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Fluridone use in furrow-irrigated rice: Palmer amaranth control and crop response

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Abstract

Rice cultivated under furrow irrigation faces weed management challenges due to the aerobic conditions favoring terrestrial weed emergence, like Palmer amaranth. Fluridone is an HRAC/WSSA Group 12 herbicide recently registered for use in rice, offering an alternative site of action for Palmer amaranth control. Four site-years of field experiments were conducted in 2022 and 2023 in furrow-irrigated rice to assess Palmer amaranth control and crop tolerance to fluridone applied preemergence (PRE) alone or with different postemergence programs. The experiment was a randomized complete block design with a split-plot arrangement and four replications. The whole-plot factor was the postemergence program, while the subplot factor was fluridone applied PRE at 0, 84, 168 (1× labeled rate), and 336 g ai ha⁻¹. Postemergence programs included no herbicide, a single florypyrauxifen-benzyl application at 6 wk after rice emergence (WAE), and a weed-free control. The 2× rate of fluridone caused the greatest visual injury compared to the 0.5× rate across site-years at two and five (WAE), ranging from 8% to 34%. The 1× and 2× rates of fluridone provided the greatest Palmer amaranth density reduction four wk after treatment (WAT). However, the effect diminished or became less prominent by eight WAT, reducing control across fluridone treatments. The follow-up application of florypyrauxifen-benzyl reduced Palmer amaranth density at rice harvest in most instances and diminished seed production by ≥ 94% compared to its absence. Fluridone application, regardless of the rate, did not affect rough rice grain yield under weed-free conditions. These findings suggest that integrating fluridone with a subsequent florypyrauxifen-benzyl application enhances Palmer amaranth management in furrow-irrigated rice compared to fluridone alone. However, sequential applications are needed for successful Palmer amaranth control.

Nomenclature: florypyrauxifen-benzyl; fluridone; Palmer amaranth, *Amaranthus palmeri* S. Watson; rice, *Oryza sativa* L.

Keywords: herbicide programs; rice injury; weed control; weed seed production

Introduction

Weed resistance to herbicides poses a substantial threat to agricultural productivity by limiting the number of herbicides available for effective weed control (Norsworthy et al. 2012). Without effective management strategies, herbicide-resistant weeds can spread in fields, resulting in diminished yields and compromised agricultural sustainability. Among the major crops produced worldwide, rice ranks third with the greatest number of cases of weeds that have evolved resistance to herbicides, with 57 species documented globally, trailing only wheat (*Triticum aestivum* L.) and corn (*Zea mays* L.) (Heap 2025).

One weed that is troublesome in furrow-irrigated rice in Arkansas is Palmer amaranth (Butts et al. 2022). Palmer amaranth is a dioecious summer annual weed (Sauer 1957; Steckel 2007) that has evolved resistance to herbicides targeting nine sites of action in the state (Carvalho-Moore 2025; Heap 2025). This extensive resistance profile is partially attributed to its reproductive biology, which relies on outcrossing, promoting high genetic diversity (Ward et al. 2013). Moreover, Palmer amaranth is wind-pollinated, and its pollen can travel extended distances. Consequently, herbicide resistance can spread extensively within fields (Chandi et al. 2013; Sosnoskie et al. 2012).

Palmer amaranth can impact crop yields depending on the time of emergence and density. In corn, at 8 plants m^{-1} of row, Palmer amaranth caused 91% yield loss compared to weed-free plots (Massinga et al. 2001). Similarly, cotton (*Gossypium hirsutum* L.) lint yield was reduced by 57% and 60% at 1.1 and 1.6 plants m^{-1} of row, respectively, when compared to the weed-free treatment (MacRae et al. 2013; Morgan et al. 2001). Palmer amaranth plants that emerged one week before rice led to a 50% yield loss within 0.40 m of the weed in a furrow-irrigated system (King et al. 2024a).

In Arkansas, the predominant method for rice cultivation involves dry-seeding followed by establishing a continuous flood at the four- to six-leaf growth stage (Hardke 2023; Henry et al. 2021). The continuous flood conditions suppress a broad spectrum of terrestrial weeds that require aerobic conditions to germinate and grow (Norsworthy et al. 2011). Typically, Palmer amaranth poses a problem only before flooding or on levees due to the suppression provided by the flood (Norsworthy et al. 2010; 2013). However, the increased adoption of furrow-irrigated rice in Arkansas has altered this dynamic. Furrow-irrigated rice is characterized by three distinct

soil moisture zones (upper aerobic, mid-field, and lower flooded). The absence of a continuous flood in the upper and middle portions of the field, combined with the limited chemical options available, makes Palmer amaranth management difficult (Bagavathiannan et al. 2011; Hardke 2021, 2023; Massey et al. 2022).

Successful control of Palmer amaranth requires multiple residual and postemergence herbicide applications (Beesinger et al. 2022a; Hill et al. 2016; King et al. 2024b). Using effective residual herbicides reduces reliance on postemergence applications and, therefore, decreases the risk of resistance evolution (Neve et al. 2011a, 2011b). Pendimethalin and saflufenacil are two residual herbicides used for controlling Palmer amaranth in rice (Barber et al. 2025). However, resistance of Palmer amaranth to these herbicides' sites of action has been documented (Heap 2025). Thus, new residual chemical options are needed with the rise in Palmer amaranth occurrence in rice fields and its increasing resistance to herbicides.

The Herbicide Resistance Action Committee (HRAC) and Weed Science Society of America (WSSA) classify fluridone as a Group 12 herbicide. In cotton, fluridone is applied preemergence and effectively controls Palmer amaranth (Grichar et al. 2020; Hill et al. 2016). Recently registered for use in rice, fluridone is an alternative option for Palmer amaranth control, offering a new site of action in rice (Anonymous 2023a). Fluridone inhibits the phytoene desaturase enzyme, a component of the carotenoid biosynthetic pathway (Bartels and Watson 1978; Sandmann and Böger 1997; Sandmann et al. 1991). The inhibition of this enzyme interrupts carotenoid synthesis, leading to the depletion of colored plastidic pigments, resulting in bleaching and death in susceptible plants (Chammovitz et al. 1991; Sandmann et al. 1991).

