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DOI: 10.1017/wsc.2024.102

Short Title: Pigweed interference in rice

Effect of Palmer amaranth (*Amaranthus palmeri*) Time of Emergence on Furrow-Irrigated Rice Yields and Weed Seed Production

Tanner A. King[1], Jason K. Norsworthy[2], Thomas R. Butts[3], Samuel B. Fernandes[4], Gerson L. Drescher[5], and Tristen H. Avent[6]

Affiliations: [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; [6]Graduate Research Assistant, 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

Furrow-irrigated rice (*Oryza sativa* L.) hectares are increasing in the Midsouth. The lack of sustained flooding creates a favorable environment for weed emergence and persistence, which makes Palmer amaranth (*Amaranthus palmeri* S. Watson) difficult to control throughout the growing season. The negative yield impacts associated with season-long *A. palmeri* interference in corn, cotton, and soybean have been evaluated. However, there is limited knowledge of the weed's ability to influence rice grain yield. Research was initiated in 2022 and 2023 to determine the effect of *A. palmeri* time of emergence relative to rice on weed seed production and grain yield. Cotyledon stage *A. palmeri* plants were marked every seven days, beginning one week before rice emergence through four weeks after rice emergence. *Amaranthus palmeri* seed production decreased exponentially as emergence timing was delayed relative to rice, and seed production increased by 447 seed plant^{-1} for every one-gram increase in weed biomass. Without rice competition and from the earliest emergence timing, *A.palmeri* produced 540,000 seeds plant^{-1}. *Amaranthus palmeri* that emerged one week before the crop had the greatest spatial influence on rice, with grain yield loss of 5% and 50% at a distance of 1.4 m and 0.40 m from the weed, respectively. As *A. palmeri* emergence was delayed, the area of influence decreased. However, *A. palmeri* plants emerging 3.5 weeks after rice emergence still negatively affected grain yield and produce sufficient seed to replenish the soil seedbank, potentially impacting long-term crop management decisions. These results show that the time of *A. palmeri* emergence is a crucial factor influencing rice grain yield and weed seed production, which can be used to determine the consequences of escapes in rice.

Key words: competition; influence; interference; seed bank

https://doi.org/10.1017/wsc.2024.102 Published online by Cambridge University Press

Introduction

For decades, *A. palmeri* has ranked among the most troublesome and common weed species in most southern row crop production systems (Norsworthy et al. 2014; Van Wychen 2020; Webster and Nichols 2012). The pernicious effects of *A. palmeri* are a result of its high competitiveness with the crop for available resources, rapid growth rate, and prolific seed production (Chandi et al. 2012; Horak and Loughin 2000). With a prolonged emergence period that aligns with most row crop production systems and noteworthy growth rate when in competition for available resources, *A. palmeri* can accumulate sufficient aboveground biomass to interfere with crop development substantially (Bell et al. 2015; Jha and Norsworthy 2009; Klingaman and Oliver 1994; Mahoney et al. 2021). As a result, negative yield impacts associated with the season-long survival of *A. palmeri* have been well documented in corn (*Zea mays* L.) (Chahal et al. 2015; Massinga et al. 2001), cotton (*Gossypium hirsutum* L. (MacRae et al. 2013; Norsworthy et al. 2016a), and soybean [*Glycine max* (L.) Merr.] (Klingaman and Oliver 1994). However, the competitive ability of *A. palmeri* is not restricted to the growing season in which it emerges because its high fecundity can affect management strategies in future years due to sufficient replenishment of the soil seedbank (Schwartz et al. 2016).

To understand the impact of *A. palmeri* on crop yields, it is important to recognize the interactions between the crop and weed at developmental stages, which will also ensure successful crop management (Myers et al. 2004). Crop yield loss is primarily influenced by weed density and interspecific interference between two species (Shekhawat et al. 2020; Smith et al. 1997). Additionally, the timing of weed emergence relative to the crop is a critical factor affecting yield loss and is the most vital component in crop-weed interactions (Knezevic et al. 1994; Kropff and Spitters 1991; Swanton et al. 2015). Thus, successful and timely weed management strategies can be applied with awareness of weed biology and establishment time relative to the crop (Korres et al. 2017; Wyse 1992).

Traditionally, *A. palmeri* has not been a problematic weed in conventional flood-irrigated rice production systems due to the continual flood acting as a weed suppression mechanism for most terrestrial weeds (Bagavathiannan et al. 2011). However, a non-flooded, furrow-irrigated rice production system has increased prominence by more than 18-fold since 2015 (Hardke et al. 2022). As a result, new weed control challenges emerge due to furrow-irrigated rice production practices being comparable to those associated with cotton, soybean, and corn production

(Norsworthy et al. 2008; Norsworthy et al. 2011). In a furrow-irrigated system, *A. palmeri* is problematic throughout the entirety of the growing season due to the aerobic conditions providing a conducive environment for weed emergence, which makes weed management increasingly problematic (Beesinger et al. 2022; Norsworthy et al. 2008; Norsworthy et al. 2011).

A 2020 survey of Arkansas rice producers and consultants showed that *A. palmeri* was the 5th and 2nd most problematic weed in flood- and furrow-irrigated rice, respectively (Butts et al. 2022). The problematic nature of *A. palmeri* in a furrow-irrigated rice systems can cause herbicide expenditures to be elevated if left uncontrolled throughout the growing season (Bagavathiannan et al. 2011; Barber et al. 2021). Additionally, *A. palmeri* has evolved resistance to many previously effective preemergence and postemergence rice herbicides (Norsworthy et al. 2016b). Therefore, growers must utilize a well-rounded approach that includes chemical, cultural, biological, and mechanical control methods to reduce weed infestations and focus on controlling *A. palmeri* early in the year (DeVore et al. 2013; Harker and O'Donovan 2013).

