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Crop Performance and Weed Suppression by Weed-Suppressive Rice Cultivars in Furrow- and Flood-Irrigated Systems under Reduced Herbicide Inputs

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Weed control in rice is challenging, particularly in light of increased resistance to herbicides in weed populations and diminishing availability of irrigation water. Certain indica rice cultivars can produce high yields and suppress weeds in conventional flood-irrigated, drill-seeded systems in the southern United States under reduced herbicide inputs, but their response to reduced irrigation inputs in these systems in not known. Rice productivity and weed control by weed-suppressive cultivars and conventional nonsuppressive cultivars were evaluated in a nonflooded furrow-irrigated (FU) system and a conventionally flooded (FL) system under three levels of weed management (herbicide inputs) in a 3-yr field study. Rice yields across all weed management levels yielded ~ 76% less in the FU system than in the FL system. The allelopathic indica cultivar, 'PI 312777', and commercial hybrid rice 'CLXL729' generally produced the highest grain yields and greatest suppression of barnyardgrass in both irrigation systems. 'Bengal' and 'Wells' were the top-yielding conventional cultivars whereas 'Lemont' and 'CL171AR' yielded the least. Weed suppression by PI 312777 and CLXL729 under ''medium'' weed management was equivalent to that of Lemont and CL171AR at the ''high'' management level, suggesting that the weed-suppressive cultivars may be able to compensate for suboptimal herbicide inputs or incomplete weed control.

Nomenclature: Barnyardgrass, *Echinochloa crus-galli* (L.) Beauv; rice, *Oryza sativa* L., 'Bengal', 'CLXL729', 'Lemont', 'PI 312777', 'Wells'.

Key words: Allelopathy, bed-planted rice, acifluorfen, bentazon, clomazone, fenoxaprop, flood irrigation, furrow irrigation, glyphosate, halosulfuron, herbicides, propanil, quinclorac, weed control, weed suppression.

Rice production throughout much of the southern United States has become increasingly challenging due to diminishing water resources (ANRC 2012). In order to maintain or increase rice yields in the future, management strategies that facilitate continued production of rice using less water must be developed. FU rice systems have been studied in the Mississippi Delta areas of southeast Missouri and northeast Arkansas since the 1990s as a means to reduce water use and costs related to levee construction, improve flexibility in chemical applications by using ground equipment, and increased harvest efficiency (Anders et al. 2012; Hefner and Tracy 1991a,b; Tracy et al. 1993; Vories et al. 2002).

The detrimental effects of weeds in direct-seeded rice systems have been a major limitation to yield and crop quality, especially in reduced-input systems, which seek to minimize the consumption of resources and environmental impacts, or in fields infested with herbicide-resistant weeds. Weed management in systems that reduce or eliminate flood irrigation is inherently challenging (Bagavathiannan et al. 2011; Borrell et al. 1997; Norsworthy et al. 2008, 2011). Historically, the commercial cultivars grown in U.S. rice systems have not readily tolerated or suppressed weeds, and thus require substantial herbicide inputs to achieve agronomic and economic viability (Gealy et al. 2003; Gealy and Moldenhauer 2012; Gealy and Yan 2012).

Indica rice germplasm is being increasingly evaluated and used in the United States due to its high yields and pest resistance, as well as its weed-suppressive traits (Dilday et al. 2001a,b; Gealy et al. 2005; Gealy and Moldenhauer 2012; Yan and McClung 2010). Several indica lines, as well as hybrid varieties, are known to suppress barnyardgrass and other weeds of rice (Dilday et al. 2001a; Gealy et al. 2003; Gealy and Yan 2012; Kong et al. 2006, 2008; Ottis et al. 2005; Seal and Pratley 2010). Recent breeding efforts with weed-suppressive rice have produced improved germplasm in China, Korea, Vietnam, and the United States with suppression

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ability and commercially acceptable quality (Chen et al. 2008; Kong et al. 2011; Ma et al. 2006; Gealy et al. 2013b; JN Rutger, personal communication).

Although weed-suppressive rice cultivars have been shown to produce commercially acceptable yields and reduce weed impacts under conventional FL systems, their potential to suppress weeds in FU systems is not well understood.

The objectives of this research were (1) to determine growth characteristics and yield potential of rice cultivars under a standard FL system in comparison to a FU system at high (aggressive), medium (moderate), and low (minimal) levels of weed management (herbicide inputs); (2) to identify the best-performing weed-suppressive and conventional (nonsuppressive) cultivars; (3) to determine the ability of cultivars to suppress or tolerate weed interference under these systems and management levels; and (4) to identify reduced levels of herbicide and irrigation input for weed-suppressive cultivars that can produce yields and suppression ability equivalent to conventional cultivars and common production standards.

Materials and Methods

Cultivar Selection. Seven rice cultivars were evaluated in a 3-yr trial. The indica lines 'PI 312777' (T65*2/Taichung Native 1) and 'Rondo' (Yan and McClung 2010) and the proprietary commercial Clearfield hybrid, 'CLXL729' (RiceTec, Katy, TX) were included for their weed suppressive potential; the medium-grain type 'Bengal' (Linscombe et al. 1993), and long-grain types, 'Wells' (Moldenhauer et al. 2007), 'Lemont' (Bollich et al. 1985), and 'CL171AR' (Horizon Ag, Memphis, TN) were included as "nonsuppressive" commercial standards.

Production Systems. *Conventional FL System*. The experimental area was located at the University of Arkansas Rice Research and Extension Center near Stuttgart, AR (34.49°N, 91.55°W), in field plots that were naturally infested with barnyardgrass. The soil was a DeWitt silt loam (fine smectitic, thermic, Typic Albaqualfs). The surface soil contained ~ 12 g organic matter kg^{-1} and had a pH of 5.8 in water. The plot area was historically managed in a 1-yr rice : 1-yr soybean rotation, and received a broadcast application of 22.4 kg P ha^{-1} as triple superphosphate and 56 kg K ha^{-1} as potassium chloride (muriate of potash) each year after disking and floating (land leveling) of the ground prior to crop planting. The plot area was prepared and flat-planted using a 10-row no-tillage drill (Almaco HDGD10R; Almaco, Nevada, IA) with a row width of 19 cm. Plots were 4.6 m long. Because severe bird predation destroyed much of the initial rice stand in the FL plots in 2010, they were replanted (Table 1). All cultivars were seeded at a density of 430 seeds m^{-2}, except CLXL729 (150 seeds m^{-2}, per seed company's recommendation). Natural rainfall was supplemented with flush irrigation as necessary to maintain healthy rice plants from germination to the four- to five-leaf stage, at which time nitrogen fertilizer (112 kg ha^{-1} N as urea) was applied. Immediately following N application a 10-cm-deep permanent flood was established (Table 1).

FU System. The FU system was established and managed as indicated by Anders et al. (2012). Spring field preparation was the same as in the FL system, except that following the preplanting cultivation (Triple-K cultivator, Kongskilde Agriculture, Hudson, IL), the plot land for the FU system was bedded using a field bedder (Eddins, Stuttgart, AR, or DickeyVator, Dickey Machine Works, Pine Bluff, AR) that built 38-cm-wide beds that were raised 10 cm above the 38-cm-wide furrows alternating between beds. The drill setup was the same as in the FL system except that the depth of each opener was set to accommodate the alternating soil surface levels established by the bedder. Plots were irrigated (flushed) periodically through the furrows between beds until the center of the beds at the top of the field was completely wet (approximately field capacity) (Table 1). N fertilizer application and timing were the same as in the FL system except that urea was treated with Agrotain N stabilizer (a urease enzyme inhibitor; Koch Agronomic Services, LLC., Wichita, KS) to minimize loss of fertilizer N into the atmosphere. Flush irrigations were applied identically in both systems until the time of N fertilization (immediately before establishing the permanent flood in the FL system) (Table 1). Thereafter, irrigation bays were flushed periodically in the FU system after the soil surface in rice plots was dry, but before the rice plants exhibited significant moisture stress symptoms (e.g., cupped leaves).