The effectiveness of fluridone is influenced by soil moisture, with higher soil moisture increasing both weed control efficacy and the potential for crop injury (Butts et al. 2024; Hill et al. 2016; Martin et al. 2018; Souza et al. 2025a). Souza et al. (2025a) reported that injury from fluridone applied to three-leaf rice at 168 and 336 g ai ha⁻¹ increased from ≤6% two weeks after treatment to over 25% four weeks after treatment in two rice cultivars following irrigation. Similarly, when applied to the same rice growth stage at 170 g ai ha⁻¹ grown in a precision-leveled Sharkey-Steele clay soil, fluridone caused approximately 30% visual injury eight weeks after treatment; however, the injury did not translate to grain yield loss (Butts et al. 2024).

Given the need for better management strategies for Palmer amaranth control in rice, fluridone emerges as an effective option for controlling this weed. However, fluridone applications are restricted to the three-leaf rice growth stage or later due to potential crop injury with the applications closer to planting (Souza et al. 2025a, 2025b). This restriction complicates Palmer amaranth management, as weeds emerging before this stage would not be effectively controlled because fluridone lacks effective postemergence activity (Anonymous 2023a; Waldrep and Taylor 1976). Further research is needed to assess rice response to preemergence fluridone applications to determine whether this herbicide is suitable for applications earlier in the season. Therefore, this study evaluated rice tolerance in a furrow-irrigated system, and the length of Palmer amaranth control offered by a range of fluridone rates applied preemergence at planting and when followed by florypyrauxifen-benzyl, a herbicide that effectively controls the emerged weed (Beesinger et al. 2022a; Miller and Norsworthy 2018; Wright et al. 2021).

Materials and Methods

A field experiment was conducted in 2022 at the Lon Mann Cotton Research Station near Marianna, AR (M2022) (34.732979° N, 90.766371° W), in 2022 and 2023 at the Pine Tree Research Station near Colt, AR (P2022 and P2023, respectively) (35.123299° N, 90.930369° W), and at the Milo J. Shult Agricultural Research and Extension Center in Fayetteville, AR (36.099631° N, 94.179310° W) in 2023 (F2023). The soil near Marianna was a Convent silt loam (9% sand, 80% silt, and 11% clay) with 1.8% organic matter and a pH of 6.5. The soil near Colt was a Calhoun silt loam (11% sand, 68% silt, and 21% clay) with 1.6% organic matter and a pH of 7.2. In Fayetteville, the soil was a Leaf silt loam (18% sand, 69% silt, and 13% clay) with 1.6% organic matter and a pH of 6.7. The field was tilled in the spring before raised beds were formed at all locations, and the study was conducted in the higher, drier zone of the field. Glyphosate (Roundup PowerMAX[®] 3, Bayer CropScience, St. Louis, MO) was applied at 1,262 g ae ha⁻¹ in all locations prior to planting. The hybrid RT 7321 FP (RiceTec, Alvin, TX) was drill-seeded into raised beds and furrows at all sites at 36 seeds m⁻¹ of row at 1.3-cm depth using a nine-row, small-plot drill with 19 cm between rows. Planting and emergence dates are listed in Table 1.

The experimental design was a randomized complete block with a split-plot arrangement and four replications. A split-plot structure was implemented to minimize the risk of

contamination from postemergence herbicide applications in adjacent plots. The whole-plot factor was the postemergence program, and the subplot factor was the fluridone (Brake[®]; SePRO Corporation, Carmel, IN) rate. The postemergence programs included 1) no herbicide applied postemergence (none), 2) a single application of florypyrauxifen-benzyl (Loyant[®], Corteva Agriscience, Indianapolis, IN) applied at 15 g ai ha⁻¹ at approximately 6 weeks after rice emergence with methylated seed oil (MES-100, Drexel Chemical Company, Memphis, TN) at 0.6 L ha⁻¹, and 3) weed-free conditions using commonly used rice herbicides and hand-weeded as needed. All fluridone treatments were applied preemergence on the day of planting. Florypyrauxifen-benzyl application dates are displayed in Table 1. Palmer amaranth average size at the time of florypyrauxifen-benzyl application was 20 cm across locations. Fluridone rates were 0 (nontreated), 84 (0.5× label rate), 168 (1× label rate), and 336 (2× label rate) g ai ha⁻¹. The subplots were 1.9 m (two beds), 3.1 m (four beds), and 3.7 m (four beds) wide by 5.2 m long at the research sites near Marianna, near Colt, and in Fayetteville, respectively.

The fields were irrigated twice weekly, starting at 5-leaf rice, except when a rainfall event of 2.5 cm or more occurred. Soil fertility at each experimental site was managed following the University of Arkansas System Division of Agriculture recommendations based on soil test values (Roberts et al. 2016). Natural Palmer amaranth populations were allowed to germinate following rice planting, and no other management efforts (excluding the fluridone treatments) were utilized prior to postemergence treatments. Nontarget weeds were controlled using fenoxaprop (RiceStar[®] HT, Bayer CropScience, St. Louis, MO) and halosulfuron + thifensulfuron (PermitPlus[®], Gowan Company, Yuma, AZ) in the entire experiment. Additionally, pendimethalin (Prowl[®] H2O, BASF Corporation, Research Triangle Park, NC), quinclorac (Facet[®] L, BASF Corporation, Research Triangle Park, NC), and propanil (Stam[®], UPL Limited, King of Prussia, PA) were used in the weed-free plots. Herbicides were applied using a CO₂-pressurized hand-held backpack sprayer calibrated to deliver 140 L ha⁻¹ at 4.8 kph equipped with AIXR 110015 nozzles (Spraying Systems Co., Glendale Heights, IL). Air temperature and precipitation data were monitored daily using a weather station within 1 kilometer of each experimental site, except for P2022 and P2023 (Figure 1). For these two sites, daily rainfall was measured with a rain gauge 1 kilometer away, while temperature data were obtained from a weather station located 20 kilometers from each site.

