The *Journal of Cotton Science 25:58–66 (2021)*
http://journal.cotton.org, © The Cotton Foundation 2021

WEED SCIENCE

Palmer Amaranth Control by Glufosinate Depends on Application Time of Day

J. Drake Copeland, A. Stanley Culpepper, Alan C. York, Lawrence E. Steckel*,
Daniel O. Stephenson, IV, and Jason A. Bond

ABSTRACT

Glufosinate is used widely to control glyphosate-resistant Palmer amaranth (*Amaranthus palmeri* S. Wats.) in cotton (*Gossypium hirsutum* L.). Previous research has shown weed control with several herbicides, including glufosinate, can be affected by application time of day. The response sometimes has been attributed to diurnal leaf movement (leaf orientation) in the weeds. The objectives of our research were to determine the influence of time of day of glufosinate application on Palmer amaranth control and to determine if the response was related to diurnal leaf orientation. Field experiments in five states evaluated Palmer amaranth control with glufosinate applied at nine intervals ranging from 1 h before sunrise to 6 h after sunrise and nine intervals ranging from 6 h before sunset to 1 h after sunset. Greatest Palmer amaranth control was achieved with glufosinate applied 2 h after sunrise to 1 h before sunset. Ammonium sulfate, added only to glufosinate 1 h before sunrise or 1 h after sunset treatments, did not improve control. Leaf angles of Palmer amaranth and velvetleaf (*Abutilon theophrasti* L.) were determined in a greenhouse at 1 h before light, 2 h after light, mid-day, 2 h before dark, and 1 h after dark. Leaves of velvetleaf oriented downward during the dark periods but time of day had no effect on leaf orientation of Palmer amaranth. These results demonstrate the need for sunlight for optimum glufosinate efficacy on Palmer amaranth.

Glyphosate-resistant Palmer amaranth (*Amaranthus palmeri* S. Wats.) has spread prolifically throughout major cotton-(*Gossypium hirsutum* L.)-producing states in the midsouthern and southeastern regions of the U.S. (Culpepper et al., 2010; Steckel, 2007). This weed can reduce cotton yields and hinder mechanical harvest (Morgan et al., 2001; Rowland et al., 1999). Palmer amaranth has been characterized as the most economically damaging and troublesome weed in the U.S. (Beckie, 2011; Van Wychen, 2016). Currently, Palmer amaranth in the U.S. has evolved resistance to the following six herbicide mechanisms of action: 5-enolpyruvylshikimate-3-phosphate (EPSP) synthase inhibitors, acetolactate synthase (ALS) inhibitors, photosystem II inhibitors, microtubule assembly inhibitors, 4-hydroxyohenylpyruvate dioxygenase (HPPD) inhibitors, and protoporphyrinogen oxidase (PPO) inhibitors (Heap, 2018).

Transgenic cotton cultivars tolerant to dicamba, 2,4-D, or glufosinate provide growers effective postemergence (POST) options for control of glyphosate-resistant Palmer amaranth (Cahoon et al., 2015a,c; Culpepper et al., 2009; Merchant et al., 2014). New cotton cultivars with herbicide tolerance to either dicamba or 2,4-D also include tolerance to glufosinate (Cahoon et al., 2015a; Merchant et al., 2014). Glufosinate inhibits the enzyme glutamine synthetase, causing an accumulation of phytotoxic ammonia in plants cells (Wild et al., 1987). Glufosinate is considered a contact herbicide that can cause plant death 2 to 5 d after treatment (Haas and Muller, 1987). Effective control of Palmer amaranth is achieved when glufosinate is applied before the weed reaches 8 to 10 cm in height (Coetzer et al., 2002; Culpepper et al., 2010). Many uncontrollable environmental factors such as temperature and relative humidity can influence the efficacy of glufosinate (Coetzer et al., 2001; Steckel et al., 2006). Control of Palmer amaranth with glufosinate was greater when relative humidity was 90% compared to 35% (90% vs 76% control) (Coetzer et al., 2001). Additionally, activity of glufosinate is reduced when applied in lower temperatures (Coetzer et al., 2001; Steckel et al., 2006).

J.D. Copeland and L.E. Steckel*, Department of Plant Sciences, University of Tennessee, 605 Airways Boulevard, Jackson, TN 38301; A.S. Culpepper, Department of Crop and Soil Sciences, University of Georgia, 1223 Old Ocilla Road, Tifton, GA 31794; A.C. York, Department of Crop and Soil Sciences, North Carolina State University, Box 7620, Raleigh, NC 27695; D.O. Stephenson, IV, Dean Lee Research Station, Louisiana State University, 8105 Tom Bowman Drive, Alexandria, LA 71302; and J.A. Bond, Department of Plant and Soil Sciences, Mississippi State University, P. O. Box 197, Stoneville, MS 38776.
*Corresponding author: lsteckel@utk.edu

