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Weed Suppression Potential of 'Rondo' and Other Indica Rice Germplasm Lines

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Research was conducted to evaluate the weed suppression potential of 'Rondo' (4484-1693; PI 657830), a sister line (4484-1665), and other indica rice lines against barnyardgrass in field plots in Stuttgart, AR, using minimal herbicide inputs in two separate 3-yr experiments. Under weed pressure, Rondo and the sister line (4484-1665) generally produced yields that were comparable to those of weed-suppressive indica standards and approximately 50% greater than those of the least-suppressive commercial cultivars, such as 'Kaybonnet', 'Katy', and 'Lemont'. Rice yield under weed pressure was correlated with weed-free yield and harvest height. Indica lines tended to produce more tillers than did the commercial cultivars. Tillering potential under weed-free conditions was not correlated with weed suppression or yield loss; however, tillering under weed pressure was strongly correlated with weed suppression and biomass, and yield and yield loss under the weed densities in these experiments. Rondo is presently being used for commercial organic rice production in Texas, in part due to its high yield potential and ability to suppress or tolerate rice pests, including weeds. Our results suggest that the weed-suppressive ability of Rondo and the other indica lines evaluated in these experiments is superior to that of many commercial cultivars.

Nomenclature: Barnyardgrass, *Echinochloa crus-galli* (L.) Beauv.; rice, *Oryza sativa* L.
Key words: Crop–weed interference, competition, indica rice.

Se realizó una investigación en dos experimentos de 3 años de duración en parcelas de campo en Stuttgart, AR, para evaluar el potencial de supresión de malezas de ¨Rondo¨ (4484-1693; PI 657830), una línea hermana (4484-1665), y otras líneas de arroz *indica* contra *Echinochloa crus-galli*, con uso mínimo de herbicidas. Bajo presión de malezas, Rondo y la línea hermana (4484-1665) generalmente produjeron rendimientos que fueron comparables con los de las variedades de *indica* estándar para supresión de malezas y aproximadamente un 50% más que los cultivares comerciales con menor capacidad de supresión, tales como "Kaybonnet", "Katy" y "Lemont". El rendimiento del arroz bajo presión de malezas estuvo correlacionado con el rendimiento en condiciones libres de malezas y con la altura al momento de la cosecha. Las líneas *indica* tendieron a producir más hijos que los cultivares comerciales. El potencial de producción de hijos bajo condiciones libres de malezas no estuvo correlacionado con la supresión de malezas o pérdida en rendimiento. Sin embargo, la producción de hijos con presión de malezas estuvo altamente correlacionada con la supresión de malezas y la biomasa, con el rendimiento y la pérdida en rendimiento bajo las densidades usadas en estos experimentos. Rondo está siendo usada actualmente para producción comercial de arroz orgánico en Texas, en parte debido a su alto potencial de rendimiento y a su habilidad de suprimir o tolerar plagas del arroz, incluyendo malezas. Nuestros resultados sugieren que la habilidad de supresión de malezas de Rondo y otras líneas *indica* evaluadas en estos experimentos es superior a la de muchos cultivares comerciales.

Traditionally, the tropical japonica rice cultivars prevalent in the southern United States are grown in intensively managed systems that rely heavily on herbicides for weed control and do not possess high inherent levels of weed-suppressive activity (Gealy and Moldenhauer 2012; Gealy et al. 2003). Another rice subspecies, indica, has not been grown extensively in the United States but is increasingly being used in breeding programs as a source of high-yield, disease-resistant germplasm and, potentially, for weed suppression (Gealy and Moldenhauer 2012; Gealy et al. 2005; Marchetti et al. 1998; Rutger and Bryant 2005; Yan and McClung 2010).

Suppressive indica rice germplasm lines with high yield and weed interference potential in drill-seeded systems of the southern United States have been identified and evaluated in recent decades (Dilday et al. 2001a,b; Gealy et al. 2005). Effective suppression against aquatic weeds and barnyardgrass with potential economic benefits has been demonstrated for a number of these indica lines (Dilday et al. 2001a; Gealy and Moldenhauer 2012; Gealy et al. 2003, 2005). Commercial hybrids have also exhibited enhanced weed suppression in similar rice systems (Gealy and Moldenhauer 2012; Gealy et al. 2005; Ottis et al. 2005).

The U.S. rice industry has the expectation for new cultivars to produce yields and grain quality similar to or better than those of current cultivars. However, quality characteristics of the most weed-suppressive indica lines, such as PI 312777 (Gealy et al. 2003), have often been substandard. Rondo (breeding line 4484-1693)(Reg. No. CV-131, PI 657830), a high-yielding indica from Asia, was recently developed for use in the United States (Yan and McClung 2010). It is shorter, less prone to lodging, has higher amylose content than its parental line ('4484'; PI 615022), and was the result of Cs-137 irradiation and mutation breeding (Dilday et al. 2001b; Yan and McClung 2010). It is resistant to all major races of blast disease [*Magnaporthe grisea* (Hebert) Barr] that commonly occur in the United States and produces yields similar to elite cultivars such as 'Francis', 'Wells', and 'Cocodrie' (Yan and McClung 2010). Because of these desirable disease and yield traits and its apparent ability to suppress or tolerate weeds, it has been evaluated and adopted