The primary goal when creating management strategies for controlling *A. palmeri* is to prevent weed seed production and the potential for herbicide resistance spread (Shekhawat et al. 2020). With *A. palmeri* having the innate ability to emerge over an extended period, effective weed management is crucial during the summer months (Jha and Norsworthy 2009). Although an economic threshold approach has been considered for some weeds (Jones and Medd 2000), researchers have recommended a "zero-tolerance" approach for *A. palmeri* because of its potential to spread over the landscape quickly (Barber et al. 2015; Norsworthy et al. 2014). Therefore, it is crucial to not rely on chemical applications alone for controlling *A. palmeri* due to herbicide resistance and lack of control under optimal climatic conditions (Bagavathiannan and Norsworthy 2012; Butts et al. 2022).

In Arkansas, soybean is commonly rotated with rice due to the convenient implementation of herbicide programs that target troublesome monocot weeds in a dicot crop (Burgos et al. 2008; Burgos et al. 2021; Nalley et al. 2022). With *A. palmeri* being among the most problematic weed species in Arkansas soybean, flood-irrigated rice tended to reduce the soil seedbank because of the weed's inability to survive anaerobic conditions (Beesinger et al. 2022; Riar et al. 2013). With the increased popularity of furrow-irrigated rice and widespread herbicide-resistant weed species across both cropping systems, *A. palmeri* infestations are likely

https://doi.org/10.1017/wsc.2024.102 Published online by Cambridge University Press

to occur each year, which may lead to increased soil seedbank inputs (Butts et al. 2022; Norsworthy et al. 2013). However, rice production systems have not quantified *A. palmeri* interference and seed production. Therefore, this research aimed to (1) evaluate the impact of *A. palmeri* interference on rice growth and yield and (2) assess *A. Palmeri* biology in response to competition with rice.

Materials and Methods

Amaranthus palmeri Area of Influence in Furrow-Irrigated Rice

A field experiment was conducted in 2022 and 2023 at the Milo J. Shult Agriculture Research and Extension Center in Fayetteville, Arkansas, to determine the impact of *A. palmeri* emergence time relative to rice on *A. palmeri* seed production and rice grain yield in a furrow-irrigated system. The experiment was set up as a completely randomized design, and the experimental area was ~0.10 hectares. *Amaranthus palmeri* emergence was random and could not be blocked, but management thereafter was controlled. In both site years, the soil was a Leaf silt loam composed of 18% sand, 69% silt, 13% clay, and 1.6% organic matter with a pH of 6.6. Before rice planting, the fields were disked, tilled, and hipped into 91-cm wide beds. The soil was amended for fertility before planting based on the University of Arkansas System Division of Agriculture Marianna Soil Test Lab fertility recommendations (Roberts et al. 2018). Additionally, the entire experimental area in both years was over-sprayed with clomazone (Command 3ME, FMC corporation, Philadelphia, PA 19104) at 336 g ai ha^{-1} before planting to minimize the occurrence of annual grasses. All herbicide applications were made with a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} at 276 kPa using four AIXR 110015 (TeeJet Technologies, Glendale Heights, IL) nozzles at 4.8 km hr^{-1}.

On April 17, 2022, a hybrid long-grain cultivar ‘RT 7301’ (RiceTec Inc., Alvin, TX 77512) was planted at 36 seeds m^{-1} of row at a 1-cm depth in a 19-cm row spacing and on April 22, 2023, a hybrid long-grain cultivar ‘Full Page RT 7321FP’ (RiceTec Inc., Alvin, TX 77512) was sown using the same planting methods. Rice emerged on May 9 and May 8 in 2022 and 2023, respectively. Within each trial, a natural population of *A. palmeri* was allowed to germinate and emerge throughout the growing season. The experiment consisted of six *A. palmeri* emergence timings, beginning one week before rice emergence to four weeks after. At each emergence timing, ten cotyledon stage *Amaranthus palmeri* plants were marked randomly and considered as replications within the experiment. There were 129, 123, 110, 64, and 54 replications for week -1, week 0, week 1, week 2, and week 3-4 evaluation timings, respectively. To reduce competition from adjacent weeds, each marked plant was at least 5 m from one another. At each evaluation, the marked *A. palmeri* plants were covered with buckets, and the trial was over-sprayed with propanil (STAM, UPL, King of Prussia, PA 19406) at 4,486 g ai ha^{-1} to remove unwanted weed species while still allowing new *A. palmeri* plants to emerge. Once the rice reached the V5 growth stage, the trials were irrigated using standard furrow-irrigated rice methods, and nitrogen, as urea (460 g N kg^{-1}), was applied at a total of 135 kg N ha^{-1} in three separate applications at two-week intervals (Barber et al 2021).

