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Rice and red rice interference. I. Response of red rice (*Oryza sativa*) to sowing rates of tropical *japonica* and *indica* rice cultivars

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Field experiments were conducted at the Rice Research and Extension Center at Stuttgart, AR, in 1997 and 1998 to evaluate the growth response of Stuttgart strawhull (Stgstraw) red rice to sowing densities of 0, 50, 100, and 150 kg ha^{-1} of 'Kaybonnet,' 'Guichao,' and 'PI 312777' rice cultivars. PI 312777 produced a greater leaf area index and tiller density than Kaybonnet when grown with red rice. In 1997, Stgstraw seed yields were lower when grown with PI 312777 and Guichao than with Kaybonnet. The increased weed population in 1998 did not increase seed yield production of red rice when grown with the three rice cultivars. The Stgstraw red rice seed yield was reduced when grown with 50 kg ha^{-1} rice when compared with its yield in monoculture and was reduced further when grown with 100 and 150 kg ha^{-1} rice. These results demonstrate that red rice was more competitive when compared with the tropical *japonica* Kaybonnet than the *indica* PI 312777. Despite its semidwarf stature, PI 312777 tended to suppress red rice more than did Guichao or Kaybonnet. The mechanisms responsible for this difference could be important keys to the effective use of weed-suppressive cultivars in reduced herbicide input systems.

Nomenclature: Red rice, *Oryza sativa* L. ORYSA; 'Stgstraw'; rice, *Oryza sativa* L.; 'Guichao', 'Kaybonnet', 'PI 312777'.

Key words: Biomass, competition, interference, grain yield, tiller density.

Rice is produced in about 95 countries around the world (Coates 2003; Street and Bollich 2003). Although the United States produces only about 1.5% of the world's annual rice crop, it supplies 15% of the world's rice exports. Eighty-six percent of the total U.S. production comes from the Southern Rice Belt: Arkansas, Louisiana, Mississippi, Missouri, and Texas.

Rice in the Southern Rice Belt is predominantly grown in a drill-seeded rice culture. This condition also favors the growth of red rice, which is a weed of the same species as rice. Red rice is one of the most problematic weeds in rice-growing areas of the United States (Gealy et al. 2002; Webster 2000) and many other temperate areas of the world (Eleftherohorinos et al. 2002). It can grow in lowland and upland rice as well as in dry- and water-seeded rice (Smith 1983). These abilities are among the reasons that red rice continues to be troublesome in rice fields despite continuous efforts to suppress it. Red rice produces more tillers, leaves, and shoot dry weight when grown with rice than when grown in monoculture (Kwon et al. 1991). Red rice plants are generally taller and more competitive than most commercial rice cultivars, thus reducing rice yield (Diarra et al. 1985). This weed has proliferated in rice fields in Italy due to the use of contaminated rice seed and the ineffectiveness of chemical control (Ticchiati et al. 1996). Gealy et al. (2000) reported that severe economic infestations of red rice in the Southern Rice Belt were estimated at 65% of the rice area in Louisiana, 25% in Arkansas, Texas, and Missouri, and 15% in Mississippi.

Before the advent of herbicide-resistant rice, there were no selective herbicides that controlled red rice in drill-seeded rice (Baldwin 2003). Red rice has been best controlled in rotation crops, where it is killed by selective herbicides. Recently introduced herbicide-resistant rice systems are promising options for red rice control (Annou et al. 2000; Gealy et al. 2003a). However, genetic, physiological, and morphological similarities in rice and red rice provide opportunities for the transfer of the herbicide-resistant traits, especially when flowering is synchronous (Estorninos et al. 2002; Gealy et al. 2003a; Zhang et al. 2003).