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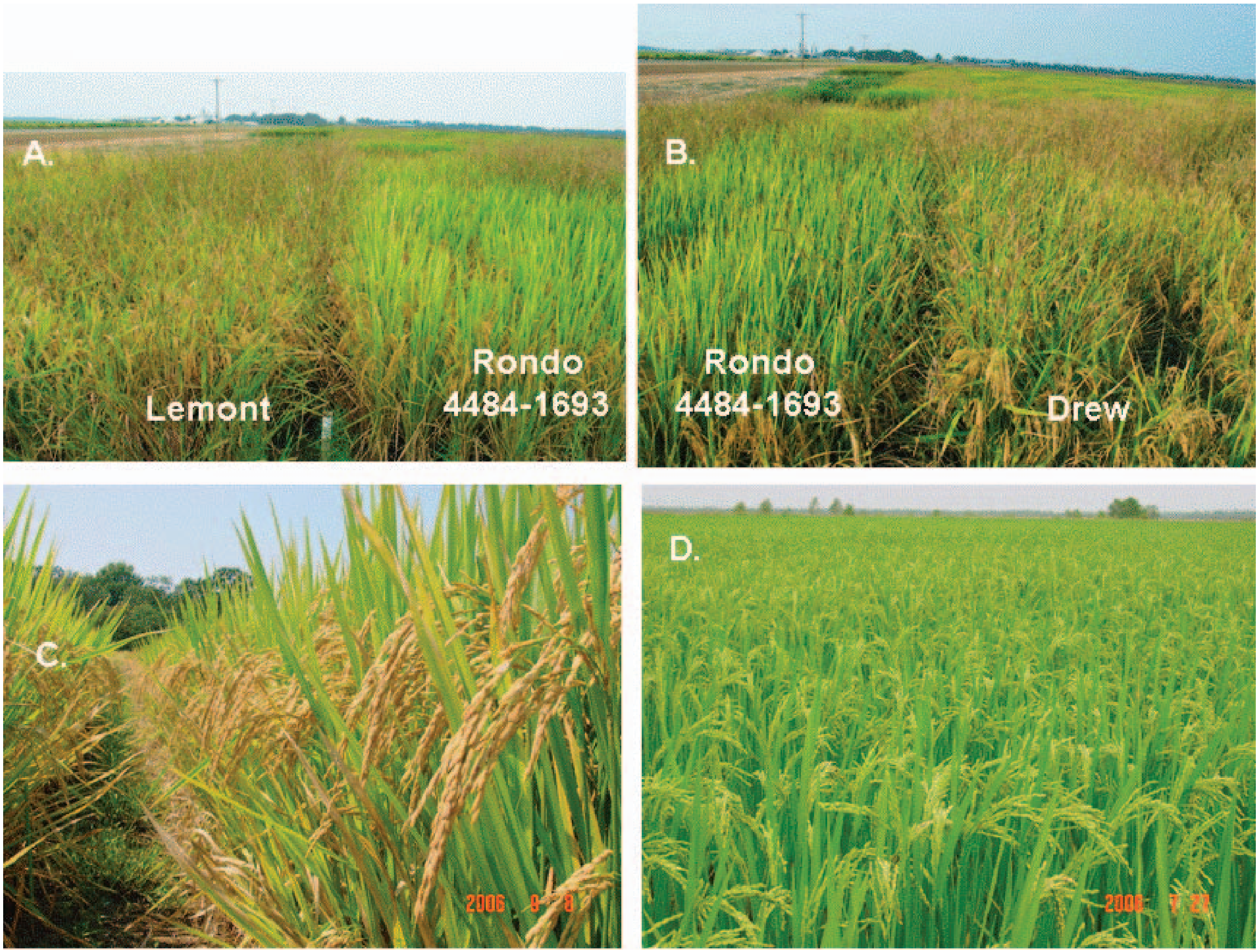

Figure 1. Rondo in demonstration plots with (A) Lemont and (B) Drew near Stuttgart, AR; plots were treated with only 1.12 kg ha^{-1} propanil (one-quarter of recommended rate) to achieve mild suppression of barnyardgrass; numerous barnyardgrass panicles can be seen protruding above the canopies of Lemont and Drew plots. (C) Rondo in a conventionally managed field plot near Brinkley, AR. (D) Rondo growing in a commercial organic rice field near China, TX.

in some organic production systems where it generally yielded more than commercial cultivars (C. Slack, personal communication; Zhou et al. 2009)(Figure 1). In 2005, to better understand its weed-suppression characteristics and resistance to yield loss under weed pressure in drill-seeded rice culture, experiments were initiated to compare Rondo, a sister line (4484-1665) derived from the same mutation project, and other Asian indica lines to U.S. commercial cultivars.

