This is a "preproof" accepted article for Weed Science. This version may be subject to change in the production process, *and does not include access to supplementary material*.
DOI: 10.1017/wsc.2025.10061

Short Title: ***Amaranthus palmeri* in rice**

Effect of Crop Density on Palmer amaranth (*Amaranthus palmeri*) Emergence and Weed Density Interference Potential in a Furrow-Irrigated Rice System

Tanner A. King[1], Jason K. Norsworthy[2], Thomas R. Butts[3], Samuel B. Fernandes[4], Gerson L. Drescher[5]

[1]Graduate Research Assistant (Orchid ID 0009-0002-6345-0634), Department of Crop, Soil, and Environmental Sciences, University of Arkansas System Division of Agriculture, Fayetteville, AR, USA; [2]Distinguished Professor and Elms Farming Chair of Weed Science, Department of Crop, Soil, and Environmental Sciences, University of Arkansas System Division of Agriculture, Fayetteville, AR, USA; [3]Clinical Assistant Professor and Extension Specialist, Department of Botany and Plant Pathology, Purdue University, West Lafayette, IN, USA; [4]Assistant Professor of Agricultural Statistics and Quantitative Genetics, Department of Crop, Soil, and Environmental Sciences, University of Arkansas System Division of Agriculture, Fayetteville, AR, USA; [5]Assistant Professor of Soil Fertility, Department of Crop, Soil, and Environmental Sciences, University of Arkansas System Division of Agriculture, Fayetteville, AR, USA

Author for correspondence: Tanner A. King; Email: tak196@msstate.edu

Abstract

There is a high demand for cultural weed management strategies targeting Palmer amaranth (*Amaranthus palmeri* S. Watson) in furrow-irrigated rice (*Oryza sativa* L.) production due to overreliance on herbicides and the lack of a continual flood to prevent weed emergence. *Amaranthus palmeri* has been shown to reduce corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), and soybean [*Glycine max* (L.) Merr.] yields when it interferes with the crop. However, minimal research has been conducted to assess the ability of this weed species to impact rice grain yield. The manipulation of rice seeding rate to enhance rice canopy formation and favor the crop over the weed have not been fully explored. Hence, research was conducted to 1) evaluate the effect of rice density on *A. palmeri* emergence, rice canopy cover, and relative yield, and 2) determine the impact of *A. palmeri* density and aboveground biomass on rice grain yield. A natural population of *A. palmeri* was allowed to emerge at varying densities throughout the growing season within furrow-irrigated rice. *Amaranthus palmeri* plants caused 12 to 87% yield loss at densities ranging from 1 to 20 plants m^{-2}, and yield loss was 45 to 80% for plants weighing 200 to 800 g m^{-2}. When furrow-irrigated rice was sown at various densities, crop canopy cover increased as rice plant density increased. Most *A. palmeri* emergence occurred within the first four weeks after rice emergence, before canopy formation could have an effect. *Amaranthus palmeri* emergence beyond 5 weeks after rice emergence decreased as rice plant density and canopy cover increased. These results indicate that *A. palmeri* has the potential to cause severe yield loss, and that residual herbicides will be vital for *A. palmeri* management in a furrow-irrigated rice system, due to the continual emergence of weeds up to crop canopy formation.

Key words: competitiveness, interference, yield loss

Introduction

Palmer amaranth (*Amaranthus palmeri* S. Watson) is one of the most problematic weeds infesting Mid-Southern United States row crops (Riar et al. 2013) and can have severe economic impacts if left unmanaged (Bensch et al. 2003; Culpepper et al. 2006; Korres et al. 2019a). The high fecundity, extreme growth patterns, and extensive emergence period of *A. palmeri* are just a few biological attributes that enable the weed to be superior in competing with other plant species for available resources (Burke et al. 2007; Chahal et al. 2018; Horak and Loughin 2000). Additionally, the negative effects of *A. palmeri* emergence extend beyond the current growing season because the high seed dispersal ensures successful establishment in multiple growing seasons (Schwartz et al. 2016; Sparks et al. 2003). These characteristics, in combination with the ability of *A. palmeri* to evolve resistance to many herbicide sites of action (Heap 2024; Norsworthy et al. 2016), result in the need for multiple weed management strategies (cultural, biological, chemical, and mechanical) to combat the weed (DeVore et al. 2012; Norsworthy et al. 2012).

Regarding rice (*Oryza sativa* L.) production, a flood-irrigated system has traditionally been the dominant practice for most rice producers in the midsouthern United States (Hardke et al. 2022). Non-aquatic weeds, such as *A. palmeri*, fail to survive season-long in flood-irrigated rice due to the anaerobic conditions associated with the production system (Norsworthy et al. 2011); however, a strong shift towards furrow-irrigated rice has occurred in recent years due to decreased input costs and convenient rotation to other row crops, such as soybean [Glycine max (L.) Merr.] (Hardke et al. 2022; Nalley et al. 2022). *Amaranthus palmeri* can thrive in a furrow-irrigated rice system due to an extended emergence period provided by consistently moist conditions favoring weed growth and development (Norsworthy et al. 2011). Therefore, creating successful weed management strategies in furrow-irrigated rice systems has become more challenging due to the lack of a continual flood helping suppress most terrestrial weeds (Bagavathiannan et al. 2011; Norsworthy et al. 2008).

In addition to the timing of weed emergence and specific weed species involved, weed density plays a vital role in determining crop yield loss (Swanton et al. 2015). For example, research conducted by Klingaman and Oliver (1994) demonstrated that just two *A. palmeri* plants m^{-1} of row emerging simultaneously with soybean, can cause a 48% reduction in crop yield. Therefore, producers must understand weed biology and emergence behavior to successfully implement weed management programs and reduce the economic impact of problematic weeds (Jha and Norsworthy 2009; Myers et al. 2004). Cultural control methods and other weed management practices have been encouraged to reduce reliance on herbicides for weed control in row crop production systems (Chauhan and Johnson 2010; Norsworthy et al 2014, Shekhawat et al. 2020). Additionally, manipulating the competitive ability of the crop could prove beneficial in reducing crop yield loss from established weeds (Gibson et al. 2002).

Crop seeding rate is an integral part of any crop production system that inevitably alters the competitive ability of both the crop and weed (Swanton et al. 2015). Adjusting the crop density changes canopy formation (Korres et al. 2019b); hence, reduced weed germination and emergence can occur due to less daily light reaching and warming the soil surface (Bell et al. 2015; Korres and Norsworthy 2017; Norsworthy 2004). Additionally, fluctuating temperatures significantly enhance the germination and emergence of small-seeded summer annuals (Baskin and Baskin 1987). Consequently, crop canopy formation reduces diurnal temperature fluctuations and has a greater effect on suppressing *A. palmeri* than changes in light quality (Jha and Norsworthy 2009). Researchers have concluded that the germination response of many *Amaranthus* species, including redroot pigweed (*Amaranthus retroflexus* L.), smooth pigweed (*Amaranthus hybridus* L.), and common waterhemp [*Amaranthus tuberculatus* (Moq.) Sauer; syn. *Amaranthus rudis* Sauer) is influenced by a reduction in the red:far-red (R:FR) ratio which can occur from crop canopy formation (Gallagher and Cardina 1998; Leon and Owen 2003; Norsworthy 2004). Furthermore, light interception influences a weed's competitive ability with the crop by affecting the growth and development of the plant. Therefore, altering crop planting density may assist in reducing weed interference from plants that emerge after the crop (Jha et al. 2008; Steckel et al. 2003).

In crop-weed interactions, successful crop competition is attributed to innate biological attributes that are influenced by the presence of weeds (Jha et al. 2017). While the relationship between increased crop density and weed emergence has been examined (Bell et al. 2015), the correlation between rice plant density and weed emergence for specific weeds, such as *A. palmeri*, remains unknown. Additionally, the impacts of competition and yield associated with *A. palmeri* emergence in rice have not been investigated. Therefore, this research was conducted to (1) determine the effect of increasing rice density on *A. palmeri* emergence, crop canopy formation, and relative yield and (2) quantify the influence of A. *palmeri* density and aboveground biomass on furrow-irrigated rice grain yield.

Materials and Methods

Effect of Rice Density on Amaranthus palmeri Emergence, Crop Canopy Cover, and Relative Yield

A field trial was initiated at the Lon Mann Cotton Research Station in Marianna, Arkansas (34.72560°N, 90.73485°W), in 2022 and at the Milo J. Shult Research and Extension Center in Fayetteville, Arkansas (36.09366°N, 94.17414°W), in 2023 to determine the effect of rice density on *A. palmeri* emergence in a furrow-irrigated rice system. The experiment was designed as a randomized complete block with four replications. The soil at the Marianna site was a Convent silt loam (coarse-silty, mixed, superactive, nonacid, thermic Fluvaquentic Endoaquepts) consisting of 9% sand, 80% silt, 11% clay, and 1.8% organic matter with a pH of 6.5, and the soil in Fayetteville was a Leaf silt loam (fine, mixed, active, thermic Typic Albaquults) comprised of 18% sand, 69% silt, 13% clay, and 1.6% organic matter with a pH of 6.6. Before rice planting, the field was cultivated and shaped into 96-cm and 91-cm wide beds in Marianna and Fayetteville, respectively. Plots were 1.9 m wide (two beds) by 5.2 m long and 1.8 m wide (two beds) by 5.2 m long in Marianna and Fayetteville, respectively.

