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Growth and yield response of peanut to simulated drift of glufosinate at vegetative and reproductive growth stages

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Abstract

The increased incidence of glyphosate-resistant weeds has led to an exponential increase in the use of glufosinate on glufosinate-resistant corn, cotton, and soybean crops. Field experiments were conducted in 2021 and 2022 to evaluate peanut response to glufosinate at 25 and 60 d after planting, corresponding to vegetative (V3) and reproductive (R4) growth stages, at 1.2, 4.7, 18.9, 75.5, and 302 g ai ha^{-1} representing 1/514 to 1/2 of the labeled rate of 604 g ha^{-1}. Peanut injury and canopy and yield reductions from glufosinate were <10% when applied at 1.2, 4.7, and 18.9 g ha^{-1}. However, at 75.5 and 302 g ha^{-1} peanut injury ranged from 24% to 72% at the V3 exposure timing and 33% to 54% at the R4 exposure timing. Similarly, glufosinate applied at 75.5 and 302 g ha^{-1} reduced peanut canopy width by 10% to 23% at the V3 exposure timing and by 43% to 57% at the R4 exposure timing. Averaged across exposure timing, peanut yield was reduced by 15% and 61% when glufosinate was applied at 75.5 and 302 g ha^{-1}, respectively. Averaged across rates, peanut yield reduction was 18% at the V3 exposure timing, with glufosinate at 298 g ha^{-1} required to cause an estimated 50% reduction in yield. Peanut yield was reduced by 20% when glufosinate was applied at the R3 peanut growth stage, whereas glufosinate applied at 243 g ha^{-1} caused an estimated 50% reduction in yield. There was no difference in normalized difference vegetative index (NDVI) values between untreated plants and peanut exposed to glufosinate at 1.2, 4.7, and 18.9 g ha^{-1}. However, peanut exposed to glufosinate at 75.5 and 302 g ha^{-1} was distinguished from untreated plants with lower NDVI values. Based on the Pearson correlation coefficient, the best timing for assessing potential yield reduction based on injury was between 2 and 4 wk after treatment.

Introduction

The increased incidence of glyphosate-resistant weeds in the United States has led to an exponential increase in the use of glufosinate on glufosinate-resistant crops such as corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), and soybean [*Glycine max* (L.) Merr.] (Takano and Dayan 2020). Glufosinate is a nonselective herbicide applied postemergence used to control various broadleaf and grass weed species, especially in fields with weed biotypes that are resistant to other herbicide modes of action (Chahal and Johnson 2012; Vann et al. 2022). In the southeastern United States peanut is commonly rotated with or grown in close proximity to corn, cotton, and soybean (Prostko et al. 2013). Glufosinate is intensively used in the southern United States where a large portion of glufosinate-resistant cotton and soybean is grown (Takano and Dayan 2020). The use of glufosinate in southern cropping systems is likely to increase the risk of drift or off-target movement of glufosinate to peanut crops in nearby fields.

Off-target movement of glufosinate is most likely to occur through particle drift of spray droplets moved by wind from the application area to neighboring fields, especially when wind speed and relative humidity are high, and when an air temperature inversion occurs (Jones et al. 2019; Ramsdale and Messersmith 2001). Off-target herbicide movement equivalent to 1/100 of the labeled rate has caused severe crop injury in susceptible crops (Al-Khatib et al. 1993). Sublethal rates of glufosinate applied to simulate drift or off-target movement have been reported to cause injury to various broadleaf agronomic crops (Al-Khatib et al. 2003; Ellis and Griffin 2002; Hale et al. 2019; Miller et al. 2003; Vann et al. 2022). Crop injury and yield reduction following simulated drift of glufosinate can vary in magnitude depending on the application rate and stage of crop growth during exposure to the herbicide (Ellis and Griffin 2002; Johnson et al. 2012; Miller et al. 2003). For example, when applied at the vegetative growth stage, glufosinate caused a greater and more consistent yield reduction of cotton and soybean when it was applied at 122.5 g ai ha^{-1} compared with 61.2 g ha^{-1} (Johnson et al. 2012). Miller et al. (2003) reported greater injury to glufosinate-sensitive cotton exposed to glufosinate between the two- to five-node stage compared with the nine-node growth stage. Conversely, Ellis and Griffin (2002) reported that soybean was more sensitive to glufosinate when the herbicide was applied at first flowering than at the two- to three-leaf stage.

Few studies have addressed the effects of simulated drift rates of glufosinate on peanut. Jordan et al. (2011) reported a 14% peanut yield reduction when glufosinate was applied at 135 g ha^{-1}, but yield reduction increased to 74% when the herbicide was applied at 538 g ha^{-1}. Similarly, Johnson et al. (2012) reported a 25% peanut yield reduction from glufosinate at 123 g ha^{-1}, but the reduction increased to 75% when glufosinate was applied at 302 g ha^{-1}. However, these studies evaluated peanut response to glufosinate at only one exposure timing, approximately 21 to 30 d after planting (DAP). The only study that addressed peanut response to glufosinate at multiple exposure timings reported 16% to 92%, 16% to 82%, and 20% to 78% yield reductions at the R1, R4 to R5, and R6 growth stages, respectively, following glufosinate applications of 41 to 656 g ha^{-1} (Prostko et al. 2013). However, that study compared only peanut yield response to glufosinate at various reproductive growth stages and did not include data on peanut injury. No information exists on the comparative effect of glufosinate on peanut at vegetative and reproductive growth stages. Furthermore, herbicide drift complaints are usually based on visible injury symptoms. Thus, a model is needed that will predict peanut yield loss based on visual injury symptoms observed to peanut crops due to glufosinate drift to help growers and agronomists make informed decisions about how to manage an injured crop.

