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Growth and fecundity of Palmer amaranth escaping glufosinate in cotton with and without grass competition

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Abstract

Field experiments were conducted at Clayton and Rocky Mount, NC, during summer 2020 to determine the growth and fecundity of Palmer amaranth plants that survived glufosinate with and without grass competition in cotton. Glufosinate (590 g ai ha^{-1}) was applied to Palmer amaranth early postemergence (5 cm tall), mid-postemergence (7 to 10 cm tall), and late postemergence (>10 cm tall) and at orthogonal combinations of those timings. Nontreated Palmer amaranth was grown in weedy, weed-free in-crop (WFIC) and weed-free fallow (WFNC) conditions for comparisons. Palmer amaranth control decreased as larger plants were treated; no plants survived the sequential glufosinate applications in both experiments. The apical and circumferential growth of Palmer amaranth surviving glufosinate treatments was reduced by more than 44% compared to the WFIC and WFNC Palmer amaranth in both experiments. The biomass of Palmer amaranth plants surviving glufosinate was reduced by more than 62% when compared with the WFIC and WFNC in all experiments. The fecundity of Palmer amaranth surviving glufosinate treatments was reduced by more than 73% compared to WFNC Palmer amaranth in all experiments. Remarkably, the plants that survived glufosinate were fecund as WFIC plants only in the Grass Competition experiment. The results prove that despite decreased vegetative growth of Palmer amaranth surviving glufosinate treatment, plants remain fecund and can be fecund as nontreated plants in cotton. These results suggest that a glufosinate-treated grass weed may not have a significant interspecific competition effect on Palmer amaranth that survives glufosinate. Glufosinate should be applied to 5 to 7 cm Palmer amaranth to cease vegetative and reproductive capacities.

Introduction

Palmer amaranth is a pervasive and ubiquitous weed across the southeastern United States (Webster and Grey 2015; Webster and Nichols 2012). Palmer amaranth exhibits relatively fast growth (0.5 to 2.5 cm d^{-1}) and high fecundity (250,000 to 500,000 seeds plant^{-1}) (Mahoney et al. 2021; Sellers et al. 2003a). Because Palmer amaranth is an obligate outcrosser, offspring will be genetically diverse, which could facilitate the survival of weed management tactics (Chandi et al. 2013; Darmency 2018; Owen 2016). Evidence of the rapid adaptation can be seen, as Palmer amaranth has developed resistance to nine unique herbicide groups, and multiple herbicide-resistant populations are common (González-Torralva et al. 2020; Heap 2024; Mahoney et al. 2020). Only a few postemergence herbicides remain effective for Palmer amaranth management in cotton grown in the southeastern United States. If not managed, Palmer amaranth can reduce yield by 54% to 98% in cotton (Morgan et al. 2001; Smith et al. 2000).

Glufosinate is an effective, nonselective, fast-acting contact herbicide that inhibits glutamine synthetase (EC 6.3.1.2; Weed Science Society of America [WSSA] Group 10), resulting in the production of reactive oxygen species that disrupt cell membrane integrity (Takano et al. 2019). Glufosinate is a contact herbicide that must be applied to small plants for adequate coverage. Palmer amaranth control is greatly reduced if glufosinate is applied to plants greater than 10 cm in height (Steckel et al. 1997). Although glufosinate is efficacious, overreliance has led to the evolution of several isolated glufosinate-resistant Palmer amaranth populations (Carvalho-Moore et al. 2022; Jones et al. 2024b; Priess et al. 2022). Although glufosinate is effective on annual broadleaf species, grass control is more variable (Beyers et al. 2002; Bradley et al. 2000; Burke et al. 2005; Culpepper et al. 2000). Additionally, glufosinate has no soil residual activity; weeds emerging later in the season will need to be managed with other tactics (Anonymous 2017; Krausz et al. 1999).

Quantifying the growth and fecundity of Palmer amaranth surviving glufosinate is important to determining interference with the crop and the number of seeds that will have to be managed in subsequent growing seasons (Everman et al. 2007; Page et al. 2012). Palmer amaranth exhibiting reduced growth due to mechanical and herbicide injury can still significantly reduce crop yield, highlighting the importance of quantifying the growth of plants escaping glufosinate (Jones et al. 2024a; Sosnoskie et al. 2014). Previous research demonstrated that large Palmer amaranth (≥10 cm) that survives glufosinate in the vegetative or reproductive stage significantly reduces fecundity (Jha and Norsworthy 2012; Jones et al. 2022; Scruggs et al. 2020). The research reporting the fecundity of Palmer amaranth in the vegetative stage surviving glufosinate did not control grass weeds or later-emerging weeds, while other research reporting the fecundity of surviving Palmer amaranth in the reproductive stage controlled other weeds before applying glufosinate (Jones et al. 2022; Scruggs et al. 2020). Controlling grass and later-emerging weeds could influence the growth and fecundity of Palmer amaranth escaping glufosinate (Qasem and Hill 1994). Previous research quantifying the growth and fecundity of Palmer amaranth that survived glufosinate with and without grass control in soybean [*Glycine max* (L.) Merr.] provided evidence that the interspecific competition had little effect (Jones et al. 2024a). However, the different vegetation architecture and production practices between cotton and soybean could yield dissimilar results. As of time research, the growth and fecundity of vegetative-stage Palmer amaranth that survives glufosinate with and without grass competition have not been documented in cotton. Thus the objective of this research was to quantify the growth and fecundity of Palmer amaranth that survives glufosinate with and without grass competition compared with weedy and weed-free nontreated Palmer amaranth in cotton.

Materials and Methods

Two separate field experiments were conducted in cotton to determine the response of Palmer amaranth growth and fecundity with and without grass competition (hereinafter referred to as the No Grass Competition and Grass Competition experiments) after surviving glufosinate. Each of the experiments was established at two locations, Edgecombe County (35.89°N, 77.68°W [Rocky Mount]) and Johnston County (35.66°N, 78.51°W [Clayton]), NC, during the 2020 growing season. The Rocky Mount site has a soil mosaic of Goldsboro fine sandy loam (fine-loamy, siliceous, subactive, thermic Aquic Paleudult) and Norfolk loamy sand (fine-loamy, kaolinitic, thermic Typic Kandiudult). The Clayton site has a soil mosaic of Norfolk loamy sand (fine-loamy, kaolinitic, thermic Typic Kandiudult), Rains sandy loam (fine-loamy, siliceous, semiactive, thermic Typic Paleaquults), Varina loamy sand (fine, kaolinitic, thermic Plinthic Paleudult), and a Wagram loamy sand (loamy, kaolinitic, thermic Arenic Kandiudult). The Palmer amaranth populations at each experiment location are resistant to acetolactate synthase (EC 2.2.1.6)-inhibiting herbicides (WSSA Group 2) and glyphosate (WSSA Group 9) (Cahoon et al. 2022; Mahoney et al. 2020). The field sites were cultivated and bedded before initiation to control established weeds, but preemergence herbicides were not applied to ensure maximum emergence of weed seedlings for each experiment. The Rocky Mount site and Clayton site was planted on June 9 and June 10, respectively. Cotton cultivar 'DP 1646' resistant to dicamba (WSSA Group 4), glyphosate, and glufosinate (Deltapine®, Bayer Crop Science, St. Louis, MO, USA) was planted on raised beds at a rate of 75,000 seeds ha^{-1} with a row spacing of 91 cm at both locations.

