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Postemergence Control and Glyphosate Tolerance of Doveweed (*Murdannia nudiflora*)

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Doveweed is a problematic weed of lawns and sod production, as well as golf course roughs, fairways, and tees. End-user reports of selective POST control options are inconsistent and control is often short-lived. In addition, inconsistent control with non-selective herbicides such as glyphosate is common. The goals of this research were: (1) evaluate selective POST doveweed control options in 'Tifway' hybrid bermudagrass turf; (2) compare efficacy of single vs. sequential applications of selective POST herbicides; (3) quantify doveweed tolerance to glyphosate; and (4) quantify recovery of foliar applied glyphosate following treatment with a C^{14}-glyphosate solution. A single application of sulfentrazone + metsulfuron; thiencarbazone + iodosulfuron + dicamba or 2,4-D + MCPP + dicamba + carfentrazone; or thiencarbazone + foramsulfuron + halosulfuron provided >60% control 2 weeks after initial treatment (WAIT). A second application of these treatments 3 WAIT improved control 6 WAIT. Two applications of 2,4-D + MCPP + dicamba + carfentrazone or thiencarbazone + foramsulfuron + halosulfuron provided ~80% control 6 WAIT. Doveweed was tolerant to glyphosate application up to 5.68 kg ae ha^{-1}. Absorption of ^{14}C-glyphosate was compared between doveweed with cuticle intact, doveweed with a disturbed cuticle, and smooth crabgrass. ^{14}C-glyphosate recovery from the leaf surface of doveweed plants with an intact cuticle was 93.6%. In comparison, ^{14}C-glyphosate recovery from the leaf surface of doveweed plants with a disrupted cuticle and the leaf surface of crabgrass plants was 79.1 and 70.5%, respectively.

Nomenclature: Bromoxynil; carfentrazone; dicamba; foramsulfuron; glyphosate; halosulfuron; iodosulfuron; mecoprop; metsulfuron; MSMA; quinclorac; sulfentrazone; thiencarbazone; 2,4-D; doveweed, *Murdannia nudiflora* (L.) Brenan; smooth crabgrass, *Digitaria ischaemum* (Schreb.) Schreb. ex Muhl.; 'Tifway' bermudagrass, *Cynodon dactylon* (L.) Pers. × *Cynodon transvaalensis* Burtt-Davy.

Key words: Golf course, turfgrass, weed control.

Doveweed's light green color and coarse texture disrupts sward quality by contrasting with the color and texture of desirable turfgrass. Doveweed is a semisucculent herbaceous plant with a sprawling, creeping habit. Identifying characteristics are linear to oblong-lanceolate leaves 3 to 7 cm long and 1 to 2 cm wide, a fringe of hairs along the lower leaf margins, small (≤1 cm) purple ephemeral flowers, and a fibrous root system (Holm et al. 1977).

Doveweed competes both laterally and vertically for soil and light resources as a result of its decumbent growth habit (Holm et al. 1977). Under favorable growing conditions, the plants form dense, pure stands that smother competing species. Doveweed is a prolific seed producer, and its stems readily root when their nodes come in contact with moist soil, especially if stems are broken or cut (Holm et al. 1977). The ability of this species to reproduce both sexually and vegetatively increases the importance of identifying effective herbicide control options. Doveweed completes its life cycle after seed production in early fall as temperatures begin to decline in the southeastern United States; a time of reduced growth of desirable turf in response to changing seasonal environmental

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conditions. If infestations are left unchecked, large voids in turf cover remain until conditions are again favorable for turf growth.

End user reports of selective postemergence (POST) doveweed control are inconsistent, and control is often short-lived. In related species, early POST applications of cloransulam applied at 0.018 kg ai ha^{-1} and lactofen applied at 0.22 kg ai ha^{-1} controlled Asiatic dayflower (*Commelina communis* L.) approximately 80% and 67%, respectively, in soybean (*Glycine max* [L.] Merr.) (Ulloa and Owen 2009). POST application of MSMA at 0.84 kg ai ha^{-1} controlled Benghal dayflower (*Commelina benghalensis* L.) 78% at 21 d after treatment (DAT) (Culpepper et al. 2004). In the same study, MSMA plus diuron applied at 0.84 + 1.12 kg ai ha^{-1} and MSMA plus flumioxazin at 0.84 + 0.072 kg ai ha^{-1} controlled Benghal dayflower 83% and 89%, respectively, 21 DAT (Culpepper et al. 2004). Previous research has not evaluated herbicides for selective POST doveweed control efficacy in bermudagrass turf.

