Utility of roller wiper applications of dicamba for Palmer amaranth control in soybean

Rodger Farr, a,b Jason K. Norsworthy, a L. Tom Barber, b Thomas R. Butts b, c and Trent Roberts a

Abstract

BACKGROUND: The commercialization of dicamba-resistant soybean has resulted in increased concern for off-target movement of dicamba onto sensitive vegetation. To mitigate the off-target movement through physical drift, one might consider use of rope wicks and other wiper applicators. Although wiper-type application methods have been efficacious in pasture settings, the utility of dicamba using wiper applicators in agronomic crops is not available in scientific literature. To determine the utility of roller wipers for dicamba applications in dicamba-resistant soybean, two separate experiments were conducted in the summer of 2020 and replicated in both Keiser and Fayetteville, AR, USA.

RESULTS: Utilizing opposing application directions and a 2:1:1 ratio of water: formulated glyphosate: formulated dicamba were the most efficacious practices for controlling Palmer amaranth. The high herbicide concentrations and wiping in opposing directions increased dicamba-resistant soybean injury when the wiper contacted the crop, but no yield loss was observed because of this injury. Broadcast applications resulted in greater Palmer amaranth mortality than roller wiper applications, and the most effective roller wiper treatments were when two sequential applications were made inside the crop canopy.

CONCLUSIONS: Dicamba applications require adequate coverage for optimum weed control. While efforts can be made to increase roller wiper efficacy by optimizing coverage and timing of applications, broadcast applications are superior to roller wiper applicators for weed control. Roller wiper applications did not reduce soybean yield, thus wiper-type applications may be safely used in dicamba-resistant soybean, albeit the likelihood for off-target damage caused by volatilization of these treatments would need to be investigated.

Keywords: herbicide application techniques; weed wiper; rope wick; wick applicator; spray drift management; resistance management

1 INTRODUCTION

Dicamba is a synthetic auxin herbicide (WSSA Group 4) that has been primarily used for broadleaf weed management. The use of dicamba in North America has been an integral aspect of weed management programs in corn (Zea mays L.), small grains, pasture, and rangeland for more than 50 years.1-3 The evolution of herbicide-resistant weeds, such as Palmer amaranth, waterhemp (Amaranthus tuberculatus (Moq.) J. D. Sauer), and horseweed (Conyza canadensis (L.) Cronq.) in soybean, has forced producers to seek alternative options for broadleaf weed management in broadleaf crops, such as the addition of dicamba.4-6 In response to the growing number of herbicide-resistant broadleaf weeds in cotton (Gossypium hirsutum L.) and soybean, Monsanto, now owned by Bayer Crop Sciences, developed crops that were resistant to both glyphosate and dicamba.7 The commercialization of the herbicide Xtendimax® plus VaporGrip® and dicamba-resistant soybean branded as RoundUpReady 2 Xtend Soybean® in 2016 enabled producers to apply dicamba in-crop for broadleaf weed control.

Combinations of glyphosate and dicamba controlled 90% to 100% of glyphosate-resistant waterhemp, Palmer amaranth, and horseweed.8 Applications of dicamba in dicamba-resistant cotton controlled 88% to 90% of protoporphyrinogen oxidase (PPO)-resistant Palmer amaranth in Arkansas at 21 days after treatment (DAT).9 Growers in Nebraska reported that the addition of dicamba to soybean herbicide programs resulted in improved weed control for 93% of growers surveyed.10 Concurrent with the commercialization of dicamba for in-crop use over soybean in 2016, there was an increase in complaints for auxin damage on non-dicamba resistant soybean. The off-target movement of dicamba was deemed to be caused primarily by three factors, volatilization, physical spray drift, and tank contamination.11,12

In order to prevent off-target movement of dicamba onto sensitive crops and vegetation, creators and researchers began to seek alternative management practices that would mitigate physical spray drift and tank contamination. The use of growing
physical barriers, such as corn and the use of hooded sprayers, to avert spray droplets from leaving the treated area have been shown to be viable options for mitigating physical, off-target herbicide movement. An additional method being considered by producers to reduce physical spray drift is the utilization of application technology that does not depend on broadcasting spray solution to control weeds. Rather than spraying droplets on weeds, wipers and wicks directly apply the herbicide onto the leaves of vegetation via contact with a saturated surface, such as a rope or fabric material. By applying herbicide directly onto the target plants, the risk of off-target movement via physical drift from a broadcast spray is greatly decreased. Wiper type applicators, such as rope wicks, roller wipers, and rotary wipers, were initially utilized for applying auxin herbicides, such as 2,4-D, above broadleaf crops to selectively control broadleaf weeds that grew above the crop canopy. Prior to the development of glyphosate-resistant crops, rope wicks and wipers were used to apply glyphosate above crop canopies to effectively control weeds, such as johnsongrass \( \text{Sorghum halepense} \) (L.) Pers., shattercane \( \text{Sorghum bicolor} \) (L.) Moench spp., and volunteer corn, as long as the target weed remained above the crop canopy. However, to prevent potential crop injury, care had to be taken to prevent leaking or dripping of herbicide from pipes or improperly calibrated systems. Previous extension research conducted in Arkansas during the onset of glyphosate-resistant Palmer amaranth in cotton investigated the utility of wiper type applicators, specifically roller wiper and rope wick applicators, for applications of paraquat and diuron to manage Palmer amaranth for rescue applications (Norsworthy, personal communication, 2019).

By using wiper-type applicators in crops resistant to herbicides, such as dicamba, the risk for crop injury would be reduced and would potentially allow for producers to use a wiper type application within the crop canopy. To effectively assess the utility and feasibility of dicamba applications using a wiper-type applicator in dicamba-resistant soybean, two separate studies were conducted in the summer of 2020. The objectives of these studies were to determine optimal practices for a roller-wiper application, evaluate application timing and coverage methods for maximizing Palmer amaranth control, evaluate crop safety from roller-wiper applications in dicamba-resistant soybean, and determine whether or not that roller wiper applications of dicamba would be viable options for Palmer amaranth control compared to broadcast applications in dicamba-resistant soybean.

2 MATERIALS AND METHODS

2.1 Experiment design and establishment

Two separate field experiments were both conducted in 2020 at the Northeast Research and Extension Center near Keiser, AR (35.68, −90.08) and at the Milo J. Shult Arkansas Agricultural Experiment Station at in Fayetteville, AR (36.09, −94.17). The purpose of these experiments was to investigate (i) the influence of weed height, herbicide concentration, and application direction on Palmer amaranth control in dicamba-resistant soybean (herbicide rate study) and (ii) the impact that application method and the use or non-use of sequential herbicide applications has on weed control in dicamba-resistant soybean (herbicide placement study). Dicamba-resistant soybean (Asgrow 46X6; Bayer CropScience, St. Louis, MO, USA) was planted on May 20 at both Keiser and Fayetteville. These locations are more 375 km apart. Row spacings were 97 cm in Keiser and 91 cm in Fayetteville. Both locations were furrow-irrigated to supplement natural rainfall. The soil texture at Fayetteville was a Captina silt loam (fine-silty, siliceous, active, mesic Typic Fragiult) with a pH of 6.4. The soil texture at Keiser was a Steele loamy sand (sandy over clayey, mixed, superactive, non-acid, thermic Aquic Udifluvent) with a pH of 6.7. Both sites had natural populations of glyphosate-resistant Palmer amaranth (Norsworthy, 2021 personal communication).