The experimental design for both experiments was a randomized complete block with four replicates. Individual plots were 3.6 m wide × 9.0 m long. Glufosinate treatments were applied at three timings, early postemergence (5-cm-tall Palmer amaranth) (EPOST), mid-postemergence (7- to 10-cm-tall Palmer amaranth) (MPOST), and late postemergence (10- to 20-cm-tall [>10 cm] Palmer amaranth) (LPOST), and at orthogonal combinations of those timings. The three application timings were separated by 7 d. Three additional treatments were included in the experiments for comparison: weedy nontreated control (NTC), weed-free in-crop (WFIC), and weed-free no-crop (WFNC), for a total of 10 treatments. The WFIC and WFNC plots were sprayed at the EPOST timing, but 10 Palmer amaranth plants were arbitrarily selected and covered with plastic cups to serve as a physical barrier from spray droplets before herbicide application. The WFIC and WFNC plots were hand weeded weekly after that. Glufosinate was applied with a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} at 165 kPa with TeeJet® XR110002 flat-fan nozzles (TeeJet® Technologies, Wheaton, IL, USA) 46 cm above the target weed height. Glufosinate was applied at a rate of 590 g ai ha^{-1} with 10 g L^{-1} ammonium sulfate at all timings. Glufosinate was applied at ±2 h of solar noon and temperatures above 30 C with relative humidity greater than 30% to avoid environment-induced control reductions (Coetzer et al. 2001; Sellers et al. 2003b). *S*-metolachlor (1,071 g ai ha^{-1}) was applied to all plots (excluding the nontreated plots) using the described application methods 3 d after the LPOST application to control later-emerging weeds and mitigate confounding effects of inter- and intraspecific competition on growth and fecundity not attributable to plants that survived glufosinate in both experiments. In the No Grass Competition experiments, clethodim (280 g ai ha^{-1}) was applied to all plots (excluding the nontreated plots) using the application methods described 10 d after the LPOST application to avoid antagonism (Burke et al. 2005). Palmer amaranth control was visually estimated 35 d after treatment (DAT) using a 0% to 100% scale, where 0% equals no control and 100% equals complete control. Palmer amaranth plants that emerged after glufosinate applications were not rated because glufosinate has no soil residual activity (Krausz et al. 1999). Density counts (plants 0.25 m^{-2}) by species were recorded 35 DAT in both experiments.

Palmer amaranth plants that survived glufosinate were marked with a flag (10 plants plot^{-1}). Plants were visually inspected for herbicide damage before flagging (i.e., chemical excisions, leaf necrosis, meristem regrowth). Ten Palmer amaranth plants were arbitrarily selected in the NTC, WFIC, and WFNC plots for data collection. Weekly measurements of plant apical height and canopy circumference (widest point) were recorded on the flagged plants from 1 wk until 6 wk after treatment (WAT). Circumference was measured as a metric for apical dominance (Cline 1997). At the end of the season, three surviving female Palmer amaranth plants (if present) were collected from each plot. If no flagged female Palmer amaranth plants remained in a plot, additional plants were selected that indicated the plant had survived a glufosinate application. Harvested plants were placed in a drier at 60 C for 72 h. After drying, the plants were weighed to determine biomass. Following drying, the plants were threshed by hand to remove

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seeds from the florets, and seeds were separated from plant residues using sieves and a forced air column separator (South Dakota Seed Blower, Seedburo Equipment Company, Chicago, IL, USA). Visual inspections (e.g., crush test) during the cleaning process determined whether seeds were viable or nonviable (Sawma and Mohler 2002). A small number of aborted seeds were separated out along with the plant residue prior to final fecundity testing. Samples were cleaned a second time with forced air to further remove plant residue. The total number of seeds produced by each female plant was extrapolated by determining the mass of five 100-seed subsamples for each treatment (Sellers et al. 2003a). The total number of seeds produced was calculated using Equation 1:

$$T = \left(\frac{W}{S}\right) * 100 \quad [1]$$

where W equals the total seed mass, S equals the average mass of the five 100-seed subsamples, and T equals the calculated number of seeds produced.

Owing to severe weed infestations and limited boll production, cotton yield was estimated after female Palmer amaranth plants were harvested (Smith et al. 2000). All harvestable bolls were counted in a 3-m row within the plots. Fifty bolls within the counted row were collected and weighed to determine an average boll weight for each treatment. The cotton yield was estimated using the equation provided by Goodman and Monks (2003):

$$y = \frac{[(a)^*(b)^*(c)]}{(r)^*k} \quad [2]$$

where y equals estimated yield, a equals grams boll^{-1}, b equals bolls 3 m row^{-1}, c equals the percentage of lint in seed cotton, r equals row spacing in centimeters, and k equals a constant to convert the grams per meter per row into kilograms per hectare. The equation assumes 100% harvest efficiency with 38% lint in seed cotton. The weedy nontreated plots were not harvested due to severe weed infestations ceasing boll production. The WFIC plots were not harvested, as the yield information would not provide any useful information.

Statistical Analysis

Palmer amaranth control, growth, fecundity, and estimated cotton yield data from both experiments were subjected to an analysis of variance using the GLIMMIX procedure with SAS 9.4 (SAS Institute, Cary, NC, USA), where $\alpha = 0.05$. Location and application timing were considered fixed effects, while replication was considered random. Palmer amaranth growth rate, biomass, control, and fecundity means were separated using Tukey's honestly significant difference test ($P \leq 0.05$). Palmer amaranth control data from nontreated plots and treatments that incurred complete control (e.g., 100% control) were excluded from statistical analysis to not violate the constant variance assumption of analysis of variance. Ninety-five percent confidence intervals were calculated to determine whether any treatment was like the treatments excluded from the analysis.

Palmer amaranth apical and circumferential growth throughout the growing season was modeled using a four-parameter Gompertz equation in SigmaPlot 14.0 (Systat Software, San Jose, CA, USA):

$$y = y_0 + a^{\left[-\frac{(x - x_0)}{b}\right]} \quad [3]$$

where y equals growth, y_0 equals the y intercept, a equals an upper asymptote, x equals the time in weeks, x_0 equals the x intercept, and b equals the slope at x. If apical or circumferential growth did fit the four-parameter Gompertz equation, the growth was modeled with a linear equation using SigmaPlot:

$$y = y_0 + a^* x \quad [4]$$

where y equals growth, y_0 equals the y intercept, a equals the slope, and x equals time in weeks. Regression parameters for the apical and circumferential growth are provided in Tables 1 and 2.

Results and Discussion

Palmer Amaranth Control Following Glufosinate Application Timings

No Grass Competition Experiment

Palmer amaranth control was affected by application timing ($P < 0.0001$), but neither location ($P = 0.75$) nor the interaction ($P = 0.99$) was significant; thus control data were analyzed by application timing averaged over location. Palmer amaranth control with the EPOST and sequential applications was greater than 95% (Table 3). Control was reduced when glufosinate applications were made at the MPOST and LPOST timings (≤79%) and were less effective compared with the EPOST and sequential applications (Table 3). Palmer amaranth control in this study with various glufosinate application timings resulted in similar responses to those found in previous studies (Coetzer et al. 2002; Everman et al. 2007; Randell et al. 2020). Clethodim effectively controlled all grass species that were not controlled by glufosinate, as demonstrated by no to minimal plants being present in the treated plots (Table 4).

Grass Competition Experiment

Palmer amaranth control was affected by application timing ($P < 0.0001$), but neither the location ($P = 0.37$) nor the interaction ($P = 0.57$) was significant; thus control data were analyzed by application timing averaged over location. Grass weed composition differed between Clayton and Rocky Mount; where large crabgrass [*Digitaria sanguinalis* (L.) Scop.] was present at Clayton, goosegrass [*Eleusine indica* (L.) Gaertn.], large crabgrass, and Texas panicum (*Panicum texanum* Buckley) were present at Rocky Mount (Table 4). Bermudagrass [*Cynodon dactylon* (L.) Pers.] was present only in soybean at Rocky Mount (Table 4).