Before planting, the soil for each trial was amended for fertility based on soil test values from the Marianna Soil Test Lab recommendations. On May 11, 2022, and May 8, 2023, a hybrid, long-grain rice cultivar, ‘Full Page RT 7321FP’ (RiceTec Inc., Alvin, TX 77512), was planted and later emerged on May 17 and May 25, 2022, and 2023, respectively. Rice was planted at 0, 32, 68, 100, 137, 168, 205, 237, 274, and 310 seeds m^{-2} at a 1-cm depth with 19-cm between rows. The commercial standard seeding rate used by Midsouth furrow-irrigated rice producers when planting hybrid cultivars is approximately 190 seeds m^{-2} (Hardke et al. 2024).

Clomazone (Command 3ME, FMC Corporation, Philadelphia, PA 19104) was broadcast applied immediately after rice planting at 336 g ai ha^{-1} at each location to provide residual control of summer annual grasses. All spray applications were made with a CO$_2$-pressurized backpack sprayer utilizing four 10015 AIXR nozzles spaced 48 cm apart (TeeJet Technologies, Springfield, IL 62703) calibrated to deliver 140 L ha^{-1} at 276 kPa.

After planting, two 1 m^2 quadrats were randomly established in each plot. *Amaranthus palmeri* densities were recorded from each quadrat every seven days, beginning one week after rice emergence and ending ten weeks after emergence. Two weeks after rice emergence, rice plants in two 1 m row sections were counted in each plot. After recording newly emerged *A. palmeri* each week, the weeds were either chemically terminated from the quadrats or hand-removed if necessary. A previous greenhouse experiment confirmed that propanil did not affect the emergence of *A. palmeri* (personal observations). Therefore, the trial was over-sprayed with propanil (STAM, UPL, King of Prussia, PA 19406) to keep the trial free of weeds other than *A. palmeri* throughout the growing season. Once the rice reached V5, the crop was irrigated every three days using conventional furrow-irrigated rice methods, and nitrogen was applied at a total of 135 kg N ha^{-1}, in the form of urea (460 g N kg^{-1}), in three separate applications at intervals of two weeks (Barber et al. 2021).

Singular crop canopy photographs (in red-green-blue) were captured at 40 m above the crop by an unmanned aerial system [DJI Mavic 2 (DJI Technology Co., LTD, Nanshan, Shenzhen, China)] at 5, 7, and 10 weeks after emergence (WAE) to assess rice canopy cover. Green pixel counts from each image were measured using Field Analyzer (Green Research Services, LLC., Fayetteville, AR) and used to determine crop percentage canopy cover at each evaluation timing after the removal of *A. palmeri* (King et al. 2025a). The entire plot was harvested once the rice reached maturity using a Kincaid 8-XP (Kincaid, Haven, KS 67543) plot combine, with a header width of 1.8 m. Rice grain collected from each plot was adjusted to 12% moisture to report yield.

Influence of Amaranthus palmeri Density and Biomass on Furrow-Irrigated Rice Yields

A field experiment was conducted at the Milo J. Shult Research and Extension Center in Fayetteville, Arkansas (36.09301°N, 94.16882°W) in 2023 and 2024 to determine the effect of *A. palmeri* density and aboveground biomass on rice grain yield. The soil was a Leaf silt loam (fine, mixed, active, thermic Typic Albaquults) composed of 18% sand, 69% silt, 13% clay, and 1.6% organic matter with a pH of 6.6.

The experimental area was field cultivated before planting and shaped into 91-cm wide beds, which then received clomazone applied preemergence at 336 g ai ha^{-1} to reduce annual weedy grass emergence. On April 22, 2023, and April 16, 2024, a hybrid, long-grain cultivar, ‘Full Page RT 7321FP’ (RiceTec., Alvin, TX 77512), was planted at the recommended rate of 36 seeds m^{-1} of row at a 1-cm depth with 18-cm between rows, and rice emerged on May 9, 2023, and April 30, 2024. Plot dimensions were established to be 3.7 m wide (four beds) by 5.2 m long, with a 0.9 m alley between replications. Once the rice plants reached the V5 growth stage, the trial was irrigated every three days using standard furrow-irrigation techniques, and nitrogen, as urea (460 g N Kg^{-1}), was administered at a cumulative rate of 135 kg N ha^{-1} in three split applications at intervals of two weeks (Barber et al. 2021).

The experiment was a completely randomized design with a total of 80 interference plots across two years (60 plots in 2023 and 20 plots in 2024) in the same field. Natural populations of *A. palmeri* were allowed to germinate and emerge in each plot after rice planting. Applications of fenoxaprop (Ricestar® HT herbicide, Gowan Co., Yuma, AZ 85364) and halosulfuron-methyl (Permit 75WG, Gowan Co., Yuma, AZ 85364) were later applied to remove other undesired weed species that emerged within the trial without affecting *A. palmeri* establishment. Additionally, six weeks after rice emergence, an application of propanil (STAM, UPL, King of Prussia, PA 19104) was used to control newly emerged cotyledon *A. palmeri* plants under the assumption that interference was already occurring from larger plants, and these larger plants although slightly injured would survive the application in a production scenario, further competing with the crop and producing seed. All herbicide applications were made utilizing a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} at 276 kPa, using four 110015 AIXR nozzles positioned 48 cm apart (TeeJet Technologies, Springfield, IL 62703). For comparison purposes, weed-free plots were randomly assigned to the experiment each year, which were maintained by hand-weeding throughout the growing season in addition to the previously mentioned herbicide applications.

All data were collected from the center 1.8 m of each plot to mitigate interference from weeds in adjacent plots. *Amaranthus palmeri* density at rice harvest was determined by counting plants in a 1 m^2 quadrat in each plot. *Amaranthus palmeri* plants were then cut at the soil surface within the quadrat, bagged, and placed in an oven at 66 C for two weeks and dried to constant mass to record dry aboveground biomass. After *A. palmeri* removal, rice panicles were harvested in the quadrat using hand-held rice sickles. The rice panicles were placed into an Almaco small bundle thresher (Almaco, Nevada, IA 50201) to obtain a weight that could be converted to rice grain yield. The grain yield collected was adjusted to 12% moisture.

Statistical Analyses for Effect of Rice Density on Amaranthus palmeri Emergence, Crop Canopy Cover, and Relative Yield

All data were analyzed in JMP Pro 17.0 using regression analysis (SAS Institute Inc., Cary, NC). An exponential three-parameter (3P) curve (Eq. 1) was used to model the relationship between *A. palmeri* emergence at 5 weeks after emergence (WAE) and beyond and crop canopy cover after achieving the lowest AIC (703.34) (Figure 1).

Eq. 1 $Y = Asymptote + Scale \times Exp(Growth\,rate \times Canopy\,Cover)$

where Y is the dependent variable (cumulative *A. palmeri* emergence m^{-2}); asymptote, scale, and growth rate are parameters, and crop canopy percentage is the explanatory variable.

Conversely, an exponential 2P curve (Eq. 2) was used to model total *A. palmeri* emergence as a function of rice density (AIC = 684.16, Figure 2).

Eq. 2 $Y = Scale \times Exp(Growth\,rate \times Density)$

where Y is the dependent variable (cumulative *A. palmeri* emergence m^{-2}), scale and growth rate are parameter estimates, and rice density m^{-2} is the explanatory variable.

The relationship between crop canopy cover and rice density at 5, 7, and 10 WAE was nonlinear; hence, a Weibull Growth model (Eq. 3) was used to fit the relationship (AIC = 1,874.54 (Figure 3A-D).

Eq. 3 $Y = Asymptote \times \{1 - Exp\left[-\left(\frac{Density}{Inflection\,point}\right)^{Growth\,rate}\right]\}$

where Y is the dependent variable (percent canopy cover) at each emergence timing; asymptote, inflection point, and growth rate are parameters, and rice density is the predictor variable.

Because the experiment was initiated in different locations, a three-parameter exponential model was also utilized to determine the maximum yield potential in 2022 and 2023 as a function of rice density to help account for year-to-year variation (data not shown). The analysis included Weibull, Gompertz, and Logistic curves, with the exponential 3P model achieving the lowest Akaike information criterion (AIC = 1285.98). The maximum yield potential in each year was 11,100 kg ha^{-1} and 7,700 kg ha^{-1} for 2022 and 2023, respectively, and is based on the asymptote of the model.

The rice grain yield from each plot was then made relative to the maximum yield potential within each year. To determine relative yield (%) as a function of rice density (plants m^{-2}), Eq. 1 was used to model the relationship in the Fit Curve Platform in JMP Pro 17. Within the model, relative yield is the dependent variable; asymptote, scale, and growth rate are parameters; and rice density is the predictor variable (Figure 4).