Establishment of Weed Management Levels. High, medium (med), and low weed management levels were established by applying different rates and timings of herbicide as indicated in Table 1 (suppliers of all herbicides used in these studies are listed in Footnote "c" of this table). Low corresponded to extremely low herbicide inputs (i.e., far below recommended rates; intended to facilitate excessive weed competitiveness against rice). Med and high corresponded to Extension or manufacturer recommendations (Scott et al. 2012), with med representing less than optimal herbicide treatments (i.e., limited number of applications at rates recommended for weed control in lightly infested fields), and high representing near-maximum rates of one or more herbicide products expected to achieve excellent weed control in heavily infested fields. The specific herbicides and rates used for med and high management were selected based on periodic inspection of the weed populations in the plots throughout each growing season. The average annual costs for weed control (chemical + application) for high, med, and low weed management levels over the 3 yr were ~ \$156, \$69, and \$22 ha^{-1}, respectively, across both irrigation systems; ~ \$111, \$70, and \$23 ha^{-1}, respectively, for the FL system; and ~ \$200, \$69, and \$22 ha^{-1}, respectively, for the FU system (detailed data not shown). The herbicide-resistant cultivars CLXL729 and CL171AR were used as proxies for hybrid and conventional rice cultivars, and thus were not grown under Clearfield management protocols. All herbicides were applied using a CO_2-powered backpack sprayer (R and D Sprayers, Opelousas, LA) with four 8001 flat fan nozzles (TeeJet/Spraying Systems, Wheaton, IL) at 51-cm spacing, and calibrated to deliver 94 l ha^{-1} at 159 kPa and a speed of 0.894 m sec^{-1} as described previously (Gealy and Yan 2012).

After planting, supplemental barnyardgrass seed was broadcast evenly over all plot areas at a density of 11.5 kg ha^{-1} to improve uniformity of weed stands. In order to lightly suppress the competitiveness of barnyardgrass in low management plots, propanil was applied POST at rates one-fourth to one-half of the recommended rates, with or without 0.053 kg ai ha^{-1} halosulfuron (Table 1). These treatments were used solely to avoid catastrophic yield failure in the event of heavy weed infestations. A weedy plot with no rice planted ("no rice"), but otherwise treated the same as other plots, was included in each weed management level.

Experimental Design. The experimental design was a split-split plot with four replications. The main plots were irrigation systems (two), the subplots were rice cultivars (seven), and the sub-subplots were weed management levels (three). Data from the rice and weed response variables were modeled using a mixed-models approach (PROC GLIMMIX; SAS version 9.3, SAS Institute Inc., 100 SAS Campus Drive, Cary, NC 27513-2414). Replications and years were considered to be random effects. Means were separated at $P = 0.05$ using least squares means with the Tukey-Kramer adjustment. This mixed model approach is useful for comparing rice lines when inferences over multiple environments are of interest (Blouin et al. 2011).

Data Collected at Preflood. Rice and barnyardgrass plants were nondestructively sampled 19, 23, and 22 d after emergence in 2009, 2010, and 2011, respectively. The number of rice leaves prior to flooding (leaf number: average number of leaves + tillers per plant) and height were determined from five randomly selected plants in each plot. Rice density was determined from plant stand counts in 0.5-m sections sampled randomly from each of the eight interior rows of each plot. Barnyardgrass plant density was determined from plant counts in two 0.25- by 0.25–m quadrats randomly placed within each plot. The number of barnyardgrass leaves prior to flooding (leaf number: average number of leaves + tillers per plant) and height were determined from a total of three plants randomly selected from the quadrat samples in each plot.

Data Collected at Late-Season. Late-season rice and weed data were obtained using the basic procedures described by Gealy and Moldenhauer (2012) and Gealy et al. 2013b. The number of days from rice emergence to 50% heading ("vegetation duration") was obtained from repeated visual estimates of the percentage of heading in each plot. Mature plant height (height) was obtained from 10 rice plants randomly sampled from the interior eight rows of each plot. The rice plants from a ~ 3.0-m-long section from the eight interior rows in each plot were cut and bundled using a binder (Yanmar BE65; Willamette Exporting, Inc., Portland, OR). Rough rice was threshed from bundles using a stationary Vogle-type thresher (Bill's Welding, Pullman, WA), air-dried, and weighed to the nearest 0.1 g; yield was adjusted to 12% (120 g kg^{-1}) moisture as described by Gealy and Yan (2012). Rice percentage of yield loss in the low and med management levels was calculated as in Gealy and Moldenhauer (2012) using the high management level in lieu of a weed-free standard.

Table 1. Chemical and irrigation treatments and timings for the low, medium, and high weed management levels used in flood and furrow irrigation systems.[a]

Year	Irrigation system	Bedded; planted; emerged[b]	Irrigation treatments	Weed management level	PRE herbicide applications[c]	POST herbicide applications[c]	Additional POST herbicide applications[c]
2009	Flood	Not bedded; planted May 29; emerged June 5	Flushed 2 times (June 10, 22); permanent flood applied June 30	Low	—	June 29: propanil @ 1.12 kg ai ha^{-1}	—
				Medium	June 2: clomazone @ 0.45 kg ai ha^{-1}	—	—
				High	June 2: clomazone @ 0.45 kg ai ha^{-1}	—	—
2009	Furrow	Bedded May 29; planted May 29; emerged June 5	Flushed 10 times (June 17, 22, 30; August 13, 25, 28, 31; September 4, 8, 11)	Low	—	June 29: propanil @ 1.12 kg ai ha^{-1}	—
				Medium	June 2: clomazone @ 0.45 kg ai ha^{-1}	—	—
				High	June 2: clomazone @ 0.45 kg ai ha^{-1}	August 10: quinclorac @ 0.37 kg ai ha^{-1} + (bentazon @ 0.56 kg ai ha^{-1} + acifluorfen @ 0.28 kg ai ha^{-1}) + 1% prime oil	—
2010	Flood	Not bedded; planted May 26; replanted June 9; emerged June 18	Flushed 4 times (June 15, 21; July 2, 9); permanent flood applied July 19	Low	May 27: glyphosate @ 1.12 kg ae ha^{-1} + 1% prime oil	July 14: propanil @ 1.12 kg ai ha^{-1}	—
				Medium	May 27: clomazone @ 0.34 kg ai ha^{-1} + glyphosate @ 1.12 kg ae ha^{-1} + 1% prime oil	—	—
				High	May 27: clomazone @ 0.34 kg ai ha^{-1} + glyphosate @ 1.12 kg ae ha^{-1} + 1% prime oil	July 14: quinclorac @ 0.28 kg ai ha^{-1} + fenoxaprop @ 0.09 kg ai ha^{-1} + halosulfuron @ 0.053 kg ai ha^{-1} + 1% prime oil	—
2010	Furrow	Bedded April 30; planted May 26; emerged June 7	Flushed 17 times (June 3, 9, 15, 21; July 2, 9, 19, 26; August 2, 14, 19, 26; September 3, 14, 21, 29; October 7)	Low	May 27: glyphosate @ 1.12 kg ae ha^{-1} + 1% prime oil	July 14: propanil @ 1.12 kg ai ha^{-1}	—
				Medium	May 27: clomazone @ 0.34 kg ai ha^{-1} + glyphosate @ 1.12 kg ae ha^{-1} + 1% prime oil	—	—
				High	May 27: clomazone @ 0.34 kg ai ha^{-1} + glyphosate @ 1.12 kg ae ha^{-1} + 1% prime oil	July 14: quinclorac @ 0.28 kg ai ha^{-1} + fenoxaprop @ 0.09 kg ai ha^{-1} + halosulfuron @ 0.053 kg ai ha^{-1} + 1% prime oil	—

Table 1. Continued.