Visible crop injury was evaluated at two and five weeks after emergence (WAE) using a scale from 0 to 100, with 0% indicating no injury and 100% representing plant death (Frans et al. 1986). Palmer amaranth control was visually assessed four and eight weeks after the preemergence treatment (WAT), using a scale from 0 to 100, with 0% representing no control and 100% indicating complete control. Palmer amaranth cumulative density was assessed at four and eight WAT using two 1-m^{-2} quadrants randomly placed in each subplot. Before rice harvest, Palmer amaranth male and female densities were recorded, and aboveground biomass was collected from two 1-m^{-2} quadrants. If only a few plants remained in the plot, all were collected, and the density was reported per square meter, considering the entire plot size. All biomass was dried in an oven at 66 C until constant mass, and the final weight was recorded. Subsequently, each Palmer amaranth female plant was threshed, and the ground plant material was separated from the seeds using a 20-mesh sieve followed by a vertical air column seed cleaner (King 2024a, 2024b; Miranda et al. 2021; Woolard et al. 2024). After cleaning, a 200-seed subsample from three random subplots per site-year was weighed, and the average weight was used to calculate the number of seeds m^{-2} . Seed production for P2022 was not assessed due to the low presence of female plants. Rough rice yield was collected at maturity using a small-plot combine that harvested the middle four rows of each subplot. Grain yield moisture was adjusted to 12%. Harvest was not possible in the plots with no postemergence herbicide application (none) because the high Palmer amaranth infestation prevented the combine from operating; therefore, rough rice yield was not reported for this postemergence program.

Data analysis

All data were analyzed in R statistical software version 4.3.3 (R Core Team 2023) and all data were fit to a generalized linear mixed model using the function *glmmTMB* (GLMMTMB package; Brooks et al. 2017). The postemergence programs 'none' and 'single application' were identical until florypyrauxifen-benzyl was applied 6 weeks after emergence in the single application program, which occurred after all rice injury evaluation assessments. Moreover, there were no differences in rice injury among these postemergence programs compared to the weed-free ($P > 0.05$). Therefore, injury at each evaluation time was averaged across postemergence programs by fluridone rate. For Palmer amaranth control and its cumulative density at four and eight WAT, only the postemergence program none was included in the analysis, as the goal was to evaluate the length of Palmer amaranth control achieved with fluridone treatments only.

Cumulative Palmer amaranth density was fit to a generalized linear mixed model, with fluridone rate and site-year as fixed effects and block as a random effect. At each evaluation, the interaction of fluridone rate and site-year was significant ($P < 0.05$), partially attributed to the drastic differences in Palmer amaranth density among site-years. Therefore, all variables were analyzed by site-year, as Palmer amaranth density can highly influence the other variables' response. For rice injury, Palmer amaranth control, and cumulative density, fluridone rate was treated as a fixed effect, and block was considered a random effect. All data were analyzed to assess whether the assumptions of normality were satisfied using the Shapiro-Wilk and Levene's test. A beta distribution was used to analyze rice injury and Palmer amaranth control, and a Poisson distribution was used for cumulative Palmer amaranth density if the data did not meet the assumptions of normality (Gbur et al. 2012; Stroup 2015).

Variables assessed at rice harvest (Palmer amaranth density, biomass, seed production, and rough rice yield) were analyzed in accordance with the split-plot arrangement. The weed-free postemergence program was excluded from the analysis of all Palmer amaranth assessments, as no weeds were present. In the rough rice yield analysis, the postemergence program 'none' was removed from the analysis, as rice harvest was not feasible due to the high Palmer amaranth infestation. Postemergence program and fluridone rate were considered fixed effects, and postemergence program and fluridone rate were nested within block, which was considered a random effect. A negative binomial distribution was used for all seed production data analysis, and a log transformation was used for Palmer amaranth biomass whenever the data did not meet the assumptions of normality. For such data, back-transformed values are presented.

Analysis of variance was conducted using Type III Wald chi-square tests with the CAR package (Fox and Weisberg 2019). Treatment-estimated marginal means (Searle et al. 1980) were calculated using the EMMEANS package (Lenth 2022) following analysis of variance. Significant differences among treatments were identified with a compact letter display generated by the 'multcomp' package (Hothorn et al. 2008). Estimated marginal means included post hoc Tukey honestly significant difference ($\alpha = 0.05$) adjustments, and the compact letter display was obtained with the *multcomp:cld* function.

Results and Discussion

In-season Rice Response and Palmer Amaranth Control with Fluridone Preemergence Without Postemergence Herbicides

Rice injury varied across site-years in response to fluridone rates (Figure 2) and consisted of bleached and chlorotic plants, characteristic symptomology caused by fluridone (Sandmann et al. 1991; Waldrep and Taylor 1976). At P2022, injury was minimal (<8%) at all fluridone rates. Regardless of the site-year, the 2× label rate caused the greatest injury (7–34%) at both evaluations. Injury from the 1× rate reached 27% at two WAE but did not exceed 11% in any site-year at five WAE, indicating crop recovery over time. Similarly, in other research, a preemergence application of fluridone at 224 g ai ha⁻¹ caused 32% rice injury at one WAE and dropped to 18% by three WAE on Dewitt and Calhoun silt loam soils prior to flood establishment (Martin et al. 2018). In Calhoun silt loam soil, fluridone caused ≤42% to the hybrid RT7321 FP at six WAE following a preemergence application of the 1× rate in a paddy system (Souza et al. 2025a). Although rice injury from the 1× rate was no more than 11% five WAE, fluridone should not be applied before the three-leaf rice growth stage, as stated by the label (Anonymous 2023a). Additionally, this study was conducted in the higher, drier portion of the field, and results could differ if the herbicide was applied to the bottom of the field, where flooding can occur.

Environmental conditions play a major role in crop response to herbicides (Beesinger et al. 2022b; Bond and Walker 2011; Godara et al. 2022; Hammerton 1967). For instance, rice plants treated with quizalofop and maintained under low temperatures experienced greater injury than those kept under warmer conditions (Godara et al. 2022). Soil moisture is another critical factor affecting crop response to herbicides, as elevated soil moisture following fluridone application resulted in increased visible rice injury (Butts et al. 2024; Martin et al. 2018). Thus, variations in rice response to fluridone across site-years might have been influenced by differences in temperature and rainfall before irrigation began at each location (Figure 1).

The 1× and 2× rates of fluridone decreased Palmer amaranth density compared to the nontreated control in all site-years at four WAT, with reductions ranging from 65% to 78% for the 1× rate and 88% to 93% for the 2× rate (Figure 3). Although there was an increase in the number of plants across treatments at eight WAT, the 2× rate of fluridone continued to suppress Palmer amaranth emergence compared to the nontreated control in three of the four site-years.

The 0.5× and 1× rates differed from the nontreated control only at M2022 and P2023. The decrease in fluridone efficacy at eight WAT was expected, as the amount of fluridone remaining in the soil diminishes over time (Banks et al. 1979; Schroeder and Banks 1986).

