

Article

Sensitivity and Recovery of Grain Sorghum to Simulated Drift Rates of Glyphosate, Glufosinate, and Paraquat

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Abstract: A field experiment was conducted in 2017 and 2018 to evaluate the sensitivity and recovery of grain sorghum to the simulated drift of glufosinate, glyphosate, and paraquat at two application timings (V6 and flag leaf growth stage). Paraquat drift caused maximum injury to sorghum plants in both years, whereas the lowest injury was caused by glyphosate in 2017. Averaged over all herbicide treatments, injury to grain sorghum from the simulated herbicide drift was 5% greater when herbicides were applied at flag leaf stage, as compared to herbicide applications at the six-leaf stage in 2017. In 2018, injury from glyphosate drift was higher when applied at the six-leaf stage than at the flag leaf stage. Paraquat and glufosinate drift caused more injury when applied at flag leaf stage than at six-leaf stage at 14 days after application in 2018. About 21% to 29% of injury from the simulated drift of paraquat led to a 31% reduction in grain sorghum yield, as compared to a nontreated check in 2017. The simulated drift of glyphosate and glufosinate did not result in any significant yield reduction compared to the nontreated check in 2017, possibly due to the recovery of sorghum plants after herbicides' drift application.

Keywords: plant height; sorghum; injury; sorghum grain yield

1. Introduction

Weed control in grain sorghum (*Sorghum bicolor* (L.) Moench) is mostly achieved through spraying herbicides such as atrazine, S-metolachlor, dimethenamid-P, and alachlor for preemergence weed control and 2,4-D, dicamba, prosulfuron, and bromoxynil for postemergence weed control [1]. However, grain sorghum is sensitive to many herbicides, including glyphosate, glufosinate, and imazethapyr [2]. In the southern United States, including Mississippi, grain sorghum is commonly grown adjacent to corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), or soybean (*Glycine max* (L.) Merr.) [2] and consequently, it becomes subjected to herbicide drift from these adjacent fields. Off-target movement of herbicides applied in corn, cotton, or soybean, is common when environmental conditions favor volatilization and/or physical drift [2]. Factors influencing the severity of the herbicide drift may include a sensitive crop, crop growth stage, environmental conditions, herbicide and formulation, droplet size, spray additive(s) and pressure, and the height of the boom [2].

Paraquat is commonly used for burndown applications prior to planting crops, but it may also be used as a harvest aid for soybean. Earlier soybean harvest allows for the possibility of grain sorghum to be exposed to paraquat. Aside from harvest aids, glyphosate and glufosinate are applied for postemergence (POST) weed control in the Roundup Ready[®] (Bayer CropScience LP, Research

Triangle Park, NC, USA) or LibertyLink® (BASF Corporation, Research Triangle Park, NC, USA) systems, respectively. Applications of these herbicides can expose grain sorghum in nearby fields to drift. Glyphosate is a non-selective and broad-spectrum herbicide used for POST emergence control of many annual and perennial grass and broadleaf weeds. Glyphosate causes plant death by translocating rapidly, from foliage to meristems. Glufosinate inhibits the glutamine synthetase enzyme in plants, which restricts the formation of glutamine from glutamate and ammonia and results into the rapid accumulation of ammonia causing chlorotic and necrotic leaves in plants [2]. Historically, glyphosate has been used as a standard treatment for burn-down weed control before crop planting in spring or summer [3]. Glyphosate-resistant or glufosinate-resistant varieties of corn, cotton and, soybean expand the window of their use in these crops.

Injury-related to herbicide drift (from chlorsulfuron, thifensulfuron, triclopyr, dicamba, glyphosate, glufosinate, etc.) has been reported in multiple crops, including sunflower (*Helianthus annuus* L.) [4,5], cotton [6], soybean [4,7], pea (*Pisum sativum* L.) [8,9], canola (*Brassica* spp.) [4,5], sugar beet (*Beta vulgaris* L.) [10], alfalfa (*Medicago sativa* L.) [11], grape (*Vitis vinifera* L.) [12], cherry (*Prunus* spp.) [13], rice (*Oryza sativa* L.) [14], and tomato (*Physalis pubescens* L.) [15]. Injury symptoms from drift of herbicides (such as glufosinate, glyphosate, Imazethapyr, and sethoxydim) include chlorosis, wilting, necrosis, and distorted leaf shape [2]. For studies conducted in Illinois, Indiana, Ohio, and Ontario, Brown, et al. [16] reported that simulated glyphosate drift at 100 and 200 g ha⁻¹ caused 11% to 61% visual injury to corn plants and reduced corn yields by 49% to 56%. In cotton, drift from 2,4-D caused higher injury than dicamba in Texas [17]. Similarly, glyphosate causes more injury to wheat plants compared to imazamox in Kansas [3]. Deeds et al. [3] reported that glyphosate drift at a 1/3x rate leads to a nearly complete kill and yield loss in wheat and there was a minor injury when applied at 1/100x rate. Visual injury to crop plants can be a good indicator of yield reduction by the herbicide drift [3]. In addition, studies have also reported greater damage from herbicide drift at later reproductive crop stages than the early growth stages of the crop [3,6,17,18]. In contrast, Lyon [19] reported that early season drift of glyphosate caused more injury to sorghum plants than later-season applications. Lyon [19] found no significant reduction in sorghum yield from glyphosate drift occurring at the bloom growth stage, as compared to the 4-inch, 12-inch, and boot growth stage drift applications. Al-Khatib et al. [2] reported grain sorghum affected by glufosinate drift exhibited symptoms of chlorosis and necrosis within two to four days after application and interveinal chlorosis and plant stunting occurred within six days of glyphosate drift. Previous work by Al-Khatib et al. [2] also reported that injury to grain sorghum increases with increasing the application rates of glyphosate from 1/100 to 1/3 of the recommended application rate and it ranges from 64% to 99% at eight weeks after the treatment application. Severe injury from herbicide drift can reduce sorghum grain yields [2]. Limited research has been conducted on the effects of glyphosate, glufosinate, and paraquat drift as well as timing of herbicide drift on grain sorghum yields in Mississippi. Therefore, the objective of this study was to evaluate the sensitivity and recovery of grain sorghum to the simulated drift of glufosinate, glyphosate, and paraquat at two application timings.