Even though herbicide-resistant rice systems are promising, alternative methods for red rice management should also be pursued. Xue and Stougaard (2002) have suggested that the focus of weed management strategies should be shifted away from the weed and toward the crop. Planting high crop populations reduced weed growth and improved rice competitiveness against weeds. High sowing rates are commonly used by Latin American farmers to suppress rice weeds (Fischer and Ramirez 1993). Dunand (1988) reported that red rice tiller density decreased by 26 to 83% and that seed production decreased by 27 to 60% when rice sowing rates doubled from 100 to 200 kg ha^{-1}. Increasing the sowing density also improved competitiveness in other crops (Mohler 2001). Blackshaw (1993) reported that increased safflower (*Carthamus tinctorius* L.) density reduced the biomass and yield of green foxtail [*Setaria viridis* (L.) Beauv.], and weedy safflower yielded three to four times higher when grown at $\geq$100 plants m^{-2} than when grown at lower densities. Biomass and yield of wild oat (*Avena fatua* L.) were reduced by 20% when the sowing rate of winter wheat (*Triticum aestivum* L.) was increased from 175 to 280 plants m^{-2} (Xue and Stougaard 2002). The amount of wild oat seed that entered the seed bank was reduced by 50% when the sowing rate of barley (*Hordeum vulgare* L.) was increased from 160 to 280 plants m^{-2} (Scursoni et al. 1999).

Recent studies have also indicated that certain rice types have affected crop productivity and weed suppressiveness. The yield potential for *indica* rice in the southern United States may be much greater than that of existing tropical *japonica* commercial cultivars (Rutger et al. 2003). *Indica* rice cultivars that yielded more than domestic tropical *japonica* cultivars under Arkansas conditions can suppress barnyardgrass (*Echinochloa crus-galli*) (Gealy et al. 2003b) and aquatic weeds (Dilday et al. 2001a). We hypothesize that these *indica* cultivars may also be capable of suppressing red rice. The objective of this study was to evaluate the effect of the sowing rates of a commercial domestic tropical *japonica* rice cultivar and two foreign, high-yielding *indica* cultivars on the growth and yield of a common local red rice type.

Materials and Methods

The experiment was conducted at the Rice Research and Extension Center, Stuttgart, AR, in 1997 and 1998 in a Crowley silt loam (fine, montmorillonitic, thermic Typic Albaqualf) soil. The experimental design was a split plot with four replications. The main plots were rice cultivars, and the subplots were sowing rates. Cultivars included 'Kaybonnet', 'Guichao', and 'PI 312777'. Kaybonnet is a tall-stature, long-grain tropical *japonica* cultivar from Arkansas (Slaton et al. 2001). Guichao is an *indica*-type cultivar from China, and PI 312777 (T65*2/TN 1) is an *indica* type from the Philippines. Both *indicas* are high-yielding with a short stature and are naturally suppressive to barnyardgrass (Dilday et al. 2001a; Gealy et al. 2003b). Stuttgart strawhull (Stgstraw), a tall-stature, awnless strawhull red rice type commonly found in Arkansas (Gealy et al. 2002), was broadcast seeded at 13 kg ha^{-1} in 1997. The red rice sowing rate was increased to 26 kg ha^{-1} in 1998 because of lower-than-expected seedling emergence in 1997. Immediately after red rice seed was broadcast, cultivated rice was drill seeded using the standard practices recommended for drill-seeded production in Arkansas (Slaton and Cartwright 2001). Rice sowing rates were 0, 50, 100, and 150 kg ha^{-1}. The sowing rate for dry-seeded rice is commonly 100 kg ha^{-1} (Slaton and Cartwright 2001). Seed was planted 2 to 3 cm deep into plots with nine 6.25-m-long rows, 0.18 m apart. A heavy roller was pulled across plots parallel to the drill rows immediately after drill sowing to firm the seedbed.

Propanil at 4 kg ai ha^{-1} and bentazon at 0.6 kg ai ha^{-1} were tank mixed and applied 25 d after emergence (DAE) using a CO_2-pressurized backpack sprayer delivering a 190-L ha^{-1} spray volume for general weed control. Nitrogen, in the form of urea, was broadcast at 135 kg ha^{-1} in three equal portions at 28, 49, and 70 DAE. A permanent flood was established 28 DAE, immediately after the first urea application, and was maintained at a depth of 5 to 10 cm until approximately 2 wk before the expected harvest date.

