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Influence of Flumioxazin Application Timing and Rate on Cotton Emergence and Yield

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Palmer amaranth is one of the most troublesome weeds in the southeast. Significant reductions in cotton yield because of Palmer amaranth competition warrant intense control efforts consisting of both PRE and POST herbicides. Flumioxazin is a soil-active, protoporphyrinogen oxidase-inhibiting herbicide that is labeled for use in cotton 14 to 21 d before planting; however, shorter preplant application intervals could increase the duration of control from this herbicide. Flumioxazin was applied at 3 rates (0.03 and 0.06 kg ai ha^{-1} in 2009 and an additional rate of 0.09 kg ai ha^{-1} in 2010 and 2011) and 6 application timings (30, 20, 15, 10, 5, and 0 d before planting cotton). Cotton emergence, height, and yield were documented. In 2009, at the Jay and Citra, FL, sites, cotton emergence, plant height, and yield were not affected by any herbicide rate or timing. At Dawson, GA, in the same year, significant reduction in cotton stand counts were observed with application timings < 10 d before planting. Cotton height was reduced similarly at Dawson, GA, but recovered to levels equal to the control by 45 d after planting (DAP). It is believed that rainfall during cotton emergence resulted in this significant level of injury at Dawson, GA. In 2010 and 2011, at Citra, FL, cotton emergence was only reduced when 0.06 and 0.09 kg ha^{-1} were applied at planting. Cotton height showed a similar pattern with additional reductions in height at 0.03 kg ha^{-1} applied at planting and 0.09 kg ha^{-1} applied 5 d before planting. In 2010 and 2011, at Citra, FL, yield was reduced when 0.09 kg ha^{-1} flumioxazin was applied 5 d before planting and when 0.06 and 0.09 kg ha^{-1} were applied at planting. These results indicate that flumioxazin application intervals can be shortened with little crop impact likely to be seen at lower use rates. However, rainfall at crop emergence has the potential to significantly injure cotton and reduce yield.
Nomenclature: Flumioxazin; Palmer amaranth, *Amaranthus palmeri* S. Wats.; cotton, *Gossypium hirsutum* L.
Key words: Broadcast, cotton emergence, preplant application.

Amaranthus palmeri es una de las malezas más problemáticas en el sureste. Reducciones significativas en el rendimiento del algodón producto de la competencia de *A. palmeri* ameritan intensos esfuerzos de control utilizando herbicidas PRE y POST. Flumioxazin es un herbicida activo en el suelo, que inhibe la enzima protoporphyrinogen oxidase y es etiquetado para su uso en algodón 14 a 21 d antes de la siembra. Sin embargo, períodos más cortos de aplicación pre siembra podrían incrementar la duración del control de este herbicida. Se aplicó flumioxazin a 3 dosis (0.03 y 0.06 kg ai ha^{-1} en 2009 y una dosis adicional de 0.09 kg ai ha^{-1} en 2010 y 2011) y en 6 momentos de aplicación (30, 20, 15, 10, 5, y 0 d antes de la siembra del algodón). La emergencia del algodón, altura, y rendimiento fueron documentados. En 2009, en los sitios Jay y Citra, FL, la emergencia del algodón, la altura de planta, y el rendimiento no fueron afectados por ninguna de las dosis o momentos de aplicación del herbicida. En Dawson, GA, en el mismo año, reducciones significativas en los conteos de algodón establecido fueron observados para los momentos de aplicación <10 d antes de la siembra. La altura del algodón fue reducida en formar similar en Dawson, GA, pero se recuperó a los mismos niveles que el testigo a 45 d después de la siembra (DAP). Se cree que la lluvia durante la emergencia del algodón resultó en este nivel de daño significativo en Dawson, GA. En 2010 y 2011, en Citra, FL, la emergencia del algodón fue reducida solamente cuando se aplicaron 0.06 y 0.09 kg ha^{-1} en la siembra. La altura del algodón mostró un patrón similar con reducciones adicionales en altura a 0.03 kg ha^{-1} aplicados en la siembra y 0.09 kg ha^{-1} aplicados 5 d antes de la siembra. En 2010 y 2011, en Citra, FL, el rendimiento se redujo cuando se aplicó flumioxazin a 0.09 kg ha^{-1} 5 d antes de la siembra y cuando se aplicó 0.06 y 0.09 kg ha^{-1} en la siembra. Estos resultados indican que los intervalos de aplicación pre siembra de flumioxazin pueden ser reducidos con poco impacto al cultivo a dosis bajas. Sin embargo, la lluvia durante la emergencia del cultivo tiene el potencial de dañar significativamente el algodón y reducir su rendimiento.