2. Materials and Methods

Two-year field studies were conducted in 2017 and 2018 at the Mississippi State University Delta Research and Extension Center in Stoneville, MS. Trials were conducted on Sharkey clay (very-fine, smectitic, thermic Chromic Epiaquerts) with 2.4% organic matter and pH 7.5. A hybrid grain sorghum variety “Pioneer ‘84P80’ (Corteva Agriscience, Indianapolis, IN, USA)” was planted in 102 cm rows at 23 seeds m⁻¹ row length on 8 June and 31 May in 2017 and 2018, respectively. This variety was selected for its high yielding characteristic and it is commonly grown around the U.S.

Experiments were set up as a randomized complete block design, with a factorial arrangement of treatments and four replications. Experiments contained two factors consisting of sorghum growth stages (V6, (sorghum plant with fully opened 6 leaves) and flag leaf (the last leaf to emerge on the sorghum plant and the panicle (head) emerges from the flag leaf sheath)) and herbicides (paraquat,

glyphosate, and glufosinate) (Table 1). Each herbicide was applied at 1/10 of the recommended 1X labeled use rate. Paraquat was applied at $0.021 \text{ kg ai ha}^{-1}$ + non-ionic surfactant at 0.25% (v/v), glyphosate at $0.060 \text{ kg ai ha}^{-1}$, and glufosinate at $0.060 \text{ kg ai ha}^{-1}$. The 1/10X rate was used to demonstrate a highly concentrated drift rate from a recommended 1X labeled rate of each herbicide used in LibertyLink® or Roundup Ready® cropping systems. In 2017, applications for the 6-leaf and flag leaf applications were made on 19 July 2017 and 1 August 2017, respectively. In 2018, the six-leaf and flag leaf applications were made on 27 June 2018 and 20 July 2018, respectively. A nontreated check was also included in the study. Herbicide applications were made using a CO₂-pressurized backpack sprayer calibrated to deliver 141 L ha^{-1} at 276 kPa. The boom consisted of 51 cm nozzle spacing, equipped with Turbo TeeJet (TeeJet Technologies, Springfield, IL, USA) Induction (TTI) 110015 nozzles.

Table 1. Herbicide treatments, trade names, and manufacturers, used in this study in 2017 and 2018.

Herbicide Treatments (Common Names)	Trade Name	Manufacturer
Glufosinate	Liberty	BASF Corporation, Research Triangle Park, NC, USA
Glyphosate	Roundup PowerMax	Monsanto Company, St. Louis, MO, USA
Paraquat	Gramoxone	Syngenta Crop Protection LLC, Greensboro, NC, USA

Injury ratings were assessed at 14 and 28 days after application (DAA) of herbicides. Visual injury assessments consisted of estimating treated plants that exhibited symptomologies such as stunting, necrosis, chlorosis, and/or bleaching. Ratings were based on a scale of 0% to 100%, with 0% being no injury and 100% being complete crop death, relative to the nontreated check. Plant heights were assessed at 14 DAA of herbicides. The yield was recorded at maturity using a Kincaid plot combine. Plots were not harvested in 2018 for yield due to unfavorable weather conditions.

All field data were analyzed using JMP Pro 13 (SAS Institute Inc., Cary, NC, USA). The herbicide treatments and application timing were considered fixed effects. Data were analyzed separately for each year since there was a significant effect of year. Means were separated using Fisher's protected Least Significant Difference (LSD) test ($\alpha = 0.05$).