A more manageable application parameter, the time of day of herbicide application, influences many herbicides, including glufosinate (Doran and Andersen, 1976; Martinson et al., 2002; Sellers et al., 2004; Stopps et al., 2013). Diurnal changes in leaf angle of velvetleaf (*Abutilon theophrasti* L.), hemp sesbania (*Sesbania herbacea* L.), and sicklepod (*Senna obtusiifolia* L.) have been reported to negatively impact herbicide activity with late-day applications (Andersen and Koukkari, 1978; Doran and Andersen, 1976; Norsworthy et al., 1999; Sellers et al., 2003). Leaf orientation also can affect spray retention and herbicide efficacy (Anderson and Koukkari, 1978; Doran and Anderson, 1976; Norsworthy et al., 1999; Sellers et al., 2003). Anderson and Koukkari (1978) concluded the change in velvetleaf leaf orientation with the resultant change in spray retention was the major cause of the time-of-day response to bentazon. Similarly, Norsworthy et al. (1999) attributed all time-of-day effect of glyphosate application to leaf orientation. However, Sellers et al. (2003) concluded that although leaf angle plays a role in reducing glufosinate efficacy, it is not the sole cause for the reduction in glufosinate activity on velvetleaf with late-day applications. They suggested some physiological process was involved. Light is required for optimum glufosinate activity (Kocher, 1983; Wild and Manderscheid, 1984). Sellers et al. (2004) found that velvetleaf with leaf angles fixed at -10° (0° would be leaf parallel to soil) had significant glutamine synthetase inhibition and ammonium accumulation when treated with glufosinate at 1400 h but not when treated at 2200 h.

Effects of application time of day and leaf orientation on Palmer amaranth control with glufosinate have not been reported. With glyphosate-resistant Palmer amaranth being a widespread problem (Culpepper et al., 2010) and growers relying more on glufosinate for its management (Sosnoskie and Culpepper, 2014), a better understanding of factors affecting efficacy is needed. Our objectives were to determine the influence of time of day of glufosinate application on Palmer amaranth control in cotton and document diurnal leaf movement of the weed.

MATERIALS AND METHODS

Glufosinate Application Time of Day. Two separate field experiments were conducted at five locations across the midsouthern and southeastern U.S. during 2012 (site details in Table 1). Glyphosate- and glufosinate-tolerant cotton cultivars FM 1944 GLB2 (Bayer CropScience, Research Triangle Park, NC), PHY 375 WRF (Dow AgroSciences, Indianapolis, IN), or PHY 499 WRF (Dow AgroSciences, Indianapolis, IN) were grown following standard production practices for each location. Plots were 7.6 to 9.1 m long and consisted of two to four rows of cotton, with row spacing varying from 76 to 102 cm. No preemergence herbicides were applied.

Table 1. Details for experiment locations in 2012[z]

Locations[y]	Soil series	Soil texture[x]	Variety	Planting date	Glufosinate application date[w] POST-1	POST-2	Palmer amaranth density
							no. m^{-2}
Stoneville, MS	**Dundee[v]**	**VFSL**	**FM 1944 GLB2**	**1 May**	**29 May**	**14 June**	**42**
Ty Ty, GA	**Tifton[u]**	**LS**	**PHY 499 WRF**	**16 April**	**5 May**	**21 May**	**87**
Clayton, NC	**Norfolk[t]**	**LS**	**PHY 499 WRF**	**2 May**	**29 May**	**14 June**	**80**
Alexandria, LA	**Coushatta[s]**	**SiL**	**FM 1944 GLB2**	**24 April**	**30 May**	**15 June**	**1**
Jackson, TN	**Lexington[r]**	**SL**	**PHY 375 WRF**	**2 May**	**8 May**	**24 May**	**63**

[z] **Both experiments were initiated in the same or neighboring fields and on the same day within each location.**

[y] **Georgia and Mississippi locations were under irrigation; other locations were dryland. The Tennessee location was in a no-tillage system while other locations were in conventional tillage systems.**

[x] **Soil texture abbreviations: LS, loamy sand; SiL, silt loam; VFSL, very fine sandy loam**

[w] **Glufosinate applied at 656 g ha^{-1} POST-1 and POST-2. POST-1applied to 10- to 12-cm Palmer amaranth. A directed lay-by application of diuron 1.1 kg ha^{-1} plus MSMA 2.2 kg ha^{-1} was applied 14 to 19 d after POST-2.**