EPOST and sequential glufosinate applications provided the highest Palmer amaranth control (greater than 95%), while the MPOST and LPOST applications on larger Palmer amaranth were less effective (no greater than 85%) (Table 3). These results align with the No Grass Competition experiment and the aforementioned studies investigating glufosinate efficacy on various weed sizes (Jones et al. 2024a). Lack of grass control with the MPOST and LPOST glufosinate treatments was evident, but the grass weed densities differed across locations, with greater grass weed density at Clayton compared with Rocky Mount (Table 4).

Table 1. Regression parameters from the four-parameter Gompertz equation to model apical and canopy circumference growth of Palmer amaranth treated with glufosinate from the No Grass Competition experiments conducted in cotton at Clayton and Rocky Mount, NC.[a]

		Apical regression parameters					Canopy circumference regression parameters				
Location	Treatment	*a*	*b*	x_0	y_0	r^2	*a*	*b*	x_0	y_0	r^2
Clayton	NTC	65.89	0.26	3.06	17.57	0.98	11.96	0.04	3.05	23.81	0.68
	WFNC	238.00	1.98	2.91	1.93	0.99	103.7	0.42	2.22	58.49	0.88
	WFIC	251.28	2.03	3.2	4.41	0.99	57.97	0.37	2.05	51.68	0.91
	EPOST	21.29	0.58	3.3	2.55	0.99	—	—	—	—	0.10
	MPOST	81.98	1.86	5.21	8.15	0.99	15.66	0.04	3.02	16.51	0.75
	LPOST	21.58	0.64	4.59	13.48	0.99	20.11	0.02	4.10	22.33	0.96
Rocky Mount	NTC	40.78	0.04	3.01	12.49	0.94	—	—	—	—	0.19
	WFNC	160.25	1.48	3.1	8.88	0.99	128.68	0.87	2.27	39.83	0.99
	WFIC	123.81	1.46	3.51	10.15	0.99	64.08	0.62	2.36	32.67	0.88
	MPOST	27.16	0.71	4.81	6.84	0.99	14.44	0	4.14	18.68	0.99
	LPOST	—[b]	—	—	—	0.75	17.73	0.01	4.14	28.31	0.71

[a]Abbreviations: EPOST, early postemergence (5 cm); LPOST, late postemergence (>10 cm); MPOST, mid-postemergence (7 to 10 cm); NTC, nontreated; WFIC, weed-free nontreated in-crop; WFNC, weed-free nontreated no-crop.
[b]Growth was best modeled with a linear equation. Apical growth: Palmer amaranth surviving the LPOST application in cotton at Rocky Mount, NC, $y = 6.8 + 3.1 * x$. Circumference growth: Palmer amaranth surviving the EPOST application at Clayton, NC, $y = 9.4 + 0.9 * x$. Palmer amaranth under NTC conditions at Rocky Mount, NC, $y = 27.8 + 8.2 * x$.

Table 2. Regression parameters from the four-parameter Gompertz equation to model apical and canopy circumference growth of Palmer amaranth treated with glufosinate from the Grass Competition experiments conducted in cotton at Clayton and Rocky Mount, NC.[a]

		Apical regression parameters					Canopy circumference regression parameters				
Location	Treatment	*a*	*b*	x_0	y_0	r^2	*a*	*b*	x_0	y_0	r^2
Clayton	NTC	111.68	1.23	3.28	17.22	0.98	7.14	0.01	3.23	29.87	0.47
	WFNC	191.25	1.51	2.56	8.02	0.99	132.27	0.52	2.28	60.54	0.8
	WFIC	151.05	1.23	2.76	18.58	0.99	72.04	0.36	1.97	43.88	0.74
	MPOST	32.2	0.23	4.76	12.19	0.99	—[b]	—	—	—	0.001
	LPOST	242.22	1.92	6.72	15.25	0.99	33.04	0.98	4.9	29.01	0.99
Rocky Mount	NTC	42.27	0.03	3.02	12.59	0.82	68.37	1.52	−1.79	−32.08	0.76
	WFNC	153.63	1.38	3.09	8.79	0.99	116.89	0.65	2.23	38.63	0.93
	WFIC	76.11	0.45	3.09	15.42	0.93	47.2	0.43	2.03	32.81	0.55
	MPOST	30.55	0.07	4.01	8.18	0.99	17.26	0.52	3.79	20.21	0.84
	LPOST	15.03	0.05	0.95	−1.48	0.37	6.08	0.04	4.14	26.89	0.35

[a]Abbreviations: EPOST, early postemergence (5 cm); LPOST, late postemergence (>10 cm); MPOST, mid-postemergence (7 to 10 cm); NTC, nontreated; WFIC, weed-free nontreated in-crop; WFNC, weed-free nontreated no-crop.
[b]Growth was best modeled with a linear equation. Circumference growth: Palmer amaranth surviving the MPOST application in cotton at Clayton, NC, $y = 24.1 - 0.1 * x$.

Growth and Fecundity of Palmer Amaranth Surviving Glufosinate

No Grass Competition Experiment

Because no Palmer amaranth plants survived sequential applications of glufosinate, the growth and fecundity cannot be reported. Significant main effects and interactions ($P < 0.0001$) were detected; thus apical and circumference growth were analyzed by location and treatment.

Apical growth. The Palmer amaranth plants growing under WFIC and WFNC conditions exhibited the greatest apical growth rate, followed by Palmer amaranth under NTC conditions and Palmer amaranth that survived glufosinate at both locations (Figure 1; Tables 1 and 5). Interestingly, differences in apical growth were observed at Rocky Mount for Palmer amaranth in the WFNC and the WFIC, but no differences were observed between these conditions at Clayton. These results suggest that the apical growth of Palmer amaranth is affected by cotton competition and varies under different environmental conditions, agreeing with Patterson (1995). A similar growth rate was observed for Palmer amaranth plants growing in the NTC when compared with the Palmer amaranth surviving glufosinate at both locations, which was likely attributable to the high levels of inter- and intraspecific competition within the plot, agreeing with Adler et al. (2018) (Figure 1; Table 4). Palmer amaranth plants that survived glufosinate grew at the same rate, regardless of application timing, at both locations (Figure 1; Tables 1 and 5). Palmer amaranth plants that survived glufosinate at Clayton and Rocky Mount resumed apical growth at 1 to 2 and 1 to 3 WAT, respectively (Figure 1). Average final height reductions for Palmer amaranth that survived glufosinate at Clayton were more than 75% compared to the nontreated Palmer amaranth plants grown under weed-free (WFIC and WFNC) conditions (Figure 1). Average final height reductions for Palmer amaranth that survived glufosinate at Rocky Mount were more than 74% compared to the Palmer amaranth plants grown under WFIC and WFNC conditions (Figure 1).

Canopy circumference growth. Palmer amaranth circumferential growth rate was not different for plants growing under NTC conditions and those surviving glufosinate applications. However, they were different for those grown under WFIC and WFNC

Table 3. Palmer amaranth control with glufosinate (590 g ai ha^{-1}) from the No Grass and Grass Competition experiments conducted in cotton at Clayton and Rocky Mount, NC, 35 d after treatment (DAT).[a,b,c]

Treatment	No Grass Competition		Grass Competition	
	% (SE)			
EPOST	99 (1)	a	100 (0)	a
POST	79 (9)	ab	85 (4)	b
LPOST	69 (5)	b	70 (3)	b
EPOST fb POST	100 (0)	a	100 (0)	a
EPOST fb LPOST	100 (0)	a	100 (0)	a
POST fb LPOST	100 (0)	a	100 (0)	a
EPOST fb POST fb LPOST	100 (0)	a	100 (0)	a

[a]Abbreviations: EPOST, early postemergence (5 cm); fb, followed by; MPOST, mid-postemergence (7 to 10 cm); LPOST, late postemergence (>10 cm).
[b]Values followed by the same letter within columns are not different according to Tukey's HSD ($P \leq 0.05$).
[c]Treatments that violated the constant variance assumption were not included in the analysis, but 95% confidence intervals were used to determine whether values were similar.

