rates evaluated were 12.5, 25, and 50% of the labeled use rate of 72 g ai ha^{-1}. Necrosis, cotton height and width reduction was observed. Cotyledon cotton was injured 69 to 86%, 80 to 91%, and 84 to 97% following the 12.5, 25, and 50% flumioxazin rates, respectively, 3 through 42 DAT. Injury of two-leaf cotton increased from 3 to 14 DAT for all flumioxazin rates with maximum injury of 40, 47, and 58% following the 12.5, 25, and 50% rates, respectively, 14 DAT, but injury decreased following the 14 DAT evaluation. Injury of four-leaf cotton was 46 to 58% 3 DAT and decreased over time regardless of rate. At 42 DAT, two- and four-leaf cotton was injured 14 to 33% and increased with flumioxazin rate. Cotton height and width averaged 40, 80, 86% of the nontreated following the cotyledon, two-, and four-leaf application timings, respectively, 42 DAT. In addition, height was more influenced by flumioxazin rate than cotton width. Yields were 24, 52, and 62% of the nontreated following the cotyledon, two-, and four-leaf applications timings, respectively. In addition, yields following the 12.5, 25, and 50% rates were 53, 45, and 40% of the nontreated. Low-doses of flumioxazin reduced revenue \$1,172 to \$2,344 ha^{-1} for lint and \$212 to 423 ha^{-1} for cotton seed. Low-doses of flumioxazin POST can have negative effects on cotton growth and yield and could cause severe economic loss for a cotton producer.

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Cotton (*Gossypium hirsutum* L.) planting dates can depend upon geographic location and environmental conditions. The United States Department of Agriculture (USDA) (2010) reported that cotton was planted in the U.S. over a seven-wk period starting March 27 in western U.S. states and ending June 21 in Kansas and Oklahoma. In Louisiana, optimal planting dates are April 15 through May 15 (LSUAC-CES, 2018). Long-term research in Georgia has shown little yield difference when cotton is planted between April 1 and May 20 (UGA-CES, 2018). Recommended cotton planting dates for Virginia are April 20 to May 25 (Frame, 2016). Regardless of geographic location, cotton is typically planted over a five- to eight-wk period. Furthermore, producers often plant cotton and soybean (*Glycine max* L.) in close geographic areas. In the U.S., soybean was planted over an eight-wk period beginning April 24 in the mid-southern U.S. states and ending July 12 in U.S. states along the Atlantic Ocean coast (USDA, 2010). This wide range in cotton and soybean planting dates could cause fields in close proximity to be planted over a range of dates and this would result in cotton at multiple growth stages on any given date.

Off-target movement of herbicides to sensitive crops can result from spray drift, volatility, and spray tank contamination and is a concern when utilizing herbicide-resistant crops (Culpepper et al. 2018; Ellis et al. 2002). Off-target droplet drift at the time of application varies between 1 and 8% for ground application and can be 20 to 35% with aerial application (Maybank et al. 1978). Wolf et al. (1992) reported 2 to 16% droplet drift from non-shielded sprayers, which can be influenced by nozzle size and wind velocity. Others have evaluated the effect of low-doses of herbicides on corn (*Zea mays* L.), cotton, grain sorghum [*Sorghum bicolor* (L.) Merr], rice (*Oryza sativa* L.), soybean, and watermelon [*Citrullus lanatus* (Thunb.) Matsum. & Nakai] (Al-Khatib et al., 2003; Bailey and Kapusta, 1993; Culpepper et al., 2018; Ellis et al., 2002, 2003; Ellis and Griffin, 2002; Matocha and Jones, 2015; Steppig et al., 2017). Collectively, they evaluated 2,4-D, dicamba, glufosinate, glyphosate, halosulfuron, imazethapyr, mesotrione, nicosulfuron, primisulfuron, quizalfop, propanil, sethoxydim, and tembotrione. Although some of the herbicides evaluated in past research would provide residual weed control, the majority of research has evaluated POST herbicides offering little residual control of weeds. Consequently, minimal information is available focusing on the effects of low-doses of soil-applied residual herbicides that are analogous to herbicide concentrations present in an off-target herbicide movement event.