Of the four site-years, fluridone at 1× and 2× rates provided similar Palmer amaranth control in two site-years (M2022 and P2022) at four WAT, ranging from 85% to 95% control, whereas in the other two site-years, the 2× rate resulted in the greatest control (Figure 4). These results suggest that fluridone applied at the 1× rate tested in the present study may be less effective in controlling Palmer amaranth than the 2× rate. When used at the 168 g ai ha⁻¹ for weed control in peanut (*Arachis hypogaea* L.) and cotton, the label requires tank-mixing with another residual herbicide (Anonymous 2023a). Based on the results presented here, a similar approach may be recommended for rice for successful Palmer amaranth control.

By eight WAT, there was an increase in Palmer amaranth density (Figure 3), and consequently, control dropped across all treatments and site-years. At this evaluation, the 2× rate resulted in greater Palmer amaranth control than the 0.5× rate in three site-years, and was comparable to the 1× rate at M2022, F2023, and P2023 (Figure 4). Similarly, fluridone applied preemergence in a Zachary silt loam soil at the 2× rate resulted in a Palmer amaranth control decrease from 96% at four weeks after treatment to 87% by seven weeks after treatment when adequate rainfall occurred (Hill et al. 2016). In the same study, under insufficient moisture, only 43% control was observed four weeks after treatment, and Palmer amaranth overtook the crop in the plots seven weeks after treatment at one of the locations tested.

At-harvest Palmer Amaranth Assessments and Rough Rice Yield with Fluridone Preemergence with Different Postemergence Programs

The interaction of the postemergence program and fluridone rate applied preemergence was significant for F2023 and P2023 for Palmer amaranth density at rice harvest (Table 2). The addition of florypyrauxifen-benzyl at six weeks after rice emergence to fluridone preemergence, regardless of the preemergence herbicide rate, resulted in the greatest reduction in Palmer amaranth in most instances across both site-years. At F2023, no fluridone preemergence followed by florypyrauxifen-benzyl was comparable to fluridone alone at the 1× and 2× rates. Similarly, at P2023, all treatments containing florypyrauxifen-benzyl were comparable to fluridone alone at the 2× rate. Averaged across fluridone rates, the postemergence program with a

single application of florypyrauxifen-benzyl resulted in the fewest Palmer amaranth escapes at the end of the season compared to 'none' for the M2022 site. No differences in male/female ratios were observed among treatments across site-years (data not shown).

Florypyrauxifen-benzyl is an effective postemergence control option for Palmer amaranth in rice when applied at the appropriate rate and weed size, especially when using sequential applications of the herbicide (Beesinger et al. 2022a; Wright et al. 2021). In this study, however, florypyrauxifen-benzyl was applied at the 0.5× labeled rate, and several Palmer amaranth plants exceeded the recommended label weed size at the time of application (≤ 20 cm; Anonymous 2023b), which likely led to Palmer amaranth escapes at the end of the season. These results suggest that florypyrauxifen-benzyl should be applied earlier and at the label-recommended rate for enhanced Palmer amaranth control.

Furthermore, sequential applications of florypyrauxifen-benzyl or other effective herbicides with postemergence activity are necessary for season-long control of Palmer amaranth, as fluridone exhibits minimal postemergence activity (Beesinger et al. 2022a; Miller and Norsworthy 2018; Waldrep and Taylor 1976). Unlike the present study, King et al. (2024b) examined a full herbicide program that employed preemergence herbicides (fluridone + clomazone at 84 and 336 g ai ha⁻¹, respectively) followed by sequential applications of residual (fluridone at 84 g ai ha⁻¹) and postemergence (florypyrauxifen-benzyl at 15 g ai ha⁻¹) herbicides, which resulted in complete Palmer amaranth control at rice maturity in most instances. No Palmer amaranth control was evaluated with fluridone alone in their research.

Regarding Palmer amaranth biomass at rice harvest, the main effect of the postemergence program was significant for P2022, F2023, and P2023 (Table 3). In all three site-years, the postemergence program, including a single application of florypyrauxifen-benzyl, resulted in the greatest biomass reduction. No effect of fluridone rate was observed on Palmer amaranth biomass. Likewise, King et al. (2024b) reported that treatments combining clomazone (336 g ai ha⁻¹) and fluridone (1× rate) preemergence and florypyrauxifen-benzyl at the same rate used in this study, applied mid-season, resulted in almost 96% reduction in Palmer amaranth biomass compared to the program without florypyrauxifen-benzyl. Furthermore, the same research reported a 95% reduction in seed production for plants remaining in the field following treatment containing florypyrauxifen-benzyl.

All treatments containing florpyrauxifen-benzyl reduced Palmer amaranth seed production by at least 94% compared to when no herbicides were applied postemergence (Table 4). Conversely, the use of fluridone alone applied preemergence, regardless of rate, never reduced Palmer amaranth seed production, pointing to the need for an effective postemergence herbicide. In other research, an average of 350 to 900 seeds m^{-2} were produced when Palmer amaranth was treated with florpyrauxifen-benzyl at 15 g ai ha^{-1} , averaged across both single and sequential applications and different weed sizes (Beesinger et al. 2022a). When growing without competition and emerging earlier in the season, Palmer amaranth can produce up to 600,000 seeds per plant (Keeley et al. 1987). Different cropping systems can also influence Palmer amaranth seed production (Burke et al. 2007; Jha et al. 2008; Massinga et al. 2001; Webster and Grey 2015). Specifically for rice, Palmer amaranth produced 115,000 seeds plant^{-1} when emerging with the crop in a furrow-irrigated system (King et al. 2024a). Moreover, Beesinger et al. (2022a) reported that Palmer amaranth survivors from early-season florpyrauxifen-benzyl applications produced more seeds than those treated later in the season, likely due to more recovery time. Although fluridone did not reduce Palmer amaranth seed production at rice harvest, its residual activity is crucial for reducing the number of Palmer amaranth plants requiring postemergence control, thereby decreasing pressure on postemergence herbicides, ultimately delaying resistance (Norsworthy et al. 2012). Combined with postemergence applications applied at the proper weed size, herbicide programs incorporating fluridone can successfully manage Palmer amaranth, ultimately preventing soil seedbank replenishment (King et al. 2024b; Hill et al. 2016).