Table 4. Weed species density with various glufosinate treatments from the No Grass and Grass Competition experiments conducted in cotton and soybean at Clayton and Rocky Mount, NC, 35 DAT.[a]

Location	Treatment	AMAPA	DIGSA	ELEIN	PANDI
		plants 0.25 m^{-2}			
No Grass Competition					
Clayton	NTC	29	50	—[b]	—
	EPOST	1	0	—	—
	MPOST	3	3	—	—
	LPOST	9	0	—	—
Rocky Mount	NTC	25	4	4	1
	EPOST	0	0	0	0
	MPOST	4	0	0	0
	LPOST	10	0	0	0
Grass Competition					
Clayton	NTC	24	36	—	—
	EPOST	0	0	—	—
	MPOST	3	7	—	—
	LPOST	11	8	—	—
Rocky Mount	NTC	34	2	6	2
	EPOST	0	0	0	0
	MPOST	6	0	2	0
	LPOST	7	0	2	1

[a]Abbreviations: AMAPA, Palmer amaranth; DIGSA, large crabgrass; ELEIN, goosegrass; EPOST, early postemergence (5 cm); LPOST, late postemergence (>10 cm); MPOST, mid-postemergence (7 to 10 cm); NTC, nontreated control; PANDI, Texas panicum.
[b]Species was not present.

conditions (Figure 2; Tables 1 and 5). The greatest circumferential growth rate was observed for the Palmer amaranth plants grown under WFNC conditions, followed by the plants under WFIC conditions, with the lowest growth rate observed for plants grown under NTC conditions and Palmer amaranth that survived glufosinate at both locations (Figure 2; Tables 1 and 5). The differential circumferential growth between Palmer amaranth plants growing under WFNC and WFIC suggests that a cotton crop imparted a measurable competition effect. Growth of Palmer amaranth plants that survived glufosinate at the MPOST and LPOST applications at Clayton ceased for 2 WAT, with growth resuming thereafter; however, new growth ceased for plants surviving the EPOST application (Figure 2). Palmer amaranth plants that survived glufosinate at the MPOST and LPOST applications at Rocky Mount did not resume circumference growth until 2 and 1 WAT, respectively (Figure 2). The average final circumferential reduction of Palmer amaranth that survived glufosinate was more than 56% and 65% compared with the Palmer amaranth plants under WFIC and WFNC conditions, respectively, at Clayton (Figure 2). Similarly, at Rocky Mount, the average final circumference reduction of Palmer amaranth that survived glufosinate was 59% and 80% compared with the Palmer amaranth plants under WFIC and WFNC conditions, respectively (Figure 2).

Accumulated female biomass. Palmer amaranth female biomass was affected by application ($P < 0.0001$) but not by location ($P = 0.75$). The interaction between the main effects ($P = 0.03$) was significant; therefore biomass data were analyzed by location and treatment.

The trends for biomass accumulation followed those observed with growth measurements where Palmer amaranth with the greatest biomass grew under WFNC conditions and were significantly greater than those grown under WFIC conditions at both locations (Table 6). The biomass of Palmer amaranth that survived glufosinate and plants growing under NTC conditions were not different at both locations as well (Table 6). The average biomass reduction of Palmer amaranth surviving glufosinate treatments was 87% and 93% compared with the Palmer amaranth plants under WFIC and WFNC conditions at Clayton, respectively, with similar results observed at Rocky Mount (62% and 92%, respectively). Differences in end-of-season biomass reinforced the effect cotton had on Palmer amaranth, with a 55% reduction in biomass when cotton was present in WFIC conditions compared with plants grown under WFNC conditions. Additionally, competition with other weeds and cotton under the NTC conditions reduced Palmer amaranth biomass to levels similar to those of plants that survived glufosinate applications.

Fecundity. The fecundity of Palmer amaranth was affected by application ($P < 0.0001$) but not location ($P = 0.2$). Although the interaction was nonsignificant ($P = 0.84$), fecundity data were analyzed by treatment and location because Palmer amaranth survived the EPOST application at Clayton.

Seed size did not differ among Palmer amaranth plants grown under WFNC or WFIC conditions or among those that survived glufosinate at Clayton. However, seeds from NTC conditions were smaller (Table 7). Seed size was not different across treatments at Rocky Mount (Table 7). The Palmer amaranth under WFNC conditions was the most fecund, followed by plants under WFIC conditions at both locations, being significantly greater than all other treatments (Table 7). Palmer amaranth that survived EPOST and MPOST application at Clayton were more fecund (1,326 to 2,537 seeds plant^{-1}) than plants under NTC conditions and those that survived the LPOST application (8,442 to 411,150 seeds plant^{-1}) (Table 7). The average fecundity reduction for Palmer amaranth surviving glufosinate was more than 73% and 91% compared with Palmer amaranth under WFIC and WFNC conditions at Clayton, respectively (Table 7). The fecundity of Palmer amaranth that survived glufosinate did not differ across application timing or grown under NTC conditions at Rocky Mount (4,525 to 6,861 seeds plant^{-1}) (Table 7). The average fecundity reduction for Palmer amaranth surviving glufosinate was 81% and 93% compared with Palmer amaranth under WFIC and WFNC conditions at Rocky Mount, respectively (Table 7). Fecundity data reinforced biomass data, suggesting greater competition in a cotton crop than for Palmer amaranth grown

Table 5. Apical and canopy circumference growth rates of Palmer amaranth treated with glufosinate from the No Grass and Grass Competition experiments conducted in cotton at Clayton and Rocky Mount, NC.[a,b]

Treatment	Apical growth				Circumference growth			
	Clayton		Rocky Mount		Clayton		Rocky Mount	
	cm wk^{-1} (±SE)							
No Grass Competition								
NTC	16 (2.2)	b	11 (1.9)	c	6 (1.0)	c	6 (0.3)	c
WFNC	29 (3.0)	a	21 (2.0)	a	30 (2.0)	a	30 (2.8)	a
WFIC	34 (1.2)	a	16 (1.8)	b	20 (1.4)	b	15 (1.5)	b
EPOST	6 (3.0)	c	NS		2 (1.2)	c	NS	
MPOST	10 (2.7)	bc	4 (1.2)	d	5.2 (1.6)	c	6 (1.7)	c
LPOST	5 (1.2)	c	7 (2.0)	d	7 (1.2)	c	7 (0.5)	c
EPOST fb MPOST	NS		NS		NS		NS	
EPOST fb LPOST	NS		NS		NS		NS	
MPOST fb LPOST	NS		NS		NS		NS	
EPOST fb MPOST fb LPOST	NS		NS		NS		NS	
Grass Competition								
NTC	20 (1.4)	b	9 (0.6)	bc	5 (0.2)	c	6 (0.1)	b
WFNC	30 (18.8)	a	26 (14.1)	a	31 (3.1)	a	28 (2.4)	a
WFIC	26 (15.3)	a	17 (12.5)	b	17 (2.6)	b	13 (1.8)	b
EPOST	NS		NS		NS		NS	
POST	15 (7.9)	b	7 (5.5)	cd	9 (0.1)	c	6 (0.5)	b
LPOST	12 (2.5)	b	3 (5.3)	d	9 (0.4)	c	6 (0.4)	b
EPOST fb POST	NS		NS		NS		NS	
EPOST fb LPOST	NS		NS		NS		NS	
POST fb LPOST	NS		NS		NS		NS	
EPOST fb MPOST fb LPOST	NS		NS		NS		NS	

[a]Abbreviations: EPOST, early postemergence (5 cm); fb, followed by; LPOST, late postemergence (>10 cm); MPOST, mid-postemergence (7 to 10 cm); NS, no survivors; NTC, nontreated; WFIC, weed-free nontreated in-crop; WFNC, weed-free nontreated no-crop.
[b]Values followed by the same letter within columns for the No Grass and Grass Competition experiments are not different according to Tukey's HSD ($P \leq 0.05$).