Inconsistent doveweed control with nonselective herbicides such as glyphosate is common. According to the Weed Science Society of America, herbicide tolerance is defined as the inherent ability of a species to survive and reproduce after herbicide treatment, without selection or genetic manipulation (Anonymous 1998). Additionally, poor control with glyphosate has been documented in Asiatic dayflower and other Commelinaceae species (Culpepper et al. 2004; Webster and Sosnoskie 2010). In one study, Asiatic dayflower biomass was not completely reduced by glyphosate applied at 6.72 kg ae ha^{-1}, and application of the 1× rate, 0.84 kg ae ha^{-1}, did not significantly reduce aboveground biomass compared to a nontreated control. This suggests tolerance of this species to glyphosate (Ulloa and Owen 2009).

The objectives of this study were 1) to evaluate selective POST doveweed control options in 'Tifway' hybrid bermudagrass turf, 2) to compare the efficacy of single versus sequential applications of selective POST herbicides, 3) to quantify doveweed tolerance to glyphosate, and 4) to quantify recovery of foliar-applied glyphosate following treatment with a [C^{14}] glyphosate solution.

Materials and Methods

POST Herbicide Control. Two studies were conducted between June and September of 2009, 2010, 2012, and 2013 to evaluate POST doveweed control options in 'Tifway' bermudagrass turf and to compare the efficacy of single and sequential POST applications. Studies were conducted on a mature stand of 'Tifway' bermudagrass established in a Vaucluse loamy sand (fine-loamy, kaolinitic, thermic Fragic Kanhapludults) with a soil pH of 6.1 and 1.4% organic matter in Augusta, GA (33°29′2.9′′N, 82°0′′38.2′′W). Routine preemergence herbicide applications had not been made to the study areas within 1 yr of study initiation. Doveweed density within the study areas was up to 85% cover.

Each study was repeated in a separate experimental area in sequential years. In both studies, initial POST applications were made when the majority of doveweed plants reached the five- to eight-leaf state. In study one, treatments were applied on July 7, 2009, and July 14, 2010. In study two, initial treatments were applied on June 28, 2012, and July 18, 2013, with sequential treatments applied 3 wk after initial treatment (WAIT). Atmospheric and soil environmental conditions for each application timing are presented in Table 1. Visual ratings were recorded 2, 4, and 6 wk after treatment (WAT) in study one and 2, 6, and 10 WAIT in study two.

Treatments were applied using a CO_2-pressurized boom sprayer calibrated to deliver a carrier volume of 187 L ha^{-1} through 8003 flat-fan nozzles (Tee Jet, Spraying Systems Co., Roswell, GA). Treatments were not irrigated within 24 h of application, and plots were irrigated thereafter as needed to prevent wilt.

Table 1. Application dates and atmospheric and soil temperatures for postemergence doveweed control studies in Augusta, GA from 2009 to 2013.

Date	Atmospheric[a]	Soil[b]
	C	
July 7, 2009	28	27
July 14, 2010	33	27
June 28, 2012	31	27
July 19, 2012	29	29
July 18, 2013	28	28
August 1, 2013	27	27

[a] Air temperature was measured using a hand-held weather meter (Kestrel 3000, Kestrel meters, Birmingham, MI) immediately after herbicide application.

[b] Soil temperature was measured at a 2.54 cm depth using a hand-held analog soil thermometer immediately after herbicide application.

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Plots measured 1.5 by 2 m and were mowed twice per week at 5 cm with clippings returned. Fertilizer was applied according to soil test recommendations and was consistent across the experimental area.

Ratings included doveweed density, using a 0% to 100% scale (0% meaning no doveweed present, 100% meaning full doveweed stand), and bermudagrass turf injury, also using a 0% to 100% scale (0% meaning no injury, 100% meaning complete plant death). Percent doveweed control was calculated as the percent decrease of doveweed density relative to the initial doveweed within each plot prior to study initiation.