Year	Irrigation system	Bedded; planted; emerged[b]	Irrigation treatments	Weed management level	PRE herbicide applications[c]	POST herbicide applications[c]	Additional POST herbicide applications[c]
2011	Flood	Not bedded; planted May 11; emerged May 23	Flushed 3 times (June 6, 16, 23); permanent flood applied July 1	Low	—	—	June 30: halosulfuron @ 0.053 kg ai ha^{-1} + 1% prime oil + propanil @ 2.2 kg ai ha^{-1}
				Medium	May 19: clomazone @ 0.34 kg ai ha^{-1}	—	June 30: halosulfuron @ 0.053 kg ai ha^{-1} + 1% prime oil
				High	May 19: clomazone @ 0.34 kg ai ha^{-1}	June 24: quinclorac @ 0.28 kg ai ha^{-1} + fenoxaprop @ 0.105 kg ai ha^{-1} + 1% prime oil	June 30: halosulfuron @ 0.053 kg ai ha^{-1} + 1% prime oil
2011	Furrow	Bedded April 8; planted May 11; emerged May 23	Flushed 14 times (June 6, 16, 23; July 5, 12, 18, 25; August 1, 5, 16, 29; September 2, 9, 22)	Low	—	—	June 30: halosulfuron @ 0.053 kg ai ha^{-1} + 1% prime oil + propanil @ 2.2 kg ai ha^{-1}
				Medium	May 19: clomazone @ 0.34 kg ai ha^{-1}	—	June 30: halosulfuron @ 0.053 kg ai ha^{-1} + 1% prime oil
				High	May 19: clomazone @ 0.34 kg ai ha^{-1}	June 24: quinclorac @ 0.28 kg ai ha^{-1} + fenoxaprop @ 0.105 kg ai ha^{-1} + 1% prime oil	June 30: halosulfuron @ 0.053 kg ai ha^{-1} + 1% prime oil

[a] Flood and furrow plots were flush-irrigated identically until date of nitrogen fertilizer application and permanent flood application to flood plots. Thereafter, furrow plots were flushed as needed to maintain rice plants in nonstressed condition, and flood plots were maintained at a flood depth of ~ 10 cm.

[b] Due to severe predation of germinating seeds and seedlings by birds, the 2010 flood plots had very poor stands, and were replanted.

[c] Sources of herbicides used: "bentazon + acifluorfen", Storm (United Phosphorus, Inc., King of Prussia, PA); clomazone (Command 3ME, FMC Corp., Philadelphia, PA); quinclorac (Facet, BASF, Research Triangle Park, NC); fenoxaprop (Ricestar HT, Bayer Cropscience LP, Durham, NC); glyphosate (Roundup Weathermax, Monsanto, St. Louis, MO) or (Mad Dog Plus, Loveland Products, Inc., Greeley, CO); halosulfuron (Permit, Gowan Company, Yuma, AZ); and propanil (Riceshot, RiceCo, Memphis, TN).

Table 2. ANOVA table showing sources of variation and P values for rice variables.

Source of variation	Before flooding			Late season		
	Plant density	Leaf number	Height	Mature height	Vegetation duration	Grain yield
	No. m row^{-1}	No. plant^{-1}	cm	cm	days	kg ha^{-1}
Cultivar	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Irrigation system	0.0005	0.8401	0.0068	< 0.0001	0.0454	< 0.0001
Management level	0.8645	0.0173	0.0003	< 0.0001	< 0.0001	< 0.0001
Cultivar × irrigation system	0.0738	0.9731	0.1369	0.0022	< 0.0001	0.0037
Cultivar × management level	0.0257	0.0516	0.8614	0.100	0.1170	0.2773
Irrigation system × management level	0.8417	0.6935	0.1536	0.0589	0.1170	< 0.0001
Cultivar × irrigation system × management level	0.9953	0.4498	0.2301	0.5631	0.8587	0.1651

Visual weed suppression ratings from 0% (no apparent difference in biomass or growth compared to weeds in no-rice plots) to 100% (complete control) were recorded after heading of barnyardgrass plants. FL plots were drained on September 18, 2009; October 1, 2010; and September 22, 2011. Weed biomass was sampled immediately prior to rice harvest. All weed biomass present in a 0.5-m-long by 1.33-m-wide section (i.e., within and between the eight interior rows) was destructively sampled, composited, and manually separated into "grass weeds" and "broadleaf weeds." Biomass of each weed type was determined to the nearest 0.1 g after drying to a constant weight at 60 C. Total weed biomass was the sum of grass + broadleaf biomass. Rice was harvested November 5 to November 13, 2009; October 18 to October 28, 2010; and October 5 to November 1, 2011.

Results and Discussion

Rice Growth and Development. *Preflood Data.* The sources and levels of variation from the statistical analysis of the rice data are presented in Table 2. Preflood rice plant density averaged 19% less in the FU than the FL system when averaged across cultivars and management levels (Table 3). However, analyses of cultivar by irrigation showed that CLXL729 ($P = 0.7892$) and Wells ($P = 0.0865$) were unaffected by irrigation system, whereas the other cultivars differed between the two systems ($P \leq 0.019$) (data not shown), suggesting that these two cultivars might be relatively more resistant to the conditions of seedling establishment in FU systems.

The low plant densities in FU plots may have been caused by reduced emergence or survival rates of rice seedlings due to the difficulty in maintaining accurate and uniform depths of seed placement in FU systems. The bedding procedure resulted in drilled seed beds that are naturally uneven. This can cause seeds to be planted deeper than the optimum in some rows, and shallower than the optimum in others. In the latter instance, germinating seeds can experience reduced moisture availability or increased predation by birds. Similar results have been reported in Australia, where rice plant density averaged 33% lower in an FU system ("intermittent irrigation") than when a permanent flood was established from sowing to harvest (Borrell et al. 1997).

Rice plant densities of CLXL729 and Lemont averaged 51 and 24% less, respectively, than all other cultivars (Table 3). The low density for CLXL729 was due primarily to its low commercially recommended seeding rate. Emergence of semidwarf rice types such as Lemont has been shown to be reduced or delayed by deeper-than-optimal drill-seeding depths and other stress conditions, and has been improved with gibberellic acid–based seed treatments (Dilday et al. 1990; Dunand 1992; Yan et al. 1993, 2004).

The cultivar by management interaction for rice density was significant ($P = 0.0257$). Densities of PI 312777, Wells, and CL171AR increased with management level, whereas those of Rondo, CLXL729, and Bengal decreased (Table 3). Rice densities over all management levels averaged ~ 21.7 plants m^{-1}. In analyses of cultivar by irrigation by management, Bengal ($P = 0.0664$), CL171AR ($P = 0.1596$), CLXL729 ($P = 0.2229$), and Wells ($P = 0.2704$) were similar across all irrigation by management combinations, whereas Rondo, Lemont, and PI 312777 were not ($P \leq 0.0146$; data not shown).

Rice leaf number was not affected by irrigation system, but was greater at low management (6.0 leaves plant^{-1}) than at the high or med weed management levels (~ 5.8 leaves plant^{-1}) (Table 3). The leaf number of CLXL729 and PI 312777 (average 6.7 leaves plant^{-1}) was greater than for

Table 3. Plant density and leaf number of seven rice cultivars before flooding in flood- and furrow-irrigated systems at three weed management levels in a 3-yr field study in Stuttgart, AR.[a]

	Plant density	Leaf number
	No. m row^{-1}	No. $plant^{-1}$
Cultivar main effect		
PI 312777	25.6 a	6.7 a
Rondo	24.6 a	6.1 ab
CLXL729	11.8 c	6.6 a
Bengal	24.6 a	5.5 bc
Wells	23.6 a	5.2 c
Lemont	18.5 b	5.2 c
CL171AR	23.6 a	5.5 bc
	$P < 0.0001$	$P < 0.0001$
Irrigation main effect		
Flood	24.1 a	5.9
Furrow	19.5 b	5.8
	$P = 0.0005$	$P = 0.8401$
Management main effect		
Low	21.9	6.0 a
Medium	21.7	5.8 b
High	21.7	5.8 b
	$P = 0.8645$	$P = 0.0173$
Cultivar × management		
Low		
PI 312777	24.7 a	6.8 ab
Rondo	25.5 a	6.5 a–c
CLXL729	13.1 d	7.1 a
Bengal	25.3 a	5.4 de
Wells	22.8 ab	5.3 e
Lemont	18.7 bc	5.1 e
CL171AR	23.0 ab	5.7 c–e
Medium		
PI 312777	26.0 a	6.7 ab
Rondo	24.8 a	6.0 b–e
CLXL729	11.4 d	6.4 a–d
Bengal	24.0 a	5.4 de
Wells	23.8 a	5.3 e
Lemont	17.9 c	5.2 e
CL171AR	24.3 a	5.5 de
High		
PI 312777	26.2 a	6.7 ab
Rondo	23.4 ab	5.9 b–e
CLXL729	11.0 d	6.4 a–d
Bengal	24.5 a	5.6 c–e
Wells	24.2 a	5.2 e
Lemont	18.9 bc	5.3 e
CL171AR	23.8 a	5.3 e
	$P = 0.0257$	$P = 0.0516$

[a] Least squares means within columns followed by the same letter were not different according to a least squares means test. Least squaresmeans not accompanied by letters indicate that $P \geq 0.05$.