Herbicides that provide residual control of weedy species, especially herbicide-resistant species, are vital in crop production. Norsworthy et al. (2012) stated that many chemical weed-management programs aimed at reducing the risk of herbicide resistance begin with a residual herbicide. To achieve season-long control and prevent seed production of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri* S. Wats.), a resistance-simulation model indicated that residual herbicides were required (Jha and Norsworthy, 2009; Neve et al., 2011). Furthermore, producers recognize that tillage and residual herbicides were effective tools for management of herbicide-resistant weeds (Prince et al., 2012).

Flumioxazin inhibits the enzyme protoporphyrinogen oxidase and is typically used preemergence (PRE) for broadleaf weed control in peanut (*Arachis hypogaea* L.) and soybean and as a preplant application in cotton (Anonymous, 2018; Shaner et al., 2014). When applied PRE, flumioxazin is absorbed primarily by the roots of treated plants with limited symplastic movement in phloem. Sensitive plants become necrotic and die shortly after exposure to sunlight. Following POST application, flumioxazin can be absorbed by the foliage causing rapid desiccation and necrosis of leaf tissue (Shaner et al., 2014). Flumioxazin PRE at 54 g ai ha^{-1} controlled Palmer amaranth 82 to 100% 20 DAT (Whitaker et al., 2011).

The use of residual herbicides at or near planting has increased in recent years in the quest to manage glyphosate-resistant weeds. This increase in use elevates the probability that a residual herbicide will move off-target. Unfortunately, no information is available pertaining to cotton growth and yield or potential economic impact following exposure to low-dose application of flumioxazin. Therefore, the objective was to determine the effect of low-doses of flumioxazin at early-season cotton growth stages measured by visual injury, cotton height, width, yield, and yield revenue.

MATERIALS AND METHODS

Studies were conducted at the Louisiana State University Agricultural Center Dean Lee Research and Extension Center near Alexandria, LA (N 31.178, W 92.411) in 2016 and 2017. Soil was a Coushatta silt loam (fine-silty, mixed, superactive, thermic Fluventic Entrudepts), with a pH of 8.0 and 1.5% organic matter. 'DP1649 B2XF' and 'DP1646 B2XF'were seeded at 102,000 seed ha^{-1} on 9 May 2016 and 8 May 2017, respectively. Phosphorus and K at 18 and 67 kg ha^{-1}, respectively, as 0-18-36 was applied and incorporated in the fall prior to planting and N as 30-0-0 was applied at 100 kg ha^{-1} when cotton was at four- to six-leaf growth stage in both yr. Cotton growth measurements in the nontreated control were utilized to determine application timing and rates of mepiquat chloride to manage cotton height.

The experimental design was a randomized complete block with nine treatments in a two-factor factorial arrangement replicated four times in both yr. Factor one consisted of application timings of cotyledon, two-, or four-leaf growth stages. Factor two was low-dose rates of flumioxazin (Valor SX, Valent U.S.A., Walnut Creek, CA 94596) at 9, 18, and 36 g ai ha^{-1} which represented 12.5, 25, and 50% of the field use rate of 72 g ha^{-1} (Anonymous, 2018). Low-dose rates were chosen to represent herbicide rates similar to those observed with off-target movement (Maybank et al. 1978; Wolf et al. 1992) or tank contamination. A nontreated control was included for comparison.

Plots comprised four 9 m rows spaced 0.97 m apart, but only the center two rows were treated. Study areas were maintained weed-free throughout the season by as-needed applications of glyphosate at 870 g ae ha^{-1} and hand weeding in all yr. Treatments were applied with a CO_2-pressurized backpack sprayer calibrated to deliver 190 kPa on May 17, May 31, and June 6, 2016 and May 16, May 27, and June 2, 2017. All treatments were applied in a constant carrier volume of 140 L ha^{-1}. The spray boom consisted of four flat-fan 11002 nozzles (AIXR TeeJet®, TeeJet Memphis, Collierville, TN).

Visual estimates of cotton injury were recorded 3, 7, 14, 28, and 42 DAT using a 0 to 100 scale (0 meaning no injury and 100 meaning cotton death). To evaluate cotton growth, cotton height and width were recorded 14, 28, and 42 DAT by measuring ten randomly selected plants in each plot. Cotton height was measured from the soil to the apical terminal of each plant. Cotton width was recorded by measuring the distance between the outermost edges of the widest portion of the plant. Yield was determined by harvesting treated rows of plots using conventional harvesting equipment. Cotton height, width, and yield (adjusted to 40% lint turnout) were converted to a percentage of the nontreated control values prior to analysis.