At rice harvest, the height of each surviving *A. palmeri* plant was recorded. Additionally, each *A. palmeri* plant was cut at the soil surface, bagged, dried at 66 C for two weeks to constant mass, and dry biomass was recorded. Each female plant was then threshed, and the residual material was separated from the seeds using a 20-mesh sieve and a vertical air column seed cleaner (Miranda et al. 2021). After cleaning, 200 seeds were counted and weighed from three plants at each emergence timing, and the average weight of the subsamples were divided by the total weight of seed for each plant in order to quantify the total seed produced. Rice grain yield was collected using rice sickles. A square ladder was made from a polyvinyl chloride (PVC) pipe measuring 2.4 m long, and quadrats within the ladder were 0.30 m wide by 0.30 m long and were used for portioning rice grain into 8 sections radiating in two directions from the center of the *A. palmeri* (Figure 1). After removing the *A. palmeri* plants in the field, the center of the first quadrat was placed directly on top of the origin where the weed emerged. Rice panicles were harvested by hand in each quadrat in opposite directions and later averaged to determine rice yield loss as a function of distance from the weed. The rice panicles were threshed using an Almaco small bundle thresher (Almaco, Nevada, IA 50201), and weighed to calculate yield in each quadrat for each marked *A. palmeri* plant. After obtaining the weight of rice in each quadrat, three random quadrat samples were combined and inserted into a DICKEY-john® mini GAC™ 2500 portable grain moisture analyzer (DICKEY-john, Auburn, IL 62615) to obtain an average moisture content. Rice yields from each quadrat were then adjusted to 12% moisture.

Statistical Analysis

All data were analyzed in JMP Pro 17.0 (SAS Institute Inc., Cary, NC). Regression analysis was used to quantify *A. palmeri* interference in furrow-irrigated rice as a function of time of emergence relative to the crop. Since two different rice hybrids were planted in separate years, a three-parameter logistic model (Logistic 3P) curve was fit by year to determine the maximum yield potential for each rice cultivar, which helped account for year-to-year variation. The initial exploratory analysis included Probit, Gompertz, Weibull, and Logistic curves, with the logistic 3P (Eq. 1) having the lowest Akaike information criterion (AIC) of 8598.25,

[1] $Maximum\ Yield\ Potential = \frac{Asymptote}{\{1+Exp[-Growth\ rate \times (Distance - Inflection\ point)]\}}$

where yield (kg ha^{-1}) is the dependent variable; asymptote, growth rate, and inflection points are the parameters; and distance (m) from the *A. palmeri* plant is the independent variable. Parameters to fit the logistic 3P curve can be found in Table 1. The model included male and female *A. palmeri* plants after determining that gender did not influence rice yield loss based on all model parameters not being statistically different at $\alpha = 0.05$ (data not shown). The maximum yield in each year was based on the asymptote of the model with hybrids 'RT 7301' and 'RT 7321 FP' reaching a maximum yield potential of 8,700 and 10,600 kg ha^{-1}, respectively.

After maximum yield potential determination, the rice grain yield of each quadrat was made relative to this potential within each year. To determine rice yield loss (%) as a function of distance from the *A. palmeri* plants, two- and three-parameter curves were fit within the Fit Curve platform in JMP with *A. palmeri* time of emergence relative to rice as a grouping variable. The three-parameter exponential decay (Exponential 3P) model (Eq. 2) achieved the lowest AIC and an $R^2 = 0.63$

[2] $Relative\ yield\ = Asymptote + Scale\ \times Exp(Growth\ rate\ \times Distance)$

where yield loss is the dependent variable; asymptote, scale, and growth rate are parameters; and the distance in meters is the independent variable (Figure 2). Parameter estimates for the exponential 3P decay model can be found in Table 2. Inverse predictions were made for the distance in meters required from *A. palmeri* plants to observe 5% and 50% yield loss for each time of emergence relative to rice (Table 3). Prediction estimates were compared using mean 95% confidence intervals. Relative grain yield and *A. palmeri* data were combined over site years to increase the number of observations and provide a stronger prediction estimate. Additionally, relative yield and weed data were pooled for *A. palmeri* plants emerging three and four weeks after the crop to make 3.5 weeks due to mortality of some plants and few observations at three and four weeks than at earlier emergence times. The increased number of observations also allowed for more accurate predictions.

https://doi.org/10.1017/wsc.2024.102 Published online by Cambridge University Press

A linear regression model was utilized to fit *A. palmeri* seed production per female plant by *A. palmeri* biomass per female plant (Norsworthy et al. 2016) using the Fit Curve platform in JMP Pro 17 (Eq. 3) (Figure 3).

[3] $Y = a + bX$

where Y is the dependent variable (seed production per female *A. palmeri* plant), b is the slope of the line, X is the independent variable (*A. palmeri* biomass per female plant), and a is the intercept when X is equal to zero. There was also a nonlinear relationship between *A. palmeri* seed production per female plant and *A. palmeri* time of emergence relative to the crop; therefore, a two-curve exponential decay (Exponential 2P) model (Eq. 4) was used to fit the relationship, considering it produced the lowest AIC and an $R^2 = 0.55$ (Figure 4).

[4] $Y = Scale \times EXP\ (Growth\ Rate \times Emergence)$

where Y is the dependent variable (seed production plant^{-1}), scale and growth rate are parameters, and *A. palmeri* emergence timing relative to rice is the explanatory variable.

Results and Discussion

Impact of Amaranthus palmeri on Furrow-Irrigated Rice Yields

Maximum rice yield potential was statistically higher in 2023 than in 2022 based on the 95% confidence intervals not overlapping for the asymptote and inflection point model parameters; however, the growth rate parameter estimate was similar for both site years, indicating that yield loss responses were consistent for both years of the experiment (Table 1). Maximum yield potential differences are attributed to the genetics of the two rice hybrids and environmental differences between years (JKN, personal communication). When the week of emergence was considered within the model, the relationship between rice yield loss and distance from the *A. palmeri* plant accounted for 62.7% of the variation in rice yield loss. Additionally, differences occurred between the week of *A. palmeri* emergence relative to rice and rice yield loss as a function of distance from the weed (Figure 2F).