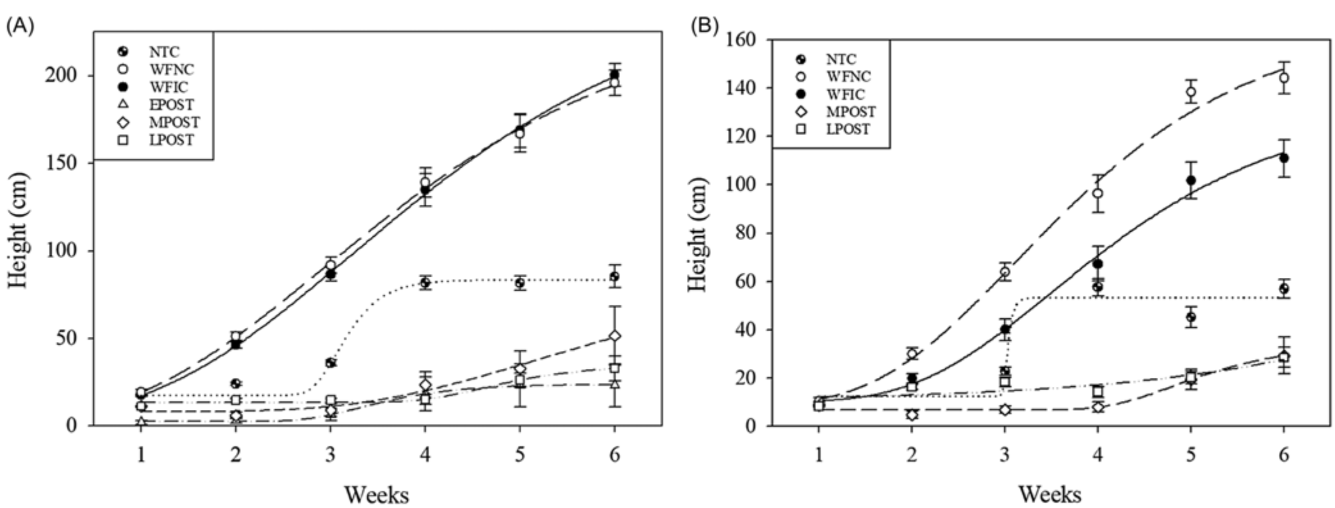

Figure 1. Apical growth of Palmer amaranth plants treated with glufosinate from the No Grass Competition experiments conducted in cotton at Clayton (A) and Rocky Mount (B), NC. Apical growth was modeled with a four-parameter Gompertz equation, except for the Palmer amaranth plants surviving the LPOST application at Rocky Mount, which were modeled with a linear equation. Abbreviations: EPOST, early postemergence (5 cm); LPOST, late postemergence (>10 cm); MPOST, mid-postemergence (7 to 10 cm); NTC, nontreated; WFIC, weed-free nontreated in-crop; WFNC, weed-free nontreated no-crop.

without a crop. The presence of weedy competition resulted in seed production similar to that of plants surviving glufosinate.

Grass Competition Experiment

Because no Palmer amaranth plants survived EPOST and sequential applications of glufosinate in either location, the growth and fecundity cannot be reported. Significant main effects and interactions ($P < 0.0001$) were detected; thus apical and circumference growth were analyzed by location and treatment.

Apical growth. The Palmer amaranth plants grown under WFIC and WFNC conditions exhibited the greatest apical growth rate at Clayton, while plants under WFNC conditions exhibited the greatest growth followed by the plants under WFIC at Rocky Mount (Figure 3; Tables 2 and 5). A similar growth rate was observed for Palmer amaranth plants growing under NTC conditions when compared with the Palmer amaranth that survived glufosinate at both locations (Figure 3; Tables 2 and 5). These results are similar to those from the No Grass Competition

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Table 6. Biomass of Palmer amaranth treated with glufosinate from the No Grass and Grass Competition experiments conducted in cotton at Clayton and Rocky Mount, NC.[a,b]

	No Grass Competition					
Treatment	Clayton		Rocky Mount		Grass Competition	
	g plant^{-1} (±SE)					
NTC[a]	22 (9)	c	52 (3)	c	41 (2)	c
WFNC	342 (57)	a	491 (118)	a	554 (120)	a
WFIC	190 (39)	b	104 (20)	b	97 (14)	b
EPOST	27 (9)	c	NS		NS	
POST	25 (8)	c	45 (6)	c	23 (5)	c
LPOST	26 (5)	c	34 (3)	c	48 (5)	c
EPOST fb POST	NS		NS		NS	
EPOST fb LPOST	NS		NS		NS	
POST fb LPOST	NS		NS		NS	
EPOST fb POST fb LPOST	NS		NS		NS	

[a]Abbreviations: EPOST, early postemergence (5 cm); fb, followed by; LPOST, late postemergence (>10 cm); MPOST, mid-postemergence (7 to 10 cm); NS, no survivors; NTC, nontreated; WFIC, weed-free nontreated in-crop; WFNC, weed-free nontreated no-crop.
[b]Values followed by the same letter within columns are not different according to Tukey's HSD (α ≤ 0.05).