Palmer amaranth is a C4 summer-annual weed (Ehleringer 1983) that continues to be common and problematic for crop production across the southeast United States (Gleason and Cronquist 1991; Horak and Loughin 2000). Although this weed has many similar features to other *Amaranthus* spp., previous research has found that Palmer amaranth produced more leaf area, dry weight, and plant volume as compared with other members of this genus (Horak and Loughin 2000; Sellers et al. 2003). Competition from Palmer amaranth can be attributed to its tremendous seed production, which ranged from 250,700 to 613,074 seed per female plant (Keeley et al. 1987; Sellers et al. 2003) and aggressive growth habits, reaching heights of 2 m (Bryson and DeFelice 2009). Because of these attributes, Palmer amaranth is considered one of the most troublesome weeds in Florida, Georgia, and South Carolina (Webster 2005).

The competitiveness of Palmer amaranth results in significant interference with crop growth and subsequent reduction in yield. In Texas, populations from 1 to 10 Palmer

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Table 1. Rainfall during critical crop emergence period at experiment sites in Florida and Georgia in 2009–2011.[a]

Location	Yr	5 DAP	5–10 DAP	10–15 DAP
		cm		
Citra, FL	2009	0	0	1.27
Jay, FL	2009	5.33	0	0
Dawson, GA	2009	6.1	4.3	0.76
Citra, FL	2010	1.27	0	8.13
Citra, FL	2011	0.7	1.8	3.1

[a] Abbreviation: DAP, days after planting.

amaranth plants within 9.1 m of row decreased cotton yield from 13 to 54% (Morgan et al. 2001), whereas Burke et al. (2007), in North Carolina, reported that one Palmer amaranth plant m^{-1} of row reduced peanut yield by 28%. Further compounding the problems associated with their aggressive competitive abilities, Palmer amaranth populations have been reported as resistant to glyphosate and acetolactate synthase-inhibiting herbicides (Culpepper et al. 2006; Wise et al. 2009). This fact dramatically reduces the number of options for in-season POST control of Palmer amaranth. Consequently, using multiple PRE and in-season herbicide applications provides the greatest likelihood of control. Considering that early season weed competition has historically proven to be the most impactful on cotton yields (Buchanan and Burns 1970), an effective PRE herbicide is likely to provide the greatest benefit.

Flumioxazin is a soil-active, protoporphyrinogen oxidase (PPO)–inhibiting herbicide (Senseman 2007) that has been previously shown to provide excellent PRE control of Palmer amaranth (Dobrow et al. 2011; Grichar 2008). However, efficacy of flumioxazin can be greatly affected by adverse environmental conditions, shortening the duration of its efficacy, especially for Palmer amaranth control (Dobrow et al. 2011). Therefore, to prevent loss of activity between the point of application and planting, flumioxazin should be applied as close to planting as possible to obtain the maximum in-season benefit of the herbicide. In cotton, label regulations stipulate that the herbicide must be applied 14 to 21 d before planting, depending on application rate (Anonymous 2010). Considering that Dobrow et al. (2011) observed flumioxazin to provide between 16 and 35 d of Palmer amaranth control in a year of little rainfall, making an application > 21 d before planting could result in little or no in-season benefit from a flumioxazin application. Therefore, it would be beneficial to determine whether these intervals could be shortened, so flumioxazin could be applied closer to cotton planting. Therefore, the objectives of this research were to determine how flumioxazin application timing and rate affects cotton establishment and yield.