Statistical Analyses for Influence of Amaranthus palmeri Density and Biomass on Furrow-Irrigated Rice Yields

Regression analysis was used to determine the impact of *A. palmeri* density and aboveground biomass on furrow-irrigated rice yields in JMP Pro 17 (SAS Institute Inc., Cary, NC). Site year was treated as a random effect to make universal conclusions across multiple environments (MacRae et al. 2013; Midway 2022). A strong nonlinear relationship occurred between rice yield loss and *A. palmeri* density and aboveground biomass. The maximum rice yield potential was calculated by averaging rice yields of the weed-free plots, which helped account for yield variability throughout the field. The rice grain yield from each interference plot was then made relative to the average weed-free yield to determine rice yield loss from *A. palmeri* interference.

To determine rice yield loss (%) as a function of *A. palmeri* density, two- and three-parameter curves were fit using the fit curve platform in JMP Pro 17. The exponential 3P model (Eq. 4) was determined to be the best fit after achieving the lowest AIC (654.51).

Eq. 4 $Yield\ loss\ = Asymptote + Scale\ \times Exp(Growth\ rate\ \times Density)$

where yield loss is the dependent variable; asymptote, scale, and growth rate are model parameters; and *A. palmeri* density is the independent variable (Figure 5). Equation 4, having the lowest AIC (560.97), was also used to describe the relationship between *A. palmeri* biomass and rice yield loss, with the independent variable being *A. palmeri* biomass in g m^{-2} (Figure 6).

There appeared to be a linear relationship between *A. palmeri* density and aboveground biomass. Hence, a linear regression model was used to fit the relationship in the fit curve platform in JMP Pro 17 after conducting a lack of fit test (P-value > 0.05) to ensure that the model was appropriate for explaining the relationship (Eq. 5) (Figure 7).

Eq. 5 $Y = a + bX$

where Y is the dependent variable (*A. palmeri* biomass in g m^{-2}), b is the slope of the line, X is the independent variable (*A. palmeri* density m^{-2}), and a is the intercept when X is equal to zero.

Results and Discussion

Amaranthus palmeri Emergence as a Function of Rice Canopy and Density

As rice canopy cover at 5 WAE increased, *A. palmeri* emergence beyond this point decreased (Figure 1). In both years, over 75% of the *A. palmeri* emerged in the first four weeks after rice emergence (data not shown); hence, rice density had no effect in the early stages of the growing season due to the lack of an appreciable canopy. As a result, total *A. palmeri* emergence data were based on weeds that emerged at 5 WAE and beyond. In this period, total *A. palmeri* emergence ranged from 0 to 132 plants m^{-2}. Based on the exponential 3P model explaining the relationship (Figure 1), *A. palmeri* emergence from 5 WAE and beyond was reduced from 47 to 15 plants m^{-2} when canopy cover was 0 and 12%, respectively. However, weed emergence was not further reduced when canopy cover exceeded 12%, suggesting that *A. palmeri* emergence will not cease even at the maximum canopy cover of 38% at 5 WAE. Jha and Norsworthy (2009) reported that 75% light interception by soybean canopy affected cumulative *A. palmeri* emergence, which ceased once soybean canopy formation reached 90%.

Total *A. palmeri* emergence decreased exponentially as rice density increased to 192 plants m^{-2}, as explained by the exponential 2P model (Figure 2). *Amaranthus palmeri* emergence was greatest in plots not containing rice, with 53 (±6) *A. palmeri* m^{-2} emerging, on average. Conversely, a rice density of 50, 100, and 150 plants m^{-2} resulted in 27 (±3), 13 (±3), and 7 (±2) total *A. palmeri* plants m^{-2}, respectively; however, rice densities beyond 150 plants m^{-2} did not aid in suppressing additional emergence of *A. palmeri* plants. These results display the extreme competitive ability of *A. palmeri* even at higher than recommended rice seeding rates and that successful *A. palmeri* suppression will likely depend on canopy formation as the growing season progresses rather than rice density alone early in the season. Additionally, these findings indicate that additional suppressive or management efforts beyond manipulating rice density will need to be implemented in an integrated approach for successful *A. palmeri* management.

Crop Canopy Cover as Influenced by Rice Density

Crop canopy cover increased as the seeding rate and subsequent rice density increased (Figure 3D). A similar relationship was shown by research conducted by Ottis and Talbert (2005), who reported that canopy cover increased linearly as rice density increased; however, the seeding rates used in that study exceeded those in this experiment, which may be attributed to differences in recommended plant densities as new rice cultivars have become available. Crop canopy cover also increased as rice matured, reaching maximum values of 38 (±4.34), 63 (±3.06), and 80% (± 2.53) at 5, 7, and 10 WAE, respectively (Figure 3A-C). At a rice density of

135 plants m^2, 38% canopy cover was achieved at 5 WAE. To reach 38% canopy cover at 7 and 10 WAE, only 50 and 10 plants m^{-2}, respectively, were required, indicating that fewer plants are needed in subsequent weeks.

Impact of Rice Density on Relative Rice Yields

Rice yields were determined to be statistically greater in 2022 than in 2023 after using nonlinear regression analysis with rice density set as the independent variable (data not shown). Within the model, the 95% confidence intervals associated with the asymptote and inflection point model parameters did not overlap; however, the growth rate parameter estimates were similar across site years according to the nonlinear regression analysis, which suggests that yield responses were analogous at both locations. Therefore, the grain yield from each plot was made relative to the maximum yield potential for each year, and the relationship between relative yield and rice density was best explained with an exponential 3P model, which accounted for 88.8% of the variation in relative yield .

Relative rice yield increased exponentially as rice density increased up to a maximum of 193 plants m^{-2} and 100% relative yield (Figure 4). Rice yields were 39 (±5.60), 77 (±6.02), and 91% (±3.67) of the maximum yield potential at densities of 5, 15, and 25 plants m^{-2}, respectively, and maximum rice yield potential was achieved at 30 plants m^{-2}. Although the ideal final plant stand for hybrid rice cultivars is 65 to 110 plants m^{-2} (Hardke et al. 2024), optimal grain yield can still be achieved at lower plant densities with appropriate crop management (Wu et al. 1998). Research has confirmed that tiller number is influenced by plant density and begins to decrease as rice density increases due to plants competing for available resources (Counce et al. 1992; Liang et al. 1986), which subsequently has an impact on grain yield (Counce and Wells 1990). Therefore, a sub-optimal plant density still reaching maximum yield potential, as observed here, may result from rice plants compensating in other yield components such as spikelets per panicle, kernel weight, or tillering capacity (Gravois and Helms 1992).

Furrow-Irrigated Rice Yield Loss as Influenced by Amaranthus palmeri Density and Biomass

When rice yields in interference plots were made relative to the weed-free control, the furrow-irrigated rice yield loss response as a function of *A. palmeri* density was best explained with a nonlinear, exponential 3P curve . With *A. palmeri* density set as the explanatory variable, the exponential 3P model accounted for 64.0% of the variation in rice yield loss. Previous research has identified that the relationship between weed density and crop yield loss is often nonlinear, indicating that this approach is acceptable for quantifying the interference potential of various *A. palmeri* densities in rice (Blackshaw et al. 1981; Cousens et al. 1985; Zimdahl 1980). Overall, rice yield loss increased as *A. palmeri* density increased up to a maximum of 47 plants m^{-2} and 100% yield loss (Figure 5), which is a well-understood relationship among many researchers (Burke et al. 2007; Knezevic et al. 1994; Massinga et al. 2001).

Rice yields were reduced by 10 (±4.43), 50 (±2.91) , and 90% (±7.75) at *A. palmeri* densities of 1, 7, and 24 plants m^{-2}, respectively (Figure 5). However, the yield loss data reported here is influenced by multiple cohorts of *A. palmeri* emerging at various times relative to the crop throughout the growing season. Hence, *A. palmeri* biomass provides a better relationship with rice yield loss because later emerging, smaller plants produced less biomass, which cannot be accounted for when looking solely at weed density. Additionally, there were few observations of weed densities greater than 30 plants m^{-2}; hence, the relationship is weaker due to less variation being accounted for at those higher densities. The degree of interference on rice and subsequent reduction in yield would likely be elevated if a single *A. palmeri* emerged with the crop due to the absence of intraspecific competition (King et al. 2025b). Furthermore, rice yield loss responses were similar once *A. palmeri* densities exceeded 15 plants m^{-2} based on the mean 95% confidence intervals overlapping with additional plants included in the model. The response likely exists because each individual *A. palmeri* plant, at a higher density, has less impact on rice yield, which indicates intraspecific competition (Smith 1998). The results in this study are slightly different than those observed by Rowland et al. (1999), who reported that *A. palmeri* densities > 8 plants m^{-1} of row triggered intraspecific weed interference when transplanted at the one true-leaf growth stage within a 5 cm distance from cotton (*Gossypium hirsutum* L.). However, fewer *A. palmeri* plants seeded simultaneously near an emerging crop are likely more uniform and have greater interference potential with the crop than those emerging at various times throughout the growing season (Swanton et al. 2015); hence, differences in competition thresholds between the two studies likely differ due to the variability in timing of *A. palmeri* seedling establishment.