[v] **Fine-silty, mixed, active, thermic Typic Endoaqualfs**

[u] **Fine-loamy, kaolinitic, thermic Plinthic Kandiudults**

[t] **Fine-loamy, kaolinitic, thermic Typic Kandiudults**

[s] **Fine-silty, mixed, superactive, thermic Fluventic Eutrudepts**

[r] **Fine-silty, mixed, active, thermic Ultic Hapludalfs**

Treatments were replicated four times within a randomized, complete block design for both experiments. In Experiment 1, treatments consisted of glufosinate-ammonium (Liberty 280 SL; Bayer CropScience, Research Triangle Park, NC) at 660 g ai ha^{-1} applied at nine intervals ranging from 1 h before sunrise to 6 h after sunrise (Table 2). In Experiment 2, treatments consisted of the same rate of glufosinate applied at nine intervals ranging from 6 h before sunset to 1 h after sunset (Table 3). Sunrise and sunset times at each location were provided by the U.S. Naval Observatory (USNO, 2018). At 1 h before sunrise and 1 h after sunset, an additional treatment of glufosinate plus 3.4 kg ha^{-1} of ammonium sulfate (AMS) was included. A nontreated check was included for comparison purposes.

Treatments were applied to 10- to 12-cm high Palmer amaranth (POST-1) and repeated 16 d later (POST-2). Additionally, all plots except the nontreated checks received a directed lay-by application of diuron (Direx® 4L; ADAMA USA, Raleigh, NC) at 1.1 kg ai ha^{-1} plus MSMA (MSMA 6 Plus; Drexel Chemical Co., Memphis, TN) at 2.2 kg ai ha^{-1} plus 1% v/v of crop oil concentrate (AGRI-DEX®; Helena Agri-Enterprises, Collierville, TN) 14 to 22 d after POST-2. Glufosinate was applied using CO_2-pressurized backpack sprayers equipped with flat-fan nozzles (XR 11002 VS, XR 11003 VS, or DG 11002, depending on location; TeeJet Technologies, Glendale Heights, IL) delivering 140 L ha^{-1} at pressures generating medium to fine droplets to maximize coverage. Herbicide application dates are listed in Table 1.

Table 2. Glufosinate treatments in Experiments 1 and 2

Experiment 1: Application during morning hours	Experiment 2: Application during afternoon hours
POST-1 and POST-2[zy]	POST-1 and POST-2[zy]
1 h before sunrise + AMS	6 h before sunset
1 h before sunrise	4 h before sunset
0.5 h before sunrise	2 h before sunset
At sunrise	1 h before sunset
0.5 h after sunrise	0.5 h before sunset
1 h after sunrise	At sunset
2 h after sunrise	0.5 h after sunset
4 h after sunrise	1 h after sunset
6 h after sunrise	1 h after sunset + AMS

[z] POST-1 applied to 10- to 12-cm Palmer amaranth followed by POST-2 16 d later at the exact same time of day.

[y] Glufosinate applied twice at 660 g ha^{-1} for each application. Ammonium sulfate (AMS) applied at 3.4 kg ha^{-1}.

Table 3. Effect of application timing on Palmer amaranth control by glufosinate applied during morning hours: Experiment 1[z]

Time of application	Days after POST-1		Days after POST-2		
	7	14	7	14	90-99
	%				
1 h before sunrise + AMS	54 d	38 d	38 e	30 e	36 c
1 h before sunrise	60 cd	44 cd	45 e	33 e	37 c
0.5 h before sunrise	57 cd	40 cd	44 e	35 e	37 c
At sunrise	65 c	52 c	57 d	50 d	38 c
0.5 h after sunrise	74 b	64 b	71 c	68 c	64 b
1 h after sunrise	76 b	69 b	84 b	80 b	78 ab
2 h after sunrise	87 a	81 a	91 ab	90 a	86 a
4 h after sunrise	88 a	88 a	93 a	94 a	80 ab
6 h after sunrise	86 a	85 a	91 ab	92 a	83 a
P-value	<.0001	<.0001	<.0001	<.0001	<.0001

[z] Means within a column followed by the same letter are not different at $p \leq 0.05$.

In both experiments, visual estimates of crop injury were made 3, 7, and 14 d after POST-1 and POST-2 using a scale of 0 (no injury) to 100% (complete crop death). Percentage control of Palmer amaranth was estimated visually 7 and 14 d after POST-1 and POST-2. Percentage of Palmer amaranth control and cotton height were determined 90 to 99 d after POST-2 (hereafter referred to as late-season). Ten plants per plot were measured for height. Plots were mechanically harvested to determine seed cotton yield at all locations except Mississippi. Nontreated checks were too weedy for mechanical harvest and yields were considered zero.

Experiments 1 and 2 were analyzed separately. In both experiments, all data were subjected to an analysis of variance using PROC GLIMMIX procedure in SAS (ver. 9.4; SAS Institute, Cary, NC). Random effects were replication, location, and replication nested within location (Blouin et al., 2011). Considering location an environmental or random effect allows inferences about treatments to be made over a range of environments (Blouin et al., 2011). Glufosinate application time of day was considered the fixed effect. In both experiments, crop response variables (visual injury, final plant height, and seed cotton yield) were initially analyzed by variety. Crop response for both PHY 375 WRF and PHY 499 WRF were similar, hence crop response data were pooled over those cultivars (hereafter referred to as WideStrike®) in the final data analyses. The DANDA.sas design and analysis macro collection (Saxton, 2013) was used to build all PROC GLIMMIX procedures, examine normality, and convert mean separation to letter groupings when appropriate using Fisher's Protected LSD at $\alpha = 0.05$. Data for nontreated checks were not included in analyses.