Regardless of when *A. palmeri* emerged relative to the crop, rice yield loss was > 50% within 0.15 m from the weed (Figure 2A-F). These results are opposite of those observed by Bensch et al. (2003), who reported that soybean yield loss was not affected by *A. palmeri* emerging within 15 cm of the crop 19 to 38 days after planting. However, these results likely differ due to variations in crop row spacing between planting methods and subsequent proximity to *A. palmeri* plants. Nevertheless, there was a reduction in rice yield loss as distance increased from the *A. palmeri* plant, and when weed emergence was delayed relative to the crop (Figure 2A-F).

Rice yield loss was most severe when *A. palmeri* emerged one week before the crop, which captures a worst-case scenario for a producer in the event a burndown application fails to control all weeds before planting. At this time, inverse predictions estimate rice yield loss to be 50% and 5% at distances of 0.40 m (+/- 0.03 m) and 1.4 m (+/- 0.16 m) from *A. palmeri*, respectively (Table 3). Based on the model predicting 5% or more rice yield loss, the crop was negatively affected in the 6.2 m^2 surrounding each *A. palmeri* plant (π x 1.40^2). Weeds that emerged 3.5 weeks after rice was predicted to cause 50% and 5% yield loss at distances of 0.17 m (+/- 0.03 m) and 0.63 m (+/- 0.13 m), a ~5-fold reduction in area where rice yield was negatively affected compared to *A. palmeri* emerging before rice. A single *A. palmeri* emerging within three to four weeks of rice emergence has the potential to impact at least 1.2 m^2 of rice, assuming a 95% yield preservation. These results show that *A. palmeri* emerging 3 to 4 weeks after rice must be removed from the crop to prevent rough rice yield loss. It should be noted that these results are from a scenario where no additional control measures are taken once *A. palmeri* emerged; hence, future research should investigate the effect of different removal timings and the subsequent influence on rice yield.

Amaranthus palmeri generally had a greater influence on rice yield when emergence coincided with rice (Figure 2A). These results display the effect of early-emerging *A. palmeri* on rice yields and the extent to which the weed can effectively compete with the rice crop for available resources. Additionally, *A. palmeri* that emerged 3.5 weeks after rice still caused significant yield losses, which was supported by Massinga et al. (2001), who observed a 7% reduction in corn yield from 0.5 *A. palmeri* plants m^{-1} of row emerging at the seven-leaf growth stage of the crop. One factor that could influence the ability of *A. palmeri* to negatively impact rice yields is its C4 photosynthetic pathway and rapid root augmentation (Black et al. 1969; Massinga et al. 2003; Wiese 1968); however, additional research is needed to confirm the effect of specific yield-limiting characteristics of *A. palmeri* in a furrow-irrigated rice system.

Amaranthus palmeri Seed Production as Influenced by Weed Biomass

Results of the linear regression model indicate that *A. palmeri* seeds $plant^{-1}$ had a positive relationship with the dry weight of each female plant across all emergence timings and both site years (Figure 3). Previous research in other crops has identified a strong relationship between *A.*

https://doi.org/10.1017/wsc.2024.102 Published online by Cambridge University Press

palmeri dry biomass plant^{-1} and seed production, indicating that weed seed set increases as *A. palmeri* weight increases (Mahoney et al. 2021; Schwartz et al. 2016; Spaunhorst et al. 2018). Seed production information may be useful in predicting the quantity of weed seed replenishment in the soil seedbank.

A one-gram increase in *A. palmeri* biomass plant^{-1} increased seed production by 447 seeds plant^{-1} up to a maximum of 2,500 g of dry biomass and 1.2 million seeds plant^{-1} (Figure 4). Similarly, Webster and Grey (2015) documented that *A. palmeri*, competing with cotton, produced 330 seeds for every gram increase in weed biomass. In general, weeds that emerge with or before the crop often produce more biomass relative to late emerging weeds (Korres et al. 2019), suggesting that seed production could be moderated if weed emergence was delayed until after the crop. The results of the previously mentioned studies and this research indicate a high fecundity potential for *A. palmeri* in rice; hence, there is an emphasis on preventing escapes and increases in soil seedbank (Norsworthy et al. 2012).

Amaranthus palmeri Seed Production as a Function of Time of Emergence

Across site years, *A. palmeri* seed production decreased exponentially as *A. palmeri* emergence relative to the crop was delayed, as described by the exponential 2P model (Figure 4). On average, *A. palmeri* emerging one week before rice produced 540,000 seeds plant^{-1}. These findings support other researchers who reported *A. palmeri* produced 446,000 to 613,000 seeds plant^{-1} without crop competition (Webster and Grey 2015; Keeley et al. 1987). *Amaranthus palmeri* seed production per plant was significantly reduced when the weed emerged simultaneously with rice, producing an average of 115,000 seeds plant^{-1}. Hence, as much as a 4-fold decrease in weed seed production occurred when there was interference between *A. palmeri* and rice (Figure 4).