The herbicide rate experiment was designed as a randomized complete-block design using a three-factor factorial \((3 \times 2 \times 2)\) treatment structure that included a non-treated control and an additional comparison treatment where plots were subjected to a typical postemergence dicamba-based broadcast spray application. The broadcast program consisted of dicamba at 560 g a.e. ha\(^{-1}\) (Xtendimax; Bayer Crop Science) plus glyphosate at 1260 g a.e. ha\(^{-1}\) (Roundup PowerMax; Bayer Crop Sciences) plus pyroxasulfone at 120 g a.i. ha\(^{-1}\) (Zidua WDG; BASF, Research Triangle Park, NC, USA) followed by dicamba at 560 g a.e. ha\(^{-1}\) + glyphosate at 1260 g a.i. ha\(^{-1}\) + acetochlor at 1260 g a.i. ha\(^{-1}\) (Warrant; Bayer Crop Sciences). The three factors of the experiment were target weed height at application (20–30 cm, 40–50 cm, 60–70 cm), herbicide concentration \((1 + \text{glyphosate} \text{ at 1260 g a.e. ha}^{-1}\) \(+ \text{V Animated technology that does not depend on broadcasting spray solutions to control weeds. However, to prevent potential crop injury, care had to be taken to prevent leakage or dripping of herbicide from pipes or improperly calibrated systems. Previous extension research conducted in Arkansas during the onset of glyphosate-resistant Palmer amaranth in cotton investigated the utility of wiper type applicators, specifically roller wiper and rope wick applicators, for applications of paraquat and diuron to manage Palmer amaranth for rescue applications (Norsworthy, personal communication, 2019).

By using wiper-type applicators in crops resistant to herbicides, such as dicamba, the risk for crop injury would be reduced and would potentially allow for producers to use a wiper type application within the crop canopy. To effectively assess the utility and feasibility of dicamba applications using a wiper-type applicator in dicamba-resistant soybean, two separate studies were conducted in the summer of 2020. The objectives of these studies were to determine optimal practices for a roller-wiper application, evaluate application timing and coverage methods for maximizing Palmer amaranth control, evaluate crop safety from roller-wiper applications in dicamba-resistant soybean, and determine whether or not that roller wiper applications of dicamba would be viable options for Palmer amaranth control compared to broadcast applications in dicamba-resistant soybean.

2 MATERIALS AND METHODS

2.1 Experiment design and establishment

Two separate field experiments were both conducted in 2020 at the Northeast Research and Extension Center near Keiser, AR (35.68, −90.08) and at the Milo J. Shult Arkansas Agricultural Experiment Station at in Fayetteville, AR (36.09, −94.17). The purpose of these experiments was to investigate (i) the influence of weed height, herbicide concentration, and application direction on Palmer amaranth control in dicamba-resistant soybean (herbicide rate study) and (ii) the impact that application method and the use or non-use of sequential herbicide applications has on weed control in dicamba-resistant soybean (herbicide placement study). Dicamba-resistant soybean (Asgrow 46X6; Bayer CropScience, St. Louis, MO, USA) was planted on May 20 at both Keiser and Fayetteville. These locations are more 375 km apart. Row spacings were 97 cm in Keiser and 91 cm in Fayetteville. Both locations were furrow-irrigated to supplement natural rainfall. The soil texture at Fayetteville was a Captina silt loam (fine-silty, siliceous, active, mesic Typic Fragiult) with a pH of 6.4. The soil texture at Keiser was a Steele loamy sand (sandy over clayey, mixed, superactive, non-acid, thermic Aquic Udifluvent) with a pH of 6.7. Both sites had natural populations of glyphosate-resistant Palmer amaranth (Norsworthy, 2021 personal communication).

The herbicide rate experiment was designed as a randomized complete-block design using a three-factor factorial \((3 \times 2 \times 2)\) treatment structure that included a non-treated control and an additional comparison treatment where plots were subjected to a typical postemergence dicamba-based broadcast spray application. The broadcast program consisted of dicamba at 560 g a.e. ha\(^{-1}\) (Xtendimax; Bayer Crop Science) plus glyphosate at 1260 g a.e. ha\(^{-1}\) (Roundup PowerMax II; Bayer Crop Sciences) plus pyroxasulfone at 120 g a.i. ha\(^{-1}\) (Zidua WDG; BASF, Research Triangle Park, NC, USA) followed by dicamba at 560 g a.e. ha\(^{-1}\) + glyphosate at 1260 g a.i. ha\(^{-1}\) + acetochlor at 1260 g a.i. ha\(^{-1}\) (Warrant; Bayer Crop Sciences). The three factors of the experiment were target weed height at application (20–30 cm, 40–50 cm, 60–70 cm), herbicide concentration \((1 + \text{glyphosate} \text{ at 1260 g a.e. ha}^{-1}\) \(+ \text{V Animated technology that does not depend on broadcasting spray solutions to control weeds. However, to prevent potential crop injury, care had to be taken to prevent leakage or dripping of herbicide from pipes or improperly calibrated systems. Previous extension research conducted in Arkansas during the onset of glyphosate-resistant Palmer amaranth in cotton investigated the utility of wiper type applicators, specifically roller wiper and rope wick applicators, for applications of paraquat and diuron to manage Palmer amaranth for rescue applications (Norsworthy, personal communication, 2019).

By using wiper-type applicators in crops resistant to herbicides, such as dicamba, the risk for crop injury would be reduced and would potentially allow for producers to use a wiper type application within the crop canopy. To effectively assess the utility and feasibility of dicamba applications using a wiper-type applicator in dicamba-resistant soybean, two separate studies were conducted in the summer of 2020. The objectives of these studies were to determine optimal practices for a roller-wiper application, evaluate application timing and coverage methods for maximizing Palmer amaranth control, evaluate crop safety from roller-wiper applications in dicamba-resistant soybean, and determine whether or not that roller wiper applications of dicamba would be viable options for Palmer amaranth control compared to broadcast applications in dicamba-resistant soybean.

2 MATERIALS AND METHODS

2.1 Experiment design and establishment

Two separate field experiments were both conducted in 2020 at the Northeast Research and Extension Center near Keiser, AR (35.68, −90.08) and at the Milo J. Shult Arkansas Agricultural Experiment Station at in Fayetteville, AR (36.09, −94.17). The purpose of these experiments was to investigate (i) the influence of weed height, herbicide concentration, and application direction on Palmer amaranth control in dicamba-resistant soybean (herbicide rate study) and (ii) the impact that application method and the use or non-use of sequential herbicide applications has on weed control in dicamba-resistant soybean (herbicide placement study). Dicamba-resistant soybean (Asgrow 46X6; Bayer CropScience, St. Louis, MO, USA) was planted on May 20 at both Keiser and Fayetteville. These locations are more 375 km apart. Row spacings were 97 cm in Keiser and 91 cm in Fayetteville. Both
inside of closed system that prevents herbicide physical drift. The wiper was placed 10 cm into the crop canopy and was moved through the plot at a speed of 8.5 kph. Treatments were wiped in succession as the tractor traveled down the rows, lowering the wiper into the canopy for plots receiving treatments and raising the wiper above the canopy to avoid treating plots not receiving treatments. Between different treatments, plots were allowed to dry in order to mitigate contamination of the tractor as the applicator moved through the field to apply different treatments.

