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Interval between sequential glufosinate applications influences weed control in cotton

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Abstract

Dicamba and 2,4-D systems control many problematic weeds; however, drift to susceptible crops can be a concern in diverse production areas. Glufosinate-based systems are an alternative, but current recommended rates of glufosinate can result in variable control. Research was conducted in 2017 and 2018 to investigate the optimum time interval between sequential glufosinate applications and determine if the addition of glyphosate with glufosinate is beneficial for controlling Palmer amaranth and annual grasses in cotton. The interval between sequential applications (1, 3, 5, 7, 10, or 14 d or no second spray) was the whole plot and herbicide option (glufosinate or glufosinate plus glyphosate) was the subplot. Combined over herbicides, Palmer amaranth 15- to 20-cm tall (at four locations) was controlled 98% to 99% with sequential intervals of 1 to 7 d compared with 70% to 88% with intervals of 10 or 14 d. Lowest biomass weight and population densities were noted with 1- to 7-d intervals. Large crabgrass 15- to 20-cm tall (at five locations) was controlled 93% to 98% with glufosinate applications 3- to 7-d apart as compared with 76% to 81% with applications 10- to 14-d apart. Lowest biomass weights were observed with 1- to 7-d intervals. When glufosinate controlled grass less than 93%, adding glyphosate was beneficial. Neither interval between sequential applications nor herbicide option influenced cotton yield. Shorter time intervals between sequential application and including glyphosate can improve the effectiveness of a glufosinate-based system in managing Palmer amaranth and large crabgrass.

Introduction

More than $900 million worth of cotton was grown on 570,000 ha in Georgia during 2018, making it the state's most valuable agronomic crop (USDA-NASS 2019a; Wolfe and Stubbs 2018). Glyphosate-resistant Palmer amaranth continues to drive weed management programs as the most impactful weedy species affecting cotton production in the state (Culpepper et al. 2006; Sosnoskie and Culpepper 2014; Webster 2009, 2013; Whitaker et al. 2018). Georgia's warm temperatures and ample rainfall offer an ideal growing environment conducive for intense weed pressure and provide optimum growing conditions for numerous weeds, including Palmer amaranth (Nichols 2018). The biological characteristics of Palmer amaranth, including prolific growth and seed production, and great genetic diversity, coupled with herbicide resistance, have made managing this troublesome weed a continuous challenge (Culpepper et al. 2010; Horak and Loughin 2000; Keeley et al. 1987; Ward et al. 2013; Webster and Grey 2015).

In 2017, new cotton technologies were commercialized, allowing topical in-crop applications of the choline salt of 2,4-D and the diglycolamine or *N*,*N*-Bis-(3-aminopropyl) methylamine salts of dicamba, as well as glyphosate and glufosinate (US-EPA 2018, 2019). Management programs including 2,4-D or dicamba consistently improve control of troublesome broadleaf weeds. including Palmer amaranth, common lambsquarters (*Chenopodium album* L.), and waterhemp [*Amaranthus tuberculatus* (Moq.) Sauer], even in glyphosate-resistant populations (Anonymous 2018; Cahoon et al. 2015; Heap 2019; Johnson et al. 2010; Merchant et al. 2014; Spaunhorst and Bradley 2013). Adoption of cotton or soybean [*Glycine max* (L.) Merr.] cultivars tolerant to dicamba or 2,4-D have led to the increased use of these herbicides during summer months (Freeman et al. 2019; Mortensen et al. 2012; USDA-NASS 2018; Whitaker et al. 2018). With more auxin applications has come an increase in the number of off-target drift complaints (US-EPA 2017a, 2017b).

In Georgia, mitigating pesticide drift is challenging because of the state's dynamic agricultural diversity. Georgia's fresh market fruit and vegetable industry, consisting of more than 30 different high-value fruit and vegetable crops, has a farm gate value exceeding $1.8 billion (USDA-NASS 2019a, 2019b; Wolfe and Stubbs 2018). It is paramount for agriculturalists to mitigate off-target pesticide movement everywhere, but this objective is especially important in areas producing fresh market fruits and vegetables. Illegal pesticide residues from off-target movement in fresh market fruits or vegetables threaten the industry's ability to remain

Table 1. Field experiment years, locations, planting dates, cotton varieties, herbicide application initiation dates, and weed heights for five cotton field experiments in Georgia.