Stands of rice and red rice were recorded 21 DAE to determine the initial densities of crop and weed that would then compete with each other throughout the growing season. The growth and development of red rice and cultivated rice based on leaf area, tiller numbers, and plant height were determined by destructive sampling in 25- by 25-cm quadrats near both ends of each plot. The total area of the two quadrats for red rice was 0.125 m^{-2}. Since two rows of rice were included in each quadrat, the effective total area of rice in the two quadrats was 0.18 m^{-2} (i.e., 36 cm by 25 cm by 2). At each sampling, the leaf area of 10 subsampled plants was measured using an automated leaf area meter.[1] Plants were then dried at 50 C for at least 3 d, and the aboveground biomass was determined and expressed as grams per square meter. The leaf area index (LAI) was calculated using the following equation:

$$\mathrm{LAI} = \mathrm{LA}/\mathrm{GA} \qquad [1]$$

where LA is photosynthetic leaf area and GA is ground area, which was the total area of the two quadrats (red rice = 0.125 m^{-2}; rice = 0.18 m^{-2}). Total leaf area in the two quadrats was estimated on the basis of the ratio of subsampled plants to total plants in each plot.

Fifteen red rice panicles in each plot were bagged with perforated, opaque plastic bags[2] at their dough stage to ensure the capture of shattered and nonshattered seeds. At maturity, the bagged red rice panicles were harvested and threshed by hand. The cultivated rice grain yield was determined by hand harvesting samples from the four middle rows (0.71 m wide) and the middle 2 m of length in each plot (1.42 m^2). Grains from red rice panicles were weighed, and the yield per panicle of red rice was determined. Red rice yields per panicle were multiplied by the total number of red rice panicles present in the 1.42-m^2 cultivated rice sampling area. All grain yields were adjusted to 12% moisture[3] and expressed as kilograms per hectare.

Data were subjected to analysis of variance (ANOVA) using SAS software.[4] There were no significant interactions between rice cultivars and sowing rates on rice growth and yield. Therefore, the means of significant main effects were separated using a protected least significant difference (LSD) test at the 5% level of probability. The initial populations of red rice in 1997 and 1998 differed greatly. Therefore, data from the 2 yr were analyzed separately.

Results and Discussion

Rice and Red Rice Seedling Emergence

Both red rice and rice emerged 6 to 9 d after sowing. Seedling stands increased with sowing rate, but there were no significant differences among rice cultivars within each sowing rate for either year at 21 DAE (data not shown). The initial red rice populations were 24 plants m^{-2} in 1997 and 40 plants m^{-2} in 1998.

Rice and Red Rice LAI

The LAI of rice differed among cultivars and sowing rates in both years, but that of red rice did not (Table 1). The LAI of Kaybonnet 70 DAE was lower than that of PI 312777 in both years. Estorninos et al. (2002) reported that the leaf expansion of Kaybonnet was considerably reduced when grown with red rice. Guichao had an intermediate leaf area expansion compared with the other cultivars. However, the greater leaf area of PI 312777 over the other two cultivars failed to significantly affect the LAI of red rice in both years. This indicates that a higher LAI does not necessarily

TABLE 1. Leaf area index, tiller number, aboveground biomass, and grain yield of rice and red rice as influenced by rice cultivars in 1997 and 1998.[a]

Cultivar	Leaf area index[b]		Tiller number[b]		Aboveground biomass[b]		Grain yield	
	Rice	Red rice	Rice	Red rice	Rice	Red rice	Rice	Red rice
			no. m^{-2}		g m^{-2}		kg ha^{-1}	
1997								
Kaybonnet	15.8 b	5.8 a	507 c	264 a	1,110 a	*	2,560 b	5,190 a
Guichao	20.8 ab	5.8 a	652 b	239 a	1,360 a	*	4,220 a	4,470 ab
PI 312777	26.9 a	6.2 a	764 a	253 a	1,400 a	*	4,260 a	4,000 b
1998								
Kaybonnet	6.1 b	9.9 a	466 b	*	490 a	1,160 a	1,790 a	7,200 a
Guichao	7.8 ab	8.5 a	523 b	*	570 a	970 a	2,260 a	6,310 a
PI 312777	10.4 a	8.8 a	671 a	*	680 a	880 a	2,370 a	5,710 a

[a] In a column within year, means followed by a common letter are not significantly different at the 5% level by protected least significant difference (LSD) test. Data were averaged over three sowing rates. Initial red rice density was 24 plants m^{-2} in 1997 and 40 plants m^{-2} in 1998.
[b] Sampled 70 d after emergence.
[c] Asterisks (*) indicate significant interactions between cultivars and rice sowing rates (see Figures 2c and 3b).