Materials and Methods

Field Experiments. Two 3-yr field experiments were conducted on a DeWitt silt loam (fine smectitic, thermic, Typic Albaqualfs) with 1.2% organic matter and a pH of 5.8 at the University of Arkansas Rice Research and Extension Center located near Stuttgart, AR (34.49°N, 91.55°W) as described previously (Gealy and Fischer 2010; Gealy and Moldenhauer 2012).

Experiment 1 was conducted with planting dates of June 1, 2005; May 18, 2006; and May 18, 2007; respectively. In this study, a sister line (4484-1665) of Rondo, was compared with the Asian indica lines, PI 312777, 4593 (PI 615031), and 4597 (PI 615035)(Dilday et al. 2001b), and to commercial U.S. long-grain ('Kaybonnet'; Gravois et al. 1995) and medium-grain ('Bengal'; Linscombe et al. 1993) cultivars. The sister line was use instead of Rondo because insufficient seed of Rondo was available initially for the field weed-suppression experiments. PI 312777, included as a ''highly suppressive'' standard, was developed in the Philippines from the cross T65*2/TN 1 (GRIN 2011). It is considered both weed-suppressive and allelopathic (Kato-Noguchi et al. 2005; Kong et al. 2006; Seal and Pratley 2010). This line and the other Asian indica lines used in our studies have proven to be suppressive to barnyardgrass in earlier field studies conducted in Arkansas (Gealy and Moldenhauer 2012; Gealy et al. 2003, 2005). All rice entries were grown in paired weedy and weed-free plots.

The plot layout was similar to that in previously described studies (Gealy and Fischer 2010; Gealy and Moldenhauer 2011). Plots were 3 m long with nine rows spaced 18 cm apart, and rice was drill-seeded approximately 2 cm deep at a density of 430 seeds m^{-2}. Barnyardgrass populations were established from a combination of natural infestations and supplemental broadcast-seeding with 12 kg live seed ha^{-1} (~1,400 live seeds m^{-2}) immediately after rice planting, and plots were firmed with a roller to facilitate barnyardgrass seed–soil contact and germination.

Herbicides were applied to weed-free plots to control barnyardgrass and other weeds as necessary. Herbicides were sprayed using a CO_2-powered backpack sprayer with 8001 flat fan nozzles on 51-cm centers, calibrated to deliver 94 L ha^{-1} at 159 kPa and a speed of 0.894 m s^{-1} enclosed in a shielded boom. Propanil plus quinclorac (4.4 kg ai ha^{-1} + 0.28 to 0.31 kg ai ha^{-1}) was applied POST when barnyardgrass plants were at the two- to four-leaf stage. The predominant weed species present in weedy plots was barnyardgrass, although other C_4 grass species, such as sprangletop (*Leptochloa* P. Beauv. spp.) and broadleaf signalgrass [*Urochloa platyphylla* (Nash) R. D. Webster](Gealy and Moldenhauer 2012), were sometimes observed. Thus, fenoxaprop (Ricestar HT; 0.09 kg ai ha^{-1} crop oil concentrate [1% v/v]) was also applied 16 to 34 d after crop emergence to assist with control of sprangletop, barnyardgrass, and other grass weed species. Propanil (1.12 kg ha^{-1}) was applied preflood to both weedy and weed-free plots with the goal of mildly suppressing barnyardgrass in the weedy plots. The mild suppression of barnyardgrass achieved by this one-quarter of the recommended rate of propanil helped reduce weed competition so that differences between cultivars could be discerned in weedy plots. Bentazon (0.55 kg ai ha^{-1}) was also applied preflood as necessary to control broadleaf weeds in all plots.

Urea at 112 kg N ha^{-1} was broadcast over all plots before flood establishment on July 15, 2005; July 7, 2006; and June 26, 2007.

In 2007, a preliminary study was conducted in the same field under the experimental conditions described for experiment 1 to compare the productivity and weed suppression traits of the original parental source (4484), Rondo, and the 4484-1665 sister line in weedy and weed-free plots.

Experiment 2 was conducted with planting dates of May 5, 2008; May 18, 2009; and May 11, 2010; where Rondo was compared with the indica lines, PI 312777 and 4612 (PI 615039)(Dilday et al. 2001b), and to commercial long-grain cultivars 'Lemont' (Bollich et al. 1985), 'Katy' (Moldenhauer et al. 1990), 'Wells', and 'Drew' (Moldenhauer et al. 1998). All experimental procedures were as described above for experiment 1, except that propanil plus quinclorac (3.9 to 4.4 kg ha^{-1} + 0.28 kg ha^{-1}) or propanil plus bensulfuron (4.4 kg ha^{-1} + 0.033 kg ha^{-1}) were applied POST to weed-free plots. Urea was applied on June 12, 2008; June 26, 2009; and June 24, 2010.

Plant Measurements. Approximately 1 mo after flood establishment ("midseason"; measurements recorded in experiment 2 only), total number of rice stems ("tillers") were counted, and rice, barnyardgrass, and remaining weed plants were cut from two 25-cm by 25-cm quadrats (avoiding the area to be harvested for rice yield). Plant types were separated by hand, dried at approximately 50 C to a constant weight, and weighed to determine midseason rice, barnyardgrass, and total weed mass, respectively. Because the quadrat width (25 cm) was not an exact multiple of the rice row width (18 cm), rice measurements at midseason were corrected to the desired per–meter-squared basis by using two full row widths (36 cm) by total quadrat length (50 cm) as the effective sampling area.