Lemont or Wells (average 5.2 leaves $plant^{-1}$) (Table 3), suggesting that rapid early formation of leaves may be advantageous to the growth, yield, and weed suppression by these cultivars later on. There was a trend ($P = 0.0516$) in which leaf number of CLXL729, Rondo, and CL171AR decreased slightly at med and high management levels while that of the other cultivars remained more constant across management levels (Table 3). Except for Rondo and CLXL729, leaf numbers of all cultivars were similar across all combinations of cultivar by irrigation by management ($P \geq 0.25$; data not shown).

The preflood rice heights were lowest for PI 312777, Rondo, and Lemont (averaging 21 cm), and greatest for Bengal and Wells (averaging 28.1 cm) ($P < 0.0001$; main effect) (Table 4). The average preflood height of rice was 3.2 cm greater in the FU than in the FL system (Table 4). However, in analyses of cultivar by irrigation, heights of Rondo ($P = 0.1425$) and PI 312777 ($P = 0.0935$) were similar in both systems, whereas the other cultivars ($P \leq 0.02$) were shorter in the FL (data not shown). Heights of Rondo ($P = 0.3595$) and PI 312777 ($P = 0.4363$) were similar at all irrigation by management combinations, but those of other cultivars were not ($P \leq 0.03$).

Preflood rice height was ~ 0.8 cm greater under low weed management levels than at the other two levels ($P = 0.0003$) (Table 3). These apparently anomalous results for both preflood rice height and leaf number (greatest values at low management levels) may have been due to temporary stress induced by clomazone herbicide (Scherder et al. 2004; Zhang et al. 2004, 2005) that was applied PRE to high and med levels of management, but not to the low. Clomazone induced high levels of chlorosis in 2009 due to its greater application rate that year. In previous studies, clomazone has sometimes caused elevated injury levels in Bengal and other medium-grain cultivars (Scherder et al. 2004; Zhang et al. 2004).

The tillering potential of the weed-suppressive lines PI 312777 and Rondo used in the present study (data not shown) exceeded that of true-breeding commercial cultivars (Gealy and Yan 2012). High tillering capacity can be an effective weed-suppressive trait in rice (Dingkuhn et al. 1999; Gibson et al. 1999; Zhao et al. 2006). However, a "weed-suppressive" line ('STG06L-35-061') derived from PI 312777 had relatively low tillering levels (Gealy et al 2013b), suggesting that its weed suppression might be associated with allelopathic activity. Other aboveground traits, such as rapid early leaf development and growth (e.g. PI 312777 in the present study), high biomass, tall plant height, and yield potential (e.g., PI 312777 and CLXL729) of rice have been shown to improve

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Table 4. Rice plant heights before flooding and late in season.[a]

	Height before flooding	Height in late season
	cm	
Cultivar main effect		
PI 312777	20.8 d	—
Rondo	20.5 d	—
CLXL729	24.4 c	—
Bengal	28.9 a	—
Wells	27.2 b	—
Lemont	21.8 d	—
CL171AR	24.3 c	—
	P < 0.0001	
Irrigation main effect		
Flood	22.4 b	—
Furrow	25.6 a	—
	P = 0.0068	
Management main effect		
Low	24.5 a	77.4 b
Medium	23.8 b	86.3 a
High	23.6 b	87.4 a
	P = 0.0003	P < 0.0001
Cultivar × irrigation interaction		
Flood		
PI 312777	—	96.0 b
Rondo	—	97.3 b
CLXL729	—	110.4 a
Bengal	—	88.3 cd
Wells	—	96.5 b
Lemont	—	81.9 de
CL171AR	—	91.9 bc
Furrow		
PI 312777	—	72.5 fg
Rondo	—	69.0 gh
CLXL729	—	84.4 c–e
Bengal	—	68.5 gh
Wells	—	78.1 ef
Lemont	—	64.5 h
CL171AR	—	72.7 fg
		P = 0.0022

[a] Least squares means within columns followed by the same letter were not different according to a least squares means test. Dash (—) indicates means not presented due to a nonsignificant *F*-test (P > 0.05).

competitiveness against weeds, often attributable to the cumulative effects of incremental differences (Chauhan and Johnson 2010a,b; Dingkuhn et al. 1999; Fischer et al. 1997; Fofana and Rauber 2000; Gealy et al. 2005; Gealy and Moldenhauer 2012; Gealy and Yan 2012; Gibson et al. 2001; Gibson et al. 2003; Perera et al. 1992; Pérez de Vida et al. 2006; Zhao et al. 2006).

Late-Season Data (Plant Height, Vegetation Duration, Grain Yield). The main effect trends for irrigation system and weed management observed for rice height at preflood were reversed in the late season in many cases as the influences of weed interference increased and the initial herbicide-induced stress diminished (Table 4). Clomazone-induced rice stress early in the growing season can subside later in the season with little detectable effect on the crop rice (Scherder et al. 2004; Zhang et al. 2004, 2005). The FU system reduced mature rice height by an average of 23% relative to the FL; however, this height reduction appeared to be more pronounced in Rondo (~ 29%) than in Wells (~ 19%) (Table 4). Low management reduced mature rice height by 11.4% (management main effect) relative to high management (Table 4). Averaged over cultivar, mature rice height was greatest for FL : high and FL : med (98 cm average) and least for FU : low (67 cm) (P = 0.0589) (data not shown). The combination of FU irrigation and low herbicide inputs severely stunted the growth of all rice cultivars. Over all management levels, CLXL729 was the tallest cultivar in both irrigation systems (Table 4).

Vegetation duration was ~ 1 and 2 d longer in the med and high management levels, respectively, compared to the low level, and was ~ 3 d longer in the FU system compared to the FL system (Table 5). However, vegetation duration was greater in the FU system for only the cultivars PI 312777 (P < 0.0001), Rondo (P = 0.0004), and Bengal (P = 0.0053) (averaging 7 d), and was similar at both irrigation levels for all other cultivars (P > 0.13) (Table 5). Borrell et al. (1997) also observed delayed heading (up to 5 d), and shorter reproductive and grain filling periods (up to 5 and 9 d, respectively) in FU systems compared to FL systems. In our studies, CLXL729 was the only cultivar for which vegetation duration was similar in all irrigation by management combinations (P = 0.1398 vs. P ≤ 0.0469 for all other cultivars), and was also the cultivar with the shortest vegetation duration overall (77 d) (data not shown). Our results suggest that FU systems may delay heading (and potentially maturity) of indica and medium-grain cultivars more adversely than those of conventional cultivars and hybrids.