3. Results and Discussion

3.1. 2017

No significant interaction was found between herbicide treatments and application timings in 2017. Injury was significantly affected by the main effects of herbicide treatments and application timing. At 14 DAA, grain sorghum injury was highest from the simulated drift of paraquat (29%) and lowest from glyphosate (3%) drift in 2017, when data was averaged over application timings (Figure 1). A simulated drift of paraquat (29%) caused 16% and 26% greater injury to grain sorghum plants than glufosinate (13%) and glyphosate, respectively at 14 DAA. Similar to 14 DAA, the injury to grain sorghum from herbicide drift at 28 DAA was greater with paraquat (21%) than glufosinate (7%) and glyphosate (4%) by 14 and 17%, respectively (Figure 2). Injury due to glufosinate and paraquat drifts was less at 28 DAA, indicating that plants recovered from their drift. Recovery may be due to injury as a localized lesion and not translocated throughout the plant. Substantial healthy leaf tissue will allow the plant to sustain normal growth and death only occur at the herbicide contact area. When data were averaged across application timings, injury at 28 DAA was statistically similar for glyphosate and glufosinate (Figure 2). Similar to our study, Al-Khatib et al. [2] reported 0%–10% injury to sorghum plants from glyphosate and glufosinate drift at 0.011 and $0.04 \text{ kg a.i. ha}^{-1}$ rates at two weeks after application. Al-Khatib et al. [2] also observed the recovery of sorghum plants from glufosinate and showed normal growth of new leaves three weeks after application, until the end of growing season.

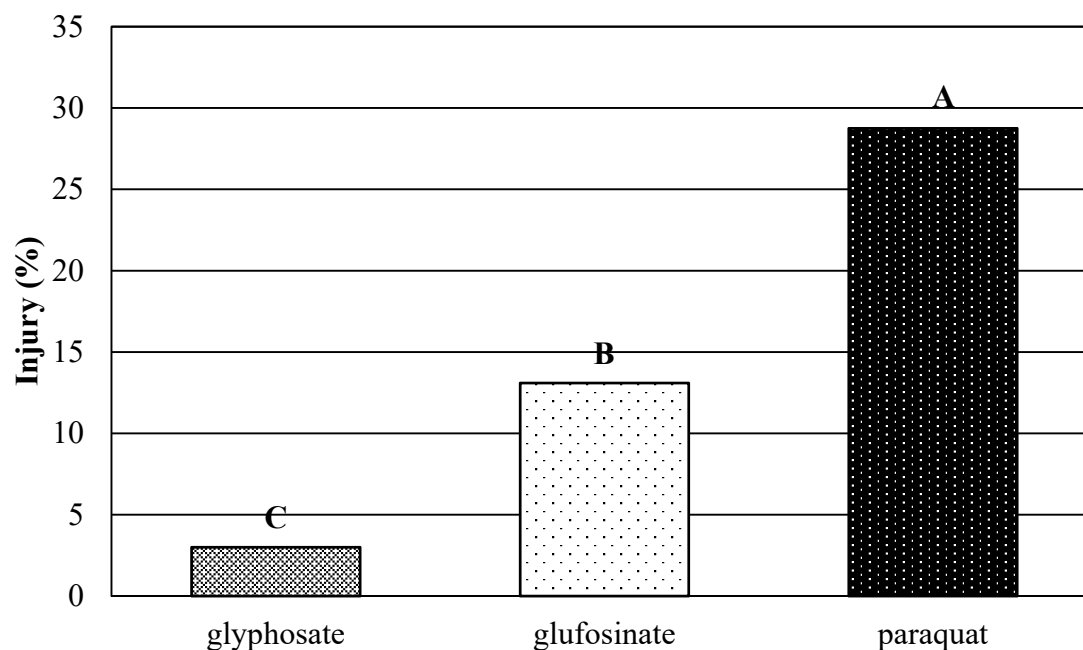


Figure 1. Grain sorghum injury from a simulated drift of glyphosate, glufosinate, and paraquat at 14 days after application (DAA) of herbicides in 2017. Data were averaged over application timings. Same letters on bars indicate no significant differences at $p < 0.05$, according to Fisher's least significant difference test.