In both experiments, the percentage of tillers with panicles exerted (heading) in each plot was estimated visually three times per week throughout the heading period. *Emergence to heading* was defined as the number of days between the emergence date and the estimated date at which 50% of panicles had headed. Visual estimates of weed suppression, in which 0% is no suppression or biomass reduction of barnyardgrass, and 100% is complete suppression or loss of barnyardgrass biomass, were recorded in weedy plots after rice heading.

At crop maturity, rice plants from the middle 2 m in the center five rows (0.9 m wide) of each plot were measured for height (10 representative plants). All rice plants in this area were then cut and bundled. Rice panicles were threshed using a stationary bundle thresher; grain was weighed, and yield was adjusted to 12% moisture.

To assess relative rice losses caused by weed pressure, an additional parameter, the *percent reduction* relative to weed-free values, was calculated for midseason tiller number and shoot biomass (experiment 2 only) and for harvest height and yield:

$$\begin{aligned} &\textit{Percent reduction} = 100 - \\ &[(\textit{value in weedy plots}/\textit{value in weed-free plots}) \times 100]. \end{aligned} \quad [1]$$

The experimental design was a split plot in which the main plots were in a randomized complete block with four replications. Main plots were rice cultivars, and subplots were weed levels (weedy and weed-free). Data were analyzed using the SAS GLIMMIX procedure (version 8.2, SAS Institute Inc., 100 SAS Campus Drive, Cary, NC 27513-2414). Using this mixed-model approach, years and replications were considered random effects. Such an approach can be useful for comparing rice lines when broad inferences over multiple environments (years, in this case) are of particular interest (Blouin et al. 2011). Means were separated at the 0.05 level using least-squares means with the Tukey-Kramer adjustment. Data analyses for the *percent reduction* values, weed biomass and weed suppression values, and the values from the weed-free plots only, were conducted separately using randomized complete-block designs (i.e., there was no weed-level split in these analyses). A multivariate analysis was conducted using Proc CORR (version 8.2, SAS Institute) to determine correlations among variables in experiment 2.

Results and Discussion

In experiment 1, the rice cultivar main effect for mature height was similar for 4484-1665 (mutated sister line of Rondo) and all other cultivars, and Kaybonnet was taller than PI 312777 and Bengal (Table 1). Plots without weeds were about 9% taller than those with weeds. The rice cultivar main effect for grain yield revealed that 4484-1665 yielded similarly

Table 1. Heading, height, and yield of the Rondo sister line (4484-1665) and other rice cultivars in a 3-yr field study: main effect means for cultivar and weed level.[a,b]

Rice cultivar	Emergence to heading	Harvest height	Grain yield
	d	cm	kg ha^{-1}
Cultivar main effect			
4484-1665	87	104 abc	5,570 a
PI 312777	89	103 bc	5,810 a
4593	88	108 ab	5,800 a
4597	87	106 ab	5,650 a
Bengal	77	98 c	5,070 ab
Kaybonnet	84	111 a	3,920 b
	P = 0.0548	P = 0.0006	P = 0.0018
Weed main effect			
Weedy	84	101 b	3,480 b
Weed-free	87	109 a	7,120 a
	P = 0.1094	P < 0.0001	P < 0.0001

[a] Plants were grown in field plots in 2005, 2006, and 2007 in a standard, drill-seeded, flooded, rice production system at Stuttgart, AR (experiment 1).

[b] Values in table are means over 3 yr. Means within columns followed by the same letter are not different according to a least-squares means test at P ≤ 0.05. Interactions of cultivar with weed level were not significant. Cultivar main effect means are averages of weedy and weed-free plots. Weed-level main effect means are averages over all cultivars in weedy and weed-free plots, respectively.

to all other indica lines and Bengal, and ~42% more than Kaybonnet did. Plots without weeds averaged more than twice the yields of those with weeds.

Under weed pressure, 4484-1665, other indica lines, and Bengal were reduced in height similarly, averaging 6.2% reduction, when compared with Kaybonnet, which was reduced by more than twice that amount (Table 2). The yield reduction in 4484-1665 was 53%, similar to all other cultivars (Table 2). However, the yield reduction in Kaybonnet was 1.6 times greater than it was in PI 312777. In a parallel 3-yr experiment, the parental line, 4484, yielded similarly and was 9 cm taller (117 cm vs. 108 cm) than was 4484-1665 in weed-free plots (P = 0.0343; data not shown). In another preliminary study in 2007, the 4484 parental line was 4 to 5 cm taller than either Rondo or 4484-1665 (data not shown), which was consistent with the findings of Yan and McClung (2010). Yields of Rondo trended higher (~14%; P = 0.08) than did those of the other two lines, and weed suppression levels were similar for all three (data not shown).