Regardless of management level or cultivar, the FU system reduced rice yield by ~ 76% relative to the conventional FL (Table 5). In 2010, yield reduction was particularly great due to periods of drought and heat stress throughout the growing season. Considerable blanking occurred in panicles of most cultivars, and Bengal in particular (data not

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Table 5. Vegetation duration and grain yield of seven rice cultivars in flood- and furrow-irrigated systems at three weed management levels in a 3-yr field study in Stuttgart, AR.[a,b,c,d]

	Vegetation duration[a]	Grain yield[a]	
	———— days ————	kg ha^{-1}	% Reduction relative to "flood-high" standard for each cultivar[a]
Management main effect			
Low	82.2 a	1440 b	—
Medium	83.1 b	2854 a	—
High	84.0 c	3402 c	—
	P < 0.0001	P < 0.0001	
Cultivar × irrigation interaction			
Flood			
PI 312777	82.7 c–f [b,c]	5224 a	15.9 d
Rondo	82.2 c–f [b,c]	4889 ab	24.8 cd
CLXL729	77.2 f [b]	5045 a	35.9 a–c
Bengal	78.6 ef [b,c]	3938 cd	31.4 b–d
Wells	83.6 b–e [b]	4144 bc	35.4 a–c
Lemont	85.1 b–d	2649 e	52.2 a
CL171AR	82.6 c–f [b]	3078 de	45.4 ab
Furrow			
PI 312777	92.6 a [c]	1627 f	74.3 C
Rondo	88.9 ab [b,c]	1279 fg	78.6 C
CLXL729	77.0 f [b]	1714 f	76.5 C
Bengal	83.8 b–e [b,c]	1001 f–h	81.0 BC
Wells	82.4 c–f [b]	658 gh	88.4 AB
Lemont	86.9 bc [b]	127 h	96.2 A
CL171AR	79.8 d–f	542 gh	88.1 AB
	P < 0.0001	P = 0.0037	P < 0.0001 (flood only; furrow only)
Irrigation × management			
Flood-low	81.0 b [d]	2430 c	54.8 a
Flood-medium	81.5 b [d]	4634 b	14.0 b
Flood-high	82.6 ab [d]	5350 a	—
Furrow-low	83.3 ab [d]	449 e	92.7 A
Furrow-medium	84.7 ab [d]	1073 d	81.8 B
Furrow-high	85.4 a [d]	1455 d	75.4 C
	P = 0.1170	P < 0.0001	P < 0.0001(flood only; furrow only)

[a] Least squares means within columns followed by the same letter were not different according to a least squares means test. In the column for grain yield reduction, lowercase letters refer to the flood-irrigated system and uppercase letters refer to the furrow-irrigated system because analyses of the two systems were conducted separately. Therefore, the values for irrigation systems in this column cannot be compared directly.

[b] Vegetation duration, cultivar × irrigation interaction: The following additional pairs are significantly different. (Rondo, furrow; Bengal, furrow), (Lemont, furrow; Wells, furrow), (Wells, flood; Bengal, flood), (PI 312777, flood; CLXL729, flood), (CL171AR, flood; CLXL729, flood), (Wells, furrow ; CLXL729, furrow), (Rondo, flood; CLXL729, FL).

[c] Vegetation duration, cultivar × irrigation: PI 312777 (P < 0.0001), Rondo (P = 0.0004), and Bengal (P = 0.0053) differed between the two irrigation systems, whereas all other cultivars were similar in both systems(P > 0.13).

[d] Vegetation duration, irrigation × management interaction: The following additional pairs are significantly different. (flood, high; flood, medium), (flood, high; flood, low), (furrow, high; furrow, low), (furrow, medium; furrow, low).

shown). Also in 2010, we observed that grain predation by birds reduced yields, particularly in CLXL729. In 2009 the early-season clomazone injury to rice in FU plots noted previously, and a late-season application of bentazon + acifluorfen to control broadleaved weeds in high-management FU plots (Table 1), also may have reduced yields. Visual injury (as leaf bronzing) in the aforementioned bentazon + acifluorfen plots on August 17 was particularly pronounced on PI 312777 (31% injury), Bengal (25%), Rondo (21%), and CLXL729 (20%), and was ≤ 15% for all other cultivars (data not shown).

Averaged over irrigation system and cultivar, med and low weed management reduced yield by 16 and 58%, respectively, compared to the high level (Table 5). In other reports, yield reduction in FU rice plots that were not treated with herbicide

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ranged from 23 to 100% less (averaging ~ 89%) compared to FU plots receiving optimal herbicide treatments (Bagavathiannan et al. 2011; Norsworthy et al. 2008, 2011).

Weed-suppressive indica cultivars and the hybrid produced yields greater than most commercial cultivars in both irrigation systems (Table 5). CLXL729 and PI 312777, averaging 3,400 kg ha^{-1}, produced the highest yields, and Lemont and CL171AR the lowest (1,600 kg ha^{-1}), with Bengal and Wells intermediate (2,440 kg ha^{-1}) (Table 5).

While yields of Lemont and CL171AR in FL plots were about 51 and 59% that of PI 312777, respectively, they were only 7.9 and 33% that of PI 312777 in FU plots (Table 5). Similarly, yields of PI 312777, Rondo, and CLXL729 were reduced proportionately less in the FU system (averaging 76%) than were the yields of Wells, Lemont, and CL171AR (averaging 91%) (Table 5).

All weed management levels in the FL system yielded more than in the FU system, and under high weed management, the FL plots out-yielded FU plots by 73% (Table 5). Grain yield in FL plots was 13% lower under med than high management, but in FU plots, it was similar at these two management levels (Table 5). Overall, the FL : high treatment produced the greatest yields (5,350 kg ha^{-1}) and the FU : low treatment produced the lowest yields (449 kg ha^{-1}) (Table 5).

When expressed relative to the FL : high standard for each cultivar, yields across all management levels in FL plots were reduced an average of only 20% in PI 312777 and Rondo compared to 49% for Lemont and CL171AR (Table 5). Similarly, yields in FU plots expressed relative to the same FL : high standard were reduced an average of 76% in PI 312777, Rondo, and CLXL729, compared to 91% for Wells, Lemont, and CL171AR (Table 5). When expressed relative to the FL : high value for PI 312777 (as a single, "high-productivity" standard), yields in FL plots were reduced by an average of ~ 16% ($P < 0.0013$) in CLXL729 and Rondo, and 30 to 55% ($P < 0.0001$) in the other cultivars, whereas in FU plots, yields of all cultivars were reduced by 73 to 98% (data not shown).

Consistent with the results from our study, reduced rice yields have been reported for other FU irrigation systems. In a comparison of hybrid varieties in different production systems on silt loam soils, yields from flooded plots averaged 10,886 kg ha^{-1}, whereas yields from row-irrigated (FU) plots were 7,157 kg ha^{-1} to 7,560 kg ha^{-1} (i.e., 31 to 34% lower) (Anders et al. 2012). A hybrid, 'CLXL745', grown under FU irrigation in a 2009 farm verification program, yielded 8,669 kg ha^{-1} compared to 9,526 kg ha^{-1} for other hybrids in the program and the overall average program yield of 9,072 kg ha^{-1} (Runsick et al. 2010). In an FU system on a clay loam soil in which irrigation water was applied on a fixed schedule, rice yield was 4,700 kg ha^{-1}, a ~ 50% decrease from the yield of 10,200 kg ha^{-1} noted for conventionally flooded systems (Stephenson et al. 2008). In their FU system, total kernels and filled kernels $panicle^{-1}$ were greater for 'XL 723' hybrid rice than for 'Cybonnet' and were greater for the rice grown on the bed than in the furrow (Stephenson et al. 2008). In FU systems on clay soils, Lemont rice yielded 41% less (Borrell et al. 1997), and 'Tebonnet' yielded 15% less (Vories et al. 2002) than in a full-season flooded system.

FU irrigation is used on a small fraction of Arkansas rice (~ 1.4% of rice area, 2007-2009; Wilson et al. 2010). These systems generally are best suited to fields with adequate irrigation pumping capacity (to insure rapid, uniform coverage of irrigated area), a water recovery system, steep or uneven slopes (that would otherwise require numerous nonproductive levees), and hybrid rice varieties (MM Anders, personal communication). Water savings have been reported for some FU systems. In the Anders et al. (2012) study, FU reduced water usage ~ 44% (21 cm ha vs. 37 cm ha) when compared to the FL system (assuming a 30% recapture of water from the low-elevation end of the field). They also estimated that FU increased the water-to-yield conversion efficiency by 15% (711 kg H_20 kg $grain^{-1}$ vs. 839 kg H_20 kg $grain^{-1}$) compared to the FL system. In the Runsick et al. (2010) test, FU reduced water usage of CLXL745 hybrid rice by ~ 47% (14.4 cm ha vs. 27 cm ha) compared to the program average. In other FU systems, Stephenson et al. (2008) estimate total irrigation water usage and combined irrigation + rainfall usage at 42.7 cm and 70.6 cm, respectively; Borrell et al. (1997) reported reduced water usage of 38%; and Vories et al. (2002) reported a decreased water usage of 70% and an increased water use efficiency of 180%, compared to conventional FL systems.