There was also a strong relationship between rice yield loss and *A. palmeri* aboveground biomass accumulation ($R^2 = 0.78$, P-value < 0.0001). Similar to the relationship between rice yield loss and weed density, an exponential 3P curve was best suited for describing the influence of *A. palmeri* biomass on crop yield loss (Figure 6). Rice yield loss increased exponentially as *A.*

palmeri biomass increased to a maximum biomass quantity of 1,313 g m^{-2}. *Amaranthus palmeri* is extremely efficient at conducting photosynthesis due to the weed being a C_4 plant (Wang et al. 1992; Ward et al. 2013); therefore, *A. palmeri* can produce extreme quantities of biomass, which aids in the competitive success of the weed with multiple crops (Ehleringer and Forseth 1980; Fast et al. 2009; Jha and Norsworthy 2009).

Amaranthus palmeri biomass of 26, 235, and 1050 g m^{-2} caused a 10 (±3.31), 50 (±3.06), and 90% (±7.81) reduction in rice yield, respectively, based on the model predictions of the regression analysis (Figure 6). A previous experiment also identified a nonlinear relationship between *A. palmeri* biomass and cotton lint yield loss, which suggested that crop yield loss increases considerably once *A. palmeri* commences the exponential stage of vegetative development (Fast et al. 2009). The innate ability of *A. palmeri* to maximize photosynthetic rate and accelerate its life cycle provides the weed with a competitive edge over other plant species that utilize a C_3 photosynthesis pathway, such as rice (Ehleringer and Forseth 1980; Shell and Lang 1976). *Amaranthus palmeri* biomass was shown to be an acceptable predictor of rice yield loss, and the correlation between biomass and crop yield loss was greater than that of weed density; however, weed density may serve as the more practical option for determining crop yield loss due to ease of implementation in the field (Klingaman and Oliver 1994).

Additionally, *A. palmeri* biomass increased linearly with *A. palmeri* density ($R^2 = 0.51$, P-value <0.0001) (Figure 7). The weaker correlation here is further evidence that multiple *A. palmeri* cohorts emerged, rather than only having plants emerging with the crop. *Amaranthus palmeri* biomass ranged from 0 to 1,313 g m^{-2} and increased by 47 g m^{-2} for every additional *A. palmeri* plant from 0 to 25 plants m^{-2}. A similar, linear relationship was reported in another study in which *A. palmeri* biomass increased 105 g m^{-2} with every single plant increase within 2 to 10 plants per 6.1 m of cotton row (MacRae et al. 2013). The linear relationship between aboveground biomass and weed density would usually indicate a lack of intraspecific competition; however, the results observed here may be attributed to the variable emergence timings and subsequent size of *A. palmeri* cohorts considering earlier emerging plants have greater interference potential (Knezevic et al. 1994; Radosevich and Holt 1984).

Because *A. palmeri* is among the most common and problematic weed species in the mid-southern U.S. (Norsworthy et al. 2014), producers must implement control strategies that minimize crop yield loss. The interference potential of *A. palmeri* in furrow-irrigated rice has not been explored, and the interactions that occur between the crop and weed are not well understood. Findings from this research support that *A. palmeri* density and aboveground biomass accumulation negatively impact crop yield loss (Rowland et al. 1999); however, assessing yield loss as a function of weed density is more practical from a producer standpoint. The results from this interference research may overestimate the impact of *A. palmeri* on rice yields due to the absence of preemergence herbicides affecting the earliest emerging cohorts; however, findings from this experiment still provide growers with valuable information when looking to build management guidelines for *A. palmeri* in a furrow-irrigated rice system. With the yield loss data presented here, a producer could apply a herbicide based on the number of *A. palmeri* plants present in the field, which will potentially help mitigate severe crop yield loss through reduced biomass production and subsequent interference with the crop. Although *A. palmeri* fecundity was not quantified in this study, the extreme seed dispersal by the weed ensures high populations of offspring in future growing seasons that can potentially cause significant yield loss.

Regarding the rice seeding rate experiment, there was limited benefit in reducing *A. palmeri* emergence and increasing rice yield with increased crop seeding rates. Based on the 2024 Arkansas enterprise budget, the estimated cost for planting imidazolinone-resistant hybrid rice at a commercial seeding rate (28 kg ha^{-1}) is \$474 ha^{-1}; hence, an above-standard seeding rate would result in increased input costs and reduced returns. Additionally, producers should consider planting earlier, likely before *A. palmeri* peak emergence, which will allow the rice canopy to have greater potential to suppress the emergence of the weed. These findings also indicate that preemergence and postemergence residual herbicides will be necessary to give rice a competitive advantage until canopy closure in furrow-irrigated fields infested with *A. palmeri*. Fluridone has been shown to provide excellent residual control of *A. palmeri* when applied postemergence in a furrow-irrigated rice system (King et al. 2025c). From 5 to 10 WAE, increased rice density and subsequent canopy coverage reduced *A. palmeri* establishment; however, none of the evaluated rice densities and canopy cover assessments prevented *A. palmeri* emergence. Based on these results, postemergence herbicides will also be needed to control late-emerging *A. palmeri*, considering weed emergence is more frequent in a furrow-irrigated rice system (Beesinger et al. 2022). Overall, both experiments display the competitive nature of *A. palmeri* in rice and the need to adopt multiple weed management tactics to maintain rice yield.

Funding

This research was not supported by any funding agency, commercial enterprise, or nonprofit entity.

Competing Interests

Competing interests: the authors declare none.

References

Bagavathiannan MV, Norsworthy JK, Scott RC (2011) Comparison of weed management programs for furrow-irrigated and flooded hybrid rice production in Arkansas. Weed Technol 25:556-562

Barber LT, Bateman N, Butts T, Hamilton M, Henry C, Lorenz G, Mazzanti R, Norsworthy J, Roberts T, Wamishe Y, Watkins B (2021) Pages 33-36 *in* Arkansas Furrow-Irrigated Rice Handbook. University of Arkansas System Division of Agriculture Research and Extension.

Baskin JM, Baskin CC (1987) Temperature requirements for after-ripening in buried seeds of four summer annual weeds. Weed Res 27:385-389

Beesinger JW, Norsworthy JK, Butts TR, Roberts TL (2022) Palmer amaranth control in furrow-irrigated rice with florpyrauxifen-benzyl. Weed Technol 36:490-496

Bell HD, Norsworthy JK, Scott RC (2015) Effect of drill-seeded soybean density and residual herbicide on Palmer amaranth (*Amaranthus palmeri*) emergence. Weed Technol 29:697-706

Bensch CN, Horak MJ, Peterson D (2003) Interference of redroot pigweed (*Amaranthus retroflexus*), Palmer amaranth (*A. palmeri*), and common waterhemp (*A. rudis*) in soybean. Weed Sci 51:37-43

Blackshaw RE, Stobbe EH, Sturko ARW (1981) Effect of seeding dates and densities of green foxtail (*Setaria viridis*) on the growth and productivity of spring wheat (*Triticum aestivum*). Weed Sci 29:212-217

Burke IC, Schroeder M, Thomas WE, Wilcut JW (2007) Palmer amaranth interference and seed production in peanut. Weed Technol 21:367-371

Chahal PS, Irmak S, Jugulam M, Jhala AJ (2018) Evaluating effect of degree of water stress on growth and fecundity of Palmer amaranth (*Amaranthus palmeri*) using soil moisture sensors. Weed Sci 66:738-745

Chauhan BS, Johnson DE (2010) Implications of narrow crop row spacing and delayed *Echinochloa colona* and *Echinochloa crus-galli* emergence for weed growth and crop yield loss in aerobic rice. Field Crops Res 117:177-182

Counce PA, Wells BR (1990) Rice plant population density effect on early-season nitrogen requirement. J Prod Agric 3:390-393

Counce, PA, Wells BR, Gravois KA (1992) Yield and harvest index responses to preflood nitrogen fertilization at low rice plant populations. J Prod Agric 5:492-497

Cousens R (1985) A simple model relating yield loss to weed density. Ann Appl Biol 107:239-252

Culpepper A, Grey T, Vencill W, Kichler J, Webster T, Brown S, York A, Davis J, Hanna W (2006) Glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) confirmed in Georgia. Weed Sci 54:620-626

DeVore JD, Norsworthy JK, Brye KR (2012) Influence of deep tillage and a rye cover crop on glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) emergence in cotton. Weed Technol 26:832-838

Ehleringer J, Forseth I (1980) Solar tracking by plants. Science 210:1094-1098

Fast BJ, Murdock SW, Farris RL, Willis JB, Murray DS (2009) Critical timing of Palmer amaranth (*Amaranthus palmeri*) removal in second-generation glyphosate-resistant cotton. J Cotton Sci 13:32-36

Gallagher RS, Cardina J (1998) Phytochrome-mediated *Amaranthus* germination, I: effect of seed burial and germination temperature. Weed Sci 46:48-52

Gibson KD, Fischer AJ, Coin TC, Hill JE (2002) Implications of delayed *Echinochloa* spp. germination and duration of competition for integrated weed management in water-seeded rice. Weed Res 42:351-358

Gravois KA, Helms RS (1992) Path analysis of rice yield and yield components as affected by seeding rate. Agron J 84:1-4

Hardke J, Barber T, Bateman N, Butts, T, Drescher G, Hamilton M, Henry C, Mazzanti R, Nicolli C, Norsworthy J, Roberts T (2024) Seeding, Emergence, and Plant Stands, Page