Rough rice yield differed among postemergence programs at P2022 and F2023 (Table 5). At both locations, the postemergence program 'weed-free' resulted in a greater yield than the program containing a single florpyrauxifen-benzyl application. As previously discussed, the postemergence program containing florpyrauxifen-benzyl resulted in some plants remaining at rice harvest (Table 2), which likely contributed to reduced rough rice yield compared to the weed-free program. According to King et al. (2024a), Palmer amaranth emerging 3.5 weeks after crop emergence can cause up to 50% reduction in rough rice yield when located 0.2 to 0.6 m from the weed in furrow-irrigated rice. When averaged across postemergence programs, no yield loss was observed as a function of fluridone rate applied preemergence. These findings differ from Butts et al. (2024), where the 2 $\times$ rate of fluridone applied at the three-leaf rice resulted in

rough rice yield penalty under weed-free conditions in a field following topsoil removal. Moreover, King et al. (2024b) reported rice yield loss in fields under weedy conditions only in the nontreated control compared to other treatments containing clomazone with single or sequential applications of florpyrauxifen-benzyl and/or fluridone at different rates.

Practical Implications

Injury from fluridone applied preemergence in the upper portion of a furrow-irrigated rice field did not translate to yield loss. However, results may differ if fluridone is applied to the lower, flooded part of the field, as previous research indicates that injury increases with higher moisture content (Butts et al. 2024; Martin et al. 2018; Souza et al. 2025a). Therefore, to minimize the risk of crop injury, fluridone should not be applied before the three-leaf rice growth stage (Anonymous 2023a).

Fluridone at 1× and 2× rates reduced Palmer amaranth density in all site-years compared to the nontreated control at four WAT; however, using fluridone alone does not fully achieve the management goal of Palmer amaranth. Additionally, growers should be aware that fluridone efficacy may decline in soils with higher clay content and/or organic matter than those evaluated in the present study (Anonymous 2023a). Including a postemergence application of florpyrauxifen-benzyl improved Palmer amaranth control, resulting in fewer escapes in the field at rice maturity and lowering seed production, aiding weed management in subsequent years by limiting soil seedbank replenishment. However, Palmer amaranth plants remained in the field and likely reduced rough rice yield. Therefore, overlapping postemergence herbicides at the appropriate weed growth stage with fluridone and/or other soil residual herbicides is paramount for achieving optimal season-long control, minimizing seed return to the soil seedbank, and thereby delaying herbicide resistance (Hill et al. 2016; King et al. 2024b; Kouame et al. 2024; Norsworthy et al. 2012).

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Competing Interests

The authors declare none.

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Table 1. Planting, rice emergence, and florypyrauxifen-benzyl application dates.^a

Site-year	Planting	Rice emergence	Florypyrauxifen-benzyl application
M2022	May 5	May 17	June 27
P2022	May 17	May 24	July 06
F2023	April 14	May 03	June 15
P2023	May 03	May 13	June 20

^aAbbreviations: M2022, Lon Mann Cotton Research Station near Marianna, AR, 2022; P2022, Pine Tree Research Station near Colt, AR, 2022; F2023, Milo J. Shult Agricultural Research and Extension Center in Fayetteville, AR, 2023; P2023, Pine Tree Research Station near Colt, AR, 2023.

Table 2. Palmer amaranth density at harvest as influenced by postemergence program, preemergence applications of fluridone, and their interaction for four site-years in Arkansas.^{a,b,c,d,e}

Postemergence program	Fluridone rate g ai ha ⁻¹	Palmer amaranth density					
		M2022	P2022	F2023	P2023		
		-----plant m ⁻² -----					
None	-	5.02	*	0.9	14.69	*	2.96
Florpyrauxifen-benzyl	-	1.84		0.1	1.83		0.08
<i>P</i> -value		0.0030	0.1449	<0.0001	<0.0001		
-	0	3.89	0.52	10.90	2.78		
-	84	4.99	0.86	11.70	1.66		
-	168	2.31	0.38	7.35	1.08		
-	336	2.53	0.20	3.08	0.57		
<i>P</i> -value		0.5924	0.8457	0.8480	0.9722		
None	0	6.68	0.76	18.75	a	5.41	a
None	84	6.73	1.54	20.75	a	3.29	b
None	168	2.86	0.74	13.75	ab	2.00	bc
None	336	3.81	0.38	5.50	bc	1.14	cd
Florpyrauxifen-benzyl	0	1.10	0.27	3.05	bc	0.15	d
Florpyrauxifen-benzyl	84	3.25	0.17	2.66	c	0.02	d
Florpyrauxifen-benzyl	168	1.75	0.02	0.95	c	0.17	d
Florpyrauxifen-benzyl	336	1.25	0.02	0.67	c	0.00	d
<i>P</i> -value		0.3634	0.1436	0.0169	<0.0001		

^aAbbreviations: M2022, Lon Mann Cotton Research Station near Marianna, AR, 2022; P2022, Pine Tree Research Station near Colt, AR, 2022; F2023, Milo J. Shult Agricultural Research and Extension Center in Fayetteville, AR, 2023; P2023, Pine Tree Research Station near Colt, AR, 2023.

^bFlorpyrauxifen-benzyl was applied approximately six weeks after rice emergence at 15 g ai ha⁻¹.

^cMale/female ratios were 1.11, 1.47, 1.17, and 0.83 for M2022, P2022, F2023, and P2023, respectively.

^dMeans within the same column are not different according to Tukey HSD ($\alpha=0.05$).

^eAsterisks (*) indicate statistical significance ($\alpha=0.05$) between postemergence programs averaged over fluridone rates for each site-year when interaction is not present.

Table 3. Palmer amaranth biomass at harvest as influenced by postemergence program, preemergence applications of fluridone, and their interaction for four site-years in Arkansas.^{a,b,c}

Postemergence program	Fluridone rate g ai ha ⁻¹	Palmer amaranth biomass			
		M2022	P2022	F2023	P2023
		-----g m ⁻² -----			
None	-	260	70*	590*	90*
Florpyrauxifen-benzyl	-	100	5	70	10
<i>P</i> -value		0.1726	0.0002	<0.0001	<0.0001
-	0	140	40	400	70
-	84	180	50	280	50
-	168	170	30	370	50
-	336	230	10	260	30
<i>P</i> -value		0.6448	0.9696	0.8371	0.8854
None	0	200	90	680	120
None	84	200	100	490	90
None	168	260	70	710	70
None	336	370	20	480	70
Florpyrauxifen-benzyl	0	80	10	130	10
Florpyrauxifen-benzyl	84	170	10	70	1
Florpyrauxifen-benzyl	168	80	4	30	20
Florpyrauxifen-benzyl	336	80	0	50	0
<i>P</i> -value		0.1828	0.0534	0.3856	0.4480

^aAbbreviations: M2022, Lon Mann Cotton Research Station near Marianna, AR, 2022; P2022, Pine Tree Research Station near Colt, AR, 2022; F2023, Milo J. Shult Agricultural Research and Extension Center in Fayetteville, AR, 2023; P2023, Pine Tree Research Station near Colt, AR, 2023.