The herbicide placement experiment was designed as a three factor (3 × 2 × 2) factorial with the first factor being the

| Location   | Experiment          | Height average (range) (cm) | Density average (range) (plants m⁻²) |
|------------|---------------------|-----------------------------|-------------------------------------|
| Fayetteville | Herbicide rate      | —                          | 8 (1–16)                            |
|            | Herbicide placement | 44 (8–72)                  | 8 (1–16)                            |
| Keiser     | Herbicide rate      | —                          | 27 (20–52)                          |
|            | Herbicide placement | 50 (37–71)                 | 22 (12–36)                          |

* Herbicide rate experiments included target heights 20–30, 40–50, and 60–70 cm as factors.

Figure 1. Air temperature in degrees Celsius during the growing season at (A) Keiser and (B) Fayetteville, AR. Vertical red lines indicate herbicide application dates.
placement of the application (over the top broadcast, at canopy roller wiper, and roller wiper 10 cm inside the soybean canopy), the second factor being the preemergence herbicide used (S-metolachlor at 534 g a.i. ha$^{-1}$ (Dual Magnum; Syngenta Crop Protection) and a combination of flumioxazin at 35 g a.i. ha$^{-1}$ and pyroxasulfone at 45 g a.i. ha$^{-1}$ (Fierce; Valent, Walnut Creek, CA, USA)), and the third factor being the presence or absence of a sequential application 14 days following the initial application. At time of initial postemergence application, ten Palmer amaranth plants were measured, marked, and counted as described for the previous experiment. Palmer amaranth densities and heights were recorded at the time of the first postemergence application (Table 1) and temperature was recorded throughout the season using a Watch Dog 2000 Series permanent weather station (Spectrum Technologies Inc.) located on site (Fig. 1).

Preemergence and broadcast applications were made using a CO$_2$-pressurized backpack sprayer calibrated to deliver 140 L ha$^{-1}$ at 276 kPa. Preemergence applications were made using TeeJet AIXR 110015 nozzles and broadcast postemergence applications were made using TeeJet TTI 110015 nozzles. Roller wiper applications were made as previously described using the Grassworks™ weed wiper. The wiper was placed 10 cm into the crop canopy for the in-canopy treatments and touching the crop canopy (0–2 cm within the crop canopy) for the canopy treatments. Ground speed of the tractor was 8.5 kph. Initial applications were made when Palmer amaranth measured 40–50 cm in height (Table 1) and soybean measured 50 cm in height.

2.2 Data collection

For both studies, visible estimates of Palmer amaranth control were rated at 7, 14, 21, and 28 DAFT on a scale of 0 to 100, where 0 represents no plant symptomology and 100 represents plant death. At 28 DAFT, marked Palmer amaranth plants were individually evaluated for mortality (dead or alive) and the total number of deceased Palmer amaranth were divided by the number of marked plants to provide mortality proportion for each plot. $^{26-28}$ Visible soybean injury was rated at 7, 14, and 21 DAFT in the herbicide placement study and at 14 and 21 DAFT in the herbicide rate study on a similar scale to that used for Palmer amaranth control. Soybean grain from the two treated rows of each plot was harvested at maturity using an ALMACO® SPC40 (ALMACO, Nevada, IA, USA) and adjusted to 13% moisture.

2.3 Data analysis

Data for both trials were analyzed in R version 4.0.3 (R Foundation for Statistical Computing, Vienna, Austria). Data were evaluated for normality using Shapiro–Wilks tests and equal variance was determined by plotting the residuals of the model prior to final model selection. $^{29}$ Variables which met both normality and homogeneity of variance assumptions were evaluated with linear models using base functions. Those models that did not satisfy the assumptions of equal variance or normal distribution were analyzed using a non-parametric factorial model using the rankFD package. $^{30,31}$ Initially, models were tested with site as a factor to test for interactions between site and other factors. Exploratory model testing of Palmer amaranth data for the herbicide placement study resulted in site by factor interaction for all variables. As a result, data were analyzed separately by site. Conversely, exploratory model testing found only two site by factor interactions for the herbicide rate study. As a result, the herbicide placement study data were pooled over site. One-way analysis of variance (ANOVA) analyses were conducted using data from the herbicide rate study to compare results from the roller wiper treatments to a broadcast comparison. Data in the herbicide placement study were subjected to Type I ANOVA, and means were separated using least significant differences with Tukey’s adjustment at $\alpha = 0.05$. Data in the herbicide rate study were subjected to Type III ANOVA using Palmer amaranth height relative to the height of the roller wiper at time of application as a covariate, and means were separated using least significant differences with Tukey’s adjustment at $\alpha = 0.05$.

3 RESULTS AND DISCUSSION

3.1 Herbicide rate study

Generally, there were differences between the two sites, primarily as it related to Palmer amaranth control, but there were no significant interactions between site and any other factor, except between site and target height for Palmer amaranth control and mortality at 28 DAFT (Table 2). As a result, data were pooled across sites rather than analyzing the data separately.

Visible Palmer amaranth control and mortality were influenced by the interaction between target weed height and site at 28 DAFT.
Palmer amaranth control at 28 days after final treatment (DAFT) and Palmer amaranth mortality at 28 DAFT by interactions location by Palmer amaranth height at time of application in 2020 at Fayetteville and Keiser, AR

| Treatment | Location x Palmer amaranth height | Palmer amaranth control (%) | 28 DAFT | Palmer amaranth mortality (%) |
|-----------|----------------------------------|-----------------------------|--------|------------------------------|
| Site      | Palmer amaranth height           |                             |        |                              |
| Fayetteville | 20–30 cm | 81 a | 53 a | ab                           |
|           | 40–50 cm | 80 a | 60 a | ab                           |
|           | 60–70 cm | 72 ab | 31 a | c                            |
| Keiser    | 20–30 cm | 59 b | 17 c |                              |
|           | 40–50 cm | 58 b | 24 c |                              |
|           | 60–70 cm | 72 ab | 38 bc |                             |

Means followed by the same letter are not statistically different based on Tukey’s (α = 0.05).