In a 3-yr study, Rondo was compared with two indica lines and four commercial, U.S., tropical japonica cultivars. In weed-free plots, representing optimum conditions, midseason tiller and shoot biomass production, emergence to heading, harvest height, and yield of Rondo were similar to the other indica lines (Table 3). Rondo values for the first three of these variables were usually similar to those for the tropical japonica lines. However, Wells headed earlier than Rondo (Table 3). Rondo's height was less than Katy and Drew, but greater than Lemont. Yield of Rondo was greater than both Wells and Drew (Table 3). When averaged over weed levels (cultivar main effect), Rondo's midseason tiller number, shoot biomass production, harvest height, and yields were similar to the other indica lines (Table 4). Rondo's tiller production was 47% greater than Drew, its shoot biomass was 34% greater

Table 2. Reduction of height and yield of the Rondo sister line (4484-1665) and other rice cultivars relative to a weed-free standard in a 3-yr field study.[a,b]

Rice cultivar	Harvest height	Grain yield
	% reduction relative to weed-free	
4484-1665	5.6 b	53 ab
PI 312777	5.3 b	42 b
4593	4.9 b	48 ab
4597	10.1 ab	50 ab
Bengal	4.9 b	55 ab
Kaybonnet	14.6 a	68 a
	P = 0.0041	P = 0.0453

[a] Plants were grown in field plots in 2005, 2006, and 2007 in a standard drill-seeded, flooded, rice production system at Stuttgart, AR (experiment 1).

[b] Values in table are from weedy plots and are expressed relative to the appropriate weed-free standard. They are means over 3 yr. Means within columns followed by the same letter are not different according to a least-squares means test at P ≤ 0.05.

than Lemont, its height was 16% greater than Lemont and 8% less than Drew, and its yield was about 40% greater than both Lemont and Katy (Table 4).

When averaged over cultivars (weed main effect), rice midseason tiller and shoot mass production, and harvest height and yield levels without weeds were 49, 39, 11, and 91% greater, respectively, than they were with weeds (Table 4). Although not significant in these studies, Rondo and other indica lines in weed-infested plots tended to lose less yield (~30%; P = 0.0826) than did Lemont (Table 5).

Midseason barnyardgrass and total weed biomass in Rondo were not significantly different from other cultivars, although their means were 47% and 49% less, respectively, compared with Lemont (Table 6). The lack of statistical significance among these weed biomass values in spite of the apparent trends, may relate to the interplot variability sometimes observed in our plots (data not shown) and to the limited area sampled by the quadrats. Weed suppression for Rondo was 1.5 and 1.3 times greater than it was for Lemont and Katy, respectively (Table 6). These trends are consistent with earlier findings that, under southern U.S. conditions, indica lines typically had greater suppression and reduction of barnyardgrass biomass than did long-grain, tropical japonica cultivars (Gealy and Moldenhauer 2012; Gealy et al. 2005), in part because of their high tillering and biomass production capacity. High tillering and biomass production have been associated with improved weed suppression in other rice systems (Fischer et al. 2001; Tuong 2000). The PI 312777 suppressive indica standard has proven to produce allelochemicals that are phytotoxic to barnyardgrass (Kong et al. 2006), which may also contribute to its weed-suppressive activity.

Several correlations between key variables were notable from the 3-yr study with Rondo (Table 7). Rice yield under weed pressure was strongly correlated (R = 0.53–0.82) with tillers, midseason shoot biomass, barnyardgrass biomass and weed suppression rating, weed-free yield, and harvest height but was not correlated with weed-free tillers. Rice yield reduction due to weeds was strongly correlated (R = 0.59–0.78) with midseason weed-free shoot biomass, midseason tillers, midseason shoot biomass, barnyardgrass biomass, total

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Table 3. Growth traits and yield of Rondo and other rice cultivars in weed-free plots in a 3-yr field study.[a–c]

Rice cultivar	Tillers	Shoot biomass	Emergence to heading	Harvest height	Grain yield
	no. m^{-2}	g m^{-2}	d	cm	kg ha^{-1}
Indica lines					
Rondo	773 ab	836 ab	86 a	107 bc	6,590 a
PI 312777	849 a	847 ab	85 a	104 c	6,730 a
4612	761 ab	825 ab	85 a	110 b	7,420 a
U.S. tropical japonica lines					
Lemont	633 ab	693 b	86 a	95 d	5,220 b
Katy	647 ab	826 ab	86 a	116 a	5,060 b
Wells	696 ab	823 ab	82 b	109 b	6,960 a
Drew	560 b	850 a	85 a	119 a	6,490 a
	$P < 0.0044$	$P = 0.0472$	$P < 0.0001$	$P < 0.0001$	$P \leq 0.0001$

[a] Plants were grown in field plots in 2008, 2009, and 2010 in a standard, drill-seeded, flooded, rice production system at Stuttgart, AR (experiment 2).

[b] Values in table are means over 3 yr. Means within columns followed by the same letter are not different according to a least-squares means test at $P \leq 0.05$.