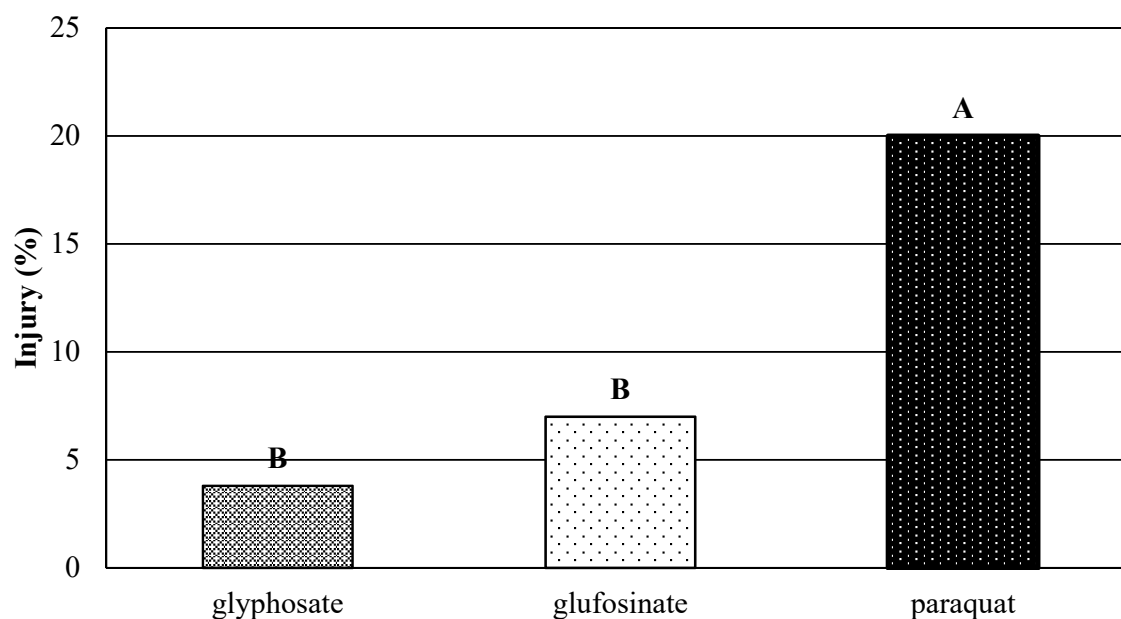


Figure 2. Grain sorghum injury from a simulated drift of glyphosate, glufosinate, and paraquat at 28 DAA in 2017. Data were averaged over application timings. Same letters on bars indicate no significant differences at $p < 0.05$, according to Fisher's least significant difference test.

Averaged over herbicide treatments, injury to grain sorghum from the simulated drift of herbicides was 5% greater when herbicides were applied at flag leaf stage, as compared to herbicide applications at the six-leaf stage at 14 and 28 DAA (Figures 3 and 4). The injury for applications made at the flag leaf stage was only 17.5% and 13% at 14 and 28 DAA, respectively. Although the injury was not extreme, exposure of herbicide drift at the flag leaf growth stage is critical for grain sorghum maturity and grain production [2]. Multiple studies in cotton and wheat have reported greater damage from herbicide drift at later reproductive crop stages than the early growth stages of the crop [2,5,16,17], however,

a study conducted in Texas, USA, reported that early season drift of glyphosate caused more injury to sorghum plants than later-season applications [19]. Lyon [19] found severe injury to sorghum from glyphosate drift at later growth stages at rates of 0.2 kg ha^{-1} or higher. Lower glyphosate rates did not cause any injury.

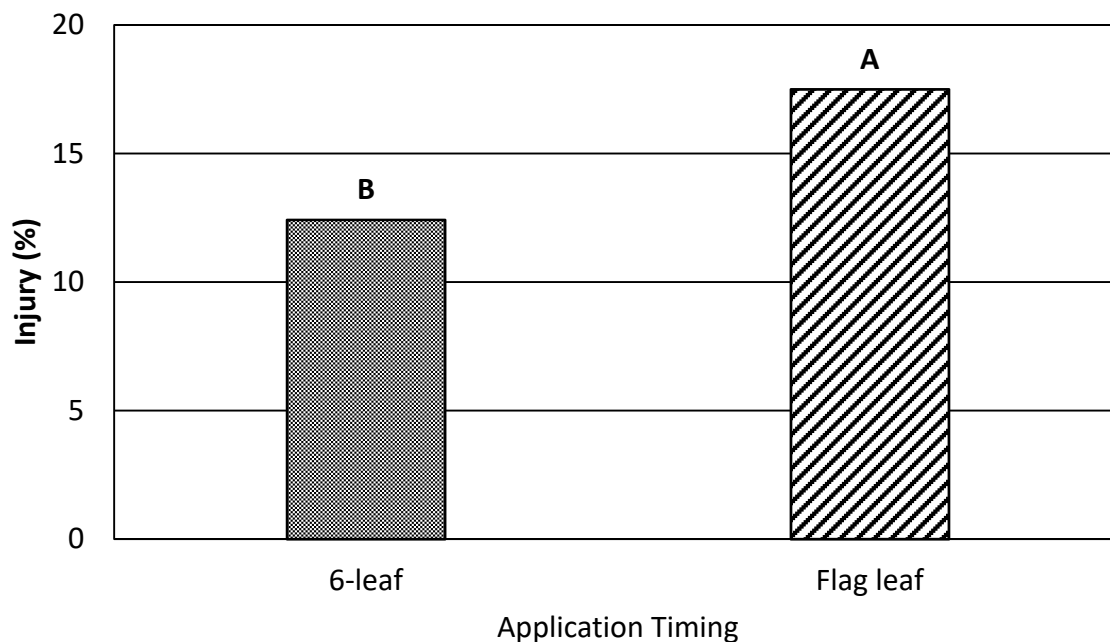


Figure 3. Grain sorghum injury from herbicide drifts at 14 DAA as affected by the application timing in 2017. Data were averaged over different herbicides used in this study. Same letters on bars indicate no significant differences at $p < 0.05$, according to Fisher's least significant difference test.