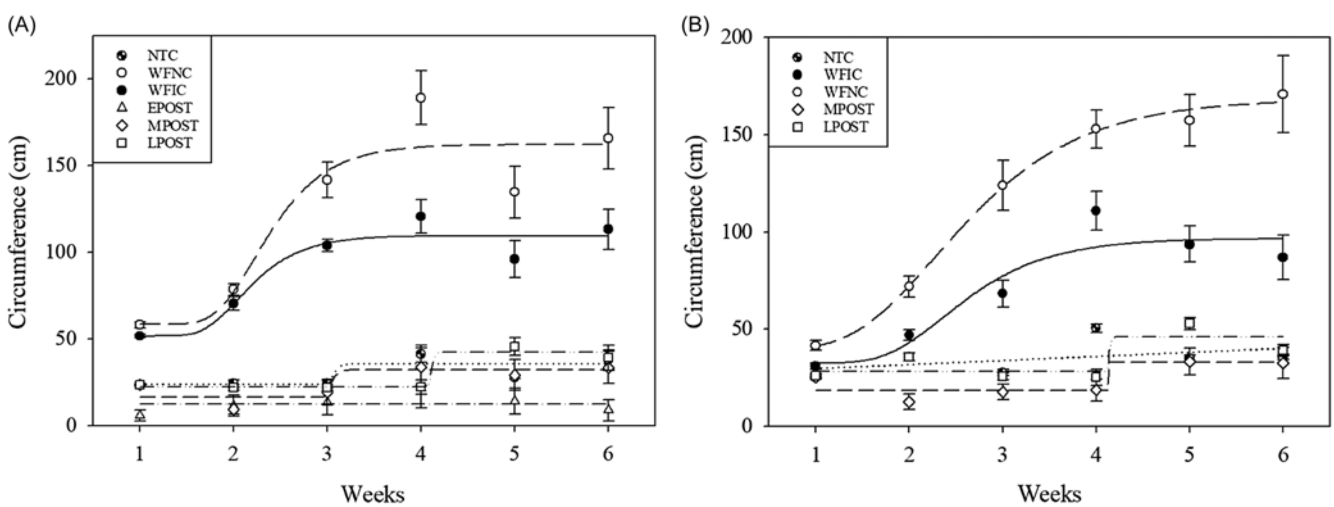

Figure 2. Canopy circumferential growth of Palmer amaranth plants treated with glufosinate from the No Grass Competition experiments conducted in cotton at Clayton (A) and Rocky Mount (B), NC. Circumferential growth was modeled with a four-parameter Gompertz equation, except for the Palmer amaranth plants surviving the EPOST application at Clayton and plants under NTC conditions at Rocky Mount, which were modeled with a linear equation. Abbreviations: EPOST, early postemergence (5 cm); LPOST, late postemergence (>10 cm); MPOST, mid-postemergence (7 to 10 cm); NTC, nontreated; WFIC, weed-free nontreated in-crop; WFNC, weed-free nontreated no-crop.

experiment, further suggesting that the apical growth of Palmer amaranth is affected by cotton competition and varies under different environmental conditions (Patterson 1995). Palmer amaranth plants that survived glufosinate at both locations did not resume apical growth until 2 WAT; however, the plants that survived the LPOST application at Rocky Mount did not resume growth (Figure 3). The average final height reduction for Palmer amaranth surviving glufosinate was more than 54% and 60% when compared with Palmer amaranth plants under WFIC and WFNC conditions at Clayton, respectively (Figure 3). The average final height reduction for Palmer amaranth surviving glufosinate was more than 50% and 73% when compared with Palmer amaranth under WFIC and WFNC conditions at Rocky Mount, respectively (Figure 3).

Canopy circumference growth. Growth rate trends for circumference were similar to the apical growth rates for Palmer amaranth of each treatment within the respective location (Figure 4; Tables 2 and 5). These results further highlight the effect of cotton competition on Palmer amaranth vegetative growth. Palmer amaranth that survived glufosinate at the LPOST application did not resume circumferential growth until 1 WAT, and plants that survived glufosinate at the MPOST application never resumed growth at Clayton (Figure 4). Palmer amaranth that survived glufosinate did not resume circumferential growth until 2 WAT at Rocky Mount (Figure 4). The average final circumference reduction for Palmer amaranth surviving glufosinate was more than 49% and 86% when compared with the Palmer amaranth plants under WFIC and WFNC conditions at Clayton, respectively (Figure 4). Similarly, at Rocky Mount, the average final circumference reduction for Palmer amaranth surviving glufosinate was more than 44% and 72% when compared with the plants under WFIC and WFNC conditions at Rocky Mount, respectively (Figure 4).

Accumulated female biomass. Palmer amaranth female biomass was affected by treatment ($P < 0.0001$), but neither the location ($P = 0.68$) nor the interaction ($P = 0.98$) was significant; thus

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Table 7. Seed mass and fecundity of Palmer amaranth treated with glufosinate from the No Grass and Grass Competition experiments conducted in cotton at Clayton and Rocky Mount, NC.[a,b]

Treatment	Seed mass				Fecundity			
	Clayton		Rocky Mount		Clayton		Rocky Mount	
	g 100 seeds^{-1} (±SE)				seeds plant^{-1} (±SE)			
No Grass Competition								
NTC	0.024 (0.0003)	c	0.037 (0.006)		1,326 (392)	d	7,989 (1,492)	c
WFNC	0.032 (0.0004)	ab	0.031 (0.0005)		108,185 (5,015)	a	139,226 (38,207)	a
WFIC	0.032 (0.0007)	a	0.031 (0.0003)		36,005 (5,015)	b	51,387 (18,959)	b
EPOST	0.030 (0.0005)	b	NS		8,422 (3,575)	c	NS	
MPOST	0.030 (0.0006)	ab	0.030 (0.0003)		11,150 (3,972)	c	7,647 (2,280)	c
LPOST	0.031 (0.0004)	ab	0.030 (0.0002)		2,537 (756)	d	13,494 (9,110)	c
EPOST fb MPOST	NS		NS		NS		NS	
EPOST fb LPOST	NS		NS		NS		NS	
MPOST fb LPOST	NS		NS		NS		NS	
EPOST fb MPOST fb LPOST	NS		NS		NS		NS	
Grass Competition								
NTC	0.030 (0.0006)	bc	0.033 (0.0006)	b	5,295 (826)	b	5,706 (1,989)	b
WFNC	0.030 (0.0004)	b	0.031 (0.0003)	b	88,554 (14,627)	a	165,139 (44,401)	a
WFIC	0.032 (0.0004)	ab	0.033 (0.0004)	b	31,890 (4,767)	b	32,275 (11,558)	b
EPOST	NS		NS		NS		NS	
MPOST	0.033 (0.0004)	a	0.032 (0.001)	b	3,140 (1,489)	b	5,549 (1,712)	b
LPOST	0.033 (0.0004)	a	0.036 (0.0001)	a	15,680 (5,567)	b	8,302 (2,188)	b
EPOST fb MPOST	NS		NS		NS		NS	
EPOST fb LPOST	NS		NS		NS		NS	
MPOST fb LPOST	NS		NS		NS		NS	
EPOST fb MPOST fb LPOST	NS		NS		NS		NS	

[a]Abbreviations: EPOST, early postemergence (5 cm); fb, followed by; LPOST, late postemergence (>10 cm); MPOST, mid-postemergence (7 to 10 cm); NS, no survivors; NTC, nontreated; WFIC, weed-free nontreated in-crop; WFNC, weed-free nontreated no-crop.
[b]Values followed by the same letter within columns for the No Grass and Grass Competition experiments are not different according to Tukey's HSD ($P \leq 0.05$).