The highest yields from our study (FL : high weed management; Table 5) were ~ 28% lower than average Arkansas farm yields (5,350 kg ha^{-1} vs. 7,426 kg ha^{-1}) and ~ 38% lower than from farms optimally managed in a verification program (3-yr average, 8,652 kg ha^{-1}) (Mazzanti et al. 2011, 2012; Runsick et al. 2010). Our later planting dates (averaging May 22 vs. April 21) and 38% lower N fertilizer rates (112 kg ha^{-1} vs. 182 kg ha^{-1})

compared to optimally managed farm verification trials (Mazzanti et al. 2011, 2012; Runsick et al. 2010) may have contributed to the overall lower yields in the present study. Because the risk of N fertilizer loss from FU systems can be greater than in FL systems, higher N rates are sometimes applied to FU fields (Runsick et al. 2010). However, in past weed-suppressive rice tests, we have routinely used reduced N rates as part of an overall approach to reduce input costs and the "environmental footprint" from all chemical sources, as well as to reduce lodging and diseases, which can result in substantial yield losses in fields infested heavily with weeds (Gealy et al. 2003; Gealy and Moldenhauer 2012; Gealy and Yan 2012; DR Gealy, unpublished data). Diseases such as false smut can also be problematic in FU systems (Brooks et al. 2010; Runsick et al. 2010).

Nutrient stress conditions are common in low-input agriculture, and "low-N" stress has been associated with enhanced allelopathic activity of PI 312777, which was accompanied by activation of genes involved in synthesis of allelochemicals (Fang et al. 2010; Song et al. 2008). Lin et al. (2010) reported that under low-N stress, increased allelopathic potential was associated with increased expression of genes involved in phenolic biosynthesis. Thus, this trait could contribute to the potential suitability of PI 312777 and similar germplasm lines for low-input systems. Stephenson et al. (2008) indicated that average head rice milling yields of FU Cybonnet and XL723 hybrid rice were greater than 60% (similar to levels in conventional rice). However, Borrell et al. (1997) found that milling yield was reduced by 33% (to an average of 33.7%) in an FU system. PI 312777 and Rondo have low milling quality compared to conventional cultivars (Gealy et al. 2003; Yan and McClung 2010). Bryant et al. (2012) showed that FU irrigation had no major impact on physicochemical properties.

PI 312777 and CLXL8 hybrid rice also produce greater fractions of their root mass near the soil surface compared to nonsuppressive conventional cultivars (Gealy et al. 2013a). Those studies suggested that root proliferation near the soil surface might work in concert with the allelochemicals released from roots, thus enhancing the weed-suppressive activity. Roots of weed-suppressive indica seedlings also proliferated relatively more in the upper rooting profile of gel-based media as compared to Lemont (Clark et al. 2011; Iyer-Pascuzzi et al. 2010). Total root mass of weed-suppressive cultivars has been reported to be greater than (Dilday et al. 2001a) or similar to (Gealy and Moldenhauer 2012; Gealy et al. 2013a) root mass of nonsuppressive cultivars.

Weed biomass has been negatively correlated with rice root growth at early as well as later growth stages (Fofana and Rauber 2000), and competitiveness against growth of target plants was reported to be greater for roots than shoots in most "root–shoot" studies (Wilson 1988). Root interference by *Echinochloa* species has been shown to be more important than shoot interference (Gibson et al. 1999; Perera et al. 1992), but in direct-seeded rice, competition from junglerice [*Echinochloa colona* (L.) Link] shoots reduced rice yields more than competition from roots (Chauhan and Johnson (2010a).

Weed Growth and Development. *Preflood Data.* The sources and levels of variation from the statistical analysis of the weed data are presented in Table 6. Means from the analyses of low management plots only are presented in Table 7. Means from the analyses that included all three management levels were omitted from this table because such a small number of weed plants survived the preflood herbicide treatment in the med and high management plots that a large number of plots with missing data resulted. In the low management plots, barnyardgrass densities were lowest in PI 312777 (60.1 plants m^{-2}) < Lemont (87.4 plants m^{-2}) and no rice (93.1 plants m^{-2}), with all other cultivars intermediate between these or nonsignificant (Table 7). Barnyardgrass density in PI 312777-FU (53 plants m^{-2}) and Rondo-FL (62.5 plants m^{-2}) was significantly less than no rice-FL (108 plants m^{-2}), with no significant differences among the remaining cultivars (data not shown). With all management levels included in the analysis, barnyardgrass densities for both med and high management levels were reduced by 96% compared to the density of 73.3 plants m^{-2} at low management ($P < 0.0001$; data not shown).

Barnyardgrass was the predominant weed species in these tests, but other species were sometimes present at low densities. These included eclipta [*Eclipta prostrata* (L.) L.], smooth groundcherry [*Physalis longifolia* (Nutt.) var. *subglabrata* (Mackenzie & Bush) Cronq..], prickly sida (*Sida spinosa* L.), and pitted morningglory (*Ipomoea lacunosa* L.), primarily in FU plots, and Amazon sprangletop [*Leptochloa panicoides* (J. Presl) A. S. Hitchc.], large crabgrass [*Digitaria sanguinalis* (L.) Scop.], fall

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Table 6. ANOVA table showing sources of variation and P values for weed variables.

Source of variation	Preflood barnyardgrass data: Plant density, Low management	Plant density, All management levels	Leaf number, Low management	Leaf number, All management levels	Height, Low management	Height, All management levels	Late-season data: Weed suppression at maturity	Weed biomass at harvest, Grass	Weed biomass at harvest, Total
	Plants m^{-2}	Plants m^{-2}	Leaves $plant^{-1}$	Leaves $plant^{-1}$	cm	cm	%	g m^{-2}	g m^{-2}
Cultivar	0.0020	0.0683	0.3439	0.3503	0.5379	0.2894	< 0.0001	< 0.0001	< 0.0001
Irrigation system	0.3018	0.5665	0.0363	0.0127	0.0112	0.0034	< 0.0001	< 0.0001	< 0.0001
Management level	—	<0.0001	—	<0.0001	—	<0.0001	< 0.0001	< 0.0001	< 0.0001
Cultivar × irrigation system	0.4806	0.8886	0.4869	0.4507	0.3596	0.5724	0.9060	0.5110	0.3418
Cultivar × management level	—	0.3241	—	0.7236	—	0.2527	0.0064	0.3639	0.4451
Irrigation system × management level	—	0.1152	—	0.7291	—	0.0051	0.0854	0.3932	0.2493
Cultivar × irrigation system × management level	—	0.9624	—	0.6547	—	0.7709	0.1815	0.0008	0.0005

panicum (*Panicum dichotomiflorum* Michx.), ducksalad [*Heteranthera limosa* (Sw.) Wild.], and redstem (e.g., *Ammannia coccinea* Rottb.), primarily in FL plots (data not shown). Similar weed flora has been noted in other FU systems (Bagavathiannan et al. 2011; Norsworthy et al. 2008, 2011).

In the low-management plots, the leaf number of barnyardgrass in the FU system was 16% greater (6.4 vs. 5.5 leaves $plant^{-1}$) than in FL (Table 7). This difference was mostly due to Bengal ($P = 0.0248$), CL171AR ($P = 0.0526$), Lemont ($P = 0.0591$), and CLXL729 ($P = 0.0620$), which averaged an increase of 20% for FU compared to FL, whereas Rondo, PI 312777, and Wells did not differ between irrigation system ($P \geq 0.15$; data not shown). The reason for this early effect due to irrigation system is unknown, but during the preflood period, the soil environments in the FU and FL systems may have differed slightly due to the fact that FU plots were bedded, which established an alternating arrangement of raised beds and sunken furrows. When all three management levels were included in the analysis, the irrigation main effect mean for barnyardgrass leaf number was less in FL than in FU (4.6 vs. 5.6; $P = 0.0127$) (data not shown). Similarly, the management main effect means for barnyardgrass leaf number were low (5.9) > med and high (4.8 and 4.5) ($P < 0.0001$) (data not shown), indicating that the relatively few weed plants that survived the early season herbicide applications had been stunted.