[c] Tiller and shoot biomass data were taken midseason.

weed biomass, and weed suppression. Rice yield reduction was less correlated ($R = 0.26$–0.42) with weed-free height and weed-free yield and was not correlated with weed-free tillers. Barnyardgrass suppression was correlated ($R = 0.30$–0.76) with midseason weed-free rice shoot biomass and barnyardgrass biomass, weed-free emergence to heading, harvest height, yield, reduction in height, and reduction in yield. However, weed suppression was not correlated with weed-free tillers. Collectively, these results suggest that the inherent yield and height potentials of the rice cultivars in this experiment were moderately predictive of yields, yield reduction, and barnyardgrass suppression under weed pressure. Tillering under weed-free conditions was not predictive of these traits. However, tillering under weed pressure was highly predictive of these traits as well as barnyardgrass biomass and total weed biomass ($R = 0.64$–0.70). One reason for the apparent lack of influence of tillering potential (i.e., weed-free conditions) on weed suppression and weed tolerance may be that the yields and weed suppression for Drew generally were as high as for the indica lines, even though its tillering capacity was among the lowest of all cultivars (Tables 3–6). Statistical analysis of the U.S. Department of Agriculture (USDA) 'Mini-Core' collection of global rice germplasm showed that grain yield was correlated with tillering capacity ($R = 0.77$), plant height ($R = 0.43$), and plant biomass ($R = 0.81$) (Li et al. 2011).

In a previous comparison of barnyardgrass suppression among indica and tropical japonica lines, weed suppression ratings were correlated with rice yield in weedy and weed-free plots, rice yield loss, and rice height reduction, suggesting that rice yield loss and height reduction could be good indicators of weed-suppression potential (Gealy and Moldenhauer 2012).

Rondo and its sister line generally yielded similarly to the other indica lines and the more-suppressive commercial cultivars, such as Bengal, Wells, and Drew, under weed pressure but yielded nearly 50% greater than the least-suppressive cultivars, such as Kaybonnet, Lemont, and Katy. In the present study, rice yields averaged about twice the levels

Table 4. Growth traits and yield of Rondo and other rice cultivars in a 3-yr field study: main effect means for cultivar and weed level.[a–c]

Rice cultivar	Tillers	Shoot biomass	Harvest height	Grain yield
	no. m^{-2}	g m^{-2}	cm	kg ha^{-1}
Cultivar main effect				
Rondo	679 ab	755 a	103 b	5,220 a
PI 312777	729 a	717 ab	101 b	5,320 a
4612	650 abc	741 a	104 b	5,830 a
Lemont	495 bc	564 b	89 c	3,720 b
Katy	522 bc	701 ab	108 ab	3,760 b
Wells	580 abc	717 ab	103 b	5,180 a
Drew	462 c	702 ab	112 a	4,860 ab
	$P = 0.0016$	$P = 0.0199$	$P < 0.0001$	$P = 0.0002$
Weed main effect				
Weedy	473 b	585 b	97 b	3,330 b
Weed-free	702 a	814 a	108 a	6,350 a
	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$

[a] Plants were grown in field plots in 2008, 2009, and 2010 in a standard, drill-seeded, flooded, rice production system at Stuttgart, AR (experiment 2).

[b] Values in table are means over 3 yr. Means within columns followed by the same letter are not different according to a least-squares means test at $P \leq 0.05$. Cultivar by weed level interactions were not significant. Cultivar main-effect means are averages of weedy and weed-free plots. Weed-level main effect means are averages over all cultivars in weedy and weed-free plots, respectively.

[c] Tiller and shoot biomass data were taken midseason.

Table 5. Reduction of growth traits and yield of Rondo and the other cultivars relative to a weed-free standard in a 3-yr study.[a–c]

Rice cultivar	Tillers	Shoot biomass	Harvest height	Grain yield
	% reduction relative to weed-free			
Indica lines				
Rondo	22	24	9.0	43
PI 312777	27	33	6.5	42
4612	22	27	10.1	43
U.S. tropical japonica lines				
Lemont	43	48	12.1	61
Katy	38	41	14.0	55
Wells	31	31	11.5	55
Drew	35	42	10.9	51
	$P = 0.1573$	$P = 0.1896$	$P = 0.3971$	$P = 0.0826$

[a] Plants were grown in field plots in 2008, 2009, and 2010 in a standard, drill-seeded, flooded, rice production system at Stuttgart, AR (experiment 2).

[b] Values in table are from weedy plots and are expressed relative to the appropriate weed-free standard. They are means over 3 yr. Means within columns followed by the same letter are not different according to a least-squares means test at $P \leq 0.05$.

[c] Tiller and shoot biomass data were taken midseason.