Materials and Methods

Field studies were initiated in 2009 at sites located in Citra and Jay, FL, and Dawson, GA. The soil types at the three sites were an Arredondo fine sand with < 1% organic material (OM), an Orangeburg fine sandy loam with 2.2% OM, and a Greenville sandy clay loam with 2% OM, respectively. The experiments were repeated at the Citra, FL, site in 2010 and 2011. Experiments at each location were conducted using a strip-tillage regime in a season-long, weed-free environment. Strip-tillage was performed before the first herbicide application, and no further soil disturbance occurred before planting. Experimental plots were four rows wide, 1 m row spacing, and 10 m long. Cotton was planted at 10 seeds m^{-1} of row between May 1 and May 15, and aldicarb (Temik 15G insecticide, Bayer Crop Science, Research Triangle Park, NC) was applied in furrow at 0.56 kg ha^{-1} for insect management. Irrigation, fertility, and insecticide treatments were applied as needed following local production practices.

In 2009, the experiments were conducted as a randomized complete block, with a factorial treatment arrangement of flumioxazin (Valor SX herbicide, Valent U.S.A. Corporation, Walnut Creek, CA) rate (0.03 and 0.06 kg ha^{-1}) and application timing (30, 20, 15, 10, 5, 0 d before planting). In 2010 and 2011, the experiment was conducted similarly, except an additional flumioxazin rate of 0.09 kg ha^{-1} was added. A nontreated check was included at each location and year.

Cotton emergence, measured as plants per meter of row, was counted at 7 and 14 d after planting (DAP). Similarly, cotton height was measured at 30 and 45 DAP. When cotton was mature, applications of ethephon and tribufos were used for boll ripening and defoliation. When defoliation was complete, the middle two rows of each plot were then harvested and weighed. These data were subjected to ANOVA to test for treatment effects and interactions. Where appropriate, data were pooled across locations, and means were separated using Fisher's Protected LSD test ($P = 0.05$). Rainfall data from study periods are presented in Table 1.

Results and Discussion

Cotton stand counts were not different between herbicide application rates and timings at the Jay and Citra, FL, locations in 2009 (Table 2). Stand counts at these locations ranged from 90 to 100% of the nontreated control, both at 7 and 14 DAP. Even when applied at planting, no herbicide rate significantly reduced cotton emergence relative to the nontreated control. Similarly, stand counts at the Citra, FL, location, from treatment years 2010 and 2011, were not different from the nontreated control at 7 or 14 DAP for any herbicide rate applied 5 to 30 d before planting. Stand counts ranged from 100 to 91% of the nontreated for 30 to 5 d before planting applications, respectively. However, when flumioxazin was applied at planting at rates of 0.06 and 0.09 kg ha^{-1}, cotton stand counts decreased to 62 and 51% of the nontreated control at 14 DAP, respectively. The lowest rate (0.03 kg ha^{-1}) was not different from the nontreated regardless of application timing. The Dawson, GA, site did not exhibit these same trends. Stand counts 7 DAP were different from the control at all herbicide rates when applied within 10 d of planting. During this period, cotton stands ranged between 29 and 86% of the nontreated control. Flumioxazin applied 15 d before planting significantly affected stand count in the higher rate (0.06 kg ha^{-1}), but not at the lower rate (0.03 kg ha^{-1}) at 7 DAP; recovery was

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Table 2. Cotton stand counts as measured by number of cotton plants per meter of row at three locations in Florida and Georgia. Values represent percentage of the nontreated control. Asterisks indicate significant differences from nontreated control.[a,b]

		Jay and Citra, FL, 2009		Citra, FL, 2010–2011		Dawson, GA, 2009	
Timing	Rate	7 DAP	14 DAP	7 DAP	14 DAP	7 DAP	14 DAP
d before planting	kg ha^{-1}	% of nontreated control					
30	0.03	92	98	101	100	101	101
30	0.06	100	100	100	100	96	93
30	0.09	—	—	96	98	—	—
20	0.03	93	94	98	99	94	101
20	0.06	95	98	98	98	90	91
20	0.09	—	—	95	94	—	—
15	0.03	90	90	101	98	91	91
15	0.06	97	100	99	99	86*	93
15	0.09	—	—	98	96	—	—
10	0.03	95	96	98	98	79*	80*
10	0.06	93	97	94	96	42*	45*
10	0.09	—	—	94	98	—	—
5	0.03	94	93	98	91	65*	64*
5	0.06	90	94	98	95	36*	35*
5	0.09	—	—	91	92	—	—
0	0.03	100	97	94	89	42*	39*
0	0.06	97	96	70*	62*	29*	29*
0	0.09	—	—	60*	51*	—	—
		NS	NS				

[a] Abbreviations: DAP, days after planting (stand counts were evaluated 7 and 14 DAP); NS, not significant.