The experimental design for both studies was a randomized complete block with three replications. Treatments were arranged in a two-factor design with herbicide and experimental year as treatment levels. Percent doveweed control and bermudagrass turfgrass injury data were visually inspected by plotting residuals for homogeneity and normality of variance prior to analysis. Data were then subjected to ANOVA for evaluation of main effects and interaction between herbicide treatment and experimental year. When herbicide treatment by year interactions were not detected, data were combined for analysis and presented over years. Where appropriate, further mean comparisons between treatments were performed using Fisher's protected LSD. All analyses were conducted using JMP Pro version 10 (SAS institute Inc., Cary, NC) and differences were based on $\alpha = 0.05$.

Dose Response of Doveweed to Glyphosate. Response of doveweed to glyphosate (Roundup ProMax, Monsanto, Saint Louis, MO) was evaluated by comparing a deionized water treatment with glyphosate applied at 0.09 (0.125×), 0.18 (0.25×), 0.36 (0.5×), 0.71 (1×), 1.42 (2×), 2.84 (4×), and 5.68 (8×) kg ae ha^{-1} following procedures modified from Seefeldt et al. (1995). Doveweed plants were prepared by first germinating seeds in petri dishes containing two sheets of Whatman No. 2 filter paper and 5 mL distilled water. Germinated seeds were then transplanted to 9-cm-diameter by 9-cm-deep pots filled with washed river sand. Plants were allowed to grow in a growth chamber set to maintain a constant temperature of 27 C with a 12 h photoperiod providing a photosynthetic photon flux density of 300 µmol m^{-2} s^{-1} using fluorescent and incandescent bulbs. During this period, plants were fertilized through subirrigation with a hydroponic growth solution (Grow-Big Hydroponic Plant Food, FoxFarm Soil and Fertilizer Company, Arcata, CA) at 1.3 mL L^{-1} every 10 d. Plants remained in the growth solution for 24 h, then were removed and allowed to drain. Between fertilization procedures, plants were surface-irrigated to field capacity every 2 d. Doveweed plants were allowed to develop to the five- to eight-leaf stage, at which point glyphosate treatments were applied. Treatments were delivered in a carrier volume of 374 L ha^{-1} deionized water with an air-pressurized spray chamber using a single 8003 flat-fan nozzle (TeeJet Technologies, Wheaton, IL) operating at 200 kPa. Shoot biomass was measured 21 DAT by clipping doveweed at soil level, drying tissue at 70 C for 48 h, then weighing. Injury ratings were expressed as percent dry weight of treated plants relative to the mean dry weight of the deionized water treated control plants (Seefeldt et al. 1995).

Experimental design was completely randomized, with three replications, and the experiment was repeated in time. Treatments were arranged in a two-factor design with glyphosate rate and experimental run serving as factors. Regression analysis was conducted, and nonlinear models were fit to the data. A three-parameter logistic equation was used to describe the nonlinear response curve in doveweed biomass:

$$y = C/\left(1 + e^{-A(X-B)}\right)$$

where y was shoot biomass, X was herbicide rate (kg ae ha^{-1}), C was the asymptote, A was the growth rate, and B was the inflection point.

Shoot Absorption of [^{14}C]Glyphosate. Shoot absorption of [^{14}C]glyphosate was compared between doveweed with an intact cuticle, doveweed with a disturbed cuticle, and smooth crabgrass. Smooth crabgrass was chosen for comparison because glyphosate is frequently applied in the field to concurrently target smooth crabgrass and doveweed. Often, field application of glyphosate results in excellent smooth crabgrass control but poor doveweed control. Separate doveweed and smooth crabgrass plants were grown in individual containers in washed river sand (previously described) to approximately the five- to eight-leaf stage. Plants were then removed and roots were washed free of potting media. Washed plants were transplanted into 50 mL test tubes, which were then filled with the hydroponic solution used to subirrigate plants.

The test tubes were wrapped with aluminum foil to protect against light intrusion into the growth solution.