Table 2. The P-values from analysis of covariance for soybean injury at 14 and 21 days after final treatment (DAFT), soybean yield, Palmer amaranth control at 14, 21, and 28 DAFT, and Palmer amaranth mortality 28 DAFT from 2020 in Fayetteville and Keiser, AR

| Source | Soybean injury (P > F) | Soybean yield (P > F) | Palmer amaranth control (P > F) | Palmer amaranth mortality (P > F) |
|--------|------------------------|-----------------------|-------------------------------|----------------------------------|
|        | 14 DAFT | 21 DAFT | | 14 DAFT | 21 DAFT | 28 DAFT | | 28 DAFT |
| Height | 0.1972 | 0.1930 | 0.8512 | 0.0661 | 0.9787 | 0.7689 | 0.2487 |
| Rate   | 0.0009 | 0.0018 | 0.6108 | 0.3293 | 0.7141 | 0.0634 | 0.0008 |
| Direction | 0.6314 | 0.0119 | 0.5511 | 0.0016 | 0.0449 | 0.0338 | 0.0004 |
| Site  | 0.9054 | 0.3324 | 0.0001 | <0.0001 | <0.001 | <0.0001 | <0.0001 |
| Height:Rate | 0.0935 | 0.0775 | 0.6215 | 0.5186 | 0.9505 | 0.7941 | 0.4521 |
| Height:Direction | 0.3833 | 0.9527 | 0.6443 | 0.9437 | 0.7320 | 0.9681 | 0.5824 |
| Rate:Direction | 0.2441 | 0.6960 | 0.8724 | 0.2013 | 0.4388 | 0.9948 | 0.4995 |
| Height:Site | 0.2539 | 0.9150 | 0.4447 | 0.4701 | 0.1162 | 0.0131 | 0.0001 |
| Rate:Site | 0.1356 | 0.1390 | 0.4908 | 0.6028 | 0.3820 | 0.4206 | 0.4258 |
| Direction:Site | 0.2966 | 0.6043 | 0.8684 | 0.2399 | 0.3952 | 0.0634 | 0.1577 |
| Height:Rate:Direction | 0.8165 | 0.7720 | 0.5331 | 0.7260 | 0.9915 | 0.5655 | 0.8378 |
| Height:Rate:Site | 0.8426 | 0.4404 | 0.5635 | 0.2627 | 0.6632 | 0.4289 | 0.9588 |
| Height:Direction:Site | 0.2488 | 0.6243 | 0.9084 | 0.0681 | 0.5000 | 0.5928 | 0.5151 |
| Rate:Direction:Site | 0.1265 | 0.6043 | 0.9840 | 0.2399 | 0.6077 | 0.0948 | 0.4272 |
| Height:Rate:Direction:Site | 0.2210 | 0.3079 | 0.5968 | 0.3964 | 0.8611 | 0.7697 | 0.4034 |

Bolded values indicate statistical significance at α = 0.05.

(Table 2). Palmer amaranth control at 28 DAFT for the two smallest target heights in Fayetteville were similar, resulting in 81% and 80% control for the 20–30 cm and 40–50 cm target heights respectively (Table 3). These levels of control were greater than those at Keiser for the same target heights, where 59% and 58% Palmer amaranth control occurred following treatment at the 20–30 cm and 40–50 cm target heights respectively. At the tallest target weed height, Palmer amaranth control was 72% at both Keiser and Fayetteville, although the control was not different from that of the smaller target weed heights (Table 3).

Palmer amaranth mortality followed a similar trend to Palmer amaranth control at 28 DAFT. An improvement in mortality occurred in Fayetteville for the two smallest target heights with 53% and 60% mortality for the 20–30 and 40–50 cm target heights compared to the 60–70 cm target height where only 31% mortality was achieved. At Keiser, mortality did not vary among the three target heights (Table 3). These discrepancies in control between the two locations may be attributed to differences in weed density (Table 1). The reduced density in Fayetteville would have allowed for greater contact between the wiper and individual weeds instead of some weeds being shielded from the wiper by other weeds in a denser population, such as in Keiser.

Soybean manifested chlorosis and necrosis following roller wiper applications (Fig. 3). Slight differences were ascertained between the two herbicide concentrations at 14 and 21 DAFT (Table 2), resulting in soybean injury that was <10% at any evaluation timing but there were no more than a 3% difference in the injury that resulted from the different herbicide concentrations. Greater phytotoxicity could be expected at higher concentrations due to the increased adjuvant load from the glyphosate formulation used, as at high concentrations, adjuvants may illicit plant injury. Chlorosis may have also been the result of increased aminomethylphosphonic acid (AMPA) concentrations, a byproduct of the metabolism of glyphosate by glyphosate-resistant soybean, that may have been caused by the increased concentration of AMPA.
concentration of glyphosate by the roller wiper. Soybean injury at 21 DAFT was also slightly influenced by the number of directions of the herbicide applications (Table 2). Applications from two directions resulted in 5% injury, whereas those with a single application direction resulted in 4% injury (Table 4). Although the injury could be associated with adjuvant burn, the difference in injury can be attributed to differences in coverage that resulted from applying herbicide to both sides of the plant. Injury was low and appeared to be transient and had no effect on soybean yield.

When compared to a typical broadcast herbicide application, the roller wiper provided inferior Palmer amaranth control and mortality (Table 5). At 14, 21, and 28 DAFT, broadcast applications controlled Palmer amaranth 86–94% compared to 70–72% control with the roller wiper applications. Greater Palmer amaranth mortality resulted from the broadcast application (83%) than from the roller wiper applications (37%) (Table 5). Deviations in mortality may be attributed to differences in herbicide coverage, where the broadcast applications were able to evenly distribute herbicide throughout the crop canopy while the roller wiper applications were only able to place herbicide at the point of contact and not place any herbicide on weeds below the height of the roller wiper. Similar results have been observed in studies investigating the effects of different droplet sizes from broadcast applications where less uniform distribution of herbicide reduced weed control. Soybean visible injury, although so low as to have no significant effect on yield, was slightly higher with the broadcast application than the roller wiper applications (Table 5). Other research also suggests that the degree of injury in this study would not affect soybean yield.

### 3.2 Herbicide placement study

Results for the herbicide placement study varied between locations, partially because of differences in weed population densities (Table 1) and climate (Fig. 1) between the two locations. At Keiser, Palmer amaranth populations were 22 plants m\(^{-2}\) compared to the 8 plants m\(^{-2}\) in Fayetteville (Table 1). Keiser was also generally warmer than Fayetteville throughout the growing season (Fig. 1), resulting in greater Palmer amaranth growth during the season. As a result, several site by treatment factor interactions emerged (data not shown); thus, the two locations were analyzed separately to better understand the results from the study (Table 6).

At Keiser, Palmer amaranth control was influenced by two factors, herbicide placement and the number of applications at 14, 21, and 28 DAFT (Table 6). At 28 DAFT, the broadcast treatment resulted in greater control compared to the at-canopy treatment only, while the inside-canopy treatment was similar to both other placements at 28 DAFT (Table 7). The lower Palmer amaranth control by the roller wiper treatments can be attributed to inferior herbicide coverage of all weeds in the plot. The roller wiper applications were limited by the relative height of the applicator, whereas the broadcast applications were made to all weed sizes. The lack of uniformity of coverage onto weeds and the inability to reach weeds below the canopy has been a shortfall of wiper-based applications as previously reported by Moyo et al. With the wiper-based applications, the herbicides were primarily applied to the top leaves of the Palmer amaranth.