[b] A dash (—) indicates no data because the 0.09 kg ha^{-1} rate was not applied in 2009.

observed by 14 DAP, and stand reductions were no longer different. In Dawson, GA, stand counts taken at 14 DAP were significantly reduced in comparison to the control at all rates when flumioxazin was applied 10 d before planting or less.

The variation in response can likely be attributed to the significant amount of rainfall (4 cm) at the Georgia site when the cotton was emerging (Table 1). Similar injury was observed in peanut (*Arachis hypogaea* L.) in a Texas study when significant rainfall (4 cm) occurred 14 DAP with a flumioxazin application (Dotray et al. 2010). Flumioxazin applied at 0.06 and 0.09 kg ha^{-1} caused 22 and 40% peanut injury, respectively (Dotray et al. 2010). Swan (2002) suggested that splashing of flumioxazin treated soil onto peanut seedlings at crop emergence was responsible for the 66 to 68% peanut injury observed in Virginia. No such heavy rainfall events occurred during emergence at either of the Florida sites (Table 1). These results indicate that, even if rainfall were to occur at cotton emergence, flumioxazin could be applied 15 d before planting at 0.03 kg ha^{-1} and not adversely affect stand counts. Further, a higher rate of 0.06 kg ha^{-1} could be used up to 20 d before planting. However, the Florida results indicate, in the absence of significant rainfall, 0.03, 0.06, or 0.09 kg ha^{-1} of flumioxazin could be applied up to 5 d before planting and would not negatively affect stand count.

Cotton height was not significantly different from the nontreated control during the 2009 season at the Jay and Citra, FL, locations for any application rate or interval used (Table 3). At these locations, cotton height varied between 90 and 101% of the nontreated at 30 and 45 DAP, respectively. The Citra, FL, data from 2010 and 2011 showed no differences in cotton height when flumioxazin was applied at the 0.03 kg ha^{-1} and 0.06 kg ha^{-1} herbicide rates at any application interval 5 d or more before planting. Applications of 0.09 kg ha^{-1} flumioxazin significantly decreased plant height when applied at both 5 and 10 d before planting, when evaluated at 30 DAP, but by 45 DAP, the cotton had recovered, and these results were not different from the control. All herbicide rates applied 0 d before planting were different from the control when measured 30 DAP, but by 45 DAP, height reduction was only observed with the two higher rates. Cotton height at the Dawson, GA, location was not significantly affected by any flumioxazin application made greater than 10 d before planting. Both 0.03 and 0.06 kg ha^{-1} were different from the control when applied 5 d before plant and measured at 30 DAP but were not different when measured at 45 DAP. The same trend followed for both herbicide rates applied 0 d before planting. Again, the difference in cotton height response between Florida and Georgia applications may be attributed to the rainfall event that occurred during emergence at the Georgia site. These results indicate that flumioxazin is not likely to affect cotton height when applied at 0.03 or 0.06 kg ha^{-1} up to 10 d before planting with a significant rainfall, or up to 5 d before plant if no rainfall is likely to occur. Cotton height may be initially affected when applied closer to planting, but the cotton has a high probability of recovering by 45 DAP. Other soil-applied PPO-inhibiting herbicides have been found to respond to rainfall in the same manner as flumioxazin. Fomesafen was found to visibly stunt cotton in Georgia after significant rainfall events when applied at planting (Main et al. 2012). In Tennessee, saflufenacil applied at 25 g ha^{-1} only minimally injured cotton, even when applied at planting, similar to the results found in the current study (Owen et al. 2011). Flumioxazin, like the other PPO-inhibiting herbicides

Table 3. Cotton height, represented as percent of the nontreated control, at three locations in Florida and Georgia. Asterisks indicated significance from nontreated control.[a,b]