^bFlorpyrauxifen-benzyl was applied approximately six weeks after rice emergence at 15 g ai ha⁻¹.

^cAsterisks (*) indicate statistical significance ($\alpha = 0.05$) between postemergence programs averaged over fluridone rates for each site-year when interaction is not present.

Table 4. Palmer amaranth seed production as influenced by postemergence program, preemergence applications of fluridone, and their interaction for four site-years in Arkansas.^{a,b,c,d}

Postemergence program	Fluridone rate g ai ha ⁻¹	Palmer amaranth seed production		
		M2022	F2023	P2023
		----- seed m ⁻² -----		
None	-	67,770*	110,470*	18,800*
Florpyrauxifen-benzyl	-	4,000	4,930	70
<i>P</i> -value		0.0031	<0.0001	<0.0001
-	0	15,550	29,540	2,910
-	84	25,290	22,000	0.04
-	168	9,720	25,270	1,200
-	336	17,570	18,080	0.09
<i>P</i> -value		0.7174	0.4226	0.9801
None	0	60,550	105,870	46,010
None	84	73,660	64,940	14,730
None	168	48,380	161,650	13,090
None	336	81,580	134,000	13,980
Florpyrauxifen-benzyl	0	3,990	8,240	183
Florpyrauxifen-benzyl	84	8,680	7,440	0
Florpyrauxifen-benzyl	168	3,790	3,950	110
Florpyrauxifen-benzyl	336	1,950	2,440	0
<i>P</i> -value		0.8660	0.1260	0.9454

^aAbbreviations: M2022, Lon Mann Cotton Research Station near Marianna, AR, 2022; F2023, Milo J. Shult Agricultural Research and Extension Center in Fayetteville, AR, 2023; P2023, Pine Tree Research Station near Colt, AR, 2023.

^bFlorpyrauxifen-benzyl was applied approximately six weeks after rice emergence at 15 g ai ha⁻¹.

^cAsterisks (*) indicate statistical significance ($\alpha = 0.05$) between postemergence programs averaged over fluridone rates for each site-year when interaction is not present.

^dSeed production data is not presented for the site "Pine Tree Research Station near Colt, AR, 2022" due to the lack of female plants across treatments.

Table 5. Rough rice yield as influenced by postemergence program, preemergence applications of fluridone, and their interaction for four site-years in Arkansas.^{a,b,c,d}

Postemergence program	Fluridone rate g ai ha ⁻¹	Rough rice yield			
		M2022	P2022	F2023	P2023
		kg ha ⁻¹			
Florpyrauxifen-benzyl	-	4,410	9,200*	7,400*	8,760
Weed-free	-	5,640	10,500	10,140	7,250
<i>P</i> -value		0.1010	0.0019	0.0058	0.4626
-	0	4,600	9,680	7,080	b 7,480
-	84	4,670	9,770	8,760	ab 7,910
-	168	5,510	10,370	9,880	a 7,710
-	336	5,280	9,570	9,350	ab 8,930
<i>P</i> -value		0.1179	0.0645	0.0166	0.7922
Florpyrauxifen-benzyl	0	3,960	8,070	5,230	7,970
Florpyrauxifen-benzyl	84	3,610	8,940	6,760	8,750
Florpyrauxifen-benzyl	168	4,800	10,610	8,480	8,930
Florpyrauxifen-benzyl	336	5,260	9,170	9,120	9,390
Weed-free	0	5,310	11,290	8,940	6,980
Weed-free	84	5,740	10,610	10,770	7,080
Weed-free	168	6,220	10,610	11,280	6,490
Weed-free	336	5,300	9,970	9,580	8,460
<i>P</i> -value		0.2987	0.0627	0.2766	0.8351

^aAbbreviations: M2022, Lon Mann Cotton Research Station near Marianna, AR, 2022; P2022, Pine Tree Research Station near Colt, AR, 2022; F2023, Milo J. Shult Agricultural Research and Extension Center in Fayetteville, AR, 2023; P2023, Pine Tree Research Station near Colt, AR, 2023.

^bFlorpyrauxifen-benzyl was applied approximately six weeks after rice emergence at 15 g ai ha⁻¹.

^cMeans within the same column are not different according to Tukey HSD ($\alpha=0.05$).

^dAsterisks (*) indicate statistical significance ($\alpha=0.05$) between postemergence programs averaged over fluridone rates for each site-year when interaction is not present.