Leaf Angle Determination. Plants were grown under greenhouse conditions. Palmer amaranth and velvetleaf were seeded in 10-cm diameter pots containing commercial potting soil (Sun-Gro Redi-Earth Plug and Seedling Mix; Sun-Gro Horticulture, Bellevue, WA) and thinned to one plant per pot after emergence. Day/night temperatures ranged from 20 to 30 °C. Sunrise and sunset were at approximately 0630 and 1900 h, respectively. Natural light was supplemented by lamps (NXT2 lamp, P.L. Light Systems, Beamsville, ON, Canada) on a 13-h photoperiod (0600 to 1900 h) delivering 400 μmol m^{-2} s^{-1} photosynthetic photon flux density. Plants received a dilute nutrient solution weekly and were watered daily.

Images of 10-cm tall and five- to seven-leaf Palmer amaranth and 12-cm tall and five- to six-leaf velvetleaf were captured of each plant at 0500, 0800, 1200, 1700, and 2000 h, corresponding to 1 h before light, 2 and 6 h after light, 2 h before dark, and 1 h after dark, respectively. Angles were produced from software (Angle Meter 360, AK Web Apps, Austin, TX) that calculates angle measurements of interest from an image. Measurements were collected for three true leaves and petioles per plant starting at the apical dominant true leaf for each weed species. Leaf and petiole angles of each species were based on a scale of -90° to +90°. Similar to Norsworthy et al. (1999), horizontal leaves were considered 0°, and vertically upward and downward leaves were considered +90° and -90°, respectively. Measurements were made for three successive days and averaged over leaves and days. The experiment contained three replications and was repeated once. Data were subjected to ANOVA and means were separated using Fisher's Protected LSD at $\alpha = 0.05$.

RESULTS AND DISCUSSION

Palmer Amaranth Control Affected by Time of Day of Glufosinate Application. Time of day of glufosinate application affected Palmer amaranth control when the herbicide was applied during both morning and afternoon hours. With morning applications, trends at 7 and 14 d after application were similar. Palmer amaranth control at 14 d was greatest (81-88% 14 d after POST-1; 90-94% 14 d after POST-2) when glufosinate was applied 2 to 6 h after sunrise, whereas the least control (38-44% 14 d after POST-1; 30-35% 14 d after POST-2) was obtained when glufosinate was applied 0.5 or 1 h before sunrise (Table 3). Control was not improved by AMS added to glufosinate applied 1 h before sunrise. Intermediate levels of control were noted when glufosinate was applied at sunrise or 0.5 or 1 h after sunrise. Within the sunrise to 1 h after sunrise time interval, control increased as the application was delayed. For example, at 14 d after POST-2, Palmer amaranth was controlled 50, 68, and 80% by glufosinate applied at sunrise, 0.5 h after sunrise, and 1 h after sunrise, respectively. Late-season Palmer amaranth control followed the same trend as control 14 d after POST-2. Greatest late-season control was obtained with glufosinate applied 1 h or later after sunrise. Late-season control was intermediate with glufosinate applied 0.5 h after sunrise, and control was least with glufosinate applied at sunrise or earlier.

With afternoon applications, control 7 and 14 d after POST-1 was similar and greatest when glufosinate was applied 0.5 h or more and 1 h or more before sunset, respectively (Table 4). Palmer amaranth was controlled 86 to 87% at 7 d after POST-1 by glufosinate applied 0.5 h or more before sunset compared with 65 to 68% control when application occurred at sunset or later. At 14 d after POST-1, Palmer amaranth was controlled 87 to 89% by glufosinate applied 1 h or more before sunset compared with 71% or less control when application occurred 0.5 h before sunset or later in the day. Following POST-2 application, Palmer amaranth was controlled 90 to 95% at 7 d and 87 to 94% at 14 d with application at 0.5 h or more before sunset compared with 84% or less at 7 d and 78% or less at 14 d with applications occurring at sunset or later. Although control with glufosinate applied 0.5 h before sunset was not different from control with earlier applications, control was nevertheless beginning to decline with the 0.5 h before sunset application and control by the sunset application was less than that with glufosinate applied 1 h or more before sunset. Late-season control was more variable, but control decreased when glufosinate was applied 1 h after sunset. Ammonium sulfate mixed with glufosinate applied 1 h after sunset did not affect control.