Timing	Rate	Jay and Citra, FL, 2009		Citra, FL, 2010–2011		Dawson, GA, 2009	
		30 DAP	45 DAP	30 DAP	45 DAP	30 DAP	45 DAP
d before planting	kg ha^{-1}	%					
30	0.03	93	94	94	93	100	100
30	0.06	100	101	91	92	90	97
30	0.09	—[b]	—	92	97	—	—
20	0.03	97	99	100	101	96	100
20	0.06	97	96	100	100	93	98
20	0.09	—	—	103	104	—	
15	0.03	93	95	104	100	100	100
15	0.06	95	97	101	102	100	100
15	0.09	—	—	96	101	—	—
10	0.03	90	93	104	103	96	98
10	0.06	97	95	100	95	90	96
10	0.09	—	—	83*	93	—	—
5	0.03	97	99	103	101	86*	96
5	0.06	99	99	93	100	80*	94
5	0.09	—		88*	93	—	—
0	0.03	92	95	85*	90	83*	94
0	0.06	90	93	68*	84*	80*	95
0	0.09	—	—	77*	81*	—	—
		NS	NS				

[a] Abbreviations: DAP, days after planting (cotton height was evaluated 30 and 45 DAP); NS, not significant.

[b] A dash (—) indicates no data because the 0.09 kg ha^{-1} rate was not applied in 2009.

described, can be used much closer to planting than the current label indicates.

Because of an uncharacteristically high incidence of boll rot, no yield data were collected at the Dawson, GA, location. At the Jay and Citra, FL, locations in 2009, cotton yield was not negatively affected by any flumioxazin application rate or timing (Table 4). Yield ranged from 90 to 100% of the nontreated control at these locations. At the Citra, FL, location, in 2010 and 2011, the 0.03 kg ha^{-1} application rate was not different from the control at any application interval. Flumioxazin applied at 0.06 kg ha^{-1} only affected yield when applied at planting. The highest rate, 0.09 kg ha^{-1}, affected yield when applied both at planting and 5 d prior. Therefore, it would not be advisable to use the 0.09 kg ha^{-1} less than 10 d before planting. These yield data are comparable to a North Carolina study that found no yield reduction using 0.07 kg ha^{-1} flumioxazin applied 0 to 10 wk before plant (Askew et al. 2002). Flumioxazin is known to adsorb to soil OM (Ferrell and Vencil 2004). However, even in the low-OM soils at the Citra, FL, location (< 1% OM), flumioxazin was relatively safe. It is likely that on higher-OM soils, this herbicide would cause less reduction in yield.

Table 4. Cotton lint yield, represented as percent of the nontreated control, at three locations in Florida. Asterisks indicated significance from nontreated control ($\alpha = 0.05$).[a,b]

Timing	Rate	Jay and Citra, FL, 2009	Citra, FL, 2010–2011
d before planting	kg ha^{-1}	% of Nontreated	
30	0.03	92	98
30	0.06	100	94
30	0.09	—	93
20	0.03	93	97
20	0.06	95	103
20	0.09	—	99
15	0.03	90	91
15	0.06	97	95
15	0.09	—	104
10	0.03	95	101
10	0.06	93	95
10	0.09	—	99
5	0.03	94	98
5	0.06	90	91
5	0.09	—	82*
0	0.03	100	90
0	0.06	97	84*
0	0.09	—	60*
Nontreated		NS	

[a] Abbreviation: NS, not significant.

[b] A dash (—) indicates no data because the 0.09 kg ha^{-1} rate was not applied in 2009.

In conclusion, flumioxazin application intervals in Florida and Georgia can likely be shortened from the 14 to 21 d before planting interval that now exists, depending on the rate of application. When applying flumioxazin at 0.03 kg ha^{-1}, stand counts, cotton height, and yield were not adversely affected when applied up to the same day as planting in Florida. Higher rates have the potential to affect these parameters when applied 5 d or less before planting. If heavy rainfall occurs during the critical emergence period, cotton injury has the potential to be severe and could result in reduced stand counts and plant height. Cotton plant height did recover after application intervals close to planting by 45 DAP. Although there is a risk of injury due to rainfall during cotton emergence, shorter application intervals will provide more robust control of weeds such as Palmer amaranth.

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