Table 6. Effect of Rondo and the other cultivars on weed biomass and percent suppression in a 3-yr study.[a–d]

Rice cultivar	Barnyardgrass biomass	Total weed biomass	Barnyardgrass suppression
	$g\ m^{-2}$	$g\ m^{-2}$	%
Indica lines			
Rondo	284	336	55 a
PI 312777	326	431	53 ab
4612	376	406	49 ab
U.S. tropical japonica lines			
Lemont	539	657	36 c
Katy	452	496	42 bc
Wells	436	562	50 ab
Drew	516	573	45 abc
	$P = 0.5783$	$P = 0.4411$	$P = 0.0002$

[a] Plants were grown in field plots in 2008, 2009, and 2010 in a standard, drill-seeded, flooded, rice production system at Stuttgart, AR (experiment 2).

[b] Values in table are means over 3 yr.. Means within columns followed by the same letter are not different according to a least squares means test at $P \leq 0.05$. Data were from weedy plots.

[c] Biomass data were taken midseason.

[d] In 2009, barnyardgrass suppression (visual estimate) by PI 312777 (51%) was greater than it was by Lemont (25%) and Katy (29%)($P = 0.0037$). In 2010, barnyardgrass suppression by Rondo (53%) and PI 312777 (53%) was greater than it was by Lemont (34%)($P = 0.0049$).

without weeds than it did with weeds. Other studies demonstrated a similar reduction of rice yield because of barnyardgrass weed species (Gealy and Moldenhauer 2012; Pérez De Vida et al. 2006). However, PI 312777 supplemented with a one-quarter rate of propanil, had a barnyardgrass-induced yield loss of only 22% (Gealy and Moldenhauer 2012), which was generally less than the yield losses measured in the present study.

In dry-seeded rice (Chauhan and Johnson 2010b), rice interference reduced the height of barnyardgrass, which was able to grow taller than the rice did, allowing its top portions to remain out of shade, and it also reduced the shoot biomass of this weed species. It was concluded that, although rice interference may reduce barnyardgrass growth, it is not likely that interference alone will provide complete control of this weed. The results from our present study and from previous studies (Gealy et al. 2003, 2005; Gealy and Moldenhauer 2012) also support this hypothesis. PI 312777 and another suppressive cultivar, 'Huagan-1', have reduced weeds to the point that, when supplemented with low-dose bensulfuron-methyl (25 g ai ha^{-1}), yield reductions due to weeds were minimal (Kong et al. 2008).

In a pot study with dry, direct-seeded rice, grain yields with or without junglerice [*Echinochloa colona* (L.) Link] were highly correlated with biomass (Chauhan and Johnson 2010a). Further, shoot competition from junglerice reduced growth and yield of rice more than root competition did, and shoot competition for light appeared to be a primary driver of the competitive outcomes.

Although not directly addressed in the present study, rice cultivars with early growth, rapid height development, good light-capture, and aggressive development of leaf area can have competitive advantages against barnyardgrass and its relatives (Caton et al. 1999; Gibson et al. 2003; Pérez de Vida et al. 2006). We did not measure rice or weed growth traits in the early season because temporary, herbicide-induced stunting of rice in the weed-free plots sometimes produced misleading results in earlier studies (D. R. Gealy, unpublished data). Cultivars that were most competitive against weeds tended to produce the highest yields (Gibson et al. 2003) and minimal yield loss under weed pressure, which have been considered desirable weed-suppression traits in rice (Fofana and Rauber 2000; Gealy et al. 2003; Gealy and Moldenhauer 2012).

Rondo has been successfully used for commercial organic rice production in Texas for several years (C. Slack, personal communication). This success has resulted in part from Rondo's high-yield potential and ability to suppress or tolerate rice pests, including weeds (Figure 1). Although our studies were not conducted using organic protocols, Rondo's performance in these minimal-herbicide–input studies suggests that its weed-suppressive ability may be superior to that of many commercial cultivars and similar to that of other Asian indica lines. The results of the present study support the contention that Rondo is well-suited to withstand the pest pressures that can be damaging to organic rice production. Furthermore, in the 2011 Uniform Rice Regional Nursery, in which replicated, elite, rice breeding lines were compared under conventional production systems in the five southern rice-producing states, Rondo rough rice yields ranked second highest out of 200 entries (data not shown). Thus, an overall implication from our research results is that inherently high-yielding ability, especially when coupled with maintenance of high tiller production and yield under weed pressure, may be a key to improved weed suppression and tolerance in rice cultivars under southern U.S. conditions. In previous research, weed suppression has sometimes been greater in tall cultivars than it is in shorter cultivars. However, the potential drawbacks to selecting for tall cultivars (e.g., lodging susceptibility) may be counterproductive, except in organic or other low-input systems to which lower rates of nitrogen

Table 7. Correlation among weed and rice variables measured in weedy or weed-free plots in a 3-yr study.[a–c]