With both morning and afternoon applications, control late in the season was generally similar to control observed earlier in the season (Tables 3 and 4). Diuron likely provided some residual control of later-emerging weeds in all treatments (Whitaker et al., 2011b), but the lay-by herbicides did not control larger Palmer amaranth present in plots where earlier control was poor (Cahoon et al., 2015b; Culpepper et al., 2010).

Cotton Response Affected by Time of Day of Glufosinate Application. Cotton cultivar FM 1944 GLB2 was planted at the Louisiana and Mississippi locations (Table 1). No visual injury from glufosinate was noted on this cultivar following POST-1 or POST-2 applications (data not shown). Similar findings were reported by Cahoon et al. (2015c), who observed no injury on FM 1944 GLB2 from sequential or co-applications of glyphosate and glufosinate. This cultivar contains both the GlyTol™ and LibertyLink® traits and is tolerant to both glyphosate and glufosinate (Wallace et al., 2011). Neither plant height nor seed cotton yield of FM 1944 GLB2 were affected by the level of weed control or injury observed as influenced by the time of glufosinate application (data not shown). Averaged over treatments, excluding the nontreated check, seed cotton yield in Louisiana was 4310 kg ha^{-1} with morning applications and 2000 kg ha^{-1} with afternoon applications. Morning and afternoon experiments were conducted in separate fields. Although differences in Palmer amaranth control were noted in Louisiana, lack of yield and cotton height response was due to the low density of weeds (Table 1). The Mississippi location was not harvested.

Table 4. Effect of application timing on Palmer amaranth control by glufosinate applied during afternoon hours: Experiment 2[z]

Time of glufosinate application	Days after POST-1		Days after POST-2		
	7	14	7	14	90-99
	%				
6 h before sunset	86 a	87 a	93 a	93 a	79 ab
4 h before sunset	86 a	88 a	93 a	92 a	86 a
2 h before sunset	87 a	89 a	93 a	93 a	79 ab
1 h before sunset	86 a	87 a	95 a	94 a	92 a
0.5 h before sunset	86 a	71 b	90 ab	87 ab	91 a
At sunset	68 b	67 b	84 b	78 bc	94 a
0.5 h after sunset	65 b	71 b	82 b	76 cd	74 ab
1 h after sunset	66 b	68 b	73 c	69 de	62 b
1 h after sunset + AMS	66 b	67 b	71 c	64 e	60 b
P-value	<.0001	<.0001	<.0001	<.0001	0.019

[z] Means within a column followed by the same letter are not different at $p \leq 0.05$.

Injury, expressed as foliar necrosis, was observed on WideStrike cotton following POST-1 and POST-2 applications during both morning and afternoon applications. At 3 and 7 d after POST-1 morning applications, differences in injury among treatments were relatively small (Table 5). However, greater injury was generally observed at 3 and 7 d after POST-1 when glufosinate was applied later in the morning. Injury had dissipated somewhat by 14 d after POST-1, with no differences among treatments. Following the POST-2 morning applications, injury at 3 and 7 d was greatest when glufosinate was applied 4 or 6 h after sunrise, intermediate with applications 0.5 to 2 h after sunrise, and least with applications at sunrise or earlier. Again, injury dissipated over time. Glufosinate applied at 4 or 6 h after sunrise injured cotton 25 to 26%, 21 to 23%, and 6 to 8% at 3, 7, and 14 days after application, respectively. A consistent response to AMS was not observed.

With afternoon applications of glufosinate, greatest injury at 3 d after POST-1 was noted with applications made 1 h or more before sunset (Table 6). At 7 and 14 d, greatest injury was noted with applications made two or more hours before sunset. Following the POST-2 application, greatest injury at 3 d was noted with applications 2 h or more before sunset, whereas injury at 7 and 14 d was greatest with applications made 4 or 6 h before sunset. As observed with morning applications (Table 5), injury from afternoon applications also dissipated over time (Table 6).

Table 5. Effect of morning application timing of glufosinate on WideStrike cotton response: Experiment 1[z]

Time of glufosinate application	Injury						Final cotton height	Seed cotton yield
	Days after POST-1			Days after POST-2				
	3	7	14	3	7	14		
	%						Cm	kg ha^{-1}
1 h before sunrise + AMS	6 e	9 d	5	8 d	6 de	4 bc	67 c	1250 c
1 h before sunrise	10 cd	10 cd	6	4 e	4 e	2 c	68 bc	1270 c
0.5 h before sunrise	7 de	9 d	5	7 de	4 e	2 c	70 bc	1300 c
At sunrise	11 bcd	13 bc	5	8 de	6 de	3 c	70 bc	1460 c
0.5 h after sunrise	12 abc	14 bc	5	13 c	8 cd	3 c	78 ab	2350 b
1 h after sunrise	13 abc	16 ab	5	16 c	11 c	3 c	87 a	3090 a
2 h after sunrise	14 a	18 a	6	22 b	16 b	5 b	88 a	3190 a
4 h after sunrise	13 ab	18 a	7	26 a	21 a	6 ab	87 a	3140 a
6 h after sunrise	12 abc	19 a	7	25 ab	23 a	8 a	88 a	3100 a
P-value	<.0001	<.0001	0.8784	<.0001	<.0001	<.0001	<.0001	<.0001

[z] Means within a column followed by the same letter are not different at $p \leq 0.05$.