A glyphosate solution was prepared to simulate a field application of glyphosate at 0.71 kg ae ha^{-1} in a 374 L ha^{-1} carrier volume. Prior to glyphosate application, the youngest fully expanded leaf proximal to the apical meristem was designated for [^{14}C]glyphosate treatment and covered with aluminum foil to shield the leaf from intercepting the spray solution. Glyphosate was then applied as previously descried in the dose-response study.

[^{14}C]glyphosate (phosphonomethyl-14C; American Radiolabeled Chemicals, Inc., Saint Louis, MO) was dissolved in a commercial glyphosate formulation (Roundup ProMax, Monsanto, Saint Louis, MO) and diluted with distilled water to simulate a spray solution prepared to deliver 0.71 kg ae ha^{-1} in 374 L ha^{-1}. The [^{14}C]glyphosate solution was prepared such that the final radioactivity concentration was 200 kBq mL^{-1}. No additional surfactant was added. Immediately prior to [^{14}C]glyphosate application, the leaf designated for treatment on each plant selected for cuticle disruption was wiped five times in the acropetal direction on the adaxial side of the leaf with 100% acetone. A micropipette was then used to deliver five 2-μL droplets of [C^{14}]glyphosate solution to each predesignated treatment leaf of each subset of plants to total 2 kBq per treatment leaf. Droplets were applied along the midrib of the adaxial leaf surface.

Three treated plants from each subset of plants were randomly selected for harvest 24, 72, and 144 h after treatment. At harvest, the treated leaf was excised from the plant and placed into a 15 mL centrifuge tube along with 7 mL of a methanol–water (1:10 v:v) solution. The excised leaf was washed within the centrifuge tube with a swirling motion for 30 s to remove any unabsorbed radioactivity. A 1-mL sample of the rinsate was then removed and placed in a 20 mL scintillation vial along with 15 mL of Optiphase HiSafe 3 (PerkinElmer, Waltham, MA) scintillation cocktail. Radioactivity was then quantified using liquid scintillation spectrometry (TriCarb 2900 Liquid Scintillation Analyzer, PerkinElmer, Waltham, MA). Radioactivity detected in the leaf wash was expressed as the percentage of the amount applied. Total recovery was 63% to 97%.

Experimental design was a completely randomized design, and the experiment was repeated in time. Treatment arrangement was a three-by-three-by-two factorial design with plant (doveweed with cuticle intact, doveweed with cuticle disturbed, and smooth crabgrass), harvest interval (24, 72, and 144 h), and experimental run serving as factors. The experiment included three single-plant replicates for each of the three plant treatments and harvest intervals. Data were subjected to ANOVA for evaluation of main effects, interaction between main effects, and interaction between main effects and experimental run. Where appropriate, further mean comparisons were performed using Fisher's protected LSD. All comparisons were based on an $\alpha = 0.05$ significance level. Analyses were conducted using JMP Pro version 10 (SAS Institute Inc.; Cary, NC).

Results and Discussion

POST Control. Turfgrass injury was not significant following any treatment application. In study one, treatment by year interaction was not detected for percent doveweed control at any rating date; therefore, data were combined between years prior to further analysis (Table 2). Doveweed control in the treated plots was significantly different than that in the nontreated plots at 2 and 4 WAT, although control was <60% across all treatments and rating dates (Table 3). MSMA provided 54% control 2 WAT, which is statistically superior to the control provided by dicamba, bromoxynil, or foramsulfuron. All combination treatments provided control similar to MSMA at 2 WAT, ranging from 34% to 48% (Table 3). 2,4-D plus MCPP plus dicamba plus sulfentrazone, and 2,4-D plus MCPP plus dicamba plus carfentrazone, controlled doveweed 39% to 45% at 4 WAT, which is significantly greater control than dicamba or bromoxynil provided alone (Table 3). Further differences between treatments were not detected 6 WAT and control in all treatments was <25% (Table 3).