Using remotely sensed data to detect the onset, extent, and location of herbicide injury in large hectares would provide growers the opportunity to estimate damage and yield potential of injured crop. Remote sensing technology using unmanned aerial vehicle (UAV) technology and derived vegetative indices from spectral reflectance indicating chlorophyll content and overall crop health have been used as a rapid method for detecting and assessing crop injury caused by herbicide drift in previous studies (Huang et al. 2010; Ortiz et al. 2011; Yao et al. 2012). Henry et al. (2004) distinguished healthy and injured corn and soybean plants to which glyphosate and paraquat had been applied using vegetative indices from spectral data. Similarly, Thelen et al. (2004) reported significant differences among herbicides and herbicide rates using the normalized difference vegetation index (NDVI) obtained from digital aerial images of soybean. However, there is limited information on the application of NDVI in estimating peanut injury from simulated herbicide drift. Therefore. the objectives of this study were to evaluate the effects of simulated glufosinate drift rates on peanut injury and yield response at vegetative (V3) and reproductive (R3) growth stages, and to determine whether UAV imagery-based NDVI provides an accurate estimation of peanut injury from glufosinate at vegetative and reproductive growth stages.

Materials and Methods

Field experiments were carried out at West Florida Research and Education Center near Jay, FL (30.776542°N, 87.147662°W), in 2021 and 2022, on a sandy loam (fine-loamy, kaolinitic, thermic Typic Kandiudult) soil with 1.6% organic matter. Meteorological data, including the monthly cumulative rainfall and average monthly temperature during the period of crop growth from May to November 2021 and 2022 are shown in Figure 1. Peanut cultivar 'Georgia-06G' (Branch 2007) was planted at 20 seeds m^{-1} of crop row on May 14, 2021, and May 10, 2022. Plots were 7.6 m long and 3.6 m wide with 4 rows.

Experimental Design and Field Management

The experiments were arranged in a split-plot design with four replications in both years. Peanut exposure timings (25 and 60 DAP corresponding to vegetative [V3] and reproductive [R4] growth stages) were assigned to the main plots. The subplot treatments were five sublethal rates of glufosinate (Ignite 280® herbicide; Bayer CropScience, Research Triangle Park, NC): 1.2, 4.7, 18.9, 75.5, and 302 g ha^{-1} representing 1/512, 1/128, 1/32, 1/8, and 1/2 of the labeled rate of 604 g ha^{-1}. In addition, an untreated, weed-free control was included for treatment comparison. Glufosinate rates were selected based on previous research that indicated significant peanut injury would occur at 1/512, 1/128, 1/32, and 1/8 of the labeled rates of other herbicides such as dicamba plus glyphosate and 2,4-D plus glyphosate (Daramola et al. 2023a, 2023b). Flumioxazin (Valor SX; Valent USA Corporation, Walnut Creek, CA) was applied at 107 g ha^{-1} immediately after peanuts were planted to provide preemergence weed control. Clethodim (Select Max; Valent USA Corporation) was sprayed at 136 g ha^{-1} beginning 6 wk after planting (WAP) to provide grass weed control. Broadleaf weeds were controlled by cultivation using an S-Tine cultivator and hand weeding at 4 WAP, and imazapic (Cadre; BASF Corporation, Research Triangle Park, NC) was applied at 70 g ha^{-1} at 8 WAP. In addition to weed control with the aforementioned herbicides, the untreated control plots were maintained weed-free with supplemental hand weeding. All herbicide treatments were applied with a CO_2-pressurized backpack sprayer equipped with TeeJet AIXR11003 nozzles (Spraying Systems Co., Glendale Heights, IL) calibrated to deliver 140 L ha^{-1} at 4.8 km h^{-1}. Fertilizer, fungicide, insecticide, and gypsum were applied based on peanut production recommendations from the University of Florida Cooperative Extension Services (Wright et al. 2016).

Data Collection

Peanut Injury

Peanut plants were observed for injury symptoms at 2, 4, and 8 WAT. Injury ratings (an aggregate of foliar chlorosis, necrosis, leaf bronzing, and plant stunting) were based on a 0% to 100% scale as follows: 0% = normal plant growth with no injury symptoms; 25% = minor foliage injury with approximately 25% of the leaves and branches showing injury symptoms including chlorosis and general plant stunting; 50% = moderate injury symptoms with approximately 50% of plant foliage showing chlorosis and severe stunted shoot growth; 75% = very severe injury symptoms with almost 75% of the foliage showing chlorosis, necrosis, leaf bronzing, and plant stunting; 100% = completely dead plants.