Table 6. Effect of afternoon/evening timing of glufosinate on WideStrike cotton response: Experiment 2[z]

Time of glufosinate application	Injury						Final cotton height	Seed cotton yield
	Days after POST-1			Days after POST-2				
	3	7	14	3	7	14		
	%						Cm	kg ha^{-1}
6 h before sunset	19 a	21 a	13 a	25 a	25 a	10 a	85 a	3166 a
4 h before sunset	18 a	20 ab	13 a	24 a	23 ab	11 a	86 a	3238 a
2 h before sunset	18 a	19 ab	10 ab	21 ab	19 bc	6 b	86 a	3431 a
1 h before sunset	16 a	17 bc	9 b	18 bc	16 cd	5 bc	83 a	3438 a
0.5 h before sunset	10 b	12 d	7 bc	13 cd	14 cd	3 cd	85 a	3642 a
At sunset	10 b	13 d	7 bc	11 de	11 def	3 bcd	83 a	3568 a
0.5 h after sunset	7 b	9 de	4 c	8 ef	9 ef	2 d	86 a	3198 a
1 h after sunset	7 b	7 e	5 c	5 f	7 f	2 d	83 a	2507 b
1 h after sunset + AMS	10 b	13 cd	7 bc	10 def	13 de	3 cd	79 a	2661 b
P-value	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	0.0161	<.0001

[z] Means within a column followed by the same letter are not different at $p \leq 0.05$.

Cotton height and seed cotton yield with morning applications were greatest when glufosinate was applied 1 h after sunrise or later (Table 5). Plant height and seed cotton yield followed trends in Palmer amaranth control (Table 3). With afternoon applications, no differences among treatments were noted for final plant height (Table 6). Seed cotton yield was reduced by competition with Palmer amaranth when applications were made 1 h after sunset. Seed cotton yield closely followed Palmer amaranth control 14 and 90 to 99 d after POST-2 (Table 4), with yield losses similar to those noted in the literature when comparing relative population densities (Morgan et al., 2001; Rowland et al., 1999).

Development of cotton with the WideStrike trait was described by Culpepper et al. (2009). This cotton contains the phosphinothricin acetyltransferase (*pat*) gene that was inserted for use as a selectable marker during plant transformation. The *pat* gene confers resistance to glufosinate, although tolerance of glufosinate with cultivars containing this trait is less than the tolerance of LibertyLink cultivars (Culpepper et al., 2009). LibertyLink cotton has excellent tolerance of glufosinate (Blair-Kerth et al., 2001; Gardner et al., 2006; Wilson et al., 2007). Minor, transient crop injury is usually noted following application of glufosinate to WideStrike cultivars but, considering the application rate and number of applications, glufosinate in the current experiments would be expected to have no adverse effect on yield of WideStrike cotton (Culpepper et al., 2009; Steckel et al., 2012; Whitaker et al., 2011a). Differences in seed cotton yield were attributed to differences in Palmer amaranth control.

Leaf Angle of Palmer Amaranth and Velvetleaf. Petiole angle of both species was not affected by time of day (Table 7). Also, leaf angle of Palmer amaranth did not vary by time of day. This supports the authors' observations that Palmer amaranth leaves do not droop at night. Similar to findings by Sellers et al. (2003), leaf angle of velvetleaf did vary among the times of day measurements were taken. Leaf angles of velvetleaf were less (-12 to -40°) during the light periods and greatest (-50 to -70°) during the dark.

Glufosinate applied during the day will provide greater control of velvetleaf when compared to applications made near sunrise or sunset (Sellers et al., 2003; Stopps et al., 2013). Greater spray interception has been observed during daytime applications of glufosinate on velvetleaf, hence the increase in control (Sellers et al. 2003). However, significant differences in Palmer amaranth leaf movement were not observed. Across all measurement timings, Palmer amaranth leaf angle varied only 24° (Table 7). In our field studies, control of Palmer amaranth treated with glufosinate 1 h after sunrise or earlier and at sunset or later was reduced. Based on data from the leaf angle experiment, we do not attribute these differences in control with glufosinate to diurnal leaf movement of Palmer amaranth. Other physiological processes apparently contribute to reduced glufosinate efficacy when applications are made near sunrise or sunset (Sellers et al., 2004). It has been documented that glutamine synthetase, the enzyme glufosinate inhibits, is less active when a plant is in darkness (Sellers et al., 2004). Sellers et al. (2004) reported greater glutamine synthetase reduction and greater glufosinate activity in light conditions.