Characteristics	Measurements at midseason								Measurements at or near maturity								
	Weed-free tillers	Weed-free shoot biomass	Tillers	Shoot biomass	% Reduct. in tillers	% Reduct. in shoot biomass	BYG biomass	Total weed biomass	Weed suppres-sion	Weed-free emergence to heading	Weed-free ht	Weed-free yield	Ht	Yield	% Reduct. in emergence to heading	% Reduct. in ht	% Reduct. in yield
	R																
Measurements at midseason																	
Weed-free tillers	1.00	−0.32*	0.31**	−0.33*	0.09	0.14	0.16	0.08	0.12	0.09	−0.31*	0.47**	−0.35*	0.06	−0.06	0.25*	0.13
Weed-free shoot biomass	−0.32*	1.00	0.29*	0.83**	−0.62**	−0.61**	−0.31*	−0.23**	0.32*	−0.36*	0.59**	−0.20	0.75**	0.38*	0.16	−0.64**	−0.59**
Tillers	0.31*	0.29*	1.00	0.53**	−0.84**	−0.75**	−0.64**	−0.66**	0.69**	−0.26*	0.15	0.38*	0.51**	0.70**	0.11	−0.63**	−0.64**
Shoot biomass	−0.33*	0.83**	0.53**	1.00	−0.81**	−0.91**	−0.63**	−0.60**	0.56**	−0.42**	0.53**	−0.03	0.81**	0.59**	0.27*	−0.76**	−0.78**
% Reduct. in tillers	0.09	−0.62**	−0.84**	−0.81**	1.00	0.85**	0.73**	0.69**	−0.62**	0.37*	−0.40*	−0.09	−0.73**	−0.64**	−0.2	0.74**	0.74**
% Reduct. in shoot biomass	0.14	−0.61**	−0.75**	−0.91**	0.85**	1.00	0.73**	0.73**	−0.68**	0.40*	−0.38*	−0.16	−0.75**	−0.69**	−0.26*	0.78**	0.78**
BYG biomass	0.16	−0.31*	−0.64**	−0.63**	0.73**	0.73**	1.00	0.93**	−0.57**	0.17	−0.20	−0.08	−0.55**	−0.53**	−0.08	0.62**	0.65**
Total weed bio-mass	0.08	−0.23*	−0.66**	−0.60**	0.69**	0.73**	0.93**	1.00	−0.62**	0.17	−0.23*	−0.18	−0.54**	−0.60**	−0.09	0.59**	0.66**
Measurements at or near maturity																	
Weed suppression	0.12	0.32*	0.69**	0.56**	−0.62**	−0.68**	−0.57**	−0.62**	1.00	−0.40**	0.30*	0.48**	0.56**	0.82**	0.07	−0.56**	−0.76
Weed-free emergence to heading	0.09	−0.36*	−0.26*	−0.42**	0.37*	0.40*	0.17	0.17	−0.40**	1.00	−0.35*	−0.30*	−0.43**	−0.49**	−0.46**	0.33*	0.40**
Weed-free ht	−0.31*	0.59**	0.15	0.53**	−0.40*	−0.38*	−0.20	−0.23*	0.30*	−0.35*	1.00	0.02	0.72**	0.34*	0.14	−0.38*	−0.42**
Weed-free yield	0.47**	−0.20	0.38*	−0.03	−0.09	−0.16	−0.08	−0.18	0.48**	−0.30*	0.02	1.00	0.05	0.58**	−0.08	−0.05	−0.26*
Ht	−0.35*	0.75**	0.51**	0.81**	−0.73**	−0.75**	−0.55**	−0.54**	0.56**	−0.43**	0.72**	0.05	1.00	0.66**	0.23*	−0.89**	−0.81**
Yield	0.06	0.38*	0.70**	0.59**	−0.64**	−0.69**	−0.53**	−0.60**	0.82**	−0.49**	0.34*	0.58**	0.66**	1.00	0.09	−0.68**	−0.90**
% Reduct. in emergence to heading	−0.06	0.16	0.11	0.27*	−0.20	−0.26*	−0.08	−0.09	0.07	−0.46**	0.14	−0.08	0.23*	0.09	1.00	−0.16	−0.16
% Reduct. in ht	0.25*	−0.64**	−0.63**	−0.76**	0.74**	0.78**	0.62**	0.59**	−0.56**	0.33*	−0.38*	−0.05	−0.89**	−0.68**	−0.16	1.00	0.82**
% Reduct. in yield	0.13	−0.59**	−0.64**	−0.78**	0.74**	0.78**	0.65**	0.66**	−0.76**	0.40**	−0.42**	−0.26*	−0.81**	−0.90**	−0.16	0.82**	1.00

[a] Plants were grown in field plots in 2008, 2009, and 2010 in a standard, drill-seeded, flooded rice production system at Stuttgart, AR (experiment 2).

[b] Rice cultivars included the indica lines Rondo, PI 312777, and 4612 and the U.S. tropical japonica lines Lemont, Katy, Wells, and Drew. All variable names refer to rice data unless indicated otherwise. *Tillers*, *shoot biomass*, *height*, and *yield* refer to rice measurements in weedy plots.

[c] Abbreviations: % reduct., percentage reduction of rice measurements in weedy plots relative to the weed-free standard; BYG, barnyardgrass.

* Significant at $P < 0.05$; ** significant at $P < 0.0001$.

fertilizer are applied and lower yields may be commercially acceptable. Given the demonstrated involvement of allelopathic activity in some indica lines, there may also be value in assessing the relative contribution of this mechanism to the overall suppression activity in Rondo and other rice lines.

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