NDVI from Aerial Multispectral Imaging

Multispectral images were collected with an Altum multispectral camera (Micasense, Seattle, WA) mounted on a DJI Matrice 100 (DJI Sky City, Shenzhen, China). Following herbicide application, the UAV was flown at 2, 4, and 8 WAT to generate color-infrared (CIR) images in red, green, and near-infrared (NIR) bands over the experimental field with a flight altitude of 30 m above ground level at a speed of 1.1 ms^{-1}. The flight plan was set using the DJI pilot

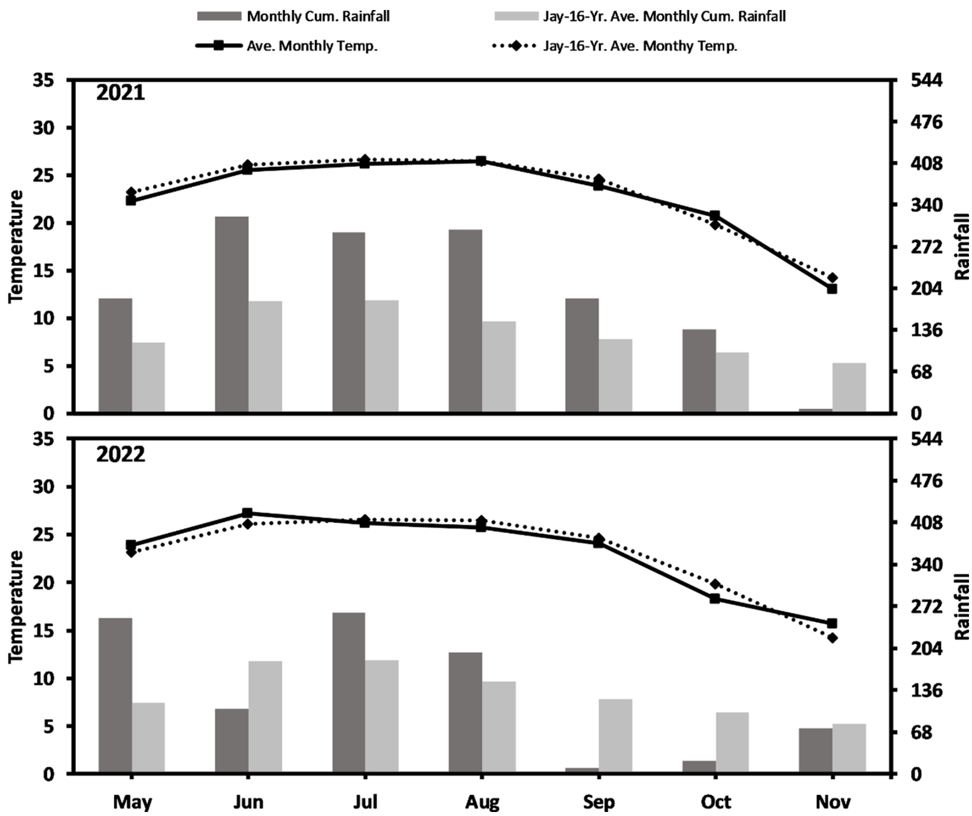

Figure 1. Average monthly temperature (C) and monthly cumulative rainfall (mm) during the period of crop growth in 2021 and 2022 and 16-yr average monthly temperature and average monthly cumulative rainfall for Jay, FL.

application as described by Ortiz et al. (2011) After UAV image acquisition, Pix4D Fields (Pix4D SA; Prilly, Switzerland) was used for radiometric calibration, to create a mosaic, and to construct orthomosaic and NDVI maps. NDVI (a good indication of upper crop vigor and upper crop canopy health) was calculated using Equation 1:

$$NDVI = \frac{NIR - Red}{NIR + Red} \quad [1]$$

where *NIR* represents the pixel value of the NIR band image, and *Red* is the corresponding pixel value of the red band image in the CIR image. Previous studies have shown that NDVI can indicate biomass vegetation and chlorophyll differences based on the principle that a plant's ability to absorb red light decreases as chlorophyll content decreases, resulting in low NDVI values, whereas plants with high chlorophyll content absorb red light and reflect energy in the NIR range, resulting in high NDVI values (Ortiz et al. 2011; Tucker 1979).

Peanut Canopy and Yield Reduction

Peanut canopy height and width were measured at 2, 4, and 8 WAT to quantify the effect of simulated drift rates of glufosinate on peanut growth. Peanut canopy height and width were measured from four plants in the two middle rows of each plot. Canopy height was measured from the ground surface to the top of the peanut canopy, while canopy width was measured from one edge of the peanut canopy to the other edge. Peanut optimum harvest timing was determined using the hull-scrape method (Willams and Drexler 1981), and yield was determined at maturity by harvesting the middle two rows of each plot. Peanuts were dug using a conventional digger-shaker-inverter and were allowed to air-dry in the field for 3 to 5 d. The yield was recorded at 10.5% moisture content using a grain moisture meter calibrated for peanuts as Mulvaney and Devkota (2020) recommended. For data analysis, peanut canopy height, width, and yield were converted to percent reduction from the weed-free check with Equation 2:

$$Percent\ reduction = \frac{Value\ for\ weed\ free\ check\ -\ Value\ for\ peanut\ exposed\ to\ herbicide}{Value\ for\ weed\ free\ check} \times 100 \quad [2]$$

Statistical Analysis

Data were subjected to ANOVA using the GLIMMIX procedure with SAS software (version 9.4; SAS Institute Inc., Cary, NC). Initial analyses were performed on all dependent variables to determine the effect of year as a fixed effect. This analysis showed that the effect of year and treatments by year interaction was not significant. Therefore, all subsequent analyses were performed with both years combined as a random effect. Data were transformed to obtain the arcsine square root to normalize data. The transformation did not affect data interpretation; hence, nontransformed data were used to interpret the results. Peanut exposure timing, glufosinate rates, and their interactions were considered fixed effects, while year, replication nested within year, and their interactions were considered random effects.