Amaranthus palmeri fecundity did not differ among emergence dates 1, 2, and 3.5 weeks after rice emergence (Figure 4). However, *A. palmeri* emerging as late as 3.5 weeks after rice could still produce 500 seeds plant^{-1}, indicating that the weed can disperse sufficient seed to contribute to increases in the soil seedbank (Crow et al. 2015; Norsworthy et al. 2020). *Amaranthus palmeri* emerging ten weeks after cotton has been shown to produce up to 880 viable seeds plant^{-1} (Norsworthy et al. 2016). In general, *A. palmeri* seed production decreased as weed emergence was delayed relative to rice, indicating the competitive ability of the crop for limited resources. Although late-emerging *A. palmeri* can become less prolific, the offspring produced later in the season can still significantly contribute to the soil seedbank and potentially impact management strategies in subsequent years; hence, producers should not allow any *A. palmeri* to escape control, which supports the recommended "Zero Tolerance" threshold and aids in diminishing the seedbank (Norris 2007; Norsworthy et al. 2014).

Overall, no peer-reviewed publications quantify furrow-irrigated rice yield loss from season-long *A. palmeri* interference. Findings from this research support that the timing of *A. palmeri* emergence relative to the crop is important for determining yield loss (Chickoye et al. 1995; Knezevic et al. 1994; Massinga et al. 2021), but that rice yields are also greatly affected outside the immediate area of the weed. As herbicide options for control of *A. palmeri* become less available and furrow-irrigated rice hectares increase, developing an understanding of the weed's biological effects on rice yields will prove vital in incorporating successful weed management programs into a production system (Beesinger et al. 2022; Korres and Norsworthy 2017).

Based on the *A. palmeri* seed production data presented here, female *A. palmeri* plants that emerge three to four weeks after rice can still successfully contribute offspring to the soil seedbank (Figure 4). As a result, producers must focus on minimizing returns to the soil seedbank, which will subsequently help mitigate the additional emergence of *A. palmeri* seedlings in future growing seasons (Norris 2007; Webster and Grey 2015). Moreover, preventing *A. palmeri* from reaching reproductive maturity will require a combination of control measures throughout the growing season, including the use of residual preemergence herbicides, considering effective weed control options decline once weeds become established in a field (Jha and Norsworthy 2009; Webster and Grey 2015). As a result of the consequences of allowing *A. palmeri* to compete with rice throughout the growing season and the need to prevent weed seed dispersal at harvest, producers should place extreme emphasis on the "zero tolerance" approach regardless of when the weed emerges (Norsworthy et al. 2016a). Although not assessed in this study, the monetary losses associated with *A. palmeri* interference in furrow-irrigated rice are exacerbated when harvest efficiency and quality are negatively impacted and the economic impact of *A. palmeri* escapes in rice will extend well beyond the year in which plants are allowed to compete and produce seed.

Funding

This research received no specific grant from any funding agency, commercial or non-for-profit sectors.

Competing Interests

Competing interests: the authors declare none.

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https://doi.org/10.1017/wsc.2024.102 Published online by Cambridge University Press

Table 1. List of model parameters for the logistic 3P curve of yield (kg ha^{-1}) predicted by distance (m) from *Amaranthus palmeri* for each site year; R^2 value is present to display the percentage of variability explained by the model.

Year	Model parameters[a,b]			n	R^2
	Asymptote[c]	Inflection point	Growth rate		
2022	8,678	0.3062	5.688	241	0.63
95% C.I.[d]	(8,377, 8980)	(0.2560, 0.3563)	(4.110, 7.267)		
2023	10,592	0.3973	5.040	239	
95% C.I.	(10267, 10917)	(0.3551, 0.4395)	(4.000, 6.081)		

[a] All model parameters were significant χ^2 ($P < 0.0001$).

[b] Sigmoidal model and parameters determined using JMP Pro 17 with the Fit Curve Platform.

[c] Asymptote was used as the maximum yield potential for each site year.

[d] Abbreviations: C.I., confidence interval

https://doi.org/10.1017/wsc.2024.102 Published online by Cambridge University Press

Table 2. List of model parameters for the exponential 3P decay model of percent yield loss by distance from *Amaranthus palmeri* at each emergence timing; R^2 value is present to display the percentage of variability explained by the model.

	Model parameters[a]				
Emergence timing	Asymptote	Scale	Growth rate	n	R^2
Week -1	-0.1714	122.4752	-2.2879	129	0.63
P-value	0.9558	<0.0001	<0.0001		
Week 0[b]	0.1710	134.3482	-3.3137	123	
P-value	0.9458	<0.0001	<0.0001		
Week 1	-4.9869	111.3632	-2.1217	110	
P-value	0.1718	<0.0001	<0.0001		
Week 2	-3.0286	102.2000	-3.1168	64	
P-value	0.4033	<0.0001	0.0006		
Week 3-4	-5.0742	104.1803	-3.7269	54	
P-value	0.1713	<0.0001	0.0045		

[a] Exponential 3P decay model and parameters determined using JMP Pro 17 with the Fit Curve Platform.

[b] The week *Amaranthus palmeri* emerged simultaneously with rice.

Table 3. The predicted distance from *Amaranthus palmeri* to observe 5% and 50% yield loss at each *A. palmeri* emergence timing relative to rice.

Yield loss	Emergence	Predicted[a]	CI of mean[b]
%		distance (m)	lower, upper
5	Week -1	1.38*	(1.06, 1.70)
	Week 0[c]	1.00	(0.76, 1.25)
	Week 1	1.13	(0.93, 1.34)
	Week 2	0.81	(0.54, 1.09)
	Week 3-4	0.63*	(0.37, 0.88)
50	Week -1	0.39*	(0.33, 0.45)
	Week 0	0.30	(0.25, 0.34)
	Week 1	0.33	(0.28, 0.39)
	Week 2	0.21*	(0.15, 0.27)
	Week 3-4	0.17*	(0.11, 0.23)

[a] The distance, in meters, from *Amaranthus palmeri* to reach the predicted percent yield loss.