In study two, a treatment by year interaction was not detected for percent doveweed control 2 or 6 WAIT. However, a treatment by year interaction was detected for percent doveweed control 10 WAIT (Table 2). Therefore, 2 and 6 WAIT data were pooled between years prior to further analysis, and 10 WAIT control data were separated and analyzed by year. All treatments controlled doveweed from 61% to 79% at 2 WAIT. At 6 WAIT, a single

Table 2. ANOVA results for postemergence doveweed control in 'Tifway' bermudagrass in Augusta, GA, July through August of 2009 and 2010 (study 1) and 2012 and 2013 (study 2).[a]

Study 1		Doveweed control			Bermudagrass injury	
Source	DF	2 WAT	4 WAT	6 WAT	2 WAT	
Treatment	7	*	*	NS	NS	
Block	2	NS	NS	NS	*	
Year	1	*	*	*	*	
Treatment × block	14	NS	NS	NS	NS	
Treatment × year	7	NS	NS	NS	NS	
Error	16					
Study 2						
Source	DF	2 WAIT	6 WAIT	10 WAIT	2 WAIT	6 WAIT
Treatment	8	*	*	*	NS	NS
Block	2	NS	NS	NS	NS	NS
Year	1	NS	*	*	NS	NS
Treatment × block	16	NS	NS	NS	NS	NS
Treatment × year	8	NS	NS	*	NS	NS
Error	18					

[a] Abbreviations: DF, degrees of freedom; NS, not significant (α = 0.05); WAIT, weeks after initial treatment; WAT, weeks after treatment.

*Significant at α = 0.05 level.

application of sulfentrazone plus metsulfuron provided 53% control, while other single application treatments provided <25% control (Table 4). A second application of dicamba plus thiencarbazone plus iodosulfuron, 2,4-D plus MCPP plus dicamba plus carfentrazone, or thiencarbazone plus foramsulfuron plus halosulfuron at 3 WAIT improved control at 6 WAIT to >60% (Table 4). Sequential application of thiencarbazone plus foramsulfuron plus halosulfuron provided 81% control at 6 WAIT. Control at 10 WAIT was incon sistent between 2012 and 2013. At 10 WAIT, no

Table 3. Doveweed control with select postemergence herbicides in 'Tifway' bermudagrass. Augusta, GA, March through September, 2009 and 2010.[a]

Treatment[c]	Rate	Doveweed control[b] 2 WAT[d]	4 WAT	6 WAT
	kg ai ha^{-1}	%		
Nontreated		0	0	0
Dicamba	0.560	13	5	0
Bromoxynil	0.560	4	5	0
Foramsulfuron	0.029	19	23	0
MSMA	2.28	54	29	11
2,4-D + MCPP + dicamba + sulfentrazone	0.636 + 0.227 + 0.100 + 0.027	37	45	24
2,4-D + MCPP + dicamba + carfentrazone	0.855 + 0.268 + 0.078 + 0.028	48	39	14
Quinclorac + MCPP + dicamba	0.839 + 0.419 + 0.112	34	27	8
$LSD_{0.05}$		32	28	NS

[a] Abbreviations: fb, followed by; NS, not significant (α = 0.05); WAT, weeks after treatment.

[b] Doveweed control was evaluated visually on a 0% to 100% scale.

[c] Trade name examples: dicamba, Banvel, Micro Flo Company, LLC; bromoxynil, Buctril, Bayer; foramsulfuron, Revolver, Bayer; MSMA, Target 6 Plus, Luxembourg-Pamol, INC.; 2,4-D + MCPP + dicamba + sulfentrazone, Surge, PBI Gordon; 2,4-D + MCPP + dicamba + carfentrazone, Speedzone, PBI Gordon; quinclorac + MCPP + dicamba; Onetime, BASF.

[d] Treatments were made on July 7, 2009, and July 14, 2010.