Previous research has found that dicamba typically translocates only to the nutrient sinks of the plant, which at the time of application was limited to the upper Palmer amaranth leaves and inflorescence. As a result, dicamba, does not typically translocate to the lower parts of the plant, resulting in symptomology being primarily concentrated near the area of application for the roller wiper applications. Conversely, the broadcast applications

---

**Table 4. Soybean injury at 14 and 21 days after final treatment (DAFT), soybean yield, Palmer amaranth control at 28 DAFT, and Palmer amaranth mortality at 28 DAFT by rate, direction, and location in Keiser and Fayetteville, AR in 2020**

| Treatment | Soybean injury | Palmer amaranth control | Mortality (%) |
|-----------|----------------|--------------------------|---------------|
|           | 14 DAFT (%)    | 21 DAFT (%)              | 28 DAFT (%)   |
| Rate      | 14 DAFT (%)    | 21 DAFT (%)              | 28 DAFT (%)   |
| High      | 9 a            | 6 a                      | 73            | 44 a          |
| Low       | 6 b            | 4 b                      | 3052          | 67            | 30 b          |
| Direction | 14 DAFT (%)    | 21 DAFT (%)              | 28 DAFT (%)   |
| One       | 7              | 4 b                      | 2973          | 66 b          | 31 a          |
| Two       | 8              | 5 a                      | 2923          | 74 a          | 43 b          |
| Site      | 14 DAFT (%)    | 21 DAFT (%)              | 28 DAFT (%)   |
| Fayetteville | 8              | 5                        | 2760 b        | 77            | 48            |
| Keiser    | 7              | 4                        | 3136 a        | 63            | 26            |

Means followed by the same letter are not statistically different based on Tukey’s (α = 0.05).
Table 5. Palmer amaranth mortality, visual control at 28 days after application, visible soybean injury 14 and 21 days after application and soybean yield for contrast analyses comparing broadcast applications of dicamba to roller wiper applications of dicamba at Fayetteville and Keiser, AR in 2020.

| Source          | Palmer amaranth control (%) | Soybean yield (kg ha⁻¹) |
|-----------------|-----------------------------|------------------------|
|                 | 28 DAFT                     | 14 DAFT                | 21 DAFT                | 7 DAFT | 14 DAFT | 21 DAFT | 28 DAFT |
| Broadcast versus wiper |                  |                        |                        |        |        |        |         |
| Broadcast       | 82.5 a                      | 94 a                   | 2 b                    | 2 b    | 2900   |        |         |
| Wiper           | 37.1 b                      | 70 b                   | 7 a                    | 5 a    | 3100   |        |         |
| P-Value         | 0.0002                      | <0.0001                | 0.0004                 | 0.0135 | 0.6786 |

Means followed by the same letter are not statistically different based on Tukey’s (α = 0.05). Bolded values indicate statistical significance at α = 0.05.

Table 6. The P-values from analysis of variance for soybean injury at 7, 14 and 21 days after final treatment (DAFT), soybean yield, Palmer amaranth control at 14, 21, and 28 DAFT, and Palmer amaranth mortality 28 DAFT from 2020 in Fayetteville and Keiser, AR.

| Source          | Palmer amaranth control (P > F)  | Soybean yield (P > F)  |
|-----------------|----------------------------------|-----------------------|
|                 | 14 DAFT  | 21 DAFT  | 28 DAFT  | 7 DAFT  | 14 DAFT  | 21 DAFT  | 28 DAFT  |
| Keiser          |          |          |          |        |          |          |         |
| PRE             | 0.0762   | 0.4984   | 0.7633   | 0.3009 | 0.7084   | 0.2831   | 0.3246   |
| Placement       | 0.0013   | 0.0130   | 0.0109   | 0.0075 | 0.0006   | 0.0806   | 0.3788   |
| Num.app         | 0.0017   | <0.0001  | <0.0001  | <0.0001| <0.0001  | 0.0043   | 0.3246   |
| PRE:Placement   | 0.8565   | 0.7820   | 0.3346   | 0.6909 | 0.7680   | 0.7415   | 0.3788   |
| PRE:Num.app     | 0.0732   | 0.1868   | 0.7534   | 0.6227 | 0.7084   | 0.7607   | 0.3246   |
| Placement:Num.app | 0.0880   | 0.5451   | 0.1587   | 0.0343 | 0.0006   | 0.7398   | 0.3788   |
| PRE:Placement:Num.app-value | 0.2244  | 0.1015   | 0.9686   | 0.9512 | 0.7680   | 0.2201   | 0.3788   |
| Fayetteville    |          |          |          |        |          |          |         |
| PRE             | 0.1416   | 0.1932   | 0.0270   | 0.0041 | 0.8136   | 0.5701   | 0.9999   |
| Placement       | 0.0727   | 0.0070   | 0.0038   | 0.0008 | 0.0019   | 0.1120   | 0.0879   |
| Num.app         | 0.0077   | 0.0105   | 0.0826   | 0.0157 | 0.2044   | 0.4802   | 0.0109   |
| PRE:Placement   | 0.3636   | 0.0595   | 0.0078   | 0.0046 | 0.3117   | 0.4867   | 0.3569   |
| PRE:Num.app     | 0.3593   | 0.4540   | 0.3698   | 0.4421 | 0.1492   | 0.3373   | 0.8277   |
| Placement:Num.app | 0.0881   | 0.0222   | 0.0287   | 0.0209 | 0.3362   | 0.3335   | 0.4294   |
| PRE:Placement:Num.app-value | 0.9063  | 0.3207   | 0.1043   | 0.2492 | 0.8943   | 0.8098   | 0.1058   |

Abbreviations: PRE = preemergence herbicide option, Place = herbicide placement, Num.app = number of herbicide applications. Bolded values indicate statistical significance at α = 0.05.

provided a more uniform distribution of herbicide on the plant, thus increasing the amount of the plant that was exposed to dicamba and resulting in more uniform dicamba uptake and Palmer amaranth control, as reported by Cuvaca et al.37, Butts et al.38, and Meyer et al.39,40. Palmer amaranth control in Keiser was also influenced by the number of herbicide applications (with or without the sequential treatment) (Table 6). Averaged over all other factors, the addition of a second application resulted in 83% Palmer amaranth control at 28 DAFT (Table 7). Control with only the single application of dicamba was lower (63%). These results are similar to those by Pries et al.41 in which a single application of dicamba resulted in 50% Palmer amaranth control and a sequential application increased control to 95% when a 14-day interval was implemented on 18-cm Palmer amaranth.

At 28 DAFT at Fayetteville, Palmer amaranth was controlled 85% and 89% with a single application of dicamba if it was applied with the roller wiper inside the canopy or if it was broadcast, respectively. However, control with two roller wiper applications did not differ between placement at canopy and inside the canopy. Mortality data were somewhat variable, but two applications placed at canopy increased control over one application (Table 7). Although not different from most other application placements, dicamba applied in two broadcast applications was numerically higher than other treatments.