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The least-square means of fixed effects were computed, and differences among least-square means were compared using Tukey's honestly significant difference test at P < 0.05 with the GLIMMIX procedure. The SLICE option for the LSMEANS command was used to partition significant interactions among fixed effects. To compare and contrast trends, linear (along with quadratic, and lack of fit partitions) and nonlinear regression models were evaluated to determine the relationship between herbicide rate and all dependent variables using the GLIMMIX procedure, after which a regression model was chosen based on statistical significance (P < 0.05) and coefficient of determination (r^2). Linear models were chosen because they were the best-fit model and strongly described (greatest r^2 values) the data parameters. Furthermore, Pearson correlation coefficients were conducted among selected dependent variables for all years combined. Correlation coefficients were determined using the CORR procedure with SAS software and were considered significant at P < 0.05.

Results and Discussion

Peanut Injury

Injury symptoms following peanut exposure to glufosinate were similar to those reported in previous studies (Johnson et al. 2012; Jordan et al. 2011; Prostko et al. 2013). Injury was characteristic of contact herbicides that manifested as necrosis, leaf bronzing, and plant stunting.

There was a significant exposure timing by glufosinate rate interaction for visual peanut injury at 2, 4, and 8 WAT (Table 1). Therefore, injury results are discussed by interaction. Peanut injury increased as the glufosinate rate increased from 1.2 to 302 g ha^{-1}. The values ranged from 7% to 72% at 2 WAT, 4% to 62% at 4 WAT, and 3% to 51% at 8 WAT. Peanut injury following glufosinate applied at 1.2, 4.7, and 18.9 g ha^{-1} was not greater than 7% at the V3 and R4 exposure timings at 2, 4, and 8 WAT, which suggests that these sublethal rates of glufosinate may not cause significant injury to peanut. However, when glufosinate was applied at 75.5 and 302 g ha^{-1} peanut injury ranged from 19% to 72% at the V3 exposure timing and from 22% to 54% at the R4 exposure timing. Regardless of exposure timing, peanut injury increased by 69% or more as the glufosinate rate increased to 302 g ha^{-1} at 2, 4, and 8 WAT. These results are consistent with those reported by Johnson et al. (2012) that peanut injury increased from 40% to 100% as the glufosinate rate increased from 16 to 302 g ha^{-1}. Similarly, Jordan et al. (2011) reported that visible injury increased relative to nontreated peanut when glufosinate was applied at 36 g ha^{-1} (approximately one-sixth of the manufacturer's suggested use rate for most crops).

The severity of peanut injury from glufosinate was also affected by exposure timing. At 2 WAT, the greatest injury (72%) was recorded from the highest glufosinate rate (302 g ha^{-1}) applied at the V3 growth stage (Table 1). This rate of glufosinate caused 36% greater injury at V3 compared with the R4 exposure timing at 2 WAT. This may be attributed to the potential of young and rapidly growing plants to absorb more herbicide than mature plants (Penner 1989). Additionally, reduced plant vigor and lack of fully developed cuticles at the early vegetative (V3) growth stage may have increased the sensitivity of peanut to glufosinate at higher concentrations (Wyrill and Burnside 1976). Better spray coverage at V3 than R4 probably contributed to greater injury at the V3 stage than the R4 stage. The lush canopy at R4 likely resulted in less spray reaching the lower canopy. When applied at 1.2, 4.7, 18.9, and 75.5 g ha^{-1}, glufosinate caused similar levels of injury at both V3 and R4 exposure timings at 2, 4, and 8 WAT. Similarly, glufosinate applied at 302 g ha^{-1} caused similar levels of injury at V3 and R4 exposure timings at 4 and 8 WAT (Table 1).

Table 1. Exposure timing by glufosinate rate interaction on peanut injury at 2, 4, and 8 wk after treatment.[a,b]

Application timing[e]	Glufosinate rate[f]	Visible injury[c,d] 2 WAT	4 WAT	8 WAT
	g ha^{-1}	%		
V3 stage	1.2 (1/512×)	6.2 d	5.2 c	3.0 c
	4.7 (1/128×)	6.8 d	5.3 c	3.3 c
	18.9 (1/32×)	6.2 d	4.2 c	3.3 c
	75.5 (1/8×)	23.7 b	23.1 b	18.5 b
	302 (1/2×)	71.8 a	61.8 a	50.6 a
R4 stage	1.2 (1/512×)	6.8 d	5.8 c	4.7 c
	4.7 (1/128×)	5.0 d	4.7 c	3.1 c
	18.9 (1/32×)	5.6 d	4.3 c	3.7 c
	75.5 (1/8×)	33.1 c	31.8 b	21.8 b
	302 (1/2×)	52.5 b	54.3 a	48.1 a

[a]Abbreviations: R4, peanut reproductive stage 4; V3, peanut vegetative stage 3; WAT, weeks after treatment.
[b]Data were combined over 2 yr (2021 and 2022).
[c]Injury ratings were based on visual estimates on 0% to 100% scale where 0% = no injury or plants similar to weed-free check, and 100% = completely dead plants.
[d]Means followed by the same non-superscript letter within a column and effect were not significantly different at P ≤ 0.05 (using Tukey's honestly significant difference test).
[e]Application timing represents 25 and 60 d after planting peanut at V3 and R4 growth stages, respectively.
[f]Simulated rates were applied as a fraction of the label rate of glufosinate at 604 g ha^{-1}.