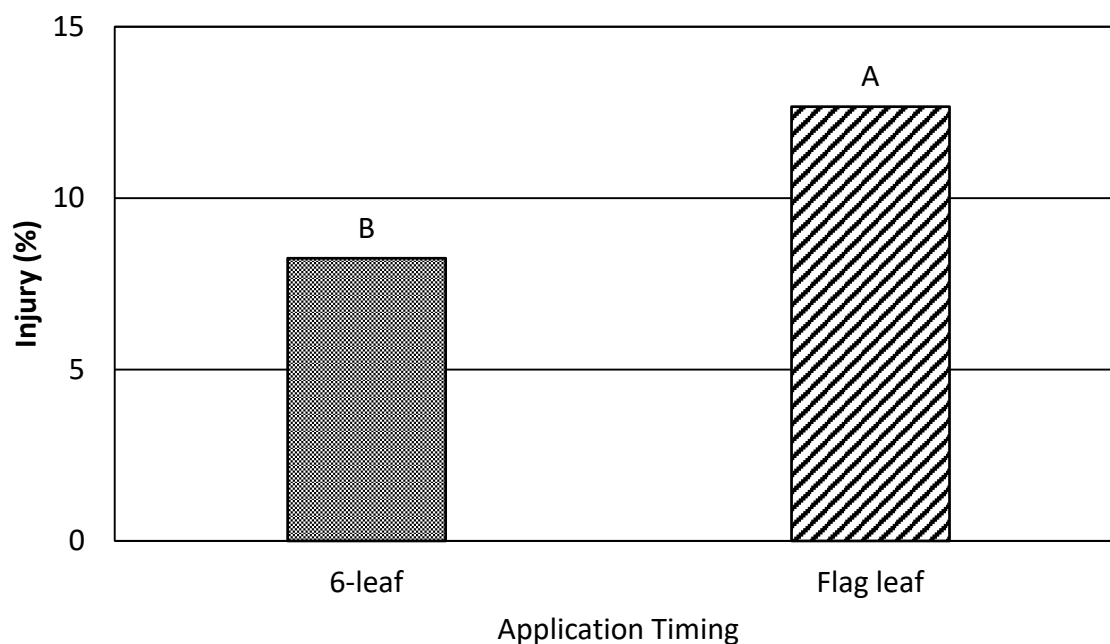


Figure 4. Grain sorghum injury from herbicide drifts at 28 DAA as affected by the application timing in 2017. Data were averaged over herbicides used in this study. Same letters on bars indicate no significant differences at $p < 0.05$, according to Fisher's least significant difference test.

In 2017, sorghum plant height and yield was significantly affected only by the herbicide treatments. Averaged over the herbicide application timings, grain sorghum plants were 5 cm taller in glufosinate and paraquat treatments than the glyphosate treatment at 14 DAA in 2017 (Figure 5). This trend in plant height was the opposite compared to the trend observed for injury at 14 DAA. Averaged over the application timing, 21% to 29% injury from the simulated drift of paraquat (2227 kg ha^{-1}) led to a 31% reduction in yield, as compared to the nontreated check (3250 kg ha^{-1}) in 2017 (Figure 6). In this study, the maximum sorghum yield was found in the glufosinate drift treatment. Averaged across application timings, the simulated drift of glyphosate (2822 kg ha^{-1}) and glufosinate (3399 kg ha^{-1}) did not result in any significant yield reduction, as compared to the nontreated check. Glyphosate drift did not reduce yield significantly, in spite of reduction in plant height. This indicates that plant height may not be a good indicator of yield reduction for glyphosate drift. The recovery of sorghum plants from glufosinate and glyphosate drift might have resulted in no yield losses. The simulated drift of paraquat resulted in a 34% reduction in yield compared to applications of glufosinate in 2017 (Figure 6). Although glyphosate caused less injury to sorghum plants, as compared to paraquat, grain sorghum yield was not significantly different between glyphosate and paraquat drifts in 2017. Al-Khatib et al. [2] found no reduction in yield due to glufosinate and glyphosate drift at rates of 0.404 and 0.011 kg ha^{-1} , respectively. However, higher drift rates of these two herbicides reduced the sorghum yield in their study [2]. Similar to our study, Kurtz and Street [20] found no yield reduction for rice from glyphosate drift occurring at the three- to four-leaf stage. In contrast, Lyon [19] found a 25% reduction in sorghum yield due to glyphosate drift at early growth stages and yield reduced up to 50% when glyphosate was applied at 0.1 and 0.2 kg ha^{-1} at the boot and bloom growth stage, respectively. Results from previous research indicates that glyphosate drift at higher rates during reproductive stages results in blasted heads and half-filled grains, causing a reduction in yield [19]. Ellis, et al. [21] reported glyphosate drift, when applied late in the season at 0.14 kg ha^{-1} , reduced corn yield by 33%, whereas early season glyphosate drift at rates of 0.035 to 0.14 kg ha^{-1} reduced corn yield by 22% to 78%. In the same study, glufosinate at 0.053 kg ha^{-1} reduced corn yield by 13% and 11% at the early and late application timing [21]. It can be concluded that the herbicide drift effects on crop yields depend upon the crop, herbicide type, application timing, and application rates.