To determine the economic impact following low-doses of flumioxazin, a loss calculation was conducted on a U.S. dollar kg^{-1} basis. The cotton market consists of two segments, lint and cotton seed. Lint is the primary price driver that sends the market signal to producers; however, yield damage will effect cotton lint and seed production. A seed conversion factor of 1.40 was applied to lint yield to capture any economic losses associated with decreased yield following the treatments. Economic losses were calculated by multiplying the reduced cotton yield by 2016 and 2017 average prices received for cotton lint and seed in Louisiana, which were \$1.55 kg^{-1} for cotton lint and \$0.20 kg^{-1} for cotton seed (USDA, 2018). A two yr average price was utilized because it corresponds to the yr the studies were conducted.

Data were subjected to analysis of variance with PROC MIXED in SAS® release 9.4 (SAS Institute, Cary, NC). Fixed effects were flumioxazin application timing, rate, and all interactions. Random effects were yr and replications within yr. Least square means were calculated and effects were separated using Tukey's honest significant difference test at $P \leq 0.05$. The ability of cotton to recover from injury over time was of interest. Therefore, regression procedures using PROC REG in SAS testing linear and quadratic functions against evaluation date were conducted to evaluate cotton's ability to recover from initial injury according to the interactions of application timing and herbicide rate. Model fit was evaluated using the goodness of fit parameters root mean square error (RMSE) (Willmott 1981) and the coefficient of determination (R^2) (Legates and McCabe 1999). RMSE was utilized to measure goodness of fit in addition to R^2, as Willmott (1981) and Willmott and Matsura (2006) suggest RMSE provides a better parameter to estimate the accuracy of a model to be utilized for predictive purposes. A smaller RMSE value represents a better fit. RMSE values for percent cotton injury ranged from 2.83 to 8.35 for all significant regressions indicating a good fit for all models (data not shown).

RESULTS AND DISCUSSION

Necrosis, in addition to visual cotton height and width reduction was observed following flumioxazin applications. Primary injury symptoms in sunflower (*Helianthus annuus* L.) following flumioxazin POST was necrosis (Jursik et al., 2011). Cotyledon cotton was injured 69 to 86%, 80 to 91%, and 84 to 97% following the 12.5, 25, and 50% flumioxazin rates, respectively, 3 through 42 DAT (Figures 1a, b, c). Although injury of cotyledon cotton averaged 86% 28 DAT and decreased to an average of 79% 42 DAT (Figure 1a, b, c) indicating some recovery, the level of injury at 42 DAT highlights the sensitivity of cotyledon cotton to low-doses of flumioxazin. Injury of two-leaf cotton increased from 3 to 14 DAT for all flumioxazin rates with maximum injury of 40, 47, and 58% following the 12.5, 25, and 50% rates 14 DAT. Regardless of flumioxazin rate, injury of two-leaf cotton decreased following the 14 DAT evaluation indicating potential recovery from flumioxazin injury. However, injury of four-leaf cotton was 46 to 58% 3 DAT and decreased over time regardless of rate. At 42 DAT, injury of two- and four-leaf cotton increased with flumioxazin rate and was similar, but injury ranged 14 to 33% across rates indicating the sensitivity of cotton to flumioxazin. These data indicate that cotton can be highly sensitive to low-dose flumioxazin POST early in the growing season. Flumioxazin at 30 g ha^{-1} injured two-leaf or four- to six-leaf sunflower 21 to 29% or 17 to 24%, respectively, seven DAT, but injury was ≤ 10% following both applications 21 to 28 DAT (Jursik et al. 2011). However, Jordan et al. (2003) found that flumioxazin POST at 50 g ha^{-1} injured peanut 47% 14 DAT. Therefore, cotton sensitivity to low-dose flumioxazin POST was more similar to peanut than sunflower.