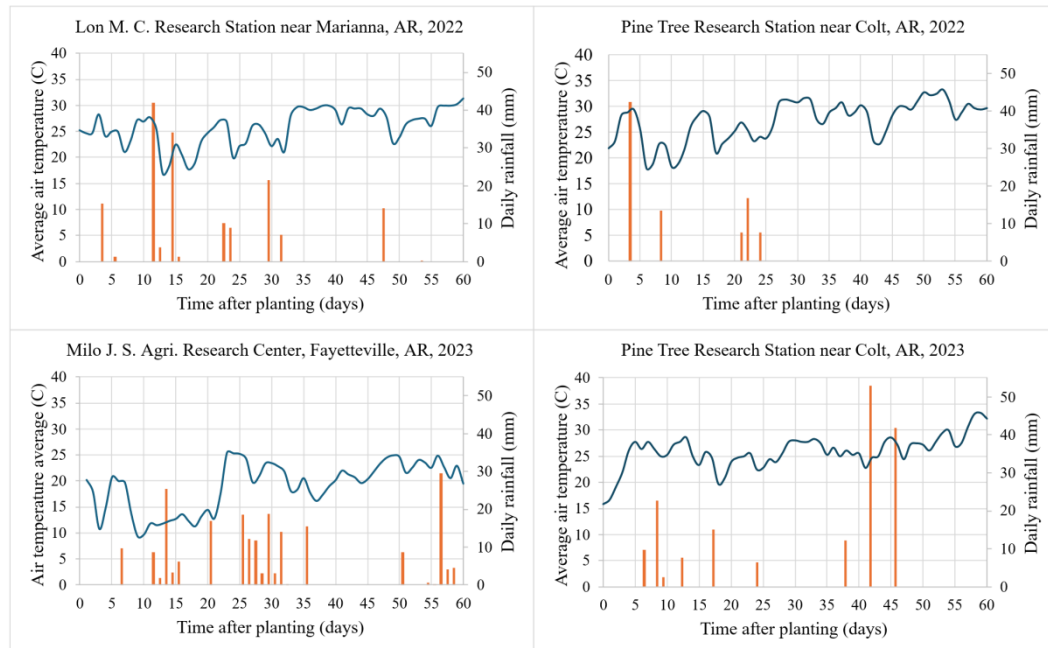


Figure 1. Daily results of observed air temperature (C) and rainfall events (mm) over a 24-hour period, from the planting until the last day of Palmer amaranth cumulative density and control evaluations. The blue line represents the daily average air temperature, and the orange bars indicate daily rainfall.

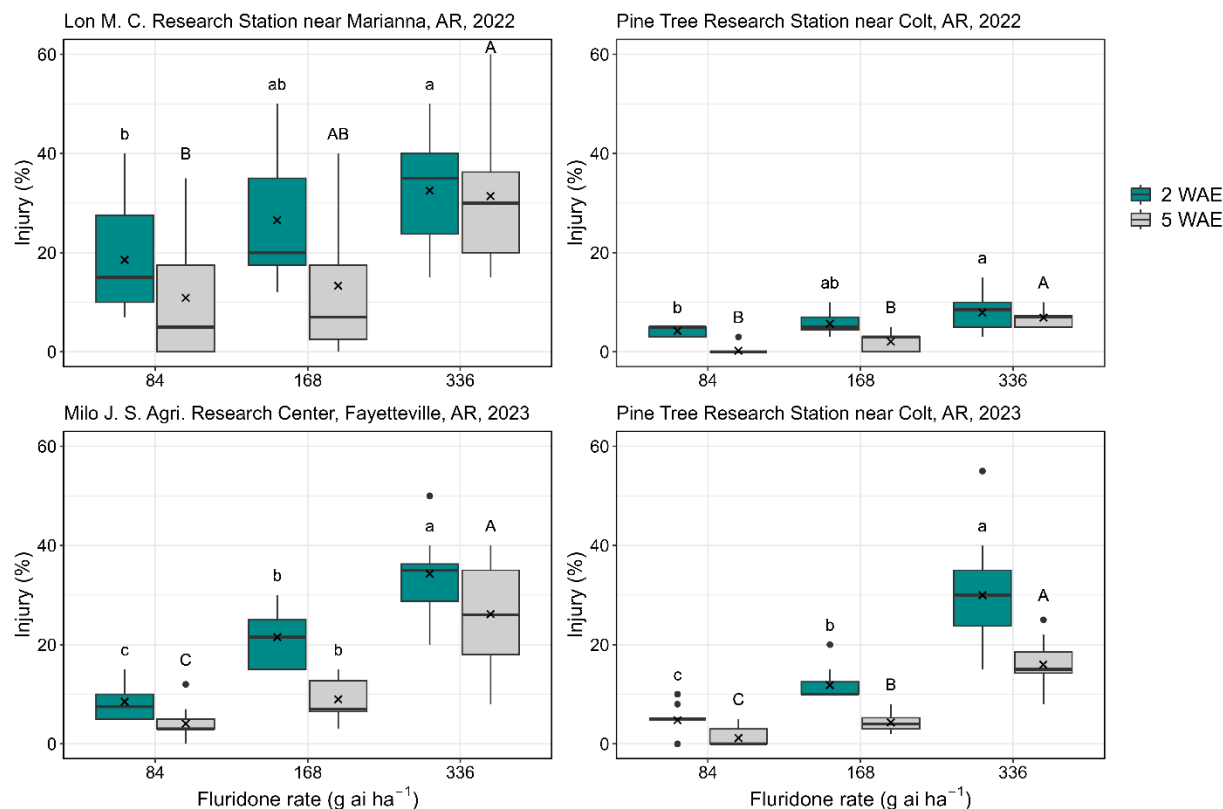


Figure 2. Distribution of rice injury (%) in response to fluridone treatments at two and five weeks after emergence (gray and green bars, respectively). Boxes represent the interquartile range (IQR), with the lower edge indicating the 25th percentile and the upper edge denoting the 75th percentile. Horizontal line within the box denotes the median, and × indicates the mean. Vertical lines (whiskers) extend to 1.5 times the IQR, and dots represent the outliers. Means followed by the same lowercase letter two weeks after emergence and means followed by the same uppercase letter five weeks after emergence are not different within the same evaluation time at each site-year according to Tukey's HSD ($\alpha = 0.05$). Abbreviations: WAE, weeks after emergence.