Year	Location	Planting date	Variety	Herbicide application[a]	Weed height[a]	
					Palmer amaranth	Large crabgrass
					cm	cm
2017	Ty Ty 1	June 1	DP 1646 B2XF	June 15	15–20	15–20
2017	Ty Ty 2	June 5	DP 1646 B2XF	July 5	15–20	15–20
2017	Ty Ty 3	June 23	DP 1646 B2XF	July 7	15–20	15–20
2018	Moultrie	May 10	PHY 430 W3FE	June 4	15–20	15–20
2018	Ideal	May 30	DP 1646 B2XF	June 3	—	15–20

[a]Date of first herbicide application and corresponding weed heights.

sustainable and must be avoided to protect consumers from unwanted direct pesticide exposure (US-EPA 1999; Winter 2012). In addition, many fruit and vegetable crops are far more susceptible to damage from pesticide drift than are agronomic crops (Culpepper and Vance 2019). One significant concern is that fruit and vegetable crops can be extremely susceptible to auxin herbicides, resulting in visual injury, delayed maturity, fruit malformations, and yield losses, even when exposed to very low levels (Colquhoun et al. 2014; Culpepper et al. 2018; Hatterman-Valenti et al. 2017; Johnson et al. 2012; Kruger et al. 2012; Mohseni-Moghadam and Doohan 2015; USDA-AMS 2016, 2019). Spatial or temporal separation between auxin-tolerant cotton or soybean technologies and fruit and vegetables is not feasible in Georgia. For example, the 72 counties that collectively produce 80% of the cotton grown in Georgia also account for at least $50,000 per county of fresh market, susceptible fruit and vegetables (Wolfe and Stubbs 2018). In areas with simultaneous production of high-value fruit and vegetable crops and cotton or soybean, effective weed management programs without 2,4-D or dicamba must be implemented.

Glufosinate can be an effective alternative for many troublesome weeds when used in tolerant cotton (Blair-Kerth et al. 2001; Culpepper et al. 2009; Green 2009). Adoption of glufosinate as a component of cotton weed management programs went from less than 1% before the discovery of glyphosate-resistant Palmer amaranth in 2005 (Culpepper et al. 2006) to greater than 25% by 2010 (Sosnoskie and Culpepper 2014). Although glufosinate can be an effective weed management tool, registered glufosinate-based programs can be less effective than dicamba- or 2,4-D–based management programs on some troublesome weeds, including Palmer amaranth (Cahoon et al. 2015; Chahal and Johnson 2012; Coetzer et al. 2002). Research is needed to improve the overall effectiveness of glufosinate-based weed management programs.

Current glufosinate registration requires 10 or more d between sequential applications in cotton; however, this interval requirement may not be the most effective approach (Riar at al. 2011). Additional research is needed on the optimum interval at which sequential applications should be implemented to improve the overall effectiveness of glufosinate-based weed management programs for control of Palmer amaranth and other problematic weeds. Also, additional research is needed to determine the response of cotton and troublesome weeds, including annual grasses, to systems with mixtures of glufosinate plus glyphosate. Therefore, the objectives for this study were to investigate the optimum time intervals between sequential POST glufosinate or glufosinate plus glyphosate applications in cotton for improved control of Palmer amaranth and large crabgrass.

Materials and Methods

Site Selection and Experiment Establishment

Field experiments were conducted during 2017 and 2018, including three sites at the Ponder research farm in Ty Ty, GA (31.507°N, 83.657°W; elevation, 109 m), one site at the Sunbelt Agricultural Expo research farm in Moultrie, GA (31.141°N, 83.717°W; elevation, 89 m), and one site at an on-farm location in Ideal, GA (32.421°N, 84.127°W; elevation, 134 m). Soils in Ty Ty consisted of a Tifton loamy sand (fine-loamy, kaolinitic, thermic Plinthic Kandiudults) with 85% to 90% sand, 7% to 9% silt, 2% to 8% clay, 0.6% to 0.7% organic matter, and a pH of 5.9 to 6.2. The soil in Moultrie was a Leefield loamy sand (loamy, siliceous, subactive, thermic Arenic Plinthaquic Paleudults) with 86% sand, 10% silt, 4% clay, 1.2% organic matter, and a pH of 6.2. The soil in Ideal was a Dothan loamy sand (fine-loamy, kaolinitic, thermic Plinthic Kandiudults) with 84% sand, 12% silt, 4% clay, 1.2% organic matter, and a pH of 6.3. During the spring of each year, land was prepared conventionally, and cotton with WideStrike® 3, Roundup Ready® Flex, and Enlist™ (Dow AgroSciences, Indianapolis, IN) or Bollgard® II and XtendFlex™ (Bayer CropScience, St. Louis, MO) seed traits, was planted on 91-cm row spacing using a vacuum planter, dropping two seeds every 22 cm. For each experiment, location, cotton planting date, cotton variety, initial herbicide application date, and weed size at herbicide program initiation are listed in Table 1. Experimental plots at each location consisted of four cotton rows with an area 3.7-m wide by 7.0-m long. Throughout the growing season, fertility, irrigation, and insect and disease management requirements were maintained following university recommendations for the region (Whitaker et al. 2018). Rainfall was supplemented by overhead irrigation to ensure crop moisture requirements were met at all locations.