In the low-management plots, barnyardgrass height in the FU system averaged 44% greater (21.5 vs. 14.9 leaves $plant^{-1}$) than in the FL (Table 7). These heights trended greater in FU plots for all cultivars ($P = 0.0577$ to 0.0025), except for PI 312777 ($P = 0.1609$), in which barnyardgrass heights were similar in both systems (data not shown). Thus, the density and leaf number of barnyardgrass in the FL PI 312777 plots tended to be lower compared to the other cultivars even though barnyardgrass height was similar (and trending higher). When all three management levels were included in the analysis for preflood barnyardgrass height, the irrigation by management interaction means followed the following trend: FL high (10.3 cm) and FL med (11.4 cm) < FL low (14.9 cm) < FU med (17.8 cm) < FU low (21.5 cm) and FU high (22.2 cm) ($P = 0.0051$; data not shown).

Late-Season Data. Weed suppression ratings averaged 21% greater in FL (70.3% suppression) than

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Table 7. Barnyardgrass plant density, leaf number, and height before flooding in seven rice cultivars grown under flood or furrow irrigation systems in plots with low management levels at Stuttgart, AR over 3 yr.[a]

Rice cultivar	Plant density	Leaf number	Height
	Plants m^{-2}	Leaves $plant^{-1}$	cm
Cultivar main effect			
PI 312777	60.1 b	—	—
Rondo	67.2 ab	—	—
CLXL729	71.4 ab	—	—
Bengal	66.0 ab	—	—
Wells	74.6 ab	—	—
Lemont	87.4 a	—	—
CL171AR	69.3 ab	—	—
No Rice	93.1 a	—	—
	P = 0.0020		
Irrigation main effect			
Flood	—	5.5 b	14.9 b
Furrow	—	6.4 a	21.5 a
		P = 0.0363	P = 0.0112

[a*] Values in table are least squares means over 3 yr. Means within columns followed by the same letter were not different according to a least squares means test. Dash (—) indicates means not presented due to a nonsignificant *F* test (P > 0.05).

in the FU system (55.2% suppression), and averaged 55 and 16% lower in low (37% suppression) and med (69% suppression) management levels, respectively, than in high management (82% suppression) (Table 8 footnote).

Weed suppression ratings for PI312777 and XL729 (average 77%) were greater than for Bengal, CL171AR, and Lemont (61% average), whereas Wells and Rondo were intermediate (P < 0.0001; cultivar main effect) (Table 8). High yield potential, as demonstrated by PI312777 and XL729 (Table 5), has been associated with weed suppression in some studies (Gealy and Moldenhauer 2012; Gealy and Yan 2012; Pérez de Vida et al. 2006; Zhao et al. 2006), but not in others (Gealy et al. 2013a).

Relative to the FL : high "conventional standard" (90% rating), the FU : low (31% rating), FL low, FU : med, FU : high, and FL med (78% rating) treatment combinations reduced weed suppression ratings by 66, 52, 33, 17, and 13%, respectively (P = 0.0854) (Table 8). Thus, the overall weed suppression in the FU : high and FL : med treatments was somewhat comparable.

Weed suppression ratings for all cultivars under high management levels were similar, averaging 88.5% (Table 8). However, weed suppression by PI 312777 (85.3%), CLXL729 (82.3%), Rondo (79.5%), and Wells (74.9%) under med management was similar to that of Bengal (86.4%), CL171AR (84.9%), and Lemont (81.4%) under high management. Importantly, weed suppression by PI 312777 under low management (58.7%) was similar to Bengal (69%), CL171AR (67.7%), and Lemont (60.5%) under med management (P = 0.0064) (Table 8).

Grass weed biomass averaged 48% greater in the FU system (288 g m^{-2}) than in FL (195 g m^{-2}) (irrigation main effect; Table 8). However, grass weed biomass for CLXL729 (P = 0.5897) and PI 312777 (P = 0.1494) were similar at both irrigation levels, whereas for all other cultivars, it was significantly lower in the FL system than in FU (P < 0.039) (Table 8). These results show that PI 312777 and CLXL729 have good potential for weed-suppressive ability in reduced irrigation systems as well as conventionally flooded systems. Grass weed biomass was 67 and 280% greater under med (186 g m^{-2}) and low (427 g m^{-2}) management, respectively, than in the conventional high management (111 g m^{-2}), and was 87 and 190% greater in CL171AR and Lemont, respectively, than in PI 312777 (management and cultivar main effects, respectively; Table 8).

There was a cultivar by irrigation by management interaction (P = 0.0008) because grass weed biomass for Lemont was greater than PI 312777 in the FL : low and FU : med treatment, and greater than PI 312777, CLXL729, and Wells in the FU : high treatment, but otherwise was similar to these cultivars for the other treatment combinations (Table 8). Grass weed biomass averages ranged from 463 g m^{-2} (FU : low) > 392 g m^{-2} (FL : low) > 234 g m^{-2} (FU : med) > 167 g m^{-2}

Table 8. Weed suppression and biomass in seven rice cultivars grown under flood or furrow irrigation systems at three weed management levels at Stuttgart, AR, over 3 yr. [a–e]

Cultivar	Irrigation system	Weed management level	Weed suppression[b]	Grass weed biomass[c]	Total weed biomass[d,e]	
			——— % ———	g m^{-2}	g m^{-2}	% Reduction from no rice–low management
PI 312777	Flood	Low	58.7 f–h	189 g–r	189 h–m	78.8 a–c
		Medium	85.3 ab	60 n–r	62 l–n	93.5 a
		High	93.8 a	9 r	9 o	99.1 a
	Furrow	Low	—	321 d–n	329 c–k	49.5 B–G
		Medium	—	80 m–r	97 k–n	85.2 AB
		High	—	38 p–r	39 m–o	94.9 A
Rondo	Flood	Low	44.1 h–j	307 d–o	307 d–k	60.2 cd
		Medium	79.5 a–d	55 o–r	55 l–o	93.9 a
		High	90.5 ab	7 r	7 o	98.9 a
	Furrow	Low	—	432 b–h	442 b–h	28.2 E–I
		Medium	—	142 i–r	180 i–o	71.9 A–C
		High	—	163 i–r	168 i–o	76.2 A–C
CLXL729	Flood	Low	49.5 g–i	353 b–k	353 c–k	58.1 cd
		Medium	82.3 a–d	100 k–r	100 k–o	89.7 ab
		High	91.8 a	5 r	6 o	99.5 a
	Furrow	Low	—	369 b–k	377 b–j	38.9 C–H
		Medium	—	129 i–r	141 i–o	79.0 A–C
		High	—	30 p–r	31 m–o	95.1 A
Bengal	Flood	Low	38.5 i–k	279 e–q	280 e–n	64.8 b–d
		Medium	69.0 c–f	93 l–r	93 k–o	89.8 ab
		High	86.4 ab	22 r	22 o	97.9 a
	Furrow	Low	—	479 a–f	486 a–f	17.6 G–I
		Medium	—	185 g–r	218 f–o	68.9 A–E
		High	—	122 j–r	136 j–o	81.4 AB
Wells	Flood	Low	35.9 i–k	337 b–m	339 c–k	54.9 cd
		Medium	74.9 b–e	99 l–r	99 k–o	88.6 ab
		High	90.8 a	28 qr	29 no	96.9 a
	Furrow	Low	—	525 a–e	530 a–e	10.4 G–I
		Medium	—	174 i–r	203 g–o	69.8 A–D
		High	—	36 p–r	41 l–o	93.4 A
Lemont	Flood	Low	26.0 k	549 a–d	549 a–d	25.0 e
		Medium	60.5 e–g	213 f–r	214 f–o	76.2 a–d
		High	81.4 a–d	37 p–r	37 m–o	95.9 a
	Furrow	Low	—	540 a–e	545 a–d	6.4 HI
		Medium	—	376 b–j	415 b–h	30.2 D–I
		High	—	325 c–n	347 c–k	48.0 B–F
CL171AR	Flood	Low	38.9 i–k	388 b–j	389 b–i	50.2 de
		Medium	67.7 d–f	100 k–r	100 k–o	88.1ab
		High	84.9 a–c	28 qr	28 no	96.5 a
	Furrow	Low	—	450 b–g	462 b–g	25.9 F–I
		Medium	—	173 h–r	227 f–o	65.4 A–F
		High	—	163 i–r	169 i–o	75.8 A–C
No rice	Flood	Low	3.6 l	733 a	733 a	—
		Medium	32.5 jk	393 b–i	395 b–j	54.1 cd
		High	39.6 i–k	298 d–p	298 d–m	63.0 b–d
	Furrow	Low	—	586 a–c	587 a–c	—
		Medium	—	608 ab	635 ab	−9.3 I
		High	—	470 a–f	478 a–f	23.9 G–I
			P = 0.0064	P = 0.0008	P = 0.0005	P = 0.0174 (flood only): P = 0.3181 (furrow only)

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Table 8. Continued.