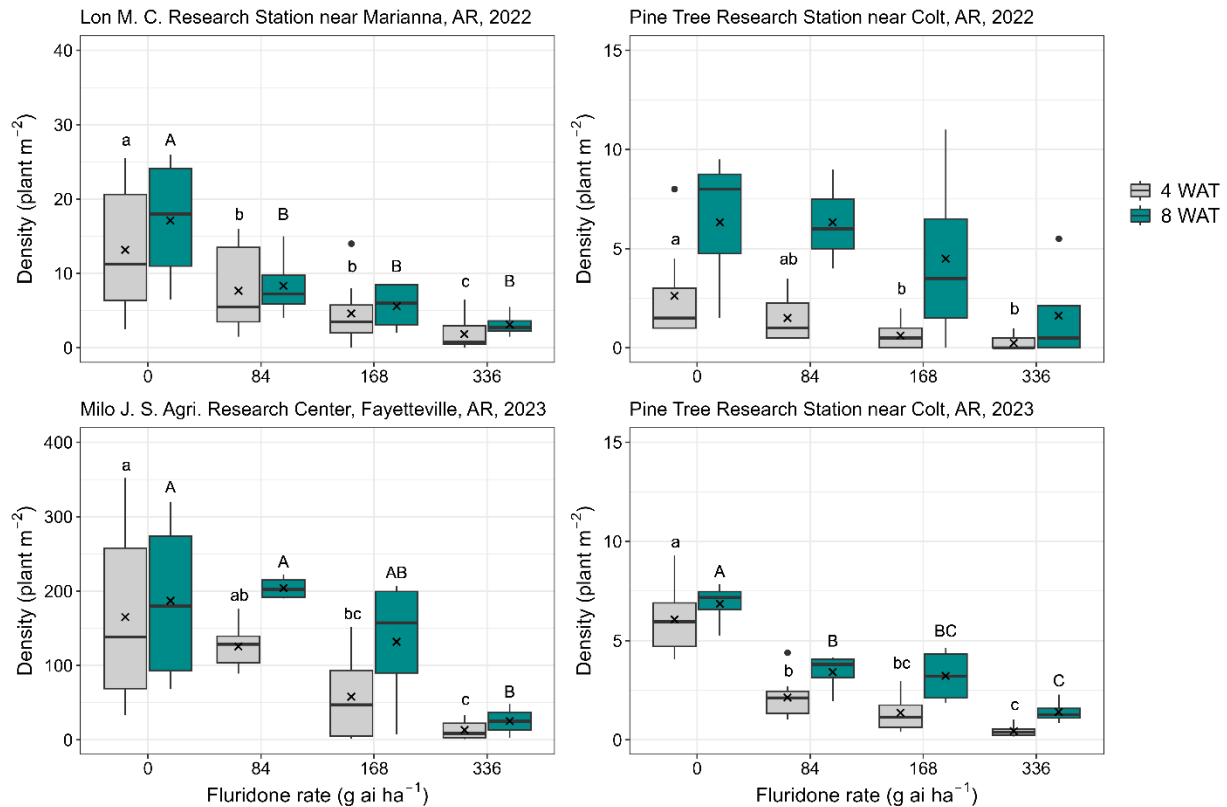


Figure 3. Distribution of Palmer amaranth cumulative density (plant m⁻²) in response to fluridone treatments at four and eight weeks after treatment (gray and green bars, respectively). Boxes represent the interquartile range (IQR), with the lower edge indicating the 25th percentile and the upper edge denoting the 75th percentile. Horizontal line within the box denotes the median, and × indicates the mean. Vertical lines (whiskers) extend to 1.5 times the IQR, and dots represent the outliers. Means followed by the same lowercase letter one month after treatment and means followed by the same uppercase letter two months after treatment are not different within the same evaluation time at each site-year according to Tukey's HSD ($\alpha=0.05$). If $P>0.05$, letters are not present. Abbreviations: WAT, weeks after treatment.

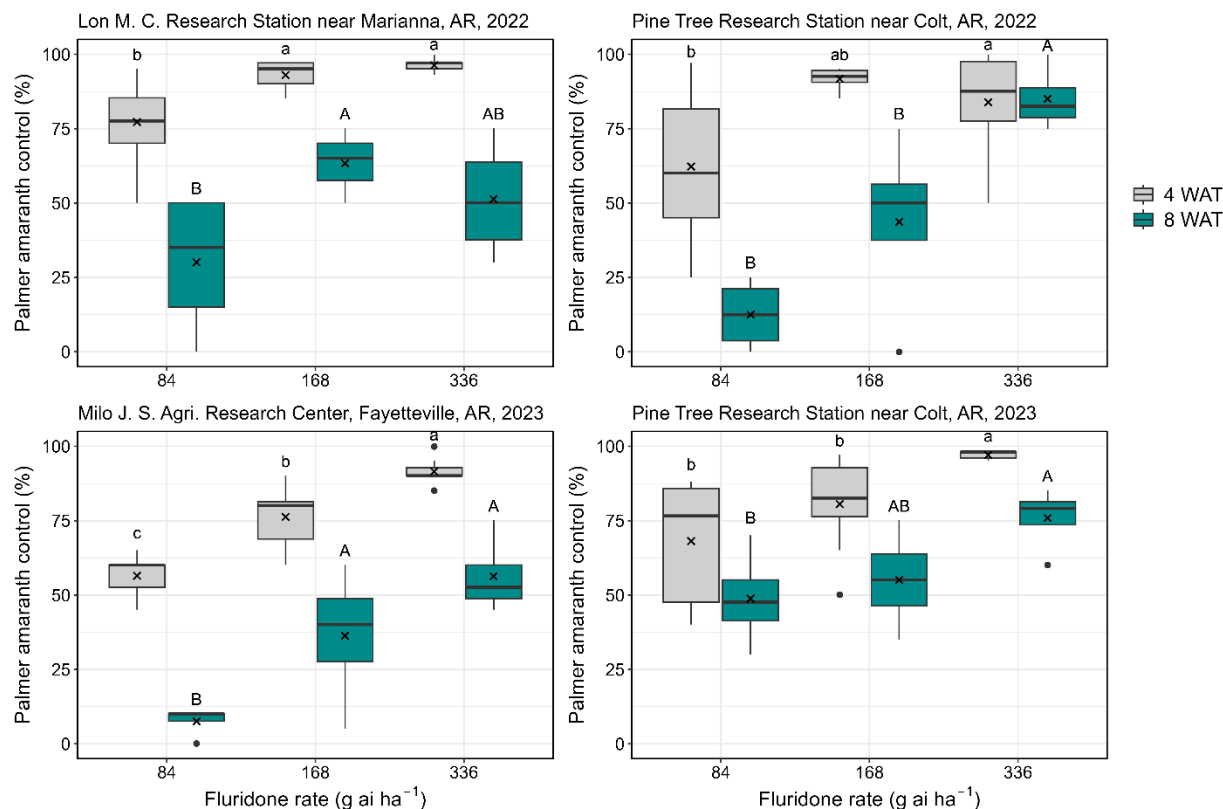


Figure 4. Distribution of Palmer amaranth visual control (%) in response to fluridone treatments at four and eight weeks after treatment (gray and green bars, respectively). Boxes represent the interquartile range (IQR), with the lower edge indicating the 25th percentile and the upper edge denoting the 75th percentile. Horizontal line within the box denotes the median, and × indicates the mean. Vertical lines (whiskers) extend to 1.5 times the IQR, and dots represent the outliers. Means followed by the same lowercase letter one month after treatment and means followed by the same uppercase letter two months after treatment are not different within the same evaluation time at each site-year according to Tukey's HSD ($\alpha = 0.05$). Abbreviations: WAT, weeks after treatment.