[b] Displays the 95% confidence limits of the distance required from *Amaranthus palmeri* to reach the predicted percent yield loss.

[c] The week *Amaranthus palmeri* emerged simultaneously with the rice crop.

* Shows the confidence limits of an emergence timing not overlapping with the week *Amaranthus palmeri* emerged with the crop at the same percent yield loss.

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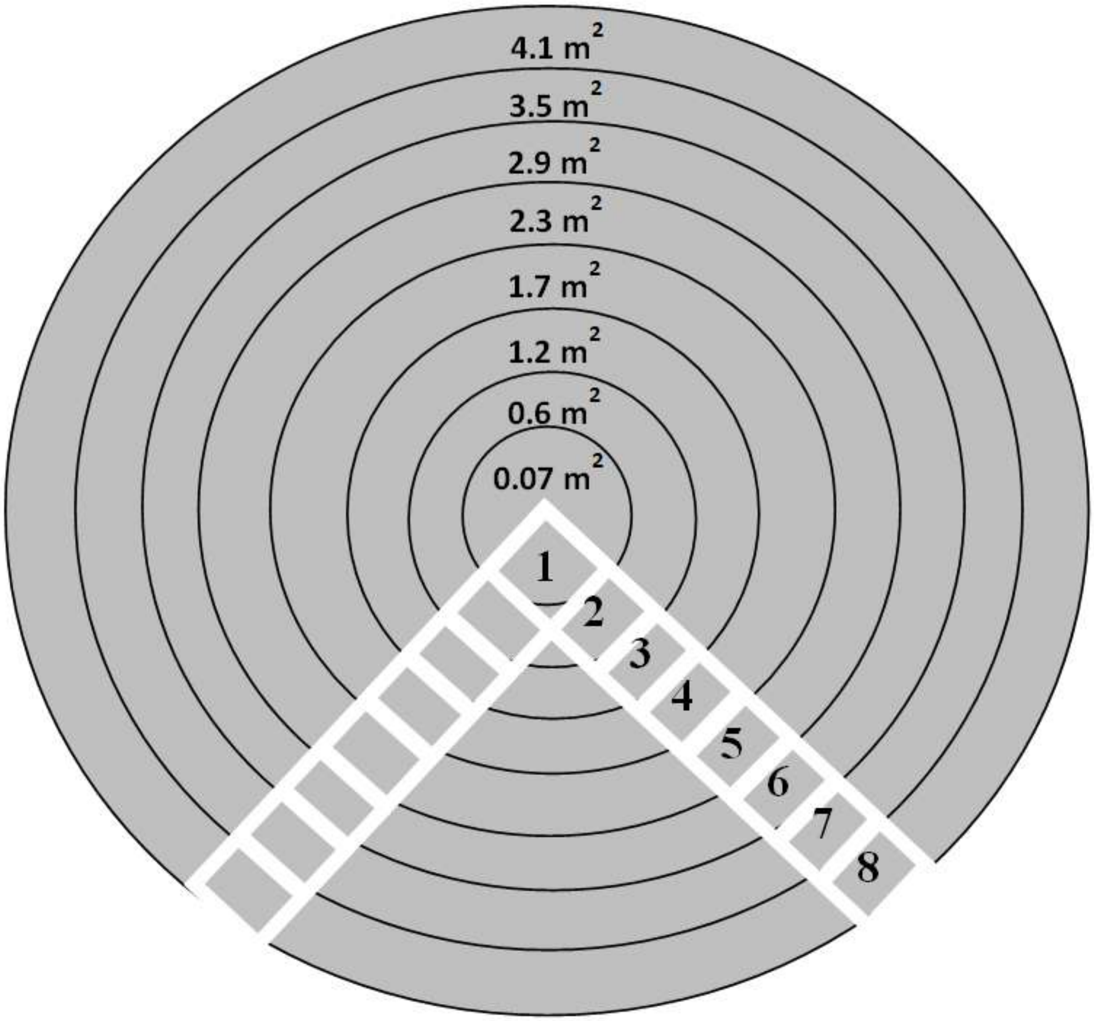

Figure 1. Rough rice yield collection as a function of distance from *Amaranthus palmeri* at each emergence timing relative to rice. The numbers inside the ladder represent each quadrant from which rice grain was collected. Quadrat one was not duplicated considering the ladder was only turned a different direction to obtain yield from a separate location.