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Table 4. Doveweed control with select postemergence herbicides in 'Tifway' bermudagrass. Augusta, GA, March through September, 2012 and 2013.[a]

Treatment[c]	Rate	Doveweed control[b]			
		2 WAIT[d]	6 WAIT	10 WAIT	
	kg ai ha^{-1}	%			
				2012	2013
Nontreated		0	0	0	0
Single application: sulfentrazone + metsulfuron[d]	0.273 + 0.027	79	53	0	44
Single application: dicamba + thiencarbazone + iodosulfuron	0.149 + 0.023 + 0.005	62	17	0	0
Single application: 2,4-D + MCPP + dicamba + carfentrazone	0.855 + 0.268 + 0.078 + 0.028	61	22	0	17
Single application: halosulfuron + foramsulfuron + thiencarbazone	0.069 + 0.045 + 0.022	70	22	0	0
Sequential application: sulfentrazone + metsulfuron	0.273 + 0.027 fb 0.168 + 0.017	-	60	0	48
Sequential application: dicamba + thiencarbazone + iodosulfuron	0.149 + 0.023 + 0.005	-	62	15	40
Sequential application: 2,4-D + MCPP + dicamba + carfentrazone	0.855 + 0.268 + 0.078 + 0.028	-	78	92	50
Sequential application: halosulfuron + foramsulfuron + thiencarbazone	0.069 + 0.045 + 0.022	-	81	25	90
$LSD_{0.05}$		18	27	27	21

[a] Abbreviations: fb, followed by; WAIT, weeks after initial treatment.

[b] Doveweed control was visually evaluated on a 0% to 100% scale.

[c] Trade name examples: sulfentrazone + metsulfuron, Blindside, FMC Corporation; dicamba + thiencarbazone + iodosulfuron, Celsius, Bayer; 2,4-D + MCPP + dicamba + carfentrazone, Speedzone, PBI Gordon; halosulfuron + foramsulfuron + theincarbazone, Tribute Total, Bayer.

[d] Initial applications were June 28, 2012, and July 18, 2013. Sequential applications were July 19, 2012, and August 1, 2013.

single-application treatment controlled doveweed >50% in 2012 or 2013. In 2012, sequential application of 2,4-D plus MCPP plus dicamba plus carfentrazone controlled doveweed 92% at 10 WAIT, while all other treatments provided ≤25% control (Table 4). In 2013, sequential application of halosulfuron plus foramsulfuron plus thiencarbazone provided 90% control, while other sequential treatments provided 40% to 50% control (Table 4). These results indicate that POST options should not be solely relied on for doveweed control. The inconsistency observed at 10 WAIT is likely due to several factors, most notably the germination of additional doveweed seeds following the 6 WAIT rating. Further research is needed to determine the effect desirable turf stand density, soil moisture, and other environmental factors may have on the germination of doveweed seedlings following selective POST herbicide applications. Sequential POST applications improve control of other species compared to single applications alone. At 14 WAIT, sequential application of MSMA plus metribuzin at 2.2 + 1.4 kg ha^{-1} increased goosegrass (*Eleusine indica* [L.] Gaertn.) control from ≤75% to ≥90% (Wiecko 2000). Purple (*Cyperus rotundus* L.) and yellow (*Cyperus esculentus* L.) nutsedge control at 15 WAIT was improved by sequential application of sulfentrazone at 0.281 fb 0.281 kg ai ha^{-1} or halosulfuron at 0.070 fb 0.070 kg ai ha^{-1} (Blum et al. 2000).

Doveweed control is often short-lived following a single POST application due to doveweed's continuous germination pattern throughout the growing season. Sequential applications improve control. However, full-season doveweed control should not be expected with only two POST applications of the herbicides evaluated. Further screening of herbicide active ingredients and combinations is needed to identify more effective options for season-long doveweed control. Additionally, combinations of PRE and POST herbicides should be explored to provide residual control following an herbicide application.

Dose Response of Doveweed to Glyphosate. Treatment by run interaction was not detected in dose-response data. Therefore, data were pooled between experimental runs prior to further analysis. Complete plant death did not occur after glyphosate application at any rate evaluated (0.09 to 5.68 kg ae ha^{-1}) (Figure 1). The highest recommended glyphosate application rate for difficult-to-control turfgrass weeds is 1.73 kg ae ha^{-1} (Anonymous 2009). The herbicide rate was calculated in this study to be lethal to 50% of the population (I_{50}) (0.63 kg ae ha^{-1}); however, application at 3× this rate, 5.68 kg ae ha^{-1}, reduced doveweed aboveground