10 *in* 2024 Rice Management Guide. Little Rock: University of Arkansas System Division of Agriculture, Cooperative Extension Service. Assessed on March 20, 2024

Hardke JT (2022) Trends in Arkansas rice production, Pages 11-18 in Arkansas Rice Research Studies 2022. Little Rock: University of Arkansas System Division of Agriculture, Cooperative Extension Service. Accessed on March 17, 2024

Heap I (2024) The international survey of herbicide resistance weeds. http://weedscience.org. Accessed March 3, 2024

Horak MJ, Loughin TM (2000) Growth analysis of four *Amaranthus* species. Weed Sci 48:347-355

Jha P, Kumar V, Godara RK, Chauhan BS (2017) Weed management using crop competition in the United States: a review. Crop Prot 95:31-37

Jha P, Norsworthy JK (2009) Soybean canopy and tillage effects on emergence of Palmer amaranth (*Amaranthus palmeri*) from a natural seed bank. Weed Sci 57:644-651

Jha P, Norsworthy JK, Riley MB, Bielenberg DG, Bridges W Jr. (2008) Acclimation of Palmer amaranth (*Amaranthus palmeri*) to shading. Weed Sci 56:729-734

King TA, Norsworthy JK, Butts TR, Barber LT, Drescher GL, Fernandes SB, Avent TH (2025a) Impact of cover crops on furrow-irrigated rice and Palmer amaranth (*Amaranthus palmeri*) emergence. Weed Technol 39:1-7

King TA, Norsworthy JK, Butts TR, Barber LT, Drescher GL, Godar AS (2025c) Palmer amaranth (*Amaranthus palmeri*) control in furrow-irrigated rice with fluridone. Weed Technol 39:1-11

King TA, Norsworthy JK, Butts TR, Fernandes SB, Drescher GL, Avent TH (2025b) Effect of Palmer amaranth (*Amaranthus palmeri*) time of emergence on furrow-irrigated rice yields and weed seed production. Weed Sci 73:1-8

Klingaman TE, Oliver LR (1994) Palmer amaranth (*Amaranthus palmeri*) interference in soybeans (*Glycine max*). Weed Sci 42:523-527

Knezevic SZ, Weise SF, Swanton CJ (1994) Interference of redroot pigweed (*Amaranthus retroflexus*) in corn (*Zea mays*). Weed Sci 42:568-573

Korres NE, Norsworthy JK (2017) Palmer amaranth demographic and biological characteristics in wide-row soybean. Weed Sci 65:491-503

Korres NE, Norsworthy JK, Mauromoustakos A (2019a) Effects of Palmer amaranth (*Amaranthus palmeri*) establishment time and distance from the crop row on biological and phenological characteristics of the weed: implications on soybean yield. Weed Sci 67:126-135

Korres NE, Reddy KN, Rouse C, King AC (2019b) Sustainable weed control in soybean. Pages 288-305 *in* Korres NE, Burgos NR, Duke SO, eds. Weed Control: Sustainability, Hazards and Risks in Cropping Systems Worldwide. Boca Raton, FL: CRC Press

Leon RG, Owen MDK (2003) Regulation of weed seed dormancy through light and temperature interactions. Weed Sci 51:752-758

Liang GS, Muo JR, Ran CF (1986) Rice physiology and ecology. Pages 159-220 *in* Chinese Academy of Agric. Sciences (ed.) Rice cultivation in China. Chinese Agric. Press, Beijing.

MacRae AW, Webster TM, Sosnoskie LM, Culpepper AS, Kichler JM (2013) Cotton yield loss potential in response to length of Palmer amaranth (*Amaranthus palmeri*) interference. J Cotton Sci 17:227-232

Miller BC, Hill JE, Roberts SR (1991) Plant population effects on growth and yield in water-seeded rice. Agron J 83:291-297

Myers MM, Curran WS, VanGessel MJ, Calvin DD, Mortensen DA, Majek BA, Karsten HD, Roth GW (2004) Predicting weed seedling emergence for eight annual species in the northeastern United States. Weed Sci 52:913-919

Nalley LL, Massey J, Durand-Morat A, Shaw A, Parajuli R, Tsiboe F (2022) Comparative economic and environmental assessments of furrow- and flood-irrigated rice production systems. Agric Water Manag 274:107964

Norsworthy JK (2004) Soybean canopy formation effects on pitted morningglory (*Ipomoea lacunosa*), common cocklebur (*Xanthium strumarium*), and sicklepod (*Senna obtusifolia*) emergence. Weed Sci 52:954-960

Norsworthy JK, Griffith GM, Griffin T, Bagavathiannan M, Gbur EE (2014) In-field movement of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) and its impact on cotton lint yield: evidence supporting a zero-threshold strategy. Weed Sci 62:237-249

Norsworthy JK, Griffith GM, Scott RC (2008) Imazethapyr use with and without clomazone for weed control in furrow-irrigated, imidazolinone-tolerant rice. Weed Technol 22:217-221

Norsworthy JK, Korres NE, Walsh MJ, Powles SB (2016) Integrating herbicide programs with harvest weed seed control and other fall management practices for the control of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*). Weed Sci 64:540-550

Norsworthy JK, Scott RC, Bangarwa SK, Griffith GM, Wilson MJ, McCelland M (2011) Weed management in a furrow-irrigated imidazolinone-resistant hybrid rice production system. Weed Technol 25:25-29

Norsworthy JK, Ward SM, Shaw DR, Llewellyn RS, Nichols RL, Webster TM, Bradley KW, Frisvold G, Powles SB, Burgos NR, Witt WW, Barrett M (2012) Reducing the risks of herbicide resistance: best management practices and recommendations. Weed Sci 60 (SPI):31-62

Ottis BV, Talbert RE (2005) Rice yield components as affected by cultivar and seeding rate. Agron J 97:1622-1625

Radosevich SR, Holt JS (1984) Weed Ecology: Implications for Vegetation Management. New York: John Wiley and Sons. 265 p.

Riar DS, Norsworthy JK, Steckel LE, Stephenson DO, Eubank TW, Scott RC (2013) Assessment of weed management practices and problem weeds in the Midsouth United States – soybean: a consultant’s perspective. Weed Technol 27:612-622

Rowland MW, Murray DS, Verhalen LM (1999) Full-season Palmer amaranth (*Amaranthus palmeri*) interference with cotton (*Gossypium hirsutum*). Weed Sci 47:305-309

Schwartz LM, Norsworthy JK, Young BG, Bradley KW, Kruger GR, Davis VM, Steckel LE, Walsh MJ (2016) Tall waterhemp (*Amaranthus tuberculatus*) and Palmer amaranth (*Amaranthus palmeri*) seed production and retention at soybean maturity. Weed Technol 30:284-290

Shekhawat K, Rathore SS, Chauhan BS (2020) Weed management in dry direct-seeded rice: a review on challenges and opportunities for sustainable rice production. Agron J 10:1264

Shell GSG, Lang ARG (1976) Movements of sunflowers leaves over a 24-h period. Agricult Meteorol 16:161-170

Smith RJ Jr. (1998) Weed thresholds in southern U.S. rice, *Oryza sativa*. Weed Technol 2:232-241

Sparks OC, Barrentine JL, Burgos NR, McClelland MR (2003) Effect of Palmer amaranth (*Amaranthus palmeri*) seedbank density on the performance of pendimethalin and fluometuron. Summaries of Arkansas Cotton Research 2003. AAES Research Series 521:167-172

Steckel LE, Sprague CL, Hager AG, Simmons FW, Bollero GA (2003) Effects of shading on common waterhemp (*Amaranthus rudis*) growth and development. Weed Sci 51:898-903

Swanton CJ, Nkoa R, Blackshaw RE (2015) Experimental Methods for Crop-Weed Competition Studies. Weed Sci Special Issue:2-11

Wang JL, Klessig DF, Berry JO (1992) Regulation of C4 gene expression in developing amaranth leaves. Plant Cell 4:173-184

Ward SM, Webster TM, Steckel LE (2013) Palmer amaranth (*Amaranthus palmeri*): a review. Weed Technol 27:12-27

Wu G, Wilson LT, McClung AM (1998) Contribution of rice tillers to dry matter accumulation and yield. Agron J 90:317-323

Zimdahl RL (1980) Weed-Crop Competition: A Review: International Plant Protection Center. Corvallis, OR: Oregon State University. 196 p