Table 7. Leaf and petiole angles of greenhouse-grown Palmer amaranth and velvetleaf as affected by time of day[z]

Time of day[x]	Light conditions	Leaf angle[y]		Petiole angle[y]	
		Palmer amaranth	Velvetleaf	Palmer amaranth	Velvetleaf
h		degrees from horizontal			
0500	1 h before light	-6	-50 bc	32	28
0700	2 h after light	-24	-12 a	19	18
1200	mid-day	-30	-25 ab	21	30
1700	2 h before dark	-12	-40 abc	26	23
2000	1 h after dark	-23	-70 c	33	28
P-value		0.2268	0.0184	0.0736	0.3325

[z] Means for velvetleaf leaf angle followed by the same letter are not different at $p \leq 0.05$.

[y] A horizontally positioned leaf or petiole would have a 0° angle; a leaf or petiole positioned vertically downward would have a -90° angle while a leaf or petiole positioned vertically upward would have a 90° angle.

[x] Sunrise and sunset were at approximately 0630 and 1900 h, respectively. Supplemental lighting was present from 0600 to 1900h.

Confounding factors, such as temperature and relative humidity, could affect glufosinate activity on Palmer amaranth when applied in early morning or late afternoon. However, our results illustrate glufosinate needs sunlight for optimum efficacy on Palmer amaranth. Palmer amaranth control was maximized when glufosinate was applied 2 h or more after sunrise or 1 h or more before sunset. Control did not appear to be related to leaf orientation.

LITERATURE CITED

Andersen, R.N., and W.L. Koukkari. 1978. Response of velvetleaf (*Abutilon theophrasti*) to bentazon as affected by leaf orientation. Weed Sci. 26:393–395.

Beckie, H.J. 2011. Herbicide-resistant weed management: focus on glyphosate. Pest Manag. Sci. 67:1037–1048.

Blair-Kerth, L. K., P.A. Dotray, J.R. Gannaway, M.J. Oliver, and J.E. Quisenberry. 2001. Tolerance of transformed cotton to glufosinate. Weed Sci. 49:375–380.

Blouin, D.C., E.P. Webster, and J.A. Bond. 2011. On the analysis of combined experiments. Weed Technol. 25:165–169.

Cahoon, C.W., A.C. York, D.L. Jordan, W.J. Everman, R.W. Seagroves, A.S. Culpepper, and P.M. Eure. 2015a. Palmer amaranth (*Amaranthus palmeri*) management in dicamba-resistant cotton. Weed Technol. 29:758–770.

Cahoon, C.W., A.C. York, D.L. Jordan, and R.W. Seagroves. 2015b. Cotton response and Palmer amaranth control with mixtures of glufosinate and residual herbicides. J. Cotton Sci. 19:622–630.

Cahoon, C.W., A.C. York, D.L. Jordan, R.W. Seagroves, W.J. Everman, and K.M. Jennings. 2015c. Sequential and co-applications of glyphosate and glufosinate in cotton. J. Cotton Sci. 19:337–350.

Coetzer, E., K. Al-khatib, and D.E. Peterson. 2002. Glufosinate efficacy on *Amaranthus* species in glufosinate-resistant soybean (*Glycine max*). Weed Technol. 16:326–331.

Coetzer, E., K. Al-khatib, and T.M. Loughin. 2001. Glufosinate efficacy, absorption, and translocation as affected by relative humidity and temperature. Weed Sci. 49:8–13.

Culpepper, A.S., T.M. Webster, L.M. Sosnoskie, and A.C. York. 2010. Glyphosate-resistant Palmer amaranth in the United States. p. 195–212 *In* V. K. Nandula (ed.) Glyphosate Resistance in Crops and Weeds. Wiley, New York, NY.

Culpepper, A.S., A.C. York, P. Roberts, and J.R. Whitaker. 2009. Weed control and crop response to glufosinate applied to 'PHY 485 WRF' cotton. Weed Technol. 23:356–362.

Doran, D.L., and R.N. Andersen. 1976. Effectiveness of bentazon applied at various times of the day. Weed Sci. 24:567–570.

Gardner, A.P., A.C. York, D.L. Jordan, and D.W. Monks. 2006. Management of annual grasses and *Amaranthus* spp. in glufosinate-resistant cotton. J. Cotton Sci. 10:328–338.

Haas, P., and F. Muller. 1987. Behavior of glufosinate-ammonium in weeds. Proc. Brit. Crop Prot. Conf. 3:1075–1082.

Heap, I. 2018. The International Survey of Herbicide Resistant Weeds [Online]. Available at http://www.weedscience.org (verified 4 March 2021).

Kocher, H. 1983. Influence of the light factor on physiological effects of the herbicide Hoe 39866. Asp. Appl. Biol. 4:227–234.