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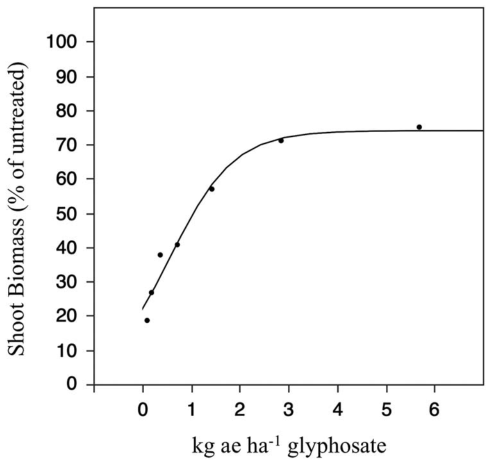

Figure 1. Effect of glyphosate on shoot biomass of doveweed. Shoot biomass was calculated as a percent dry weight of treated plants relative to the mean dry weight of the deionized water treated control plants. The data were analyzed using the nonlinear regression equation $y = C/(1 + e^{-A(X-B)})$ where y was shoot biomass, X was herbicide rate (kg ae ha^{-1}), C was the asymptote, A was the growth rate, and B was the inflection point. Estimates for equation parameters A, B, and C were 1.08, 0.78, and 74.20, respectively. Summary of fit statistics Akaike's Information Criterion, Schwarz Bayesian Information Criterion, Mean Squared Error, and r^2 were 64.66, 44.45, 19.29, and 0.97, respectively.

biomass only 76% at 21 DAT (Figure 1). These data are consistent with field reports of doveweed tolerance to glyphosate.

Benghal dayflower and Asiatic dayflower are species related to doveweed that have become troublesome weeds in agronomic crops because of their relative tolerance to glyphosate (Webster and Sosnoskie 2010). In one study, differences in aboveground biomass between nontreated Asiatic dayflower and Asiatic dayflower treated with 0.84 kg ae ha^{-1} could not be detected at 21 DAT, and full control was not achieved at the 16× rate, 13.76 kg ae ha^{-1} (Ulloa and Owen 2009). In another study, glyphosate application at 0.84 kg ai ha^{-1} controlled Benghal dayflower 70% at 21 DAT. Smaller plants (<6 cm) were completely controlled, while larger plants were not (Culpepper et al. 2004). Similar to these related species, it appears doveweed is also tolerant to glyphosate.

Absorption of [^{14}C]Glyphosate. A treatment by run interaction was not detected in glyphosate recovery data; therefore, data were pooled between runs prior to further analysis (Table 5). Additionally, time after treatment was not significant (P = 0.512), so recovery data was pooled across harvest intervals (Table 5). Recovery of [^{14}C]glyphosate was 93.8% from the leaf surface in doveweed plants with an intact cuticle. In comparison, [^{14}C]glyphosate recovery from the leaf surface of doveweed plants with a disrupted cuticle and from crabgrass plants was 79.1% and 69.5%, respectively (Table 6). Comparison of [^{14}C]glyphosate recovery between doveweed with an intact cuticle, doveweed with a disrupted cuticle, and smooth crabgrass suggests that lack of doveweed control with glyphosate could be due to poor movement of the glyphosate molecule across doveweed's cuticle layer. By treating doveweed's cuticle layer with 100% acetone, the integrity of the cuticle layer was compromised, allowing for penetration of the glyphosate molecule through the cuticle layer.

Foliar absorption rate, and therefore efficacy of herbicide application, depends largely on the permeability of the target plant cuticle (Baker and Bukovac 1971). A range of chemical groups comprise the

Table 5. ANOVA results for recovery of [^{14}C]glyphosate after application to doveweed with cuticle intact, doveweed with cuticle disrupted, and smooth crabgrass at 24, 71, and 144 hours after application.[a]

Source	DF	[^{14}C]glyphosate recovery
Plant	2	*
Harvest interval	2	NS
Run	1	NS
Plant × harvest interval	4	NS
Plant × run	2	NS
Harvest interval × run	2	NS
Error	41	

*Significant at α = 0.05 level.

[a] Abbreviations: DF, degrees of freedom; NS, not significant.