[a] Least squares means within columns followed by the same letter were not different according to a least squares means test.

[b] Weed suppression data presented in the table are means for cultivar × management interaction (averaged over irrigation level). Main effect means for weed suppression at low, med, and high management levels were 36.9 < 69.0 < 82.4%, respectively ($P < 0.0001$); and for the flood-irrigated and furrow-irrigated systems were 70.3 > 55.2%, respectively ($P < 0.0001$). Cultivar × irrigation interaction: the percentage of weed suppression for flood-irrigated systems was > furrow-irrigated systems for all cultivars ($P < 0.006$) (data not shown).

[c] Grass weed biomass: Main effect means for grass weed biomass for the flood-irrigated and furrow-irrigated systems were 195 < 288 g, respectively ($P < 0.0001$) (data not shown). Cultivar × irrigation interaction: grass weed biomass for CLXL729 ($P = 0.5897$), PI 312777 ($P = 0.1494$), and no rice ($P = 0.0664$) was similar at both irrigation levels, but for all other cultivars, grass weed biomass in flood-irrigated was < furrow-irrigated ($P < 0.039$) (data not shown).

[d] Total weed biomass (g m^{-2}): Main effect means for the flood-irrigated and furrow-irrigated systems were 196 < 303 g, respectively ($P < 0.0001$) (data not shown). Cultivar × irrigation interaction: total weed biomass was similar at both irrigation levels for CLXL729 and PI 312777 ($P \geq 0.05$), but for all other cultivars, total weed biomass flood-irrigated was < furrow-irrigated ($P < 0.05$) (data not shown).

[e] The analysis of % reduction of total weed biomass from "no rice–low management" was conducted separately for flood-irrigated and furrow-irrigated. The lowercase letters and uppercase letters following the means apply only to flood-irrigated and furrow-irrigated values, respectively.

(FU : high) = 139 g m^{-2} (FL : med) > 54 g m^{-2} (FL : high) (irrigation by management interaction; detailed data not shown).

Barnyardgrass and other grass weeds such as Amazon sprangletop, large crabgrass, and fall panicum dominated the population of weeds present in this study. Thus, total weed biomass production was usually similar to that of the grass weed biomass (Table 8). The cultivar by irrigation by management interactions for total weed biomass ($P = 0.0005$) were similar to those described for grass weed biomass above (Table 8).

Although FU plots were infested with the grass species such as barnyardgrass, fall panicum, crabgrass, and Amazon sprangletop, they were sometimes highly infested with broadleaf species such as eclipta, smooth groundcherry, prickly sida, and morningglory species. Weeds infesting FL plots consisted mostly of barnyardgrass, but sometimes included ducksalad and red stem if the rice stands were low (data not shown). Thus, proportionately more broadleaved weeds were present in FU than FL (i.e., causing a disproportionate increase in FU total weed biomass relative to grass weed biomass. Total biomass overall averaged 55% greater in the FU (303 g m^{-2}) than in the FL system (196 g m^{-2}) (Table 8).

In an FU system growing imidazolinone-resistant hybrid rice, combinations of clomazone and imazethapyr have been used for PRE control of prickly sida, Palmer amaranth (*Amaranthus palmeri* S. Wats.), pitted morningglory, barnyardgrass, and broadleaf signalgrass (*Urochloa platyphylla* (Nash) R.D. Webster) (Norsworthy et al. 2008). In a similar (but non–herbicide-resistant) hybrid rice system, clomazone PRE followed by propanil POST provided the best overall control of a similar weed species spectrum (Bagavathiannan et al. 2011). Weeds in these systems emerged throughout the growing season, and terrestrial species such as Palmer amaranth frequently required additional "as-needed" herbicide treatments later in the season (Bagavathiannan et al. 2011; Norsworthy et al. 2011). Morningglory species typically tolerate flooding poorly (Gealy 2003), and thus do not usually affect rice yield appreciably in FL systems. Borrell et al. (1997) showed that weed biomass levels in Lemont averaged ~ 16 times greater in an FU system compared to a flooded system. Thus, additional herbicide or management costs can be required in nonflooded systems (Bagavathiannan et al. 2011; Borrell et al. 1997; Norsworthy et al. 2011).

Total weed biomass was 76 and 275% greater under med (202 g m^{-2}) and low (431 g m^{-2}) management, respectively, than in the conventional high management (115 g m^{-2}) (Table 8). Based on the irrigation by management interaction (not shown), most of the influence of broadleaf weeds appeared to be from the FU : med treatment, where total weed biomass was 13% greater than grass biomass (Table 8). By contrast, total biomass in the FU : high and FU : low treatments was 4.8 and 1.5% greater respectively, than grass biomass, and the grass and total biomass were similar among FL treatments (Table 8).

Under FL irrigation, the reduction of total weed biomass relative to a "no rice–low management" standard ranged from 25% for Lemont to 79% for PI 312777 with low management, and was greater than 96% for all cultivars with high management ($P = 0.0174$) (Table 8). Under FU irrigation however, the

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reduction of total weed biomass (expressed as above) ranged from only 6% for Lemont to 50% for PI 312777 with low management, and from 48% for Lemont to ~ 95% for PI 312777 and CLXL729 (P=0.3181) with high management (Table 8).

Results from Tables 4 and 8 support earlier studies in which cultivar height at preflood or late-season were not associated with the greater weed suppression by weed-suppressive cultivars (Gealy et al. 2013a; Gealy and Moldenhauer 2012; Gealy et al. 2013b; Gealy and Yan 2012). In other studies, however, taller cultivars have suppressed weeds more effectively (Fischer et al. 1997; Gibson et al. 1999; Pérez de Vida et al. 2006;). In a comparison of three flooded and two nonflooded systems, total weed biomass was negatively correlated ($r^2 = 0.80$) with total water use in the different irrigation systems (Borrell et al. 1997).

In these studies, weed-suppressive cultivars outperformed conventional cultivars in both irrigation systems. In some cases, suppressive cultivars (e.g., PI 312777 and CLXL729) under med management suppressed weeds as much as nonsuppressive cultivars (e.g., Lemont and CL171AR) at high management. Yield and weed suppression for the commercial cultivars in this study were highest for CLXL729 and Bengal and lowest for Lemont and CL171AR under the broadest range of treatments. The highest grain yields and the lowest weed biomass was produced in plots of the weed-suppressive cultivars, even though overall rice productivity was markedly reduced in the FU system at all management levels. The weed-suppressive cultivars, therefore, exhibited relatively greater yield potential and feasibility for use in FU systems than do the conventional nonsuppressive cultivars. Weed-suppressive cultivars performed best in both FL and FU systems, and in some cases, yields and weed suppression at reduced levels of herbicide management for these cultivars were equal to those of conventional nonsuppressive cultivars at higher management levels. Weed control and crop productivity of weed-suppressive cultivars in related reduced-input intermittent-flooding experiments have been promising (DR Gealy, unpublished data), and have been shown to be highly water-efficient (~ 369 kg H_2O kg grain^{-1}) while yielding only ~ 5% less than flooded plots under weed-free conditions (Anders et al. 2012).

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