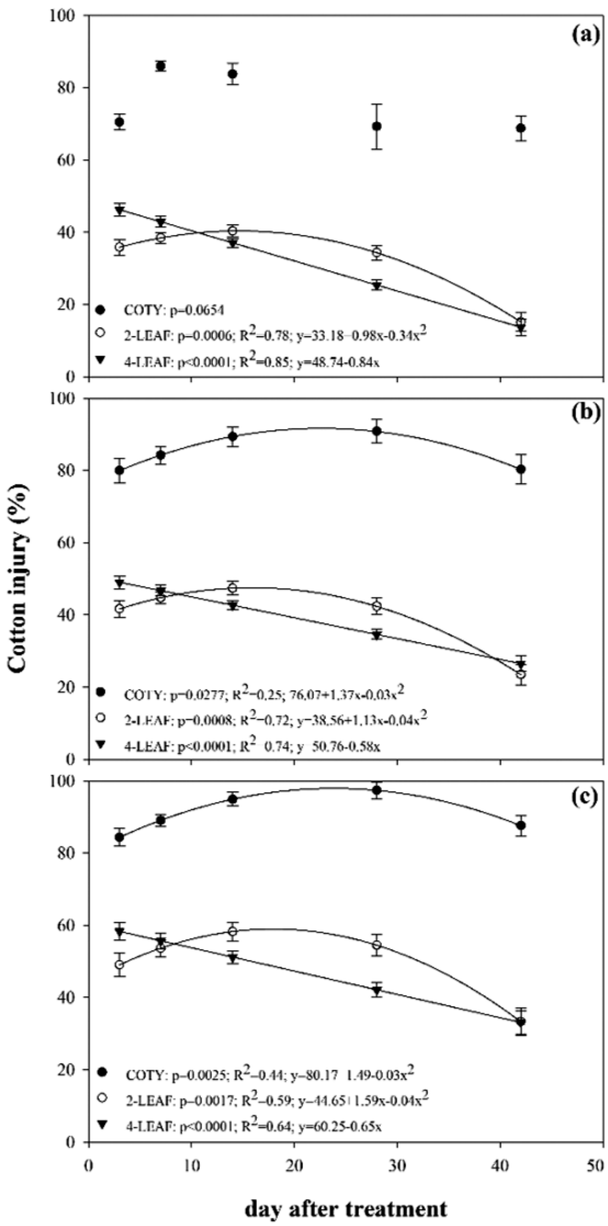

Figure 1. Cotton injury following low-dose flumioxazin applied to cotyledon (COTY), 2- and 4-leaf cotton as a function of d after treatment at (a) 12.5, (b) 25, and (c) 50% of the labeled use rate 72 g ai ha^{-1}. Sample means represent 3, 7, 14, 28, and 42 d after treatment. Error bars represent ± 1 standard error.

Cotton height and width data support visual injury observations. Cotton height following the cotyledon, two-, and four-leaf applications was 39, 63, and 68% of the nontreated, respectively 14 DAT with no difference between the two- and four-leaf application timings (Table 1). Similar trends were observed 28 and 42 DAT, with two- and four-leaf cotton heights of 72 and 83% at 42 DAT of the nontreated indicating recovery from early-season injury. However, cotyledon cotton height was 40% of the nontreated 42 DAT, which supports cotyledon cotton visual injury observations (Figure 1a, b, c). Furthermore, heights were 75, 67, and 53% of the nontreated 42 DAT, following application of the 12.5, 25, and 50% flumioxazin rates with the no difference between the 12.5 and 25% rates (Table 1). Cotton width following the cotyledon, two-, and four-leaf applications was 35, 57, and 60% of the nontreated 14 DAT, respecively (Table 1). Like height, cotton width following the cotyledon application was only 40% of the nontreated 42 DAT, but widths following the two- and four-leaf application timings improved to 88 and 89% of the nontreated, respectively (Table 1). Width data supports visual injury and height observations that cotyledon cotton is more susceptible to low-dose flumioxazin POST than two- or four- leaf cotton and that two- and four-leaf cotton can potentially recover from early season injury. However, flumioxazin rate did not influence cotton width at 14 or 42 DAT with widths ranging 65 to 78% of the nontreated 42 DAT indicating that low-dose flumioxazin influences cotton height greater than cotton width.