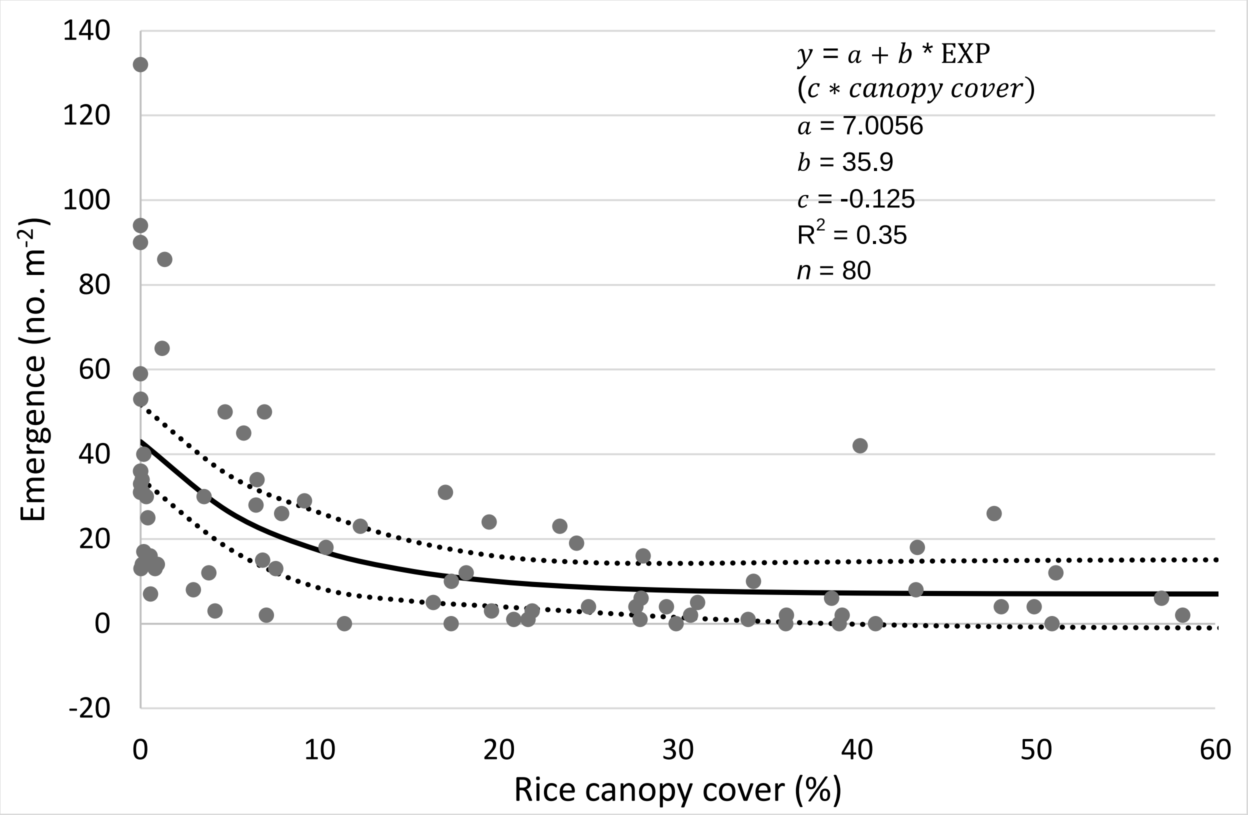

Figure 1. Three-parameter exponential model $[y = a + b * \exp(c * rice\ \text{canopy cover})]$, where a = asymptote (P = 0.0916), b = scale (P < 0.0001), and c = growth rate (P = 0.0427), to determine the relationship between *Amaranthus palmeri* emergence 5 weeks after emergence (WAE) and beyond and rice canopy cover at 5 WAE. The solid line represents the fit of the exponential 3P model, and the dotted lines represent the 95% confidence interval of the fitted line.

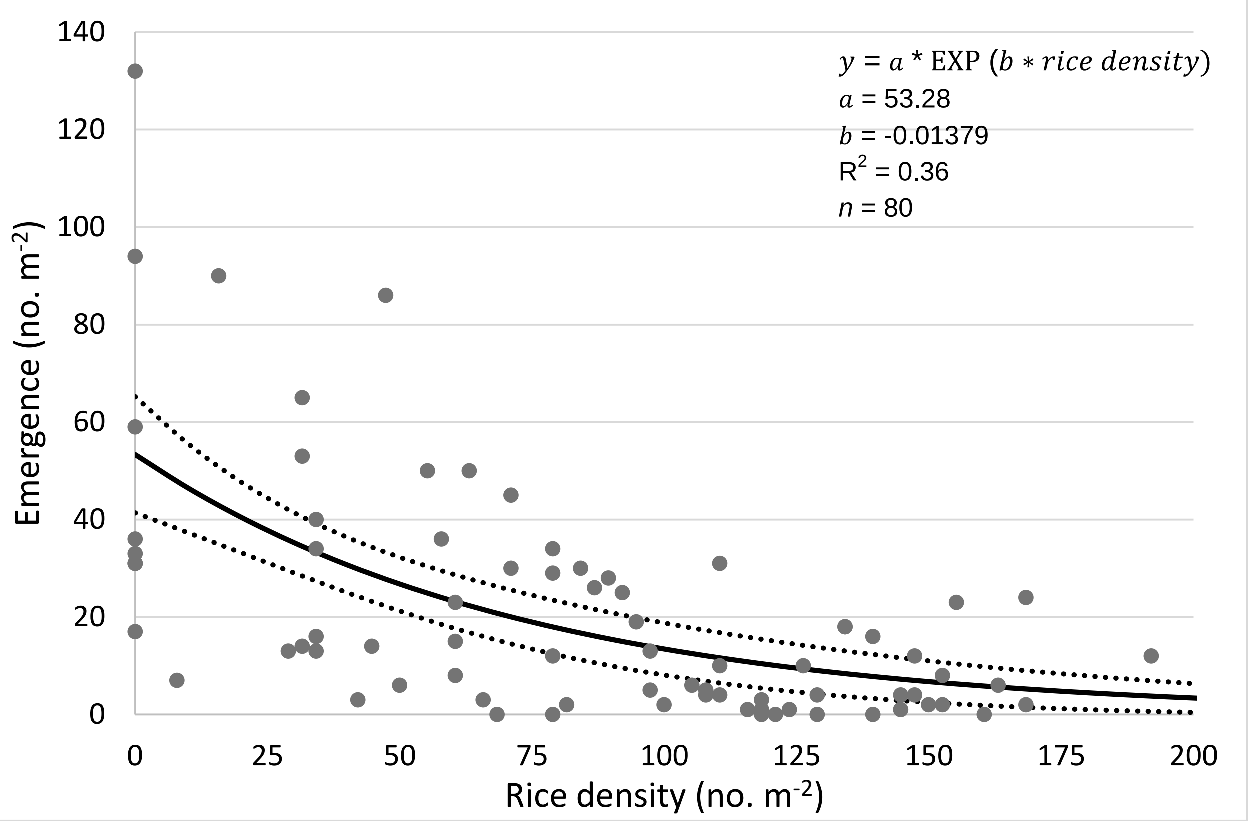

Figure 2. Two-parameter exponential model [$y = a * \exp(b * rice$ density)], where a = scale ($P < 0.0001$) and b = growth rate ($P < 0.0001$) to determine the relationship between *Amaranthus palmeri* emergence 5 weeks after crop emergence and beyond and rice density. The solid line represents the fit of the exponential 2P model, and the dotted lines represent the 95% confidence interval of the fitted line.

