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Corresponding author:
Thomas R. Butts; Email: buttst@purdue.edu

Effects of bed width and crop row spacing on barnyardgrass (*Echinochloa crus-galli*) emergence and seed production in furrow-irrigated rice

Noah H. Reed[1], Thomas R. Butts[2,3], Jason K. Norsworthy[4], Jarrod T. Hardke[5], L. Tom Barber[6], Nick R. Bateman[7], Aurelie M. Poncet[8] and Koffi B. J. Kouame[9]

[1]Graduate Research Assistant, Department of Crop, Soil, and Environmental Sciences, University of Arkansas, Fayetteville, AR, USA; [2]Associate Professor, Extension Weed Scientist, Department of Crop, Soil, and Environmental Sciences, University of Arkansas System Division of Agriculture, Lonoke, AR, USA; [3]Current: Clinical Assistant Professor, Extension Weed Scientist, Department of Botany and Plant Pathology, Purdue University, West Lafayette, IN, USA; [4]Distinguished Professor and Elms Farming Chair of Weed Science, Department of Crop, Soil, and Environmental Sciences, University of Arkansas, Fayetteville, AR, USA; [5]Professor, Department of Crop Soil and Environmental Sciences, University of Arkansas System Division of Agriculture, Stuttgart, AR, USA; [6]Professor, Extension Weed Scientist, Department of Crop, Soil, and Environmental Sciences, University of Arkansas System Division of Agriculture, Lonoke, AR, USA; [7]Associate Professor/Crop Entomologist, Department of Entomology and Plant Pathology, Stuttgart, Arkansas, USA; [8]Assistant Professor, Department of Crop, Soil, and Environmental Sciences, University of Arkansas, Fayetteville, AR, USA and [9]Postdoctoral Research Fellow, Department of Crop, Soil, and Environmental Sciences, University of Arkansas System Division of Agriculture, Lonoke, AR, USA

Abstract

Furrow-irrigated rice (*Oryza sativa* L.) has become a popular option for rice production in Arkansas. Highly troublesome weeds like barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.] are a major problem for producers in all rice production systems. Cultural tactics should become a priority to enhance crop growth and competitiveness. This research aimed to determine the effects of bed width (irrigation furrow spacing) and crop row spacing manipulation on *E. crus-galli* emergence and seed production in a furrow-irrigated rice system. Three bed widths (76, 97, and 152 cm) (whole-plot factor) were used, and plots were drill seeded in four crop row spacings (13, 19, 25, and 38 cm) (subplot factor). The widest width of 152 cm had a slight increase in *E. crus-galli* density in the early rice life cycle but, by the end of the season, did not differ from the narrower bed widths. Conversely, a decrease in *E. crus-galli* seed production was observed as the bed width increased. Similar rice canopy coverage and yields occurred among all three bed widths. As for crop row spacing, as the width increased, *E. crus-galli* density also increased. The 13-cm crop row spacing had the lowest preflood *E. crus-galli* density, preharvest panicle count, and seed production. No effect of crop row spacing was observed on rice canopy coverage; however, the 13-cm crop row spacing produced the greatest rice yield. The 13-cm crop row spacing paired with the 152-cm bed width may be the optimum combination of ecological strategies in furrow-irrigated rice to reduce *E. crus-galli* seed production while maintaining rice growth and yield.

Introduction

With rice (*Oryza sativa* L.) being a staple food source across the world, concerns have steadily increased that field production and labor requirements will not be able to meet the demand of the increasing world population (Prasad et al. 2017). In the 2022 to 2023 crop season, Arkansas was the lead producer in rice production in the United States, accounting for 49% of the country's total rough rice yield production (USDA-NASS 2023). One problem that rice production in Arkansas is faced with is the decline of groundwater used throughout the eastern part of the state (Young et al. 2004). Decreased use of water in a rice production system can cause yield losses upward of 70% to 80%, and increased weed pressure places more stress to the crop (Dass et al. 2017). One method to potentially conserve water use in Arkansas rice is by using a furrow-irrigation system, which can reduce water use by 40% to 48%, depending on the cultivar planted (He 2010).