Martinson, K.B., R.B. Sothern, W.L. Koukkari, B.R. Durgan, and J.L. Gunsolus. 2002. Circadian response of annual weeds to glyphosate and glufosinate. Chronobiol. Int. 19:405–422.

Merchant, R.M., A.S. Culpepper, P.M. Eure, J.S. Richburg, and L.B. Braxton. 2014. Controlling glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) in cotton with resistance to glyphosate, 2,4-D, and glufosinate. Weed Technol. 28:291–297.

Morgan, G.D., P.A. Baumann, and J.M. Chandler. 2001. Competitive impact of Palmer amaranth (*Amaranthus palmeri*) on cotton (*Gossypium hirsutum*) development and yield. Weed Technol. 15:408–412.

Norsworthy, J.K., L.R. Oliver, and L.C. Purcell. 1999. Diurnal leaf movement effects on spray interception and glyphosate efficacy. Weed Technol. 13:466–470.

Rowland, M.W., D.S. Murray, and L.M. Verhalen. 1999. Full-season Palmer amaranth (*Amaranthus palmeri*) interference with cotton (*Gossypium hirsutum*). Weed Sci. 47:305–309.

Saxton, A.M. 2013. DANDA.sas: Design and analysis macro collection version 2.11. Univ. Tennessee, Knoxville, TN.

Sellers, B.A., R.J. Smeda, and W.G. Johnson. 2003. Diurnal fluctuations and leaf angle reduce glufosinate efficacy. Weed Technol. 17:302–306.

Sellers, B.A., R.J. Smeda, and J. Li. 2004. Glutamine synthetase activity and ammonium accumulation is influenced by time of glufosinate application. Pestic. Biochem. Physiol. 78:9–20.

Sosnoskie, L.M., and A.S. Culpepper. 2014. Glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) increases herbicide use, tillage, and hand-weeding in Georgia cotton. Weed Sci. 62:393–402.

Steckel, L.E. 2007. The dioecious *Amaranthus* spp.: here to stay. Weed Technol. 21:567–570.

Steckel, L.E., C.C. Craig, and R.M. Hayes. 2006. Glyphosate-resistant horseweed (*Conzya canadensis*) control with glufosinate prior to planting no-till cotton (*Gossypium hirsutum*). Weed Technol. 20:1047–1051.

Steckel, L.E., D. Stephenson, J. Bond, S.D. Stewart, and K.A. Barnett. 2012. Evaluation of WideStrike® Flex cotton response to over-the-top glufosinate tank mixtures. J. Cotton Sci. 16:88–95.

Stopps, G.J., R.E. Nurse, and P.H. Sikkema. 2013. The effect of time of day on the activity of postemergence soybean herbicides. Weed Technol. 27:690–695.

United States Naval Observatory [USNO]. 2018. Sun or Moon Rise/Set Table for One Year [Online]. Available at http://aa.usno.navy.mil/data/docs/RS_OneYear.php (verified 26 Sept. 2018). https://www.usno.navy.mil/USNO/astronomical-applications/data-services/rs-one-year-us

Van Wychen, L. 2016. 2016 Survey of the most common and troublesome weeds in broadleaf crops, fruits & vegetables in the United States and Canada. Weed Science Society of America National Weed Survey Dataset [Online]. Available at http://wssa.net/wp-content/uploads/2016_Weed_Survey_Final.xlsx (verified 4 March 2021).

Wallace, R.D., L.M. Sosnoskie, A.S. Culpepper, A.C. York, K.L. Edmisten, M.G. Patterson, M.A. Jones, H.L. Crooks, G.L. Cloud, and J. Pierson. 2011. Tolerance of GlyTol® and GlyTol® + LibertyLink® cotton to glyphosate and glufosinate in the southeastern U.S. J. Cotton Sci. 15:80–88.

Whitaker, J.R., A.C. York, D.L. Jordan, and A.S. Culpepper. 2011a. Weed management with glyphosate- and glufosinate-based systems in PHY WRF 485 cotton. Weed Technol. 25:183–191.

Whitaker, J.R., A.C. York, D.L. Jordan, A.S. Culpepper, and L.M. Sosnoskie. 2011b. Residual herbicides for Palmer amaranth control. J. Cotton Sci. 15:89–99.

Wild, A., and R. Manderscheid. 1984. The effect of phosphinothricin on the assimilation of ammonia in plants. Z. Naturforsch. C. 39:500–504.

Wild, A., H. Sauer, and W. Ruhle. 1987. The effect of phosphinothricin (glufosinate) on photosynthesis. I. Inhibition of photosynthesis and accumulation of ammonia. Z. Naturforsch. 42:263–269.

Wilson, D.G., Jr., A.C. York, and D.L. Jordan. 2007. Effect of row spacing on weed management in glufosinate-resistant cotton. Weed Technol. 21:489–495.