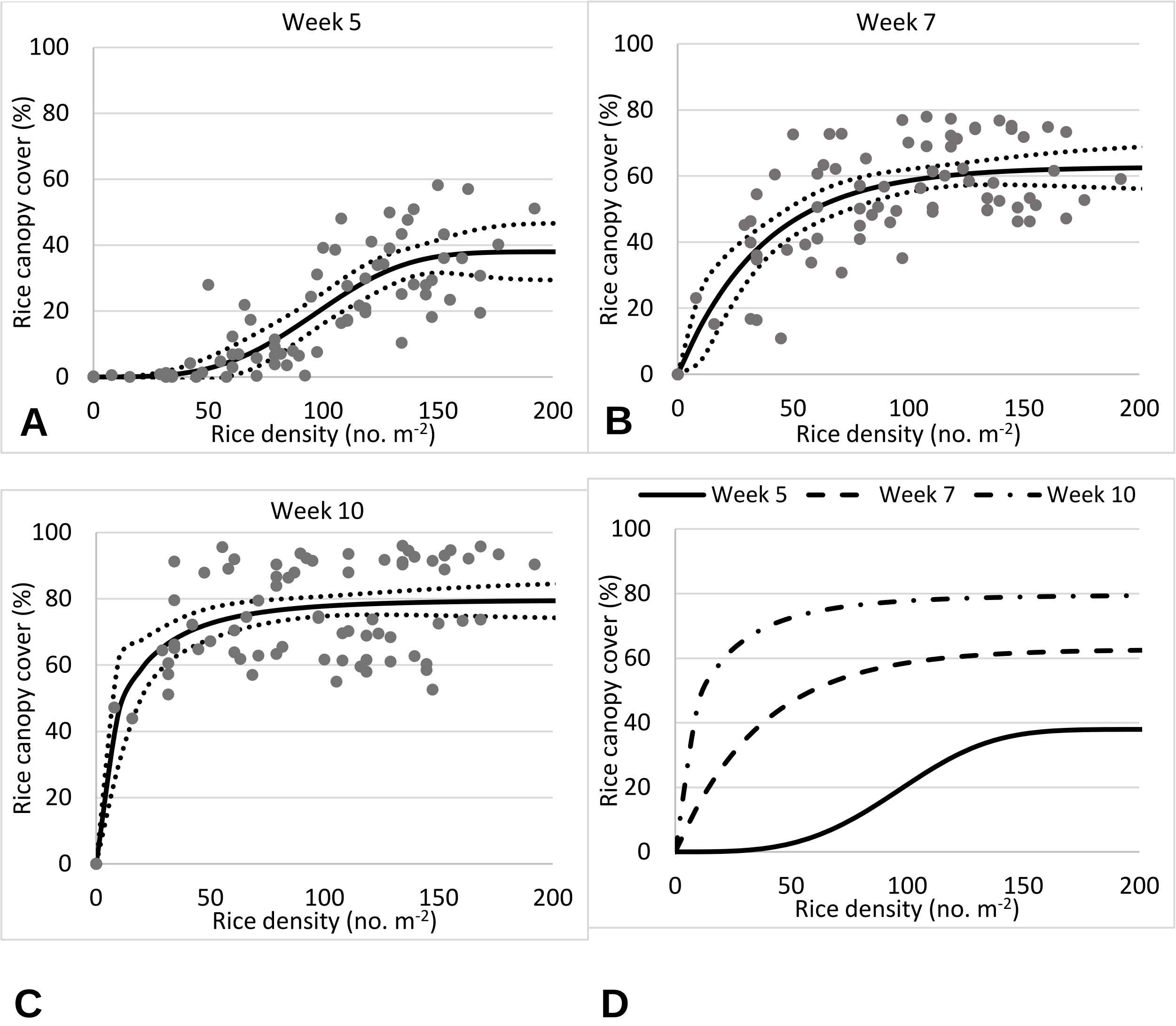

Figure 3A-D. Weibull growth curve $\left(y = a * \left(1 - \exp\left(-\left(\frac{rice\ density}{b}\right)^{c}\right)\right)\right)$, where a = asymptote, b = inflection point, and c = growth rate, to estimate rice canopy cover as a function of rice density at 5, 7, and 10 weeks after emergence ($P < 0.0001$). Figures 3A-C show the individual prediction line for each canopy cover assessment and corresponding 95% confidence interval, highlighted by the solid and dotted line, respectively. Figure 3D displays the predicted lines of the entire model.

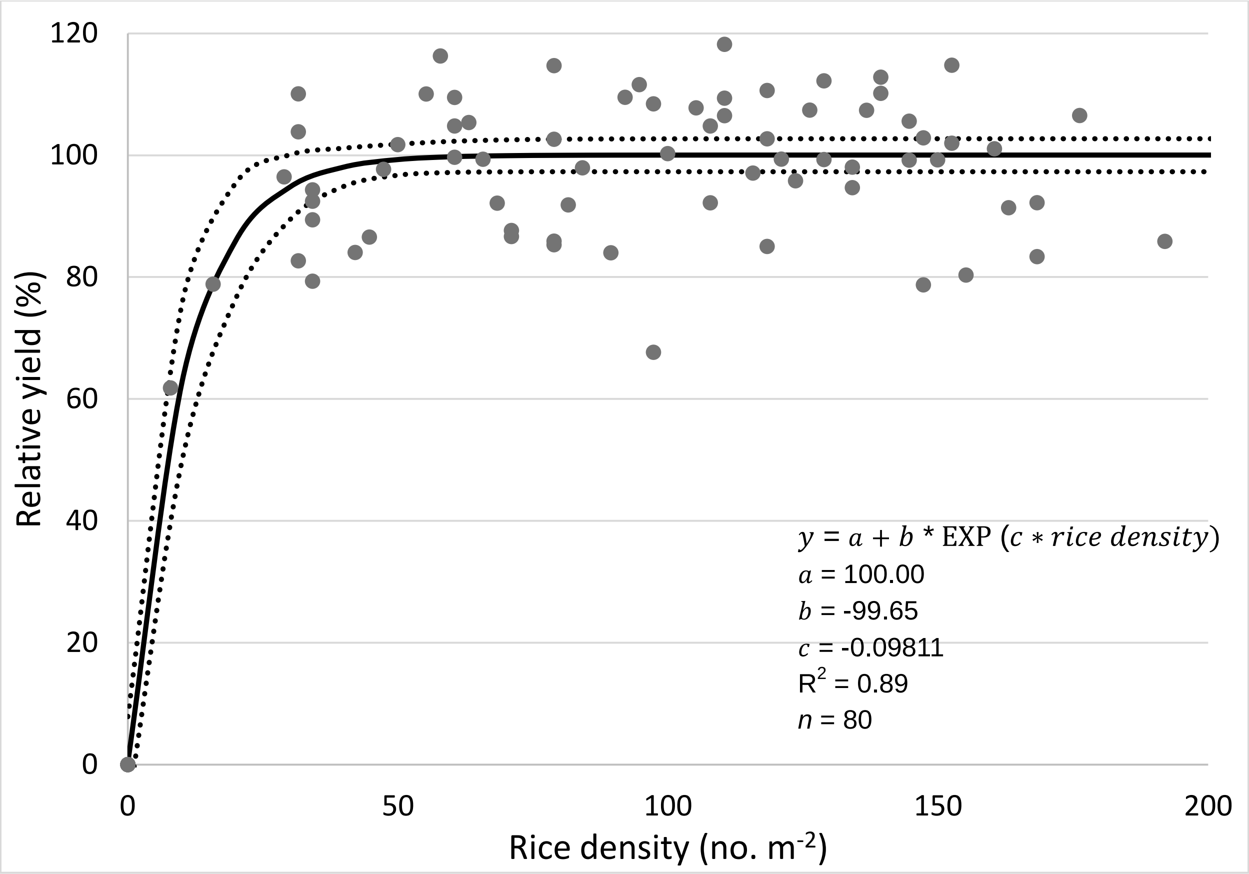

Figure 4. Three-parameter exponential model $[y = a + b * \exp(c * rice\ \text{density})]$, where a = asymptote ($P < 0.0001$), b = scale ($P < 0.0001$), and c = growth rate ($P < 0.0001$), to predict relative rice yield as a function of rice density. The solid line represents the fit of the exponential 3P model, and the dotted lines represent the 95% confidence interval of the fitted line.

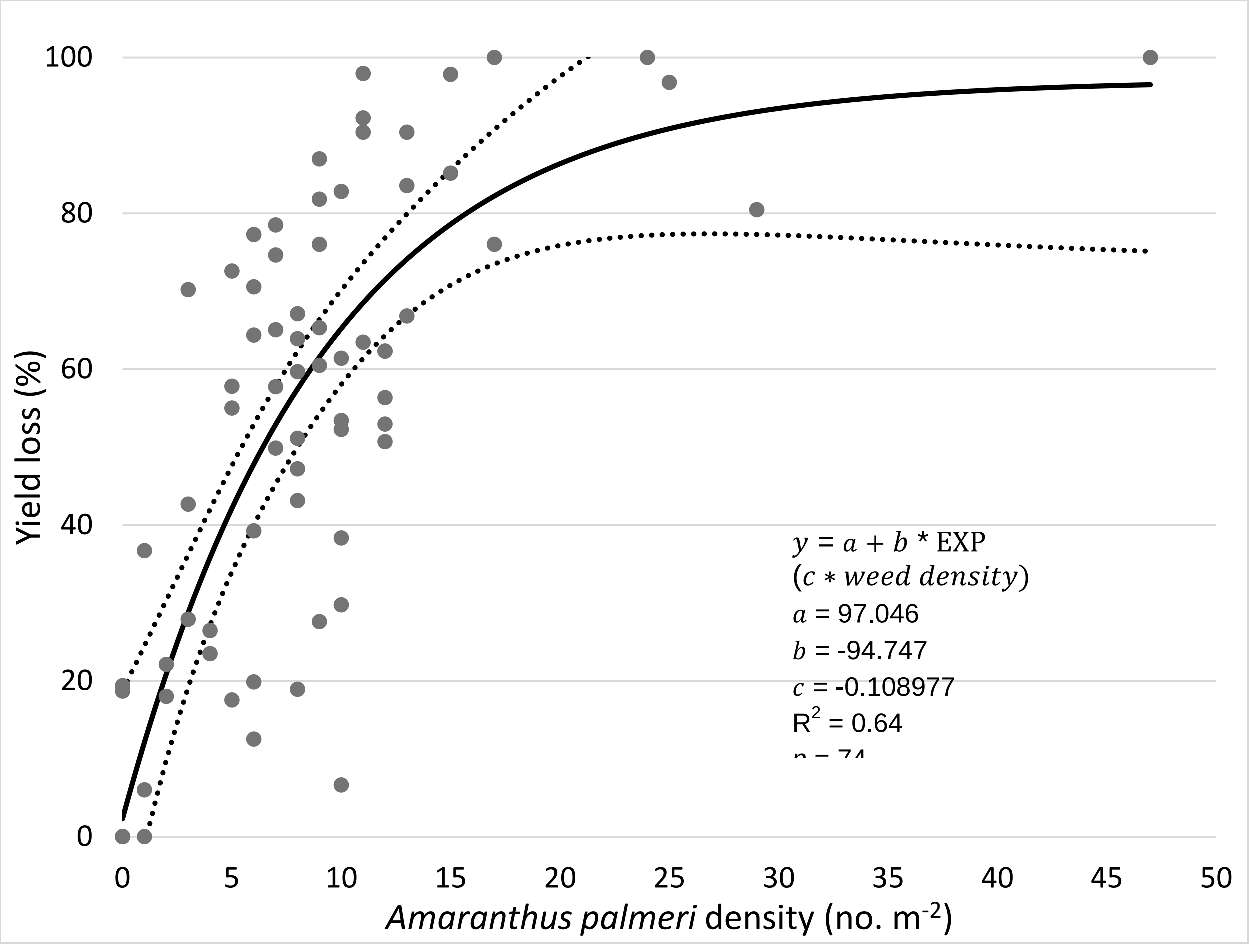

Figure 5. Three-parameter exponential model $[y = a + b * \exp(c * weed\ \text{density})]$, where a = asymptote ($P < 0.0001$), b = scale ($P < 0.0001$), and c = growth rate ($P < 0.0001$), to estimate rice yield loss as a function of *Amaranthus palmeri* density. The solid line represents the fit of the exponential 3P model, and the dotted lines represent the 95% confidence interval of the fitted line.