Furrow-irrigated rice is a relatively new production method with slow adoption likely because of reduced yield compared with the standard flooded system in some instances (Vories et al. 2002). In a flooded system, the entire field is flooded until maturity, while in a furrow-irrigated system, the land is slightly sloped and bedded to be watered in the furrows on a scheduled basis (Norsworthy et al. 2011). On raised beds, slower crop development has been observed along with weeds atypical to a rice system, because the cultural tactic of flooding is not available to prevent weed germination and emergence as in in a traditional paddy rice system (Ockerby and Fukai 2001; Singh et al. 2006). In a previous study in Arkansas, a 20% reduction in weed control and 13% to 14% less yield occurred in a furrow-irrigated rice system compared with a flooded rice system (Bagavathiannan et al. 2011). With the greater weed pressure and alternative weed species to combat, additional methods must be introduced to provide the crop with a competitive advantage in furrow-irrigated rice (Bagavathiannan et al. 2011). Previous research in soybean [*Glycine max* (L.) Merr.] identified an appropriate bed width (irrigation furrow spacing) and crop row spacing to accomplish this feat, both of which could be strong candidates in furrow-irrigated rice (Butts et al. 2016; Graterol et al. 1996).

Using a furrow-irrigated, raised-bed planting system is a major shift in production practices in rice, and understanding of the subsequent ecological impacts on weeds is lacking (Singh et al. 2006). Little research has been conducted evaluating the influence of bed width in a furrow-irrigated rice system on weed emergence and development. Previous research has shown that a reduction in soybean row spacing produced greater yield and weed control, allowing for greater economic returns (Mcpherson and Bondari 1991; Smith et al. 2019). In a wheat (*Triticum aestivum* L.) study, results indicated that as bed width increased, yield also increased, and the amount of irrigation water used decreased (Tewabe et al. 2019). With little research on the appropriate bed width in Arkansas, further work is needed to identify the impact of bed width on weed and rice growth.

Crop row spacing manipulation is another cultural tactic that can be used in row-crop production. Little research has been conducted evaluating the influence of crop row spacing on weed emergence and seed production in rice. In one rice study, crop row spacings of 15 cm and 10–20–10 cm had reduced weed biomass and greater grain yield than a crop row spacing of 30 cm (Chauhan and Johnson 2011). In previous soybean research, a narrower crop row spacing produced an overall increased profitability compared with a wider crop row spacing (Lambert and Lowenberg-DeBoer 2003), and with greater tillering hybrid rice, similar results may be possible. In a review of use of crop competition for weed management in rice, narrow row spacings of 15 to 25 cm were determined to be an optimum crop row spacing to produce greater yield and reduce weed infestations (Dass et al. 2017). In the state of Arkansas, the recommended crop row spacing for rice is between 10 and 25 cm depending on the grower's equipment (Hardke 2022). Recent research in Arkansas found that a narrower width of 8.2 cm could produce greater yield and stand density compared with a 19 to 38 cm width (Lytle et al. 2021). Due to increased herbicide resistance, concerns for *E. crus-galli* management in rice, and the need for additional strategies in furrow-irrigated rice, alternative cultural tactics need to be evaluated for their ecological impact on problematic rice weed species (Butts et al. 2022). As a result, the objective of this research was to determine the effects of bed width and crop row spacing manipulation on *E. crus-galli* emergence and seed production in a furrow-irrigated rice system across diverse environments. The null hypotheses of this research were: (1) a narrow bed width (76 cm) would not reduce *E. crus-galli* densities or seed production or increase rice canopy coverage or rough rice yield compared with wider bed widths; and (2) a narrower crop row spacing (13 and 19 cm) would not reduce *E. crus-galli* densities or seed production or increase rice canopy coverage or rough rice yield compared with wider bed widths.

Materials and Methods

Field Sites

Field experiments were conducted across three Arkansas locations in 2021 and 2022 for a total of 5 site-years. Sites consisted of the University of Arkansas Pine Bluff Small Farm Outreach Center near Lonoke, AR (34.85°N, 91.88°W) in 2021 and 2022, the University of Arkansas System Division of Agriculture Pine Tree Research Station near Colt, AR (35.13°N, 90.96°W) in 2021 and 2022, and the University of Arkansas System Division of Agriculture Rohwer Research Station near Watson, AR (33.79°N, 91.29°W) in 2022 only. The soil at the Lonoke site was an Immanuel silt loam (fine-silty, mixed, active, thermic Oxyaquic Glossudalfs) consisting of 14% sand, 72% silt, 14% clay, and 1.25% organic matter with a pH of 5.6. The soil at the Pine Tree site was a Calhoun silt loam (fine-silty, mixed, active, thermic Typic Glossaqualfs) consisting of 12% sand, 70% silt, 18% clay, and 1.02% organic matter with a pH of 5.6. The soil at the Rohwer site was a Sharkey clay (very-fine, smectitic, thermic Chromic Epiaquerts) consisting of 2% sand, 45% silt, 53% clay, and 1.98% organic matter with a pH of 6.8. The sites were drill seeded with rice on the following dates: Lonoke, June 16, 2021, and May 16, 2022; Pine Tree, July 7, 2021, and June 7, 2022; and Rohwer June 28, 2022.