The experimental design at each location consisted of a factorial arrangement of treatments in a split-block design, with whole plots arranged in a randomized complete block, including four replications for each treatment. With the primary focus of the experiment on time interval between sequential POST applications, the interval between POST 1 and a second POST (POST 2) application represented the whole plot. Seven whole-plot options included intervals of 1, 3, 5, 7, 10, or 14 d between sequential applications plus an additional treatment with no POST 2 or sequential application. Herbicide option, either glufosinate at 660 g ai ha^{-1} alone or in combination with 1,260 g ae ha^{-1} glyphosate, represented the subplot. Adjuvants were not included with any treatment and control strips at least 3.7-m wide, which did not receive herbicide, surrounded the experimental areas, for weed infestation comparisons. Treatments were applied with a CO_2-pressurized backpack sprayer

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and boom equipped with 11002 Air Induction XR wide-angle flat-spray nozzles (Teejet Technologies, Wheaton, IL) delivering 140 L ha^{-1} at 165 kPa, 61 cm above the cotton or weed canopy. To minimize impact of glufosinate application time-of-day effect, as previously reported, each herbicide application occurred no earlier than 1 h after sunrise and was completed before noon (Anonymous 2017; Stewart et al. 2009).

When Palmer amaranth and large crabgrass plant heights ranged from 15 to 20 cm, the POST 1 application was made at each location (Table 1). Palmer amaranth and large crabgrass densities at time of the initial herbicide application ranged from 18 to 58 and 17 to 107 plants m^{-2}, respectively. To avoid the impacts of weeds emerging after sequential applications were completed, a third POST (POST 3) maintenance application was made. The POST 3 applications were applied 14 d after each POST 2 application and included the same herbicide treatment (either glufosinate or glufosinate plus glyphosate) as previously applied. For the system without a POST 2 application, the POST 3 application was made 21 d after POST 1 applications. Although current registrations do not support all glufosinate application intervals and rates used in this research, selected intervals and rates were chosen to obtain additional data in support of a new label in development that is expected to allow higher use rates and shortened time intervals between sequential applications. At 14 d after the POST 3 application, a directed layby application was implemented including diuron (1,120 g ai ha^{-1}) plus monosodium methylarsenate (1,680 g ai ha^{-1}) plus crop oil concentrate (1% vol/vol) for all treatments. Cotton stage of growth for POST 1, POST 2, POST 3, and layby applications consisted of 2 to 7, 2 to 10, 5 to 13, and 12 to 18 leaves, respectively.

Data Collection

Visual cotton injury (chlorosis, necrosis, plant stunting) was recorded on a 0% to 100% scale (0% representing no injury; 100% representing complete plant death), beginning 2 d after POST 1 application and continued once weekly until harvest. To record differences in crop growth, plant height data were recorded for 20 plants from each plot (10 plants from rows 2 and 3 of each four-row plot) two to five times through the completion of injury assessments. Palmer amaranth and large crabgrass control was evaluated weekly, after each herbicide application and before harvest, using a 0% to 100% scale (0% representing no control; 100% representing complete control). To further quantify weed control, Palmer amaranth population densities were collected by hand-cutting plants from an area 1.85 by 7 m in each plot just before harvest. In addition, Palmer amaranth and large crabgrass postharvest biomasses were determined by hand-cutting and immediately weighing the aboveground portions of each plant from the same area where Palmer amaranth population counts were made. Seed cotton yield was collected using a spindle picker modified for small-plot harvesting for all Ty Ty locations; harvest was not feasible in Moultrie due to inclement weather from Hurricane *Michael*.