Table 6. Percent recovery of [^{14}C]glyphosate after application to doveweed with cuticle intact, doveweed with cuticle disrupted, and smooth crabgrass.[a]

Sample	Mean[b]
	% of applied
Doveweed (cuticle intact)	93.8
Doveweed (cuticle removed)	79.1
Smooth crabgrass	69.5
$LSD_{0.05}$	7.9

[a] Leaves were spotted with five 2-μL droplets of glyphosate, corresponding to a 0.71 kg ae ha^{-1} application rate, with 0.20 KBq mL^{-1} radioactivity.

[b] Time after treatment was not significant in ANOVA (P = 0.512), thus data within treatments were combined across harvest intervals.

plant cuticle. Cuticle composition is different for different species. The cuticle of creeping bentgrass (*Agrostis stolonifera* L.) is primarily comprised of primary alcohols, specifically 1-hexacosanol. Other constituents include various long-chain alkanes, fatty acids, one aldehyde, and a group of unidentified compounds (Bethea 2012). A study investigating the chemical composition of a barley (*Hordeum vulgare* L.) cuticle determined that it was 89% primary alcohols (Giese 1975). In comparison, the cuticle of Benghal dayflower is composed almost entirely of hydrocarbons (*n*-alkanes), and is therefore relatively hydrophobic. In a study evaluating foliar uptake of [^{14}C]glyphosate in Benghal dayflower, absorption was 66% after 72 h, lower than that observed in morningglory (*Ipomoea grandifolia* [Dammer] O'Donell) (80%) and smooth pigweed (*Amaranthus hybridus* L.) (90%) (Monquero et al. 2004). There is a close phylogenetic relationship between doveweed and Benghal dayflower; thus, it is possible that the chemical composition of doveweed's cuticle layer prevents diffusion of glyphosate. Further research should determine the chemical composition of the doveweed cuticle so that herbicides with potential for doveweed control can be screened based in part on chemical properties.

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Literature Cited

Anonymous (1998) Herbicide resistance and herbicide tolerance defined. Weed Technol 12:789

Anonymous (2009) Roundup ProMax product label. Monsanto Publication No. 6302813-10. Saint Louis, MO: Monsanto

Baker EA, Bukovac MJ (1971) Characterization of the components of plant cuticles in relation to the penetration of 2,4-D. Ann App Biol 67:243–253

Bethea F (2012) Drought Induced Morphological and Compositional Changes in Creeping Bentgrass (*Agrostis stolonifera* var. L. Palustris) Cuticle as It Influences Foliar Nitrogen Absorption. Master's thesis. Clemson, SC: Clemson University. 43 p

Blum RR, Isgrigg J, Yelverton FH (2000) Purple (*Cyperus rotundus*) and yellow nutsedge (*C. esculentus*) control in bermudagrass (*Cynodon dactylon*) turf. Weed Technol 14:357–365

Culpepper AS, Flanders JT, York AC, Webster TM (2004) Tropical spiderwort (*Commelina benghalensis*) control in glyphosate-resistant cotton. Weed Technol 18:432–436

Giese BN (1975) Effects of light and temperature on the composition of epicuticular wax of barley leaves. Phytochemistry 14:921–929

Holm LG, Plucknett DL, Pancho JV, Herberger JP (1977) Commelinaceae, spiderwort family. The world's worst weeds distribution and ecology. Honolulu, Hawaii: University Press of Hawaii

Monquero PA, Christoffoleti PJ, Osuna MD, De Prado RA (2004) Absorption, translocation and metabolism of glyphosate by plants tolerant and susceptible to this herbicide. Planta Daninha 22:445–451

Seefeldt SS, Jensen JE, Fuerst EP (1995) Log-logistic analysis of herbicide dose-response relationships. Weed Technol 9:218–227

Ulloa SM, Owen MD (2009) Response of asiatic dayflower (*Commelina communis*) to glyphosate and alternatives in soybean. Weed Sci 57:74–80

Webster TM, Sosnoskie LM (2010) Loss of glyphosate efficacy: a changing weed spectrum in Georgia cotton. Weed Sci 58: 73–79

Wiecko G (2000) Sequential herbicide treatments for goosegrass (*Eleusine indica*) control in bermudagrass (*Cynodon dactylon*) turf. Weed Technol 14:686–691

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