Experimental Design

The experiments were designed as a randomized complete block split-plot design (12 treatments) replicated four times. Each experiment consisted of a whole-plot factor of three bed widths: 76, 97, and 152 cm. The subplot was four crop row spacings: 13, 19, 25, and 38 cm. Rice was drill seeded with a FullPage long-grain hybrid (RT7521 FP, RiceTec, Alvin, TX 77512) at 128 seeds m^{-2}. Irrigation furrows and beds were made parallel with the drill rows immediately following seeding with a DickeyVator adjustable bedder roller (Dickey Machine Works, White Hall, AR 71602). Plots were 3.8-m wide and 7.6-m long. Standard recommendations from the University of Arkansas were used for nutrients, pests, and irrigation (Hardke 2022).

High levels of weed infestation and previous survey results indicated commercial rice fields typically receive four herbicide applications: a preemergence and three postemergence applications (Butts et al. 2022). As a result, the decision was made to apply a noncommercial herbicide program within this research targeting grass, sedge, and broadleaf weed species. This noncommercial program included two herbicide applications (one preemergence and one postemergence) to allow assessment of the cultural factors but provide the opportunity for trials to be harvested for yield assessment. Herbicide applications were made using a CO_2-pressurized sprayer mounted on either a tractor three-point hitch or an all-terrain vehicle and were equipped with AI110015 nozzles (TeeJet® Technologies, Springfield, IL 62703) to deliver 94 L ha^{-1} at 8 km h^{-1}. Across site-years, a preemergence application of clomazone at 315 g ai ha^{-1} (Command® 3ME, FMC, Philadelphia, PA 19104) and saflufenacil at 75 g ai ha^{-1} (Sharpen®, BASF, Morrisville, NC 27709) was applied. Different postemergence applications were made across site-years depending on the weed species and density present in the experiment. The postemergence application at the Lonoke and Pine Tree locations in 2021 consisted of cyhalofop at 313 g ai ha^{-1} (Clincher® SF, Corteva Agriscience, Indianapolis, IN 46268) and halosulfuron + thifensulfuron at 35 + 4.5 g ai ha^{-1} (Permit Plus®, Gowan, Yuma, AZ 85366). The postemergence application at the Lonoke site in 2022 was bentazon applied at 560 g ai ha^{-1} (Basagran®, Winfield Solutions, St Paul, MN 55164). The postemergence application at the Pine Tree and Rohwer locations in 2022 consisted of fenoxaprop at 122 g ai ha^{-1} (Ricestar® HT, Gowan), bispyribac-sodium at 3.5 g ai ha^{-1} (Regiment®, Valent U.S.A., Walnut Creek, CA 94596), and halosulfuron + thifensulfuron at 35 + 4.5 g ai ha^{-1}.

Data Collection

Echinochloa crus-galli density assessment was averaged from two 0.25-m^2 quadrants per plot at the 5- to 6-leaf rice stage (preflood). At the preharvest stage, *E. crus-galli* panicles were counted and averaged from the same two 0.25-m^2 quadrants per plot. Density and panicle data were then converted to a square-meter (m^2) scale.

A small, unmanned aircraft system (Inspire 2, DJI Technology, Nanshan, Shenzhen, China) was manually flown to take digital images from directly above each plot at the preflood and panicle differentiation rice stages to assess rice canopy coverage. Images were captured from 45.7 m above ground level across all plots for consistency in the analysis software. Aerial images were then analyzed using FieldAnalyzer software (Green Research Services, Fayetteville, AR 72701). Green pixel counts were measured in each plot to determine the canopy coverage percentage. Hue and saturation settings within the software were adjusted to delineate between crop and weeds within the trial area.