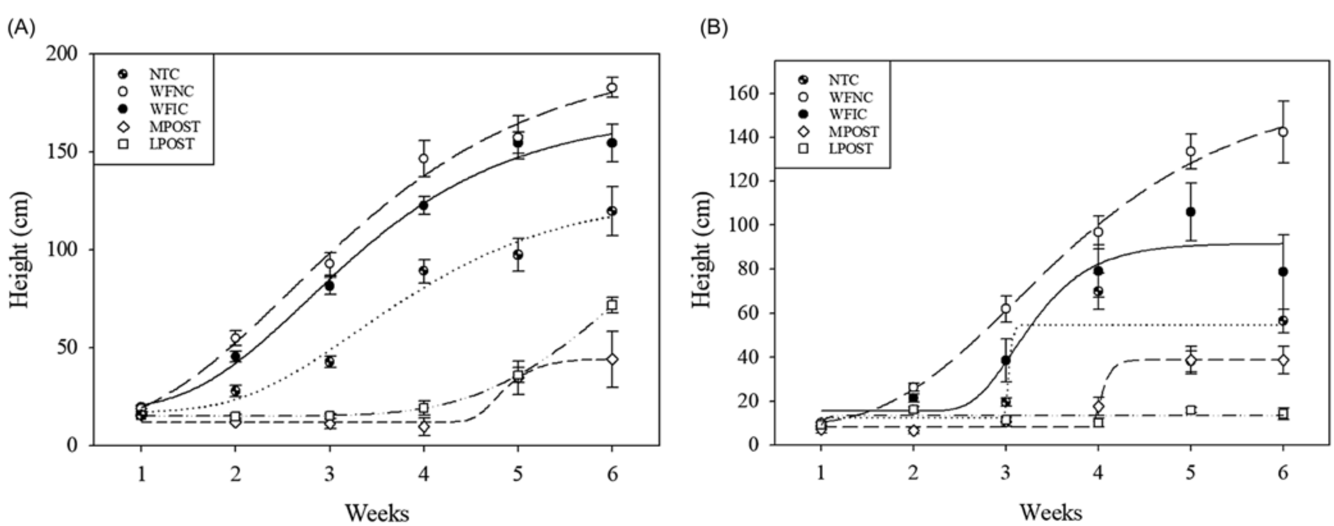

Figure 3. Apical growth of Palmer amaranth plants treated with glufosinate from the Grass Competition experiments conducted in cotton at Clayton (A) and Rocky Mount (B), NC. Apical growth was modeled with a four-parameter Gompertz equation. Abbreviations: EPOST, early postemergence (5 cm); LPOST, late postemergence (>10 cm); MPOST, mid-postemergence (7 to 10 cm); NTC, nontreated; WFIC, weed-free nontreated in-crop; WFNC, weed-free nontreated no-crop.

biomass data were analyzed by application timing averaged over location. Palmer amaranth biomass across locations and treatments was nearly identical to the No Grass Competition experiment as described earlier (Table 6). The average biomass reduction of Palmer amaranth that survived glufosinate was 62% and 92% compared with WFIC and WFNC Palmer amaranth, respectively (Table 6). These results further enforce the effect of cotton competition on Palmer amaranth biomass.

Fecundity. Palmer amaranth fecundity was affected by application timing ($P < 0.0001$) but not by location ($P = 0.1$). The interaction between the main effects was significant ($P = 0.02$); thus fecundity data were analyzed by location and application.

Palmer amaranth that survived glufosinate had the largest seeds, followed by plants under WFIC, WFNC, and NTC conditions, at Clayton (Table 7). Palmer amaranth that survived glufosinate at the LPOST application produced the largest seed

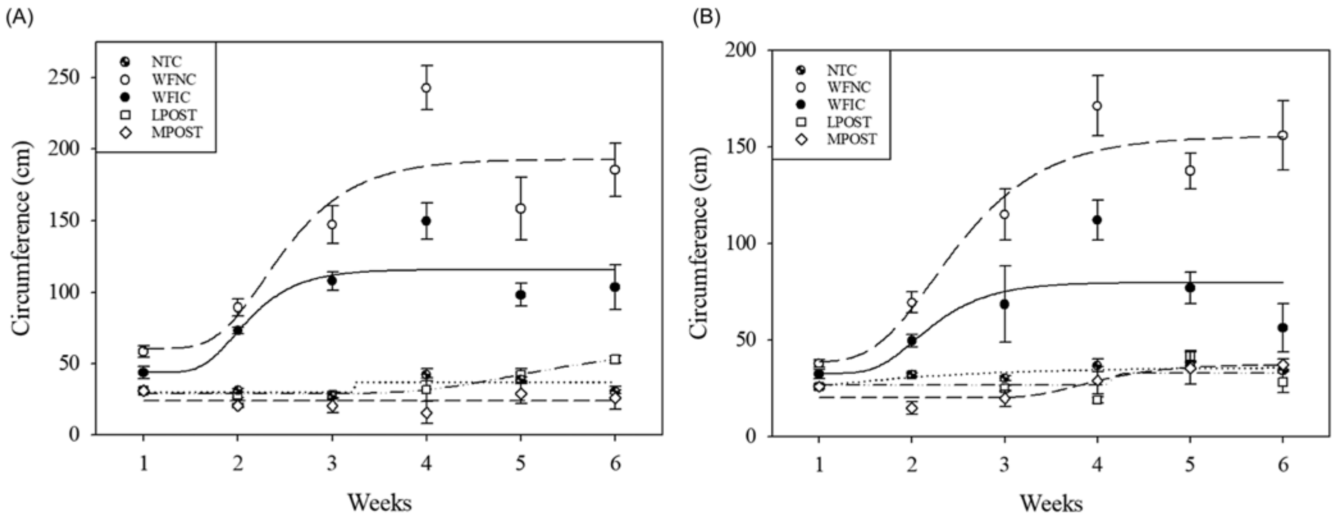

Figure 4. Canopy circumferential growth of Palmer amaranth plants treated with glufosinate from the Grass Control experiments conducted in cotton at Clayton (A) and Rocky Mount (B), NC. Circumferential growth was modeled with a four-parameter Gompertz equation, except for the Palmer amaranth plants surviving the MPOST application at Clayton, which were modeled using a linear equation. Abbreviations: EPOST, early postemergence (5 cm); LPOST, late postemergence (>10 cm); MPOST, mid-postemergence (7 to 10 cm); NTC, nontreated; WFIC, weed-free nontreated in-crop; WFNC, weed-free nontreated no-crop.

Table 8. Cotton lint yield estimates with various glufosinate treatments from the No Grass Competition experiments conducted in Clayton and Rocky Mount, NC.[a,b]

Treatment	Cotton lint yield		
	Clayton	Rocky Mount	
	kg ha^{-1} (±SE)		
EPOST	6.2 (2.2)	26.0 (4.4)	ab
MPOST	0 (0)	12. (2.3)	bc
LPOST	0.6 (0.6)	4.3 (1.5)	c
EPOST fb MPOST	8.1 (2.7)	28.9 (3.4)	a
EPOST fb LPOST	6.6 (2.7)	28.2 (2.8)	a
MPOST fb LPOST	6.4 (1.8)	16.0 (5.4)	a–c
EPOST fb MPOST fb LPOST	5.2 (2.5)	29.7 (1.0)	a

[a]Abbreviations: EPOST, early postemergence (5 cm); fb, followed by; LPOST, late postemergence (>10 cm); MPOST, mid-postemergence (7 to 10 cm).
[b]Values followed by the same letter within columns are not different according to Tukey's HSD ($P \leq 0.05$).

Table 9. Cotton lint yield estimates with various glufosinate treatments from the Grass Competition experiments conducted in Clayton and Rocky Mount, NC.[a,b]

Treatment	Cotton lint yield		
	Clayton	Rocky Mount	
	kg ha^{-1} (±SE)		
EPOST[a]	5.7 (2.0)	24.1 (2.6)	ab
MPOST	2.1 (2.1)	12.0 (2.2)	b
LPOST	6.4 (2.6)	8.8 (3.5)	b
EPOST fb MPOST	7.0 (2.7)	28.8 (1.6)	a
EPOST fb LPOST	3.2 (2.6)	27.8 (2.2)	a
MPOST fb LPOST	3.2 (1.9)	21.3 (8.1)	ab
EPOST fb MPOST fb LPOST	6.0 (0.9)	29.6 (4.5)	a

[a]Abbreviations: EPOST, early postemergence (5 cm); fb, followed by; LPOST, late postemergence (>10 cm); MPOST, mid-postemergence (7 to 10 cm).
[b]Values followed by the same letter within columns are not different according to Tukey's HSD ($P \leq 0.05$).

compared with seeds from the plants of the other treatments (Table 7). The Palmer amaranth plants under WFNC conditions were the most fecund, followed by the plants under WFIC conditions, plants under NTC conditions, and Palmer amaranth surviving glufosinate treatment at both locations (Table 7). The fecundity of Palmer amaranth that survived glufosinate did not differ across application timings within a location (Clayton, 3,140 to 115,686 seeds plant^{-1}; Rocky Mount, 5,549 to 8,302 seeds plant^{-1}) (Table 7). Remarkably, the Palmer amaranth plants that survived glufosinate were as fecund as the Palmer amaranth plants under WFIC conditions within a location (Table 7). These results further suggest that there is greater competition in cotton compared with Palmer amaranth grown without cotton and that the presence of weedy competition resulted in similar fecundity as plants surviving glufosinate. The average fecundity reduction for Palmer amaranth surviving glufosinate was 89% and 96% compared with the Palmer amaranth plants under WFNC conditions at Clayton and Rocky Mount, respectively (Table 7).