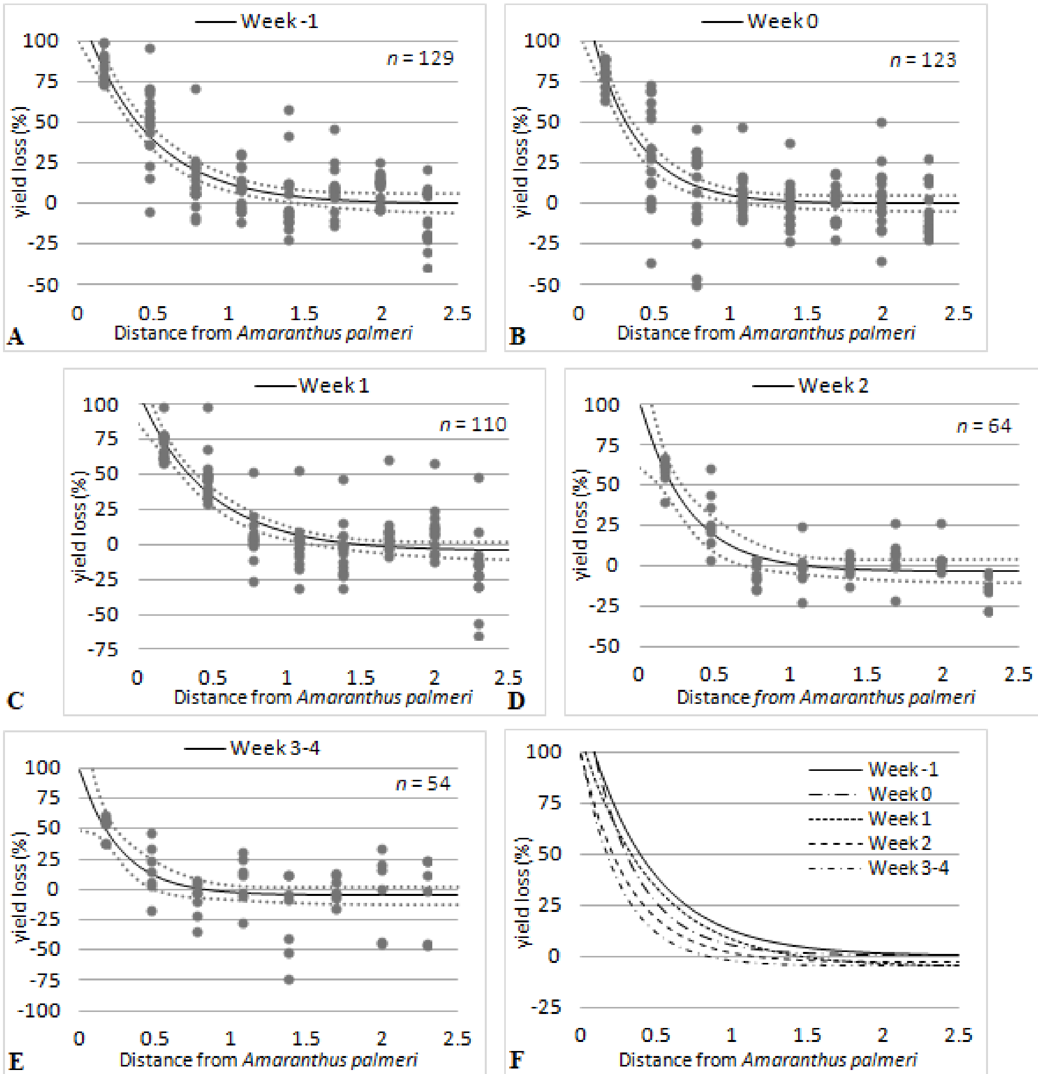

Figure 2A-F. Three-parameter exponential decay model [$y = a + b * \mathrm{EXP}\ (c * \mathrm{distance})$], where a = asymptote, b = scale, and c = growth rate, to determine yield loss data as a function of distance from *Amaranthus palmeri* in 2022 and 2023. Inverse predictions were made from the fitted lines giving an accurate representation of the required distance from *A. palmeri* to observe 5% and 50% rice yield loss (Table 3). Figures 3A-E show the individual predicted line for each weed emergence timing and corresponding 95% confidence interval, highlighted by the solid and dotted lines, respectively. Figure 3F displays the predicted lines of the entire model for the five emergence timings of *A. palmeri* relative to rice.