Before rice harvest, *E. crus-galli* panicles were clipped from two 0.25-m^2 quadrants per plot and placed in paper bags. *Echinochloa crus-galli* inflorescences were dried at 66 C for 3 to 5 d to constant mass. The panicles were then hand threshed and cleaned to separate the *E. crus-galli* seed. The mass of 100 *E. crus-galli* seeds was recorded and divided by the total mass of cleaned seed to determine the seed production per 0.25 m^2 of each plot. Seed production was then transformed to a square-meter (m^2) scale.

Rough rice grain yield was collected at harvest with a small-plot research combine. The entire width of the plot was harvested at the Lonoke and Rohwer locations. At the Pine Tree location, two different plot combines were used according to the crop row spacing of the plot. A 51-cm header was used to harvest two rows of the 25-cm crop row spacing and four rows of the 13-cm spacing per plot. A 72-cm header harvested two rows of the 38-cm crop row spacing and four rows of the 19-cm spacing per plot.

Statistical Analyses

Echinochloa crus-galli seed production and rough rice grain yield data were subjected to ANOVA using JMP Pro v. 17.0 (SAS Institute, Cary, NC 27513) with a normal distribution (selected based on the best fit using the least log-likelihood). *Echinochloa crus-galli* density and panicle counts were subjected to ANOVA using PROC GLIMMIX and Poisson distribution in SAS v. 9.5 (SAS Institute). Rice canopy coverage was subjected to ANOVA using SAS v. 9.5 with PROC GLIMMIX and a beta distribution. For all response variables, bed width and crop row spacing were evaluated as fixed effects and site-year was evaluated as random. Site-year was selected to be a random variable to allow for broader conclusions to be drawn across diverse environments, as indicated in the overall objective, and with 5 site-years of data, it was deemed statistically beneficial (Midway 2022). All means were separated using Tukey's honestly significant difference with an alpha value of 0.05.

Results and Discussion

Across all response variables, no interaction between bed width and crop row spacing was observed (Table 1). At the preflood rice stage, *E. crus-galli* densities were affected by both bed width and crop row spacing. The fewest *E. crus-galli* plants were observed in the 76-cm bed width with 13 plants m^{-2} (Table 2). As the bed width increased to 152 cm, *E. crus-galli* density also increased to 16 plants m^{-2}.

For the crop row spacing main effect, an increase in crop row spacing also increased *E. crus-galli* density at the preflood stage (Table 2). The fewest *E. crus-galli* plants were present in the 13-cm crop row spacing with 11 plants m^{-2}. The 19- and 25-cm crop row spacings both had 14 plants m^{-2}, while the greatest density at the preflood stage was observed in the widest crop row spacing of 38 cm with 19 plants m^{-2}. There was a 72% increase in *E. crus-galli* plants m^{-2} in the widest crop row spacing of 38 cm compared with 13 cm. The wider crop row spacing allowed for more weeds to germinate and emerge, likely due to increased solar radiation and diurnal temperature fluctuations, thereby requiring additional efforts to reach equivalent numbers as the narrower crop row spacings (Norsworthy and Oliveira 2007; Thompson and Grime 1983). It has been found that a narrow crop row spacing increased soil shading from enhanced crop canopy and reduced the capability of weeds to germinate (Forcella et al. 1992). Previous soybean research found that a greater leaf area index occurred in narrower crop row spacings of 19 and 38 cm compared with 76 cm, and fewer weeds would likely emerge as a result (Harder et al. 2007). An alternative explanation for the increased *E. crus-galli* germination and emergence in wider crop spacings may be due to increased fluctuations in soil moisture (Boyd and Van Acker 2003). Overall, further research is needed to fully identify the specific mechanism for reductions in *E. crus-galli* germination and emergence in conjunction with crop competition.

At the rice preharvest stage, *E. crus-galli* panicle counts were not affected by bed width but were impacted by the crop row spacing main effect (Table 1). Results were similar to those observed for the preflood *E. crus-galli* density counts. Again, the fewest panicles were in the 13-cm crop row spacing with 5 panicles m^{-2} (Table 2). An increase in panicles occurred when the crop row spacing was increased to 38 cm with 8 panicles m^{-2}. A narrower crop row spacing reduced early-season emergence and growth of *E. crus-galli* and in return led to fewer panicles at the end of the growing season compared with wider crop row spacings. Previous research in corn (*Zea mays* L.) found that narrower crop row spacings reduced weed height, biomass, and seed production more than wider crop row spacings did, because the crop outcompeted the weeds more rapidly in the growing season (Fahad et al. 2014).