The reduced control and mortality from the single at-canopy treatment may stem from the height of the roller wiper placement at which the herbicide only reached weeds that would be at or above the canopy, whereas, the in-canopy placement would reach weeds just below the crop canopy, and the broadcast placement could make contact with all weeds in the crop canopy. The lack of a significant difference between the single and sequential applications with the in-canopy placement as opposed to at-canopy placement may be a function of Palmer amaranth growth patterns following dicamba applications. Following the first application, the shorter plants that had not contacted the wiper potentially grew taller. As a result, a greater number of Palmer amaranth may have come in contact with the wiper as it moved through the plots. Meanwhile the plants that had been wiped with the previous application may have been controlled more effectively. This effect may have been exacerbated by the height of the roller wiper placement.
grown downwards as the result of epinasty from the prior dicamba application. With the second application taking place at a greater height from the ground due to the continued growth of the soybean crop, the plants that had previously been wiped did not receive a second in-canopy application. Conversely, with the at-canopy application, the wiper was able to contact more weeds that had grown taller because fewer weeds were treated with the first application as a result of their uninterrupted growth.

The same interaction was observed for Palmer amaranth mortality in Keiser, where there were no differences among the different placements following a single application (Table 7). There was, however, a difference between the broadcast herbicide placement and the two roller wiper placements following two postemergence applications; the at-canopy and in-canopy applications resulted in reduced mortality compared to the broadcast treatment (Table 7). Due to dense weed populations at Keiser, the benefits of the broadcast placement may not have been completely materialized.

### Table 7. Visible Palmer amaranth control at 28 days after final treatment (DAFT), Palmer amaranth mortality, visible soybean injury at 7, 14, and 21 DAFT and soybean grain yield from Fayetteville and Keiser AR in 2020

| Treatment | Palmer amaranth control (%) | Palmer amaranth mortality | Soybean injury (%) | Soybean yield (kg ha\(^{-1}\)) |
|-----------|-----------------------------|---------------------------|-------------------|-------------------------------|
| **Fayetteville** | | | | |
| Herbicide placement | | | | |
| At-canopy | 76 | 47 | 4b | 3 | 1 | 2500 |
| Inside canopy | 82 | 48 | 8a | 4 | 2 | 2400 |
| Broadcast | 92 | 80 | 4b | 2 | 1 | 2700 |
| Preemergence option | | | | |
| S-Metolachlor | 89 | 70 | 5 | 3 | 1 | 2500 |
| Flumioxazin + pyroxasulfone | 77 | 47 | 6 | 3 | 1 | 2600 |
| **Number of applications** | | | | |
| One | 80 | 49 | 5 | 3 | 1 b | 2600 |
| Two | 86 | 68 | 6 | 4 | 2 a | 2500 |
| Placement × number of applications | | | | |
| Number of application | Herbicide placement | | | |
| One | At canopy | 65 c | 23 c | 5 | 3 | 1 | 2600 |
| Inside canopy | 87 ab | 50 abc | 6 | 3 | 3 | 2600 |
| Broadcast | 88 ab | 74 ab | 4 | 3 | 2 | 2600 |
| Two | At canopy | 87 ab | 71 ab | 3 | 3 | 0 | 2500 |
| Inside canopy | 77 bc | 46 bc | 10 | 6 | 1 | 2300 |
| Broadcast | 95 a | 86 a | 4 | 2 | 0 | 2700 |
| Preemergence × herbicide placement | | | | |
| Preemergence option | Herbicide placement | | | |
| S-Metolachlor | At canopy | 85 a | 59 ab | 4 | 4 | 1 | 2300 |
| Inside canopy | 94 a | 75 a | 8 | 5 | 2 | 2400 |
| Broadcast | 89 a | 75 a | 3 | 2 | 1 | 2700 |
| Flumioxazin + pyroxosulfone | At canopy | 67 b | 34 b | 5 | 2 | 0 | 2700 |
| Inside canopy | 70 b | 22 b | 8 | 4 | 2 | 2500 |
| Broadcast | 95 a | 86 a | 5 | 3 | 2 | 2700 |
| **Keiser** | | | | |
| Herbicide placement | | | | |
| At-canopy | 66 b | 19 | 3 | 1 | 0 | 3800 |
| Inside canopy | 69 ab | 21 | 3 | 1 | 0 | 3900 |
| Broadcast | 83 a | 43 | 0 | 1 | 0 | 4100 |
| **Number of applications** | | | | |
| One | 63 b | 12 | 4 | 2 a | 0 | 3900 |
| Two | 83 a | 43 | 0 | 0 b | 0 | 3900 |
| Placement × number of applications | | | | |
| Number of application | Herbicide placement | | | |
| One | At canopy | 50 | 6 b | 5 a | 0 | 1 | 3700 |
| Inside canopy | 64 | 14 b | 5 a | 0 | 0 | 4100 |
| Broadcast | 75 | 15 b | 0 b | 0 | 0 | 4100 |
| Two | At canopy | 83 | 32 b | 0 b | 2 | 0 | 3800 |
| Inside canopy | 74 | 28 b | 0 b | 2 | 0 | 3700 |
| Broadcast | 92 | 70 a | 0 b | 1 | 0 | 4200 |

Means followed by the same letter within a factor or for multiple factors are not statistically different based on Tukey’s (\(\alpha = 0.05\)).
following a single application, possibly due to a great number of larger Palmer amaranth that protected smaller Palmer amaranth beneath the canopy. This taller overgrowth may have allowed for those plants underneath to survive the single application. With the addition of the second application, those larger Palmer amaranth plants that were initially treated by the broadcast would have significantly reduced their surface area after 14 days following the dicamba application, allowing for the second application to contact the weeds that had previously been shielded.

Palmer amaranth control at 28 DAFT and mortality in Fayetteville were influenced by an interaction between herbicide placement and the preemergence option (Table 6). Broadcast treatments of flumioxazin + pyroxasulfone preemergence controlled Palmer amaranth 95%, which was similar to control with S-metolachlor preemergence followed by at-canopy, in-canopy, and broadcast postemergence placements (Table 7). Both roller wipe treatments, at-canopy and in-canopy, that followed flumioxazin + pyroxasulfone preemergence resulted in lower Palmer amaranth control than the broadcast applications. The differences between the two application methods (roller wiper versus broadcast) as influenced by the preemergence option and the mortality of the Palmer amaranth may be attributed to the differences in efficacy of the preemergence options. The premix of flumioxazin + pyroxasulfone may have provided a longer residual compared to S-metolachlor; pyroxasulfone has a half-life of 71 days compared to a half-life of 27 days for S-metolachlor. Residual activity may have delayed growth of Palmer amaranth in the plots treated with flumioxazin + pyroxasulfone preemergence. Furthermore, the use of two separate, effective herbicides with the use of flumioxazin + pyroxasulfone compared to the single herbicide used with the treatments utilizing S-metolachlor would also explain the increase in Palmer amaranth suppression by those plots treated with flumioxazin + pyroxasulfone. Therefore, for the roller wiper applications, weeds may have been shorter at application following flumioxazin + pyroxasulfone compared to Palmer amaranth following S-metolachlor, resulting in reduced contact by the roller wiper and decreased Palmer amaranth control.