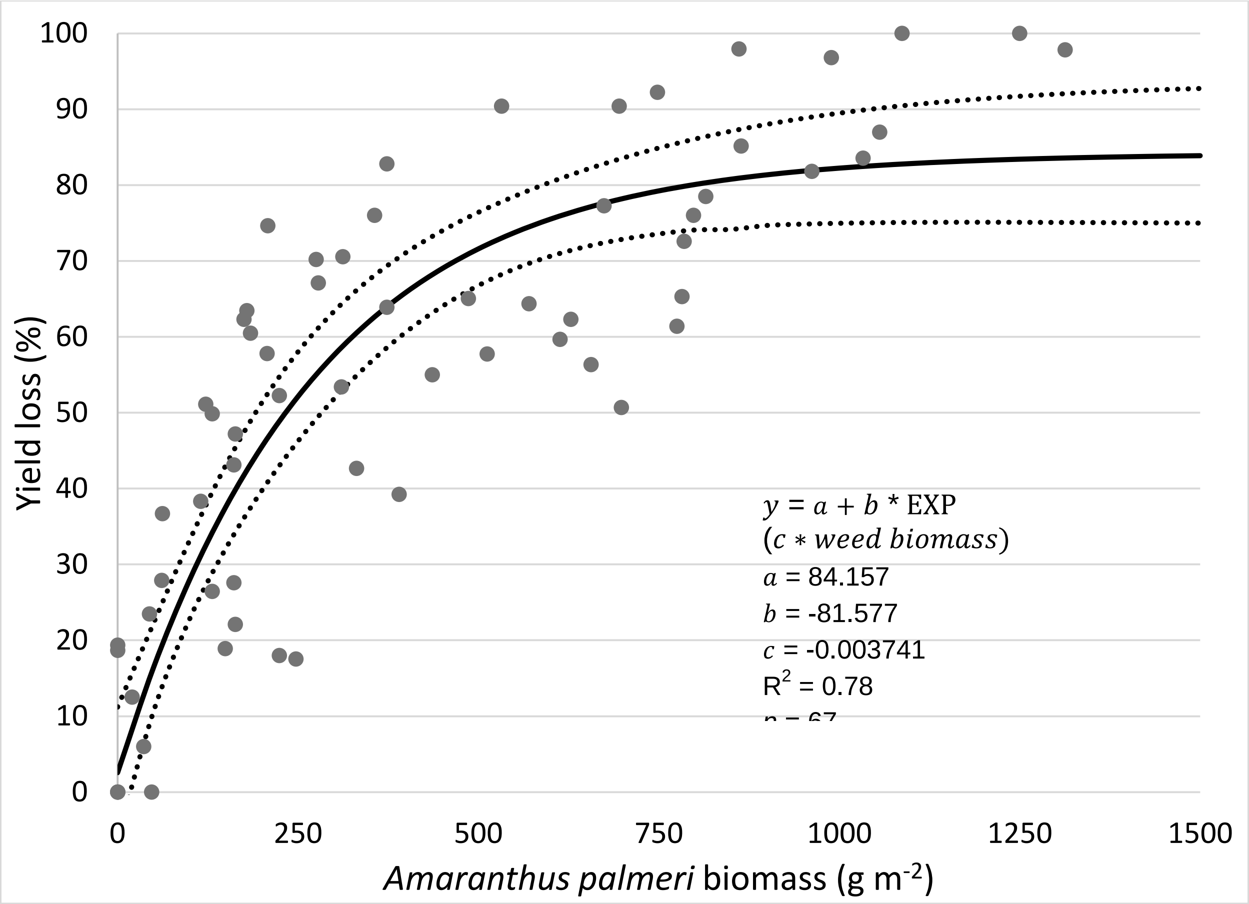

Figure 6. Three-parameter exponential model $[y = a + b * \exp(c * weed \text{ biomass})]$, where a = asymptote ($P < 0.0001$), b = scale ($P < 0.0001$), and c = growth rate ($P < 0.0001$), to predict rice yield loss as influenced by *Amaranthus palmeri* aboveground biomass. The solid line represents the fit of the exponential 3P model, and the dotted lines represent the 95% confidence interval of the fitted line.

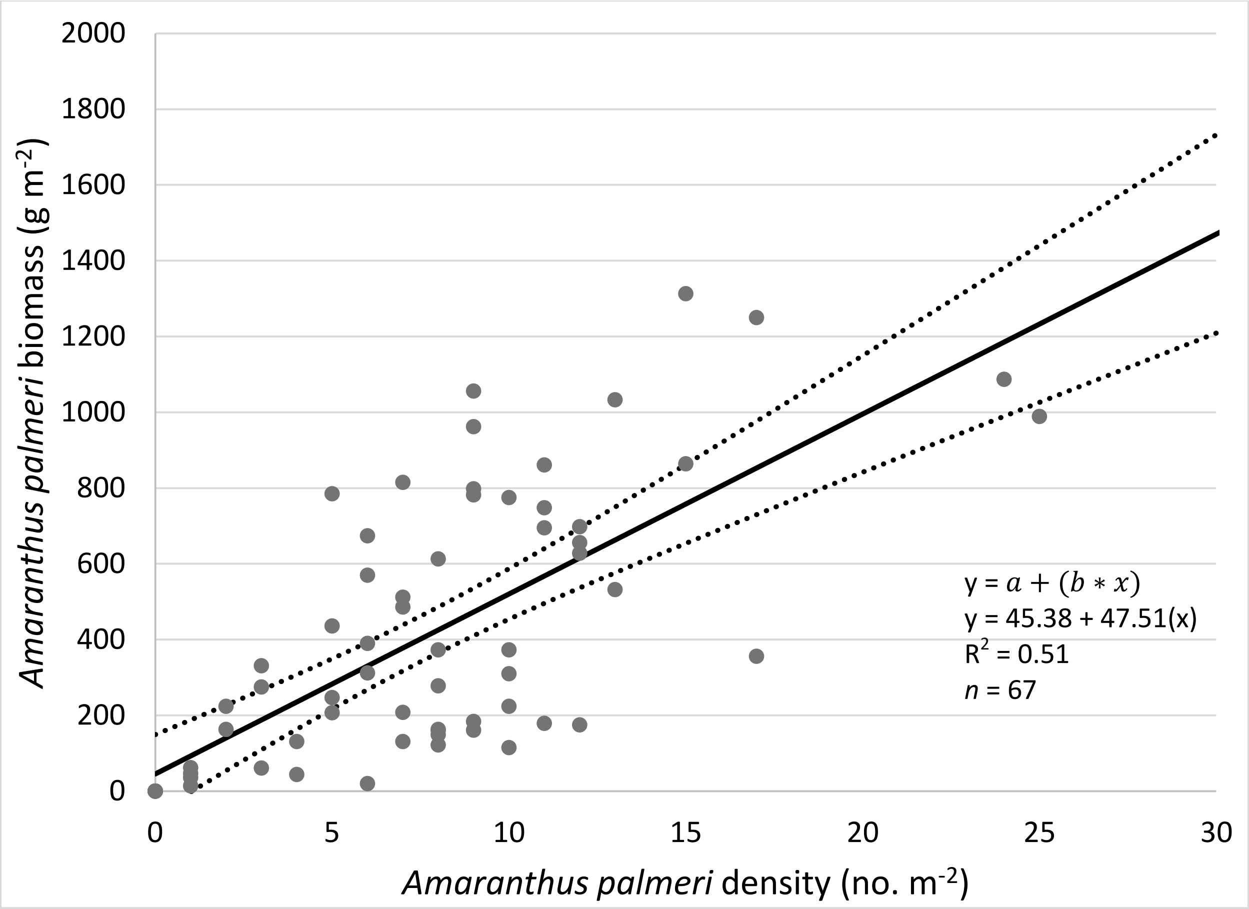

Figure 7. Relationship between *Amaranthus palmeri* biomass and *A. palmeri* density. The solid line represents the fit of the linear regression model ($P < 0.0001$), and the dotted lines represent the 95% confidence interval of the fitted line. R^2 value displays the percentage of variability explained by the fit of the line.