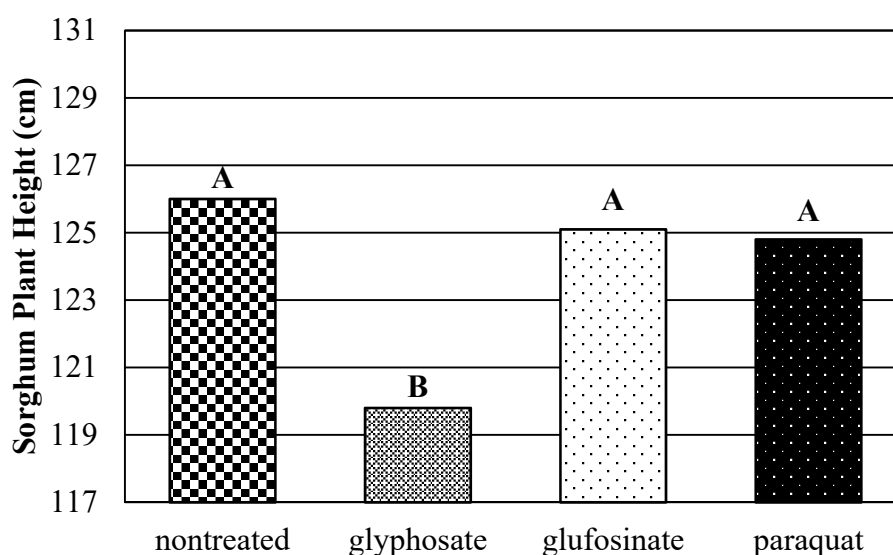


Figure 5. Grain sorghum heights for each herbicide treatment, averaged over application timing, at 14 DAA in 2017. Same letters on bars indicate no significant differences at $p < 0.05$, according to Fisher's least significant difference test.

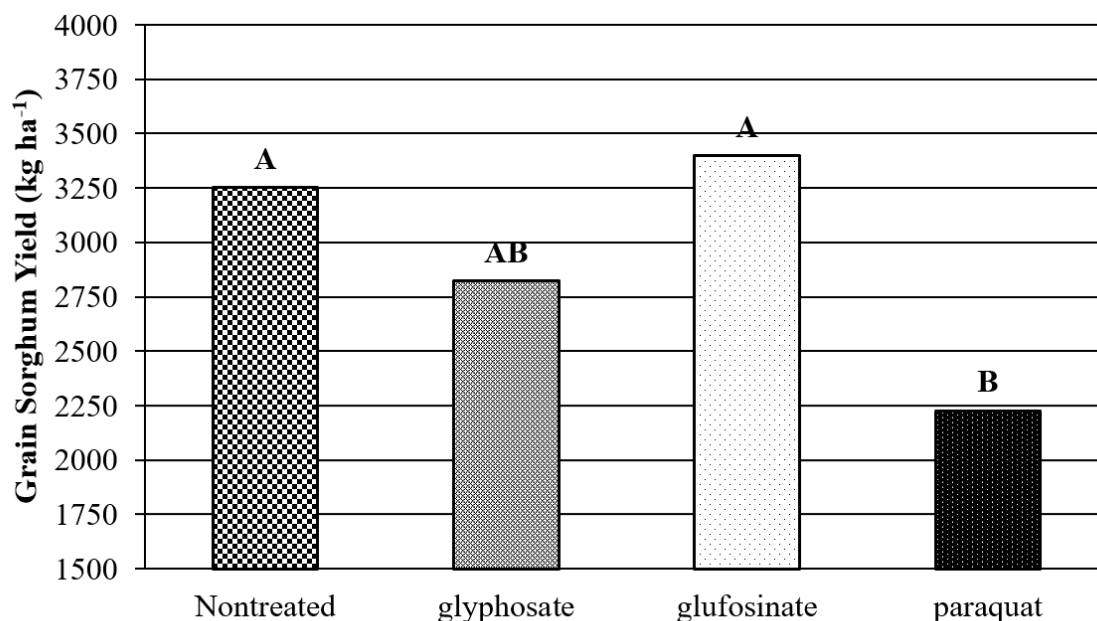


Figure 6. Grain sorghum yield as affected by herbicide drift of glyphosate, glufosinate, and paraquat in 2017. Data is averaged over application timing. Same letters on bars indicate no significant differences at $p < 0.05$, according to Fisher's least significant difference test.