Statistical Analysis

Significant interactions among treatment effects, study sites, and years were investigated to determine if sequential application intervals and herbicide options affected cotton (i.e., injury, growth, and yield) or weed (i.e., control, population, and biomass) development. Palmer amaranth and seed cotton yield data were not different based on location; therefore, data have been combined, with the exception of yield data not collected from Moultrie. Although collected throughout the season, weed control evaluations prior to harvest were used for analysis, because of ongoing treatment applications during assessment intervals.

Data were assessed for normality and subjected to ANOVA using the GLIMMIX procedure in SAS, version 9.4 (SAS Institute, Cary, NC). Sequential application intervals, herbicide options, and their interactions were treated as fixed effects. Locations, years, and replications nested within location were treated as random effects (Moore and Dixon 2015). When appropriate, significant means were separated and adjusted using the Tukey honest significant difference method at a significance level of 0.05 (McHugh 2011). To further identify differences within Palmer amaranth and large crabgrass populations and biomass, contrast comparisons were performed using the GLIMMIX procedure in SAS, designating the LSMESTIMATE option. Contrasts are reported by giving the probability in parentheses after the reference (Onofri et al. 2009).

Table 2. Palmer amaranth visual control, population densities, and biomass at harvest and seed cotton yield as influenced by sequential POST applications of glufosinate and glufosinate plus glyphosate, applied at seven sequential application intervals.[a]

Application interval[b]	Control[c]	Population	Biomass	Yield
	%	plants ha^{-1}	kg ha^{-1}	kg ha^{-1}
1	99 a	489 a	8 a	2,930 a
3	99 a	326 a	2 a	3,110 a
5	98 a	553 a	4 a	3,050 a
7	99 a	716 a	8 a	3,030 a
10	88 b	20,689 a	64 ab	2,780 a
14	86 b	27,943 a	125 b	2,700 a
No POST 2	70 c	232,434 b	475 c	1,890 b

[a]Data shown for Palmer amaranth, 15 to 20 cm (four sites in 2017 and 2018) at time of initial herbicide application were combined across herbicide option (i.e., glufosinate or glufosinate plus glyphosate).
[b]Number of days after the first POST application of glufosinate or glyphosate plus glufosinate; a sequential application (POST 2) of the same treatment was made 1, 3, 5, 7, 10, or 14 d later. An additional treatment with no POST 2 was included.
[c]Treatment means within a column followed by the same letter do not statistically differ according to Tukey honestly significant difference test at $\alpha = 0.05$.

Results and Discussion

Cotton Injury and Height

No significant location by treatment or year by treatment interactions were detected for visual cotton injury and heights; therefore, data have been combined across year and location. Visual cotton injury, reported for assessments after the completion of POST 2 applications, was less than 11% for all treatments (data not shown). Injury differences among treatments were not detectable during this or any other evaluation during the season. Similarly, cotton height was not influenced by treatments throughout the season (data not shown). Previous research has shown sequential glufosinate applications have little to no impact on plant height in WideStrike 3 Roundup Ready Flex and Bollgard II XtendFlex cotton technologies (Blair-Kerth et al. 2001; Cahoon et al. 2015; Culpepper et al. 2009; Steckel et al. 2012; Whitaker et al. 2011).

Palmer Amaranth, 15 to 20 cm

Visual control, population densities, and biomass at harvest were influenced by the interval between sequential applications but not

Table 3. Large crabgrass visual control and biomass at harvest as influenced by sequential POST applications of glufosinate and glufosinate plus glyphosate, applied at seven sequential application intervals.[a]

Application interval[a]	Control[b]		Biomass[b]	
	Glufosinate[c]	Glufosinate + glyphosate	Glufosinate	Glufosinate + glyphosate
	%	%	kg ha^{-1}	kg ha^{-1}
1	92 bc	99 a	45 ab	1 a
3	98 ab	99 a	12 a	1 a
5	96 ab	98 ab	16 a	4 a
7	93 abc	98 ab	35 ab	12 a
10	81 de	98 ab	123 ab	12 a
14	76 e	92 bc	291 c	95 ab
No POST 2	67 f	86 cd	525 d	195 bc

[a]Number of days after the initial application (POST 1) of glufosinate or glyphosate plus glufosinate; a sequential application (POST 2) of the same treatment was made 1, 3, 5, 7, 10, or 14 d later. An additional treatment with no POST 2 was included.
[b]Control data were combined across five sites and biomass data were combined across four sites in 2017 and 2018 for large crabgrass, 15 to 20 cm.
[c]Treatment means within control or biomass columns followed by the same letter do not statistically differ according to Tukey honestly significant difference test at $\alpha = 0.05$.