Echinochloa crus-galli seed production was affected by both main effects of bed width and crop row spacing (Table 1). As bed width increased, *E. crus-galli* seed production decreased (Table 2). The greatest number of seeds was present in the 76-cm bed width with 7,410 seeds m^{-2}. Seed production then decreased as bed width increased to 97 cm (6,290 seeds m^{-2}) and 152 cm (6,140 seeds m^{-2}). One potential reason for a decrease in *E. crus-galli* seed production in wider bed widths could be that water stress developed in one of two ways (Grattan et al. 1988). The wider bed widths may not have allowed the *E. crus-galli* to reach adequate amounts of water for similar seed production compared with a narrower bed width where water was more easily accessible throughout the beds. Conversely, *E. crus-galli* may have had greater access to an adequate water supply in narrow bed widths, resulting in greater seed production than in wider bed widths. Parfitt et al. (2017) found that under a certain

Table 1. P-values from ANOVA for preflood *Echinochloa crus-galli* density, preharvest *E. crus-galli* panicle counts, rice canopy coverage at preflood and panicle differentiation, *E. crus-galli* seed production before harvest, and rough rice yield across site-years[a,b]

	E. crus-galli density	Panicle count	Rice canopy coverage[c]			
Source	Preflood	Preharvest	Preflood	Panicle differentiation	*E. crus-galli* seed	Rough rice yield
	P > F					
Bed width	<**0.0001**	0.3270	0.9902	0.2223	<**0.0001**	0.6819
Crop row spacing	**0.0376**	**0.0427**	0.7861	0.5245	<**0.0001**	<**0.0001**
Bed width * crop row spacing	0.1693	0.2839	0.8699	0.9960	0.1089	0.9998

[a]Bolded values indicate statistical significance at α = 0.05
[b]*Echinochloa crus-galli* density, panicle count, and *E. crus-galli* seed factors were combined across 5 site-years, rice canopy coverage at preflood and panicle differentiation were combined across 2 site-years, and rough rice yield was combined across 4 site-years.
[c]Rice canopy coverage is from the 2022 Lonoke and Pine Tree site-years only due to excessive weed pressure and software limitations at other site-years.

Table 2. Preflood *Echinochloa crus-galli* density, preharvest panicle count, and seed production across all 5 site-years[a]

	E. crus-galli density	Panicle count	
Main effect	Preflood	Preharvest	Seed production
	no. m^{-2}		
Bed width (cm)			
76	13 b	7 a	7,410 a
97	15 ab	6 a	6,290 b
152	16 a	6 a	6,140 c
Crop row spacing (cm)			
13	11 c	5 b	5,070 c
19	14 b	7 ab	7,010 b
25	14 b	7 ab	6,650 b
38	19 a	8 a	7,960 a

[a]Means followed by the same letter within a main effect and column are not different based on Tukey's honestly significant difference (α = 0.05).

Table 3. Rice canopy coverage at preflood and panicle differentiation across the 2022 Lonoke and Pine Tree sites and rough rice yield across 4 site-years[a]

	Rice canopy coverage		
Main effect	Preflood	Panicle differentiation	Rough rice yield[b]
	%		kg ha^{-1}
Bed width (cm)			
76	14 a	40 a	6,860 a
97	13 a	45 a	7,150 a
152	13 a	49 a	6,770 a
Crop row spacing (cm)			
13	12 a	49 a	8,030 a
19	13 a	45 a	6,730 b
25	15 a	45 a	7,300 ab
38	14 a	40 a	5,660 c

[a]Means followed by the same letter within a main effect and column are not different based on Tukey's honestly significant difference (α = 0.05).
[b]Rough rice yield for Rohwer, AR, was not collected due to extreme weed pressure and late planting date.

amount of water stress, rice tends to perform better than *E. crus-galli*, indicating a wider bed width may be suited for furrow-irrigated rice production to reduce the weed soil seedbank while maintaining adequate rice growth and development.