In general, peanut injury from glufosinate was less pronounced as time progressed when applied at the V3 growth stage, possibly because the plants had more time to recover and produce new vegetation. Linear regression indicated that the injury intercept reduced from 3% at 2 WAT to <1% at 8 WAT for the V3 exposure timing but injury increased from 1% to 3% at the R4 exposure timing (Table 2). Greater injury predicted by linear regression analysis at R4 compared with V3 may be attributed to the retention of injured leaves by the plants and reduction in new leaf growth at the reproductive (R4) growth stage compared with the vegetative (V3) growth stage that allowed sufficient time for new tissues to form without injury symptoms. There was 0.1% to 1.7% injury per 1% of the labeled rate of glufosinate applied at the V3 growth stage between 2 and 8 WAT (Table 2), whereas injury per 1% of the labeled rate of glufosinate at the R4 exposure timing was at least 24% higher (2.1% to 2.9%).

Normalized Difference Vegetation Index

There was a significant application timing by glufosinate rate interaction for NDVI at 2, 4, and 8 WAT. Therefore, the results of NDVI are discussed by interaction (Table 3). NDVI was generally lower (0.15 to 0.64) following peanut exposure to glufosinate at the V3 exposure timing compared with the R3 timing (0.60 to 0.93) across all the glufosinate rates at 2 WAT. This trend was also observed in untreated control plots where NDVI was 0.63 at the V3 growth stage compared with 0.92 at the R4 growth stage (Table 3). Lower NDVI values at the early stage of crop growth were probably due to reduced peanut canopy and less chlorophyll. Greater peanut canopy at the R3 growth stage enhanced the contrast between the injured and the newly grown foliage with relatively large NDVI values. The lowest NDVI value at 2 WAT was observed when

Table 2. Regression parameters for peanut injury response to increasing rates of glufosinate at vegetative and reproductive growth stages at 2, 4, and 8 wk after treatment.[a,b]

Rating week	Application timing[c]	Intercept (P-value)	Linear (P-value)	r^2 (P-value)
2 WAT	V3	3.38 (0.5013)	1.65 (<0.0001)	0.96 (<0.0001)
	R4	1.32 (0.7061)	2.92 (<0.0001)	0.97 (<0.0001)
4 WAT	V3	0.13 (0.9480)	0.92 (0.0084)	0.96 (<0.0001)
	R4	0.19 (0.9463)	2.93 (<0.0001)	0.97 (<0.0001)
8 WAT	V3	0.03 (0.9821)	0.07 (0.6501)	0.99 (<0.0001)
	R4	2.59 (0.2607)	2.14 (<0.0001)	0.98 (<0.0001)

[a]Abbreviations: R4, peanut reproductive stage 4; V3, peanut vegetative stage 3; WAT, weeks after treatment.
[b]Data were combined over 2 yr (2021 and 2022).
[c]Application timing represents 25 and 60 d after planting peanut at V3 and R4 growth stages, respectively.

Table 3. Application timing by glufosinate rate interaction on peanut NDVI at 2, 4, and 8 wk after treatment.[a,b,c]

Application timing[d]	Glufosinate rate[e]	2 WAT	4 WAT	8 WAT	Canopy width reduction
	g ha^{-1}		NDVI		
V3 growth stage	1.2 (1/512×)	0.62 c	0.88 abc	0.93 a	2.0 d
	4.7 (1/128×)	0.64 c	0.88 abc	0.91 a	0.3 d
	18.9 (1/32×)	0.59 cd	0.89 abc	0.92 a	2.3 d
	75.5 (1/8×)	0.52 e	0.80 c	0.92 a	9.8 d
	302 (1/2×)	0.15 e	0.40 e	0.5 c	42.9 a
	Untreated control	0.63 a	0.88 abc	0.91 a	–
R4 growth stage	1.2 (1/512×)	0.93 a	0.94 a	0.90 a	2.8 d
	4.7 (1/128×)	0.90 ab	0.93 a	0.90 a	3.1 d
	18.9 (1/32×)	0.91 ab	0.94 abc	0.91 a	4.5 d
	75.5 (1/8×)	0.82 b	0.86 bc	0.91 a	23.4 c
	302 (1/2×)	0.60 c	0.64 d	0.41 b	56.3 b
	Untreated control	0.92 a	0.9 a	0.90 a	–

[a]Abbreviations: NDVI, normalized difference vegetation index; WAT, weeks after treatment.
[b]Data were combined over 2 yr (2021 and 2022).
[c]Means followed by the same non-superscript letter within a column and effect were not significantly different at P ≤ 0.05 (using Tukey's honestly significant difference test).
[d]Application timing represents 25 and 60 d after planting peanut at the V3 and R4 growth stages, respectively.
[e]Simulated rates were applied as a fraction of the label rate of glufosinate at 604 g ha^{-1}.

glufosinate at 302 g ha^{-1} was applied to peanut at the V3 stage, whereas the highest NDVI value at 2 WAT was observed in untreated plants and plants that had been exposed to glufosinate at 1.2, 4.7, or 18.9 g ha^{-1} at the R4 stage (Table 3).