Cotton Yield Estimates

No Grass Competition Experiment

The main effects and interactions were significant for cotton yield estimates; thus yield data were analyzed across locations and glufosinate applications. Cotton yield estimates were higher at Rocky Mount (20.7 kg ha^{-1}) when compared with Clayton (4.7 kg ha^{-1}). Yield estimate differences among treatments were not detected at Clayton (Table 8). The greatest cotton yield estimates were achieved with sequential and EPOST glufosinate applications at Rocky Mount (Table 8). The MPOST and LPOST glufosinate applications resulted in lower cotton yield estimates compared with the sequential applications in general (Table 8).

Grass Competition Experiment

The main effects and interactions were significant for cotton yield estimates; thus yield data were analyzed across locations and glufosinate applications. Like in the No Grass Competition experiment, cotton yield estimates were greater at Rocky Mount (21.8 kg ha^{-1}) than at Clayton (4.8 kg ha^{-1}). Yield estimate differences among treatments were not detected at Clayton either (Table 9). Cotton yield estimates followed a similar trend as in the No Grass Competition experiment at Rocky Mount (Table 9).

Cotton yield estimates were low, likely due to late planting and minimal inputs. While the cotton yield estimates were much lower than those of previous research comparing similar treatments, the yield separation between select treatments was apparent and parallel (Everman et al. 2007; Kroger et al. 2007). These results suggest that relying solely on glufosinate applied POST will likely result in relatively low yield, and late applications will result in reduced yield (Tables 8 and 9).

These results indicate that vegetative growth of Palmer amaranth that survives glufosinate is reduced regardless of grass weed competition when compared with Palmer amaranth plants under WFIC and WFNC conditions. The vegetative growth of Palmer amaranth growing under WFNC and WFIC was similar to that of plants growing under comparable conditions in previous research (Keeley et al. 1987; Webster and Grey 2015). The apical and circumferential growth of Palmer amaranth plants surviving glufosinate will resume shortly after treatment regardless of inter- and intraspecific competition and will continue to interfere with the crop. The loss of apical dominance or increased circumference growth was not realized with Palmer amaranth plants surviving glufosinate treatment in either experiment, which is parallel to the response of reduced branching exhibited by glufosinate-treated Palmer amaranth in fallow and soybean (Haarmann et al. 2021; Jones et al. 2024a). Previous research has demonstrated the irreparable biomass of plants treated with glufosinate at different sizes (Jones et al. 2024a; Tharp et al. 1999). This result further demonstrates that Palmer amaranth exhibits the plasticity to accumulate biomass of similar size regardless of size when treated with glufosinate, grass competition, or crops. Plant gender was not determined for Palmer amaranth plants; previous research has provided evidence that gender does not affect the vegetative growth of dioecious *Amaranthus* spp. (Jones et al. 2019; Mahoney et al. 2021).

Because the collected female Palmer amaranth surviving glufosinate from all experiments produced seed, the female Palmer amaranth surviving glufosinate applications produced viable ovules (stigmas). Previous research has shown nontreated Palmer amaranth grown in weed-free cotton to produce several hundred thousand seeds plant^{-1} (Keeley et al. 1987; Mahoney et al. 2021; Webster and Grey 2015). The fecundity of the Palmer amaranth plants under WFIC conditions has been observed in other previous research with parallel intraspecific competition levels (Bensch et al. 2003; Webster and Grey 2015). Palmer amaranth in the vegetative stage surviving glufosinate treatment in these experiments was more fecund than the reproductive-stage Palmer amaranth that survived glufosinate (Jha and Norsworthy 2012; Scruggs et al. 2020). While the Palmer amaranth in the reproductive stage surviving glufosinate investigated by Jha and Norsworthy (2012) and Scruggs et al. (2020) produced fewer seeds, the glufosinate rate (656 to 820 g ai ha^{-1}) was significantly higher than what was used in this research (590 g ai ha^{-1}). The higher glufosinate rate applied to the flowers of reproductive-stage Palmer amaranth may be more effective in reducing fecundity. Vegetative-stage Palmer amaranth that survived glufosinate in soybean exhibited similar fecundity (3,800 to 25,000 seeds plant^{-1}), suggesting that competition from both crops is similar (Jones et al. 2024a).

Palmer amaranth in the vegetative stage surviving glufosinate regardless of grass competition should be taken very seriously. While Palmer amaranth surviving glufosinate incurs a growth and fecundity reduction, the results of all experiments provide evidence that surviving plants will resume growth shortly after glufosinate treatment and will remain fecund (producing several thousand seeds plant^{-1}). Palmer amaranth surviving glufosinate will still interfere with the crop and produce offspring that must be controlled in the subsequent growing season. Sequential glufosinate applications will effectively control Palmer amaranth, ceasing vegetative and reproductive capacities. However, sequential glufosinate applications must be cautiously recommended to reduce the selection pressure for the evolution of glufosinate-resistant weed species. Thus glufosinate should be applied to 5- to 7-cm Palmer amaranth (concordant with the current label) to cease vegetative and reproductive capacities while not overexerting selection pressure. Although direct comparisons cannot be made across experiments, Palmer amaranth surviving glufosinate with and without grass competition exhibited similar growth and fecundity in both crops (Jones et al. 2024a). This result suggests that the vegetative architectures of cotton and soybean influence the growth and fecundity of Palmer amaranth surviving glufosinate more than does grass competition. Future research should determine the growth and fecundity of Palmer amaranth surviving glufosinate in glufosinate-tolerant corn (*Zea mays* L.) due to corn's vastly different vegetative architecture compared with cotton and soybean (Hartzler et al. 2004; Jones et al. 2024a; Nordby and Hartzler 2004). The injury incurred by the grass weeds from glufosinate in this research may have minimized any competitive advantage compared with grass weeds treated with a herbicide with no grass control (i.e., 2,4-D or dicamba) (Terra et al. 2007). Similar research should be conducted in locations with more arid and cool conditions, as these environments can influence glufosinate activity.

Practical Implications

The results of this study highlight the need to apply glufosinate to small Palmer amaranth plants to cease growth and seed production. Cotton yield estimates from the research suggest that applying glufosinate at EPOST or sequential application timings can also protect cotton yield. However, yield estimates were low, highlighting the importance of effectively managing Palmer amaranth in cotton. Palmer amaranth that survives glufosinate in cotton will produce approximately 2,500 to 15,000 seeds plant^{-1}: a significant number of seeds being added to the soil seedbank to be managed in the subsequent growing season. Although farmers would not be likely to rely solely on glufosinate to manage all weed species in a field, these data support the idea that glufosinate-only weed management will not be effective. Sequential glufosinate applications effectively controlled Palmer amaranth in these studies, ceasing vegetative and reproductive capacities. However, sequential glufosinate applications must be cautiously recommended to reduce the selection pressure for the evolution of glufosinate-resistant weed species. Thus we recommend that glufosinate be applied to 5- to 7-cm Palmer amaranth (concordant with the current label) to cease vegetative and reproductive capacities and implement other chemical and nonchemical tactics so as not to overexert selection pressure.

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Competing interests. The authors declare no conflicts of interest.

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