The crop row spacing main effect impacted *E. crus-galli* seed production conversely to bed width, but similarly to the previous trend observed in the density and panicle counts. As the crop row spacing increased, seed production also increased (Table 2). The greatest number of seeds was observed in the 38-cm width with 7,960 seeds m^{-2}. The 19- and 25-cm crop row spacings had seed production similar to one another, while the 13-cm crop row spacing had the fewest seeds produced with 5,070 seeds m^{-2}. A narrower crop row spacing would be a beneficial component in conjunction with other integrated strategies in furrow-irrigated rice production for reducing the *E. crus-galli* soil seedbank compared with a wider crop row spacing. Effectively reducing the soil seedbank reduces the number of herbicide resistance genes and, over time, might allow herbicide applications to become more efficient (Norsworthy et al. 2012). A narrower crop row spacing might also reduce the number of herbicide applications required throughout the growing season compared with a greater width, thereby enhancing environmental stewardship and producer profitability.

No differences were observed for rice canopy coverage at either the preflood or panicle differentiation rice stages (Tables 1 and 3). Past evidence has shown that slower crop development occurs in a furrow-irrigated rice system compared with traditional paddy rice production (Ockerby and Fukai 2001). This could be a reason why differences in canopy coverage were not observed between bed widths and crop row spacings in this research, as the prolonged development masked minor treatment differences that may have occurred. Additionally, due to the practice of creating irrigation furrows after drill seeding and parallel with the rice rows, a common method used commercially, additional rice seed may have been disturbed, altering the overall geometric pattern for effective canopy coverage. Future research should explore this phenomenon in conjunction with additional seeding and irrigation furrow implementation strategies in furrow-irrigated rice.

Rough rice yield was affected by the crop row spacing main effect (Table 1). The greatest yield occurred in the 13-cm crop row spacing with 8,030 kg ha^{-1} (Table 3). The 19- and 25-cm crop row spacings had yields similar to one another (6,730 and 7,300 kg ha^{-1}, respectively), and the lowest yield occurred in the 38-cm crop row spacing with 5,660 kg ha^{-1}. Rice in a wider row spacing, like 38 cm, in a furrow-irrigated system may have had reduced yield because the plants may not have been able to tiller as intensely due to the slower crop development previously mentioned (Ockerby and Fukai 2001). This would not allow for the wider crop row spacings to compensate for the greater intraspecific competition occurring between individual rice plants within the same row compared with the narrower widths with less intraspecific competition. This competition and increased interrow space would also likely result in reduced crop light interception efficiency. Dunn et al. (2020) found similar results in rice where wider crop row spacings of 36 cm produced lower grain yield than widths less than 27 cm because plants could not compensate for the wider spacing. Rice yield differences due to the bed-width treatment may not have been observed, as occurred with *E. crus-galli* seed production because studies have shown that rice was more tolerant to drought stress than *E. crus-galli* (Parfitt et al. 2017). The rice was able to produce similar yields across bed widths despite greater water stress in a wider bed width. The drought tolerance of rice compared with *E. crus-galli* may also help to explain the similar results in rice canopy coverage across bed widths and crop row spacings. However, further research investigating soil moisture content and evapotranspiration rates with regard to weed species and crop is needed to validate these hypotheses.

Overall, the relationship between bed width and *E. crus-galli* emergence and growth was complex, resulting in the rejection of parts of the stated hypotheses and failure to reject other parts of the hypotheses. Earlier in the growing season (preflood), the wider bed width (152 cm) allowed for greater *E. crus-galli* density to emerge; however, by the end of the season, the wider bed width decreased *E. crus-galli* seed production compared with narrower bed widths (97 cm). This could be because *E. crus-galli* was facing more water stress in the wider bed widths late in the season, resulting in reduced seed production that would be beneficial in reducing the soil seedbank of herbicide-resistant *E. crus-galli*. Similar yields between bed widths were also observed, and it may therefore be advisable to use the 152-cm bed width in furrow-irrigated rice, as rice yield can be maintained while *E. crus-galli* seed production can be minimized. Additional integrated ecological strategies and other methods to enhance crop competition would be required to achieve long-term *E. crus-galli* suppression. The 13-cm crop row spacing provided the greatest reductions in *E. crus-galli* density, panicle counts, and seed production, as well as maximized rough rice yield. In a furrow-irrigated rice system, the 13-cm crop row spacing may be a viable option for providing rice with a competitive advantage over *E. crus-galli* and enhancing yield potential. Additional research should be conducted to identify the optimal weed management program, appropriate cultivar selection, and economics of converting to a 13-cm crop row spacing.

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