Regardless of exposure timing, glufosinate applied at 1.2, 4.7, or 18.9 g ha^{-1} resulted in NDVI values (0.60 to 0.94) that were similar to those of the untreated plants (0.63 to 0.92) at 2, 4, and 8 WAT. This indicates that NDVI values derived from UAV imagery were not effective in indicating peanut exposure to glufosinate at 1.2, 4.7, or 18.9 g ha^{-1} when applied at the V3 and R4 growth stages, possibly because peanut exhibited low and transient injury symptoms at those rates. These results are consistent with those reported by Henry et al. (2004) that moderately injured plants following glyphosate application at 16, 31 and 125 g ha^{-1} (1/64 to 1/8 of the labeled rate of 1,120 g h^{-1}) were indistinguishable from untreated plants using NDVI values from corn and soybean. However, in the present study, peanut injured from glufosinate applied at 75.5 and 302 g ha^{-1} (1/8 and 1/2 of the labeled rate of 604 g ha^{-1}) were distinguished from uninjured control 2 WAT by lower NDVI values at V3 and R4 exposure timings. Compared with untreated plants, peanut exposed to glufosinate at 75.5 g ha^{-1} exhibited 17% lower NDVI at the V3 exposure timing and 11% lower NDVI at the R4 exposure timing at 2 WAT. At 4 and 8 WAT, however, peanut exposed to glufosinate at 75.5 g ha^{-1} at the V3 exposure timing had similar NDVI values as the untreated plants. In contrast, at R4 exposure timing, peanut injury from glufosinate applied at 75.5 g ha^{-1} was distinguishable from the untreated control plants with a 4% lower NDVI value at 4 WAT (Table 3). Peanut at the R4 growth stage exposed to glufosinate at higher rates retained injured leaves for an extended period due to the reduction in new leaf growth at the reproductive growth stages, resulting in lower NDVI values. Compared with untreated plants, peanut exposed to glufosinate at 302 g ha^{-1} exhibited at least 44% lower NDVI at the V3 stage and at least 54% lower NDVI at the R4 stage at 2, 4 and 8 WAT (Table 3). As injury caused by glufosinate was greater at 302 g ha^{-1}, a generally lower trend of NDVI values indicating poor crop health and reduced vigor was observed as expected. These results indicate that NDVI values from aerial imagery can be used to distinguish injured from uninjured peanut plants up to 8 wk after exposure to glufosinate at 302 g ha^{-1} (1/2 of the labeled rate) at V3 or R4 growth stages. This can be attributed to the greater severity and less recovery from the injury symptoms at 1/2 of the labeled rate of glufosinate compared with lower rates of application. Previous studies have also reported lower NDVI values in plants treated with 1/2 and 1/8 of the labeled rate of glyphosate (1,120 g ha^{-1}) and paraquat (450 g ha^{-1}) applied to corn, cotton, and soybean (Henry et al. 2004; Ortiz et al. 2011).

Peanut Canopy Reduction

Exposure timing by glufosinate rate interaction was significant for peanut canopy width reduction at 4 WAT. The greatest peanut

Table 4. Regression parameters for peanut canopy height reduction at 4 WAT, canopy width reduction at 4 WAT, NDVI at 4 WAT, LAI at 4 WAT, and yield reduction with different exposure timing to increasing rates of glufosinate.[a,b]

Variable	Application timing[c]	Intercept (P-value)	Linear (P-value)	r^2 (P-value)
Height reduction	V3	1.45 (0.7605)	0.12 (0.7595)	0.93 (<0.0001)
	R4	1.68 (0.7077)	0.34 (<0.0001)	0.88 (<0.0001)
Width reduction	V3	0.84 (0.7163)	1.13 (<0.0001)	0.96 (<0.0001)
	R4	1.05 (0.8028)	2.03 (<0.0001)	0.94 (<0.0001)
NDVI	V3	0.89 (0.0499)	0.003 (0.1686)	0.98 (<0.0001)
	R4	0.95 (0.0239)	0.007 (0.0003)	0.96 (<0.0001)
Yield reduction	V3	3.99 (0.3785)	1.05 (<0.0001)	0.86 (<0.0001)
	R4	4.73 (0.3625)	1.17 (<0.0001)	0.94 (<0.0001)

[a]Abbreviations: LAI, leaf area index; NDVI, normalized difference vegetation index; WAT, weeks after treatment.
[b]Data were combined over 2 yr (2021 and 2022).
[c]Application timing represents 25 and 60 d after planting peanut at the V3 and R4 growth stages, respectively.

width reduction at 4 WAT (56%) was observed when glufosinate was applied at 302 g ha^{-1} at the V3 exposure timing (Table 3). There was no difference in peanut canopy width reduction between V3 and R4 exposure timings from glufosinate applied at 1.2, 4.7, and 18.9 g ha^{-1}. However, at higher rates (75.5 and 302 g ha^{-1}), glufosinate caused at least 30% greater canopy width reduction at the R4 timing compared with the V3 exposure timing (Table 3). Linear regressions indicated that peanut canopy width reduction intercept was <1% for exposure to glufosinate at V3 and 1% for exposure at R4 (Table 4). There was a 1.1% peanut canopy width reduction per 1% of the labeled rate of glufosinate at the V3 exposure timing (Table 4), while peanut width reduction per 1% of the labeled rate of glufosinate at the R4 exposure timing was about two times higher (2.0%). Glufosinate at 1.2, 4.7, 18.9, and 75.5 g ha^{-1} applied at V3 exposure timing resulted in <10% reductions in peanut canopy width at 4 WAT. However, at 302 g ha^{-1}, glufosinate caused a 56% reduction in peanut canopy width at the V3 stage (Table 3). Similarly, at the R4 stage, canopy width reduction following peanut exposure to glufosinate at 1.2, 4.7, and 18.9 g ha^{-1} was <5% at 4 WAT (Table 3). However, canopy width reduction from glufosinate was 24% at 75.5 g ha^{-1} and 43% at 302 g ha^{-1}. These results are similar to those reported for other herbicides such as glyphosate, dicamba, and 2,4-D in similar studies (Blanchett et al. 2017; Daramola et al. 2023a, 2023b). Daramola et al. (2023a) reported as much as 75% reduction in canopy width following peanut exposure to dicamba plus glyphosate at 25 DAP at similar application rates. The present study showed that peanut is susceptible to greater canopy width reduction when exposed to glufosinate at the R4 growth stage than the V3 stage at 75. 5 and 302 g ha^{-1}.