3.2. 2018

Injury to grain sorghum at 14 and 28 DAA was affected by an interaction of application timing and herbicide treatments in 2018 (Figures 7 and 8). The injury to sorghum plants at 14 DAA was 10 and 15% higher with glyphosate (25%) as compared to paraquat (15%) and glufosinate (10%), respectively, when herbicides were sprayed at the six-leaf stage. At 14 DAA, injury due to herbicide drift was 19% and 38% higher with paraquat (44%) than with the glufosinate (25%) and glyphosate (6%) drift, respectively, when herbicides were sprayed at the flag-leaf stage (Figure 7). At 14 DAA, both glufosinate and paraquat drift cause more injury to plants when applied at the flag leaf stage as compared to the six-leaf stage, by 15% and 29%, respectively (Figure 7). No significant differences were observed for injury to grain sorghum at 28 DAA between six-leaf and flat leaf application timings for glufosinate drift (Figure 8). Similar to 14 DAA, paraquat drift causes 23% more injury to plants when applied at the flag-leaf stage, as compared to the six-leaf stage at 28 DAA. In contrast, glyphosate drift causes less injury when applied at the flag leaf compared to the six-leaf stage, indicating that it causes more adverse effects on early growth than the later growth stages.

Averaged over application timing, grain sorghum plants were 14 and 18 cm taller in glufosinate and paraquat treatments than the glyphosate, respectively, at 14 DAA in 2018 (Figure 9). Glyphosate drift caused 6% to 25% injury at different application timings, which might have resulted in poor plant growth, consequently reducing sorghum plant heights. Similar to our results, Brown et al. [16] also reported an 81% reduction in corn height due to a glyphosate drift rate of 0.1 kg ha^{-1} . Ellis et al. [21] found that glyphosate at 0.07 and 0.14 kg ha^{-1} reduced corn and rice height by 6% to 87% and 51%, respectively, but glufosinate caused no decrease in plant height [21]. In 2018, yield was not recorded due to inclement weather. Excessive rainfall from August to October in 2018 resulted in wet soil conditions which prevented harvest data collection (Table 2).

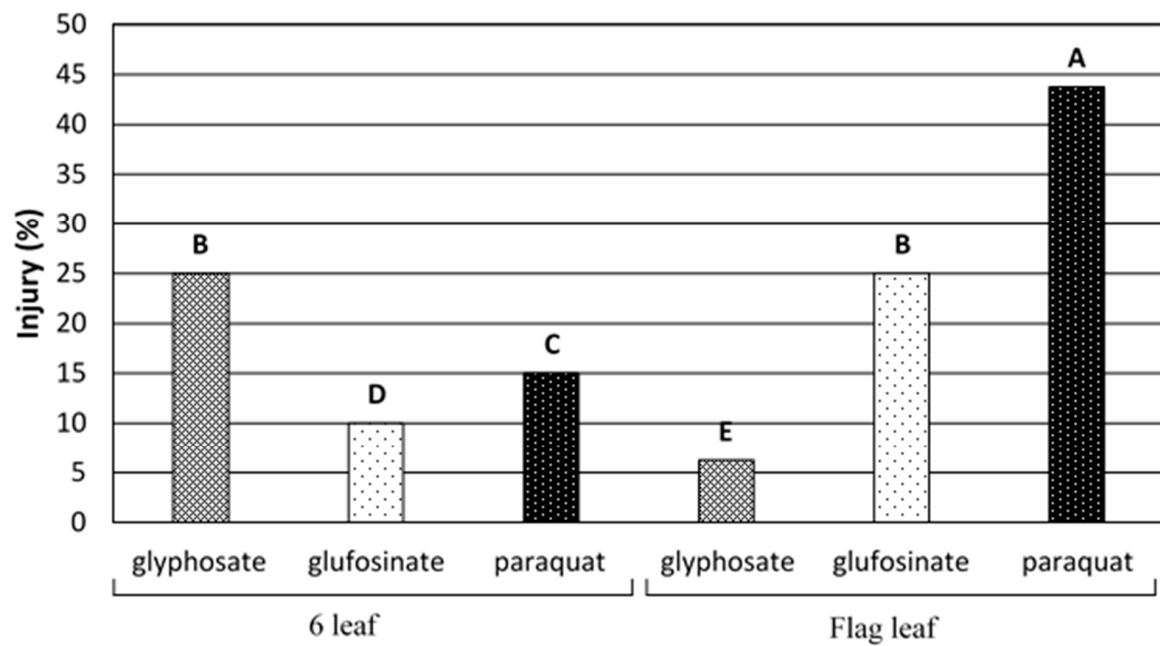


Figure 7. Grain sorghum injury from a simulated drift at 14 DAA as affected by the interaction of herbicides and application timing in 2018. Same letters on bars indicate no significant differences at $p < 0.05$, according to Fisher's least significant difference test.