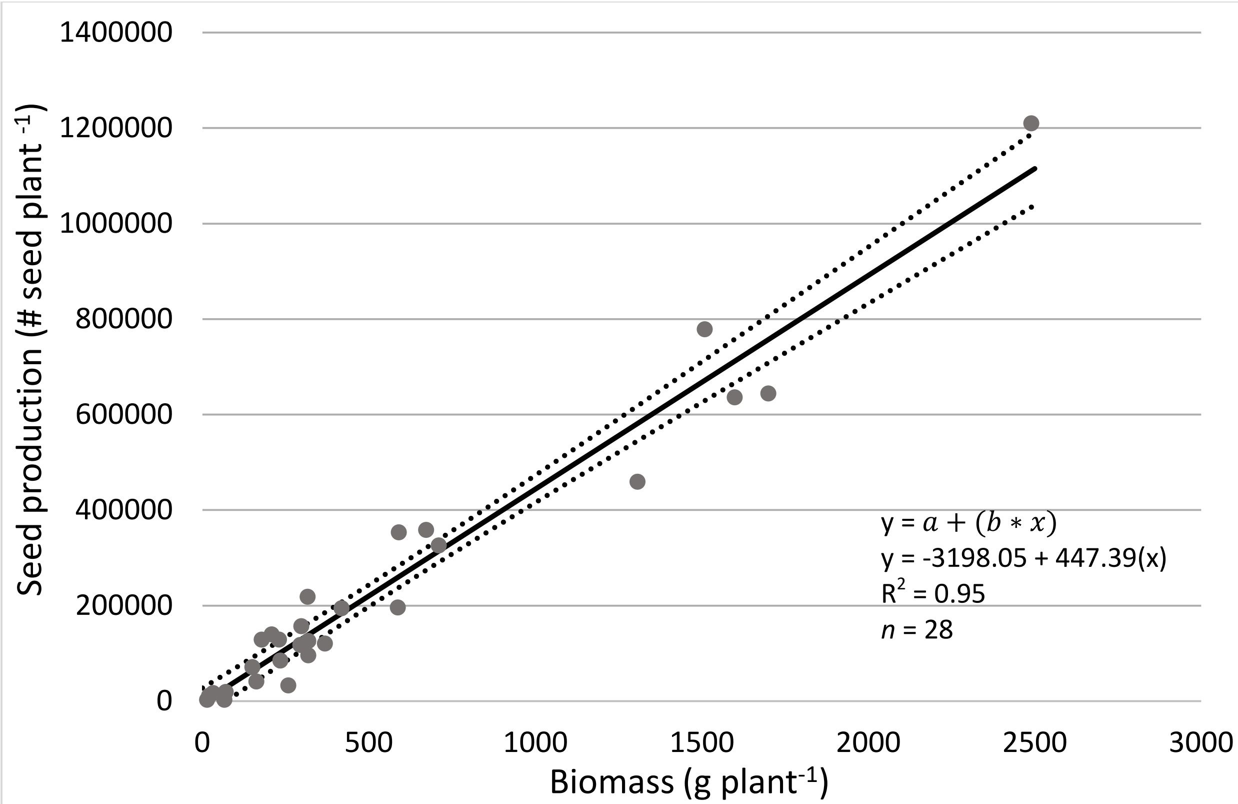

Figure 3. Relationship between *Amaranthus palmeri* dry biomass and seed production per female plant in field studies conducted in 2022 and 2023. The solid line represents the fit of a linear regression model, and the dotted lines represent the 95% confidence interval of the fitted line. R^2 value displays the percentage of variability explained by the fit of the line.

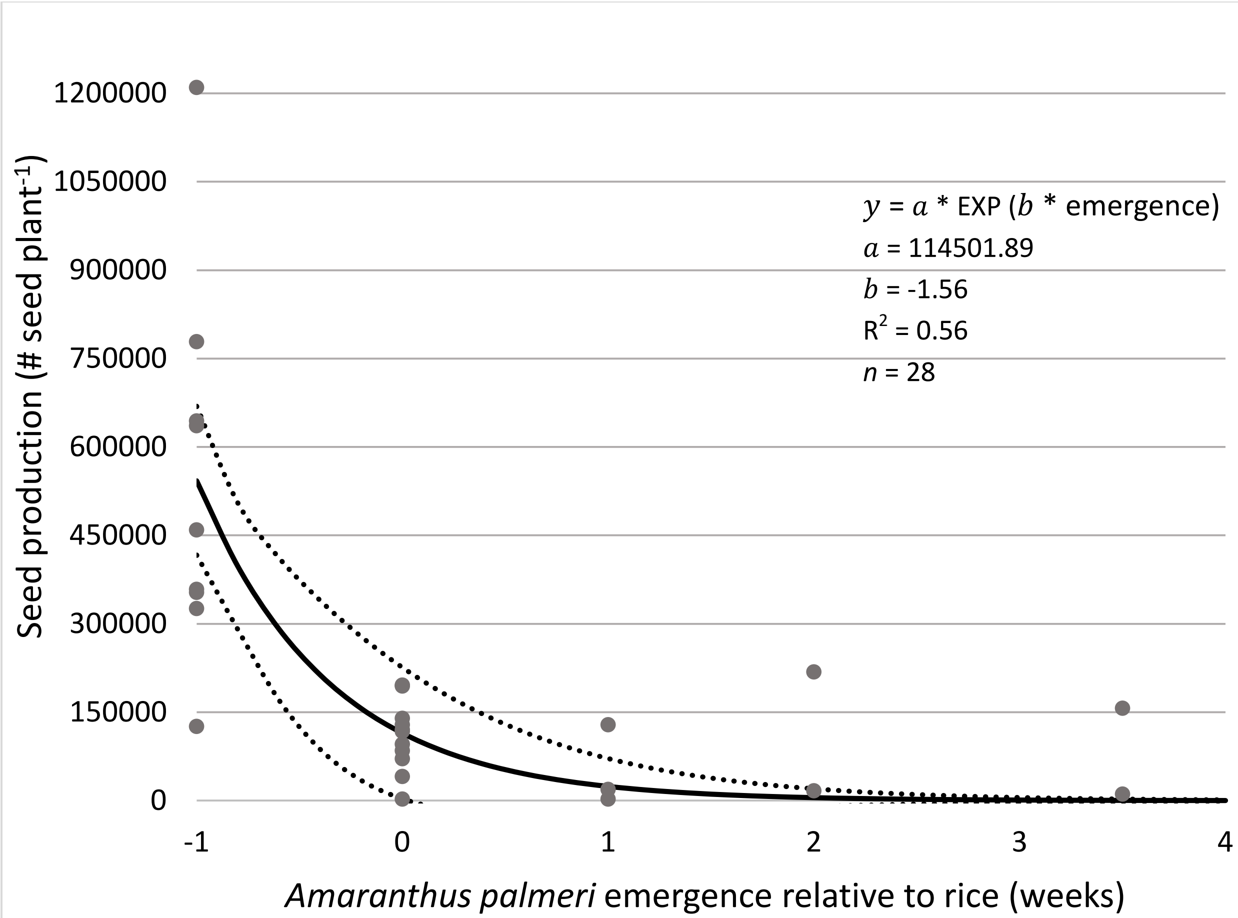

Figure 4. Two-parameter exponential decay model [$y = a * \mathrm{EXP}\ (b * \mathrm{emergence})$], where a = scale and $b =$ growth rate, to estimate *Amaranthus palmeri* seed production per female plant as a function of *A. palmeri* time of emergence relative to rice. The solid line represents the fit of the two-parameter exponential decay model, and the dotted lines represent the 95% confidence interval of the fitted line. Week 0 is the week *A. palmeri* emerged with the crop.

https://doi.org/10.1017/wsc.2024.102 Published online by Cambridge University Press