Exposure timing and glufosinate rate had a significant effect on peanut canopy height reduction at 4 WAT, whereas exposure timing by glufosinate rate interaction was not significant (Table 4). Peanut exposure to glufosinate at the V3 growth stage resulted in 50% greater canopy height reduction (14%) than at the R4 growth stage (7%) (Table 5). The R4 peanut growth stage is the beginning of pod development with no rapid internode elongation occurring on the main axis of the plant (Boote 1982), which could explain the lower peanut height reduction following exposure to glufosinate at the R4 growth stage. Additionally, at the R4 growth stage resources are mostly diverted to pod/seed filling; in turn, little canopy height response or reduction was observed. Greater peanut height reduction following exposure to glufosinate at the V3 growth stage was most likely due to the reduction in internode elongation that occurred at this stage of rapid node development (Boote 1982). These results are consistent with those reported by Daramola et al. (2023a, 2023b) who observed that peanut was susceptible to greater canopy height reduction at the V3 growth stage compared with the R3 stage following exposure to simulated drift of dicamba plus glyphosate (1.1 + 2.5 to 71 + 160 g ha^{-1}) and 2,4-D plus glyphosate (2.1 + 2.2 to 135 + 142 g ha^{-1}). Peanut canopy height reductions following exposure to glufosinate at 1.2, 4.7, 18.9, and 75.5 g ha^{-1} were similar (≤5%). However, glufosinate applied at 302 g ha^{-1} caused a 35% reduction in peanut canopy height at 4 WAT (Table 5). Similar peanut height reductions have been reported from other herbicides such as dicamba (Seale et al. 2020), 2,4-D (Blanchett et al. 2017), and glyphosate plus dicamba (Daramola et al. 2023b).

Table 5. Effect of peanut exposure timing and glufosinate rate on peanut canopy height reduction and yield reduction.[a,b,c]

Effect	Height reduction[d]	Yield reduction
	%	
Application timing[e]		
V3	13 a	18 a
R4	7 b	20 a
P-value	0.0005	0.3874
Glufosinate rate[f]		
1.2 (1/512×)	2 b	7 c
4.7 (1/128×)	3 b	4 c
18.9 (1/32×)	2 b	9 c
75.5 (1/8×)	5 b	15 b
302 (1/2×)	35 a	61 a
P-value	<0.0001	<0.0001
T × R	ns	ns

[a]Abbreviations: R, glufosinate rate; T, application timing.
[b]Data were combined over 2 yr (2021 and 2022).
[c]Means followed by the same non-superscript letter within a column and effect were not significantly different at P ≤ 0.05 (using Tukey's honestly significant difference test).
[d]Height reduction was measured at 4 wk after treatment.
[e]Application timing represents 25 and 60 d after planting peanut at the V3 and R4 growth stages, respectively.
[f]The glufosinate rates are presented in grams per hectare (g ha^{-1}). Reduced rates were applied as a fraction of the 1× labeled rate of glufosinate at 604 g ha^{-1}.

Peanut Yield Reduction

Neither timing nor exposure timing by glufosinate rate interaction were significant. However, glufosinate rate did affect peanut yield (Table 5). Peanut yield reductions (18% to 20%) averaged across glufosinate rates were similar at both V3 and R4 exposure timings (Table 5). These results are consistent with those reported by Prostko et al. (2013), who observed no significant difference following peanut exposure at R1 (30 DAP) or R4 (60 DAP) growth stages when glufosinate was applied at 41 to 656 g ha^{-1}. Prostko

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Table 6. Correlation analyses among peanut injury, NDVI value, and canopy height, width and yield reductions as influenced by simulated drift of selected herbicides applied at V3 and R3 growth stages.[a,b]

	Injury			NDVI			Height reduction			Width reduction			
	2 WAT	4 WAT	8 WAT	2 WAT	4 WAT	8 WAT	2 WAT	4 WAT	8 WAT	2 WAT	4 WAT	8 WAT	Yield reduction
Injury													
2 WAT	1												
4 WAT	0.92	1											
8 WAT	0.93	0.96	1										
NDVI													
2 WAT	−0.63	−0.50	−0.53	1									
4 WAT	−0.87	−0.83	−0.96	0.76	1								
8 WAT	−0.77	−0.75	−0.77	0.56	0.91	1							
Height reduction													
2 WAT	0.53	0.47	0.51	−0.45	−0.56	−0.51	1						
4 WAT	0.82	0.79	0.77	−0.70	−0.92	−0.90	0.59	1					
8 WAT	0.80	0.77	0.77	−0.69	−0.89	−0.83	0.57	0.93	1				
Width reduction													
2 WAT	0.67	0.64	0.51	−0.50	−0.61	−0.53	0.83	0.61	0.62	1			
4 WAT	0.92	0.93	0.92	−0.60	−0.88	−0.80	0.54	0.82	0.82	0.61	1		
8 WAT	0.88	0.91	0.96	−0.55	−0.85	−0.76	0.48	0.77	0.77	0.66	0.82	1	
Yield reduction	0.80	0.85	0.59	−0.50	−0.75	−0.69	0.39	0.73	0.72	0.56	0.79	0.85	1

[a]Abbreviations: NDVI, normalized difference vegetation index; WAT, weeks after treatment.
[b]All correlation coefficient values were significant at $P \leq 0.0001$.

et al. (2013) reported that the amount of glufosinate needed to reduce peanut yield by 50% (266 g ha^{-1}) was the same for R1 and R4 exposure timings. In the present study, linear regression analysis showed that the yield reduction intercept was 3.9% at V3 and 4.7% at R4 exposure timings. Also, the slope was 1.05% when glufosinate was applied at the V3 stage and 1.17% at the R4 stage (Table 4). These results indicated that a greater amount of glufosinate (298 g ha^{-1}; 43.8% of labeled rate) was required to cause a 50% yield reduction at the V3 stage compared with the R4 stage (243 g ha^{-1}, or 38.6% of labeled rate). These results showed that peanut was more susceptible to glufosinate at the R4 growth stage than at the V3 stage, possibly because the plants had less time to recover from glufosinate injury at the R3 stage compared with the V3 stage.