by the herbicide option. Combined over four sites and herbicide options, Palmer amaranth was controlled 98% to 99% at harvest when sequential applications were separated by 1 to 7 d (Table 2). Extending the herbicide application interval out to 10 or 14 d resulted in 86% to 88% control, with only 70% control when no sequential application was implemented. Although glufosinate labels note Palmer amaranth should be 10 cm or shorter at time of application for optimum control, Palmer amaranth between 15 and 20 cm is common during grower applications because the plants can grow rapidly (Sosnoskie et al. 2011). As Palmer amaranth size increases, the likelihood of complete control decreases (Coetzer 2002). Although increasing the rate of glufosinate may improve control of Palmer amaranth taller than 10 cm (Craigmyle et al. 2013; Tharp et al. 1999), timely sequential applications have resulted in more effective control in similar studies at the same locations (data not shown).

Palmer amaranth population counts at harvest were variable but fewer than 717 plants ha^{-1} with application intervals of 1 to 7 d, 20,689 to 27,943 plants ha^{-1} at intervals of 10 to 14 d, and more than 232,433 plants ha^{-1} when no sequential application was made (Table 2). Palmer amaranth biomass at cotton harvest was less than 9 kg ha^{-1} when sequential applications were made 7 or fewer days apart, which was at least 15 times less than for an application interval of 14 d or when no sequential application occurred. When contrast comparisons were made, combined intervals of 7 d or fewer were more effective in reducing Palmer amaranth populations and biomass when compared with extended application intervals of 10 d ($P = 0.0041$ and $P = 0.0009$, respectively) or 14 d ($P = 0.0002$ and $P < 0.0001$, respectively). Weed management systems that reduce the number of Palmer amaranth plants producing seed will reduce the number of seeds added to the weed seed bank, benefitting future cropping cycles (Gallandt 2006).

Large Crabgrass, 15 to 20 cm

There were no significant location by treatment or year by treatment interactions for large crabgrass. Significant interactions between sequential application interval and herbicide option were observed for large crabgrass control, combined over five sites, and plant biomass at harvest, combined over four sites. Sequential applications of glufosinate applied 10 to 14 d apart, which is representative of a current labeled use, resulted in 76% to 81% control (Table 3). Control improved at least 11% as the time interval between the sequential applications was reduced. Mixing glyphosate with glufosinate is expected to improve grass control, which did occur when sequential intervals of 1, 10, or 14 d were implemented (Corbett et al. 2004; Whitaker et al. 2011). The addition of glyphosate did not improve the control above that observed with glufosinate alone made at 3, 5, or 7 d apart. For biomass, sequential glufosinate intervals of 7 d or fewer were more effective than the 14-d interval (<46 kg ha^{-1} vs. 291 kg ha^{-1}, respectively). Although variability in biomass measurements was observed, the 10-d interval was less effective than the intervals of 7 d or fewer ($P = 0.0041$ and $P < 0.0001$, respectively). The addition of glyphosate to glufosinate reduced biomass levels when intervals were 14 d apart and when no POST 2 application was made (Table 3).

Cotton Yield

Combined over locations, yield loss was noted only when no POST 2 application (1,890 kg ha^{-1}) was made, when compared with programs with sequential applications of 7 d or fewer (2,930 to 3,110 kg ha^{-1}) (Table 2). Weeds at these locations were 20 cm or smaller, and although all sequential systems did not provide complete weed control, control was high enough to remove weed competition and harvesting losses. Seed cotton yield was not affected by herbicide option, regardless of interval between sequential applications.

Understanding the influence of time intervals between sequential glufosinate applications in cotton can be used to improve control of Palmer amaranth and large crabgrass in the southeastern United States. In this experiment, a time interval of 1 to 7 d between sequential glufosinate applications maximized control of 15- to 20-cm tall Palmer amaranth and large crabgrass. In addition, adding glyphosate to glufosinate can improve large crabgrass control. Thus, adjustments in current glufosinate label directions supporting shortened sequential application intervals would be beneficial for southeastern cotton production systems. Additional research evaluating residual herbicide-mix partners in combination with glufosinate when applied with shorter plant-back intervals would be beneficial in regard to crop tolerance and prolonged herbicide utility through delaying selection of herbicide-resistant weed biotypes to glufosinate.

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