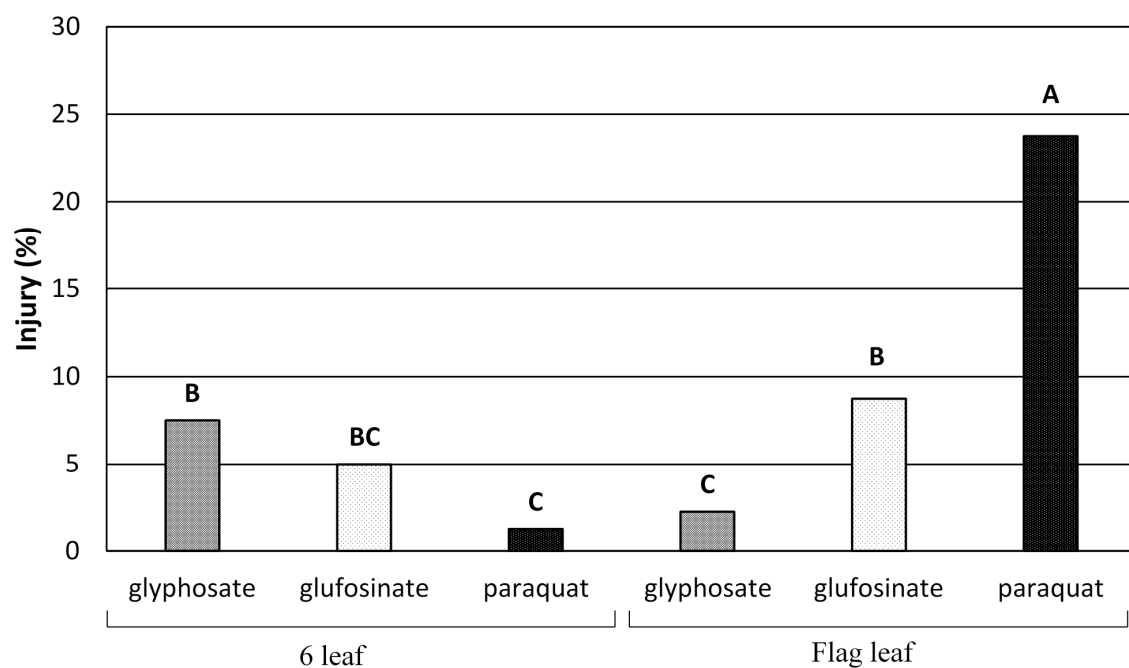


Figure 8. Grain sorghum injury from a simulated drift at 28 DAA as affected by the interaction of herbicides and application timing in 2018. Same letters on bars indicate no significant differences at $p < 0.05$, according to Fisher's least significant difference test.

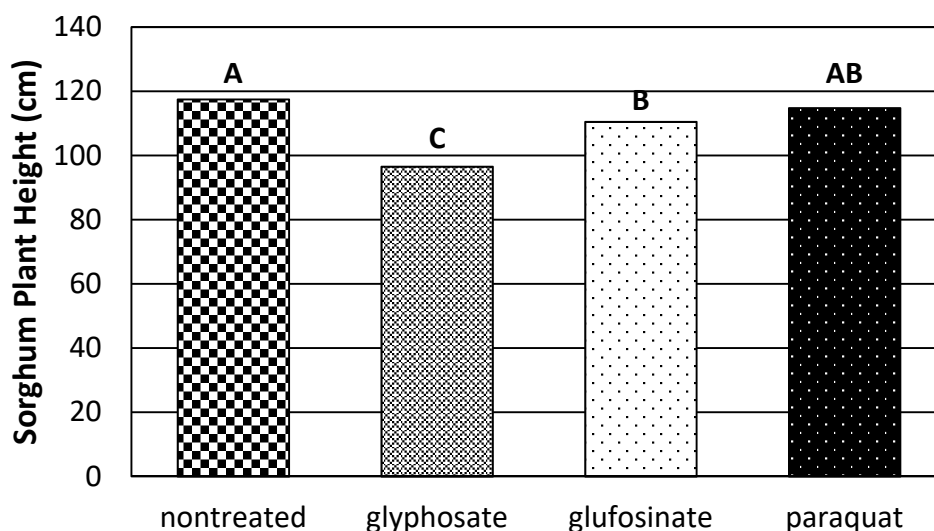


Figure 9. Grain sorghum heights as affected by each herbicide drift treatment averaged over application timing at 14 DAA in 2018. Same letters on bars indicate no significant differences at $p < 0.05$, according to Fisher's least significant difference test.

Table 2. Total monthly rainfall received at the study location in 2017 and 2018.

Month	Total Monthly Precipitation (mm)	
	2017	2018
May	98	56
June	136	79
July	95	68
August	260	231
September	22	166
October	43	67
November	46	167

4. Conclusions

Results from our study indicate that sensitivity and recovery of grain sorghum from herbicide drift depends upon the type of herbicide used and time of drift occurrence, whereas degree of injury varies by year. The level of grain sorghum physical injury from the simulated drift rates of herbicide applications was the following: Paraquat > glufosinate > glyphosate. Based on this study, there is a possibility of grain sorghum yield reduction from glyphosate drift. Grain sorghum yield was not affected by glufosinate drift, regardless of application timing. Paraquat drift on sorghum provided the most adverse effects on yield. Drift applications at the flag leaf stage of sorghum caused more damage than the early V6 growth stage application. These results were based on a single drift event. However, in a multiple drift event, when grain sorghum will be exposed to two or three drift events, the damage to grain sorghum, in terms of physical injury and yield reduction, may get worse. Therefore, applicators should be cautious when applying paraquat, glyphosate, or glufosinate when grain sorghum is near or adjacent to the treated areas.

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Conflicts of Interest: The authors declare no conflict of interest.

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