The greatest peanut yield reduction (61%) was observed when glufosinate was applied at 302 g ha^{-1}, whereas yield was reduced by 15% when glufosinate was applied at 75.5 g ha^{-1}. We observed no difference in peanut yield reduction when glufosinate was applied at 1.2, 4.7, or 18.9 g ha^{-1} (≤9%; Table 3). These results are consistent with those reported by previous researchers who evaluated the effect of simulated drift rates of glufosinate on peanut (i.e., Johnson et al. 2012; Jordan et al. 2011; Prostko et al. 2013). Jordan et al. (2011) and Prostko et al. (2013) reported that no major reductions in yield occurred when peanut was exposed to glufosinate at V3 and R4/R5 growth stages at rates less than 67 g ha^{-1}. Johnson et al. (2012) reported significant peanut yield reductions ranging from 33% to 75% when glufosinate was applied 21 DAP at just 1/2 and 1/4 of the labeled rate.

Correlation Analysis

Correlation analysis showed a highly significant ($P \leq 0.0001$) positive relationship between peanut yield reduction and visual injury ($r^2 = 0.59$ to 0.85), canopy height ($r = 0.39$ to 0.73), and width reductions ($r^2 = 0.56$ to 0.85) from 2 WAT to 8 WAT (Table 6). Similarly, correlation analysis showed a highly significant ($P \leq 0.0001$) positive relationship between peanut injury and canopy height ($r^2 = 0.47$ to 0.82) and width reductions ($r^2 = 0.51$ to 0.96) from 2 WAT to 8 WAT. These results indicate a reduction in peanut canopy and yield with increasing visual injury following glufosinate application. This observation is consistent with that made by Jordan et al. (2011) who noted that visible injury at 3 WAT and peanut yield were negatively correlated ($r^2 = -0.845$). Based on the highest observed values for r^2 in this study, the best timing for assessing potential yield reduction based on injury was between 2 and 4 WAT with r^2 values of 0.80 and 0.85, respectively (Table 2).

NDVI from UAV imagery was negatively correlated ($P \leq 0.0001$) with visual injury rating ($r = -0.50$ to -0.87), canopy height reduction ($r = -0.45$ to -0.87), canopy width reduction ($r = -0.50$ to -0.88), and peanut yield reduction ($r = -0.50$ to -0.75) from 2 WAT to 8 WAT (Table 6). This illustrates that greater injury, and consequently canopy and yield reductions, were indicated by lower NDVI values obtained via remote sensing using a UAV. Based on the highest observed values for r^2, the best timing for assessing potential yield reduction based on NDVI was 4 WAT with an r^2 value of 0.75 (Table 6).

Practical Implications

This study provides information on the sensitivity of peanut to glufosinate. The severity of peanut injury and yield reduction from applications of glufosinate were affected by application rate, exposure timing, and application rate by exposure timing interaction. No significant visual injury or peanut canopy or yield reductions occurred when glufosinate was applied at rates ≤18.9 g ha^{-1} (1/32 of the label rate of 604 g ha^{-1}). However, at 75.5 and 302 g ha^{-1} (1/8 and 1/2 of the labeled rate), injury was as high as 72% and yield reduction was ≥16%. Therefore, caution should be taken to ensure that off-target movement of glufosinate onto neighboring peanut fields does not occur. Likewise, glufosinate tank contamination should be avoided by ensuring proper tank cleanout. Linear regression analysis showed that peanut was more sensitive to glufosinate at the R4 growth stage than the V3 stage, possibly because the plants had less time to recover from glufosinate injury at the R3 stage compared with the V3 stage. In many situations, it is difficult for growers and practitioners to determine the herbicide rates (drift or tank contamination) to which the crop was exposed. In the present study, NDVI values obtained from UAV imagery often corresponded with peanut canopy and yield reductions, and thus served as a valuable tool for estimating potential yield reduction. Peanut exposed to glufosinate at 75.5 and 302g ha^{-1} was distinguishable from untreated plants with lower NDVI values at least up to 4 WAT regardless of exposure timing. However, other factors such as environmental conditions, peanut variety, and management practices can influence crop recovery and yield response following peanut exposure to sublethal rates of glufosinate, and should therefore be considered when using these data. Based on the Pearson correlation coefficient (i.e., *r* values), the best timing for assessing potential yield reduction based on injury was between 2 and 4 WAT. Evaluating potential yield reduction from early season visual injury at 2 WAT would give growers enough time to replant or change crop if the injury indicated that potential yield loss was such that termination of damaged peanut was warranted. NDVI early in the growing season at 4 WAT is a relatively good predictor of yield reduction when glufosinate injury occurs to a peanut crop. NDVI determined via aerial imagery will be helpful in accelerating the detection of injury in large hectarages with greater accuracy compared with a visual injury rating, which can be influenced by individual estimation mistakes.

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