Analysis indicated that flumioxazin application timing, but not rate influenced treated cotton lint yield. Nontreated cotton lint yield was 1990 kg ha^{-1}. Yields were 24, 52, and 62% of the nontreated following the cotyledon, two-, and four-leaf applications timings, respectively (Table 2). In addition, lint yields following the 12.5, 25, and 50% rates were 53, 45, and 40%, respectively, of the nontreated. Based upon lint and cottonseed prices of \$1.55 and \$0.20 kg^{-1}, low-doses of flumioxazin reduced revenue \$1,172 to \$2,344 ha^{-1} for lint and \$212 to 423 ha^{-1} for cotton seed (Table 2). Visual injury, height, width, yield reductions, and revenue loss indicate that early-season exposure to low-dose flumioxazin POST can be devastating to a producer. Jursik et al. (2011) observed no yield reduction in sunflower following application of flumioxazin at 30 g ha^{-1} to two- or four- to six-leaf sunflower. However, flumioxazin POST at 50 g ha^{-1} reduced peanut yield 15% when applied six to eight wk after emergence (Jordan et al., 2003).

Low-dose flumioxazin exposure to cotton at the cotyledon, two-, and four-leaf stage can injure cotton and reduce cotton height, width, and yield. Visual injury increased with rate and diminished over time following all application timings. However, data highlights the severe impact of flumioxazin exposure even at very low concentrations on cotyledon cotton. Although visual injury, height, and width data indicates that two- and four-leaf cotton may recover following low-dose flumioxazin, yields indicate that cotton does not fully recover from early-season flumioxazin damage. Low-doses of flumioxazin POST can have negative effects on cotton growth, yield, and could cause severe economic loss for a cotton producer; therefore, cotton producers should avoid exposing young cotton to flumioxazin via spray drift or tank contamination.

Table 1. Cotton height and width as a percent of the nontreated following low-doses of flumioxazin applied to cotyledon, 2-, or 4-leaf cotton.[z]

Application timing[y]	Cotton height			Cotton width		
	14 DAT[w]	28 DAT	42 DAT	14 DAT	28 DAT	42 DAT
	% of nontreated					
Cotyledon	39 b	35 b	40 b	35 b	34 b	40 b
2-leaf	63 a	70 a	72 a	57 a	75 a	88 a
4-leaf	68 a	76 a	83 a	60 a	82 a	89 a
Flumioxazin rate[x]						
12.5%	60 a	65 a	75 a	54 a	66 ab	78 a
25%	58 ab	63 ab	67 a	54 a	67 a	73 a
50%	51 b	53 b	53 b	43 a	57 b	65 a

[z] Means for cotton height and width 14, 28, and 42 DAT for both independent variables followed by the same letter are not different according to Tukey's honest significant difference test at $P \leq 0.05$.

[y] Data pooled across flumioxazin rates of 12.5, 25, and 50% of the labeled rate of 72 g ai ha^{-1}.

[x] Data pooled across application timings of cotyledon, 2-, and 4-leaf cotton growth stages.

[w] Abbreviations: DAT, d after treatment.

Table 2. Cotton lint yield and cotton lint, cottonseed, and lint and cottonseed revenue loss following low-doses of flumioxazin applied to cotyledon, 2-, and 4-leaf cotton.[z, y]

Application timing[v]	Cotton lint yield[x]	Revenue loss	
		Lint	Cottonseed[w]
	% of nontreated	US dollar ha^{-1}	
Cotyledon	24 b	2,344	423
2-leaf	52 a	1,481	267
4-leaf	62 a	1,172	212
Flumioxazin rate[u]			
12.5%	53 a	1,450	262
25%	45 a	1,696	306
50%	40 a	1,851	334

[z] Economic losses were calculated by multiplying cotton lint yield by 2016 and 2017 average prices received for cotton lint and seed in Louisiana of \$1.55 and \$0.20 kg^{-1}, respectively.

[y] Means for cotton lint yield followed by the same letter are not different according to Tukey's honest significant difference test at $P \leq 0.05$. Economic loss data not subjected to analysis of variance.

[x] Nontreated yield in flumioxazin study was 1990 kg ha^{-1}.

[w] Seed conversion factor of 1.4 was multiplied by nontreated cotton lint yield to calculate cottonseed loss.

[v] Data pooled across flumioxazin rates of 12.5, 25, and 50% of the labeled rate of 72 g ai ha^{-1}.

[u] Data pooled across application timings of cotyledon, 2-, and 4-leaf cotton growth stages.

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