Visible soybean injury at Fayetteville was influenced by herbicide placement at 7 DAFT (Table 6). The at-canopy and broadcast treatments both resulted in 4% injury while the in-canopy treatments resulted in 8% injury (Table 7). The increased injury from the in-canopy treatments may be attributed to the increased contact by the roller wiper in these plots as the wiper was placed deeper into the soybean canopy than the other treatments. Soybean injury was once again significant at 21 DAFT as a function of the number of herbicide applications (Table 6), where 2% soybean injury was recorded following the single application while there was only 1% injury following the second application, potentially due to higher temperatures following the first application (Fig. 1) these greater temperatures may have contributed to greater adjuvant injury as opposed to the cooler temperatures that followed the second application in Fayetteville. Conversely, at 14 DAFT in Keiser, there was 2% soybean injury following the use of two applications where there was no injury following the use of a single application. Warmer temperatures in Keiser (Fig. 1) following the first application, relative to the second application, may have allowed for the soybean to recover and grow faster. At 7 DAFT in Keiser, visible soybean injury was dependent on an interaction between application placement and the number of herbicide applications (Table 6). Following the single application, both roller wiper placements resulted in 5% injury while no injury was observed in the broadcast treatment (Table 7). The presence of injury as the result of the roller wiper applications may be attributed to physical contact and abrasion from the roller wiper and small sized tractor moving through the plots coupled with the increased concentrations of adjuvants from higher concentrations of formulated product that may have caused most of the injury (chlorotic or necrotic leaves). There was no visible injury at 21 DAFT in Keiser and no differences in soybean grain yield were observed in both studies (Table 6). These results infer that any injury observed at 7 days after application was cosmetic and did not impact the grain production of the soybean. These results are not unlike previous works that have shown that low levels of injury from labeled applications do not correlate to yield loss.

4 CONCLUSIONS
These studies suggest that the use of roller wiper applicators for weed control are not as effective as broadcast applications of dicamba. If roller wiper applicators are to be used, it is recommended that these applications be done in a way that maximizes herbicide coverage onto target weed species. The use of multidirectional applications with increased herbicide concentrations as well as sequential applications may be necessary for adequate control and to deliver a lethal rate in an attempt to curb herbicide resistance development through sub-lethal doses of dicamba. During these studies, many of the weeds were above labeled heights according to current labels for dicamba herbicides. Further research may need to be conducted to investigate if applications may be optimized earlier in the season when both soybean and Palmer amaranth are smaller than 20 cm. At this point, broadcast applications of residual herbicides at the same time as the roller wiper applications should be utilized to prevent any further weed emergence before canopy closure by the soybean. The use of roller wipers was found to be relatively safe for soybean production systems as yields were not reduced because of roller wiper applications.

ACKNOWLEDGEMENTS
Funding for this research was provided by the Arkansas Soybean Promotion Board.

CONFLICT OF INTEREST
No conflicts of interest have been declared.

DATA AVAILABILITY STATEMENT
Research data are not shared.

REFERENCES
1 Hartzler B, A historical perspective on dicamba, in 2017 Proceedings of the 72nd Annual Meeting of the North Central Weed Science Society. North Central Weed Science Society, Westminster, CO, p. 98 (2017).
2 Keelin J and Abernathy J, Woolyleaf bursage (Ambrosia grayi) and Texas blueweed (Helianthus ciliaris) control by dicamba. Weed Technol 2:12–15 (1988).
3 Schroeder J and Banks P, Soft red winter wheat (Triticum aestivum) response to dicamba and dicamba plus 2,4-D. Weed Technol 3:67–71 (1989).
4 Heap I (2020) International Survey of Herbicide Resistant Weeds. Available: http://www.weedscience.org/Summary/Species.aspx?WeedID= 14 (22 September 2020).

Pest Manag Sci 2022; 78: 2151–2160 © 2022 The Authors. Pest Management Science published by John Wiley & Sons Ltd on behalf of Society of Chemical Industry.
5 Kruger GR, Davis VM, Weller DC and Johnson WG, Control of horseweed (Conyza canadensis) with growth regulator herbicides. Weed Technol 24:425–429 (2010).
6 Norsworthy JK, Griffith GM, Scott RC, Smith KL and Oliver LR, Confirmation and control of glyphosate-resistant Palmer amaranth (Amaranthus palmeri) in Arkansas. Weed Technol 22:108–113 (2008).
7 Clemente TE, Dumitr u R, Paul C, Feng C, Flasinski S, Weeks DP, in press. Modified dicamba monooxygenase enzyme and methods of its use. US patent US7884262B2 (2007).
8 Johnson WG, Young BG, Marquardt P, Bradley KW, Culpepper AS, Al-Khatib K et al., Weed control in dicamba-resistant soybeans. Crop Manag 9:1–23 (2010).
9 Coffman MF, Baldwin TW, Norsworthy JK and Kruger GR, Effect of dicamba rate and application parameters on protoporphyrinogen oxidase inhibitor-resistant and -susceptible Palmer amaranth (Amaranthus palmeri) control. Weed Technol 35:22–26 (2021).
10 Werle R, Oliveira MC, Haja AJ and Proctor CA, Survey of Nebraska farmers’ adoption of dicamba-resistant soybean technology and dicamba off-target movement. Weed Technol 32:754–761 (2018).
11 Cundiff GT, Reynolds DB and Mueller TC, Evaluation of dicamba persistence among various agricultural crop types and cleanout procedures using soybean (Glycine max) as a bio-indicator. Weed Sci 65:305–316 (2017).
12 Stockel LE, Chism C, Thompson A (2010) Cleaning plant growth regulator (PGR) herbicides out of field sprayers. https://extension.tennesse e.edu/publications/Documents/WDC-Applicants. NALS pdf (10 February 2020).
13 Vieira BC, Butts TR, Rodrigues AO, Golus JA, Schroeder KP and Kruger GR, Spray particle drift mitigation using field corn (Zea mays L.) as a drift barrier. Pest Manag Sci 74:2038–2046 (2018).
14 Foster HC, Sperry BP, Reynolds DB, Kruger GR and Claussn S, Reducing herbicide particle drift: effect of hooded sprayer and spray quality. Weed Technol 32:714–721 (2018).
15 Ozkan HE, Herbicide application equipment, in Handbook of Weed Management System, ed. by Smith AM, Marcel Dekker Inc, New York, pp. 155–216 (1995).
16 Davison JG and Derrick PM, Weed Response to spray and “wiper” applications of translocated herbicides, in 10th International Congress of Plant Protection. Brighton, England. British Crop Protection Council, Farnham, UK, p. 520 (1983).
17 Hoette GD, Livingston SD, Peters EJ (1982) Rope wick applicators. Available: http://extension.missouri.edu/webster/documents/resources/agriculture/ropewick/G4920_Rope_Wick_Applicators.pdf [10 February 2020].
18 Wills GD and McWhorter CG, Developments in post-emergence herbicide applicators. Outlook Agric 10:337–341 (1981).
19 Keeley PE, Carter CH, Thullen RJ and Miller JH, Comparison of ropewick applicators for control of Johnsongrass (Sorghum halepense) in cotton (Gossypium hirsutum) with glyphosate. Weed Sci 32:431–435 (1984).
20 Schneider GL, Koehler CB, Schepers JS and Burnsise OC, Roller applicator for shattercane (Sorghum bicolor) in control in row crops. Weed Sci 39:301–306 (1991).
21 Brekels CW, Cole DE and Bork EW, Canada thistle (Cirsium arvense) and pasture forage responses to wiping with various herbicides. Weed Technol 19:298–306 (2005).
22 Meyers SL, Jennings KM, Schultheis JR and Monks DW, Evaluation of wick-applied glyphosate for Palmer amaranth (Amaranthus palmeri) control in sweet potato. Weed Technol 30:765–772 (2016).
23 Moyo C, Harrington KC, Kemp PD and Eerens JPJ, Wiper application of herbicides to Californian thistle. N Z Plant Prot 59:361 (2008).
24 USDA-Natural Resources Conservation Service, United States departments of agriculture. Web Soil Survey Available: http://websoilsurvey.sc.egov.usda.gov/ [1 February 2021].
25 Anonymous (2010) Clarity herbicide label. CDMS. Available: http://www.cdms.net/id/797012.pdf [1 January 2021].
26 Butts TR, Samples CA, Franca L, Dodds DM, Reynolds DB, Adams JW et al., Spray droplet size and carrier volume effect on dicamba and glufosinate efficacy. Pest Manag Sci 74:2020–2029 (2018).
27 Butts TR, Samples CA, Franca LX, Dodds DM, Reynolds DB, Adams JW et al., Droplet size impact on efficacy of a dicamba-plus-glufosinate mixture. Weed Technol 33:66–74 (2019).
28 Franca L, Dodds DM, Butts TR, Kruger GR, Reynolds DB, Mills JA et al., Evaluation of optimal droplet size for control of Palmer amaranth (Amaranthus palmeri) with aciflurofen. Weed Technol 34:1–30 (2020).
29 Kniss AR, Streibig JC (2018) Statistical analysis of agricultural experiments using R. Available: https://rstats4ag.org. [1 February 2021].
30 Brunner E, Dette H and Munk A, Box-type approximations in nonparametric factorial designs. J Am Statistical Assoc 92:1494–1502 (1997).
31 Brunner E, Bathke AC and Konietzcke F, Designs with three and more factors, in Rank and Pseudo-Rank Procedures for Independent Observations in Factorial Designs; Springer, Dordrecht, pp. 333–355 (2019).
32 Bernards M (2011) Yellow Flash in Soybean. Plant Health Exchange. American Pathological Society. Available: https://www.planthealthexchange.org/soybean/Pages/GROW-SOY-05-11-062.aspx [24 April 2021].
33 Guo P and Al-Khatib K, Temperature effects on germination and growth of redroot pigweed (Amaranthus retroflexus), Palmer amaranth (A. palmeri), and common waterhemp (A. tuberosus). Weed Sci 51:869–875 (2003).
34 Wittyson MB and Shaw DR, Effect of adjuvants on weed control and soybean (Glycine max) tolerance with AC 263,222. Weed Technol 5:817–822 (1991).
35 Reddy KN, Rimando AM and Duke SO, Aminomethylphosphonic acid, a metabolite of glyphosate, causes injury in glyphosate-treated, glyphosate-resistant soybean. J Agric Food Chem 52:5139–5143 (2004).
36 Cuvaca I, Currie R, Roozeboom K, Fry J and Julgulam M, Increased absorption and translocation contribute to improved efficacy of dicamba to control early growth stage Palmer amaranth (Amaranthus palmeri). Weed Sci 68:27–32 (2020).
37 Moyo C, Harrington KC, Ghanizadeh H, Kemp PD and Eerens JPJ, Spectrophotometric technique for measuring herbicide deposition from spray logs. Weed Sci 60:412–412 (2016).
38 Andersen SM, Clay SA, Wrage LJ and Matthees D, Soybean foliage residues of dicamba and 2,4-D and correlation to application rates and yield. Agron J 96:750–764 (2004).
39 Meyer CJ, Peter P, Norsworthy JK and Beffa R, Uptake, translocation, and metabolism of glyphosate, glufosinate, and dicamba mixtures in Echinocloa crus-galli and Amaranthus palmeri. Pest Manag Sci 76:3078–3087 (2020).
40 Zaccaro ML, Norsworthy JK and Brabham CB, Dicamba translocation in soybean and accumulation in seed. Weed Sci 68:333–339 (2020).
41 Priess GL, Norsworthy JK, Barber LT and Castner MC, Timing between sequential applications of dicamba and glufosinate, in Summaries of Arkansas cotton Research 2019. ed. by Bourland F, University of Arkansas Cooperative Extension Service, Little Rock, AR, pp. 57–60 (2020a).
42 Van De Stroet, BM (2018) Palmer Amananth in South Dakota: Growth, Herbicidal Control, and Soybean Yield Loss. Thesis. Available: https://openprairie.sdstate.edu/cgi/viewcontent.cgi?article=3493&context=etd. [17 November 2020].
43 Priess GL, Norsworthy JK, Barber LT, Mauromoustakos A, Butts TR and Robers TL, Impact of auxin herbicides on Palmer amaranth ground cover. Weed Technol Preproof 35:768–778 (2021). https://doi.org/10.1017/wet.2021.74.
44 Mueller TC and Steckel LE, Efficacy and dissipation of pyroxasulfone and three chloroacetanilides in a Tennesse field soil. Weed Sci 59:574–579 (2011).
45 Norsworthy JK, Ward SM, Shaw DR, Llewellyn RS, Nichols RL, Webster TM et al., Reducing the risks of herbicide resistance: best management practices and recommendations. Weed Sci 60:31–62 (2012).
46 Purcell LC, Salmeron M, Ashlock L (2014) Soybean Growth and Development. Available: https://www.uaex.edu/publications/pdf/mp197/chapter2.pdf. [17 November 2020].
47 Priess GL, Norsworthy JK, Roberts TL and GBur EE Jr, Impact of post-emergence herbicides on soybean injury and canopy formation. Weed Technol 34:1–26 (2020b).
48 Kapusta G, Jackson LA and Mason DS, Yield response of weed-free soybeans (Glycine max) to injury from postemergence broadleaf herbicides. Weed Sci 34:644–651 (1986).
49 Tehranchian P, Norsworthy JK, Dierck JB, Powles S, Bararouz MT, Bagavathiannan MV, Barber T et al., Recurrent sublethal-dose selection for reduced susceptibility of Palmer amaranth (Amaranthus palmeri) to dicamba. Weed Sci 65:206–212 (2017).
50 Vieira BC, Luck JD, Amundsen KL, Werle R, Gentes TA and Kruger GR, Herbicide drift exposure leads to reduced herbicide sensitivity in Amaranthus spp. Sci Rep 10:2146 (2020).
51 Sarangi D and Haja AJ, Palmer amaranth (Amaranthus palmeri) and velvetleaf (Abutilon theophrasti) control in no-tillage conventional (non-genetically engineered) soybean using overlapping residual herbicide programs. Weed Technol 33:95–105 (2018).