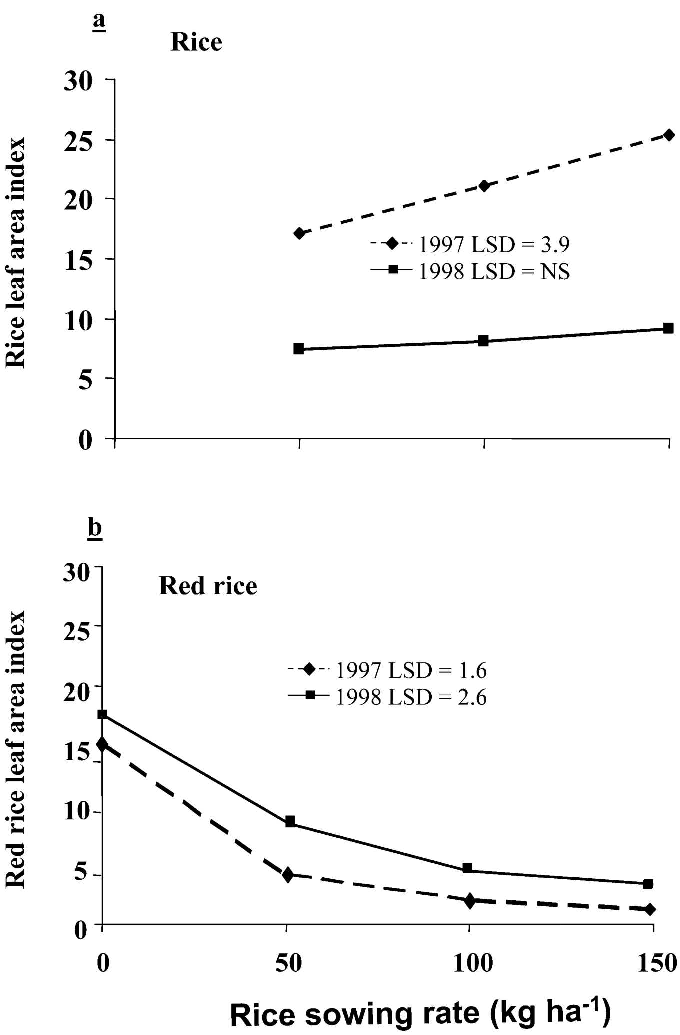

FIGURE 1. Leaf area index in (a) rice and (b) red rice as influenced by rice sowing rates in 1997 and 1998. Data were averaged over three rice cultivars. Least significant difference (LSD) test (0.05) compares sowing rate means in each year.

result in reduced red rice leaf area expansion, although these semidwarf *indicas* consistently reduced the growth of barnyardgrass (Gealy et al. 2003b). The LAI of rice increased with the sowing rate in 1997 but was not affected by sowing rates in 1998 (Figure 1a). The LAI of red rice was generally lower in 1997 than in 1998 but was not affected by the rice cultivars in either year (Table 1). The LAI of rice cultivars was approximately 50% higher in 1997 than in 1998, suggesting that the interference effect of red rice against cultivated rice was greater at higher red rice populations (Figure 1a). These results are supported by the lower average reduction of red rice leaf area when grown with rice (relative to the 0 kg ha^{-1}) in 1998 (63%) than in 1997 (83%) (Figure 1b). The LAI of red rice each year was two to eight times higher when planted as a monoculture than when grown in interspecific interference with rice. The LAI of red rice was reduced further when the rice sowing rate increased from 50 to 100 kg ha^{-1} and plateaued from 100 to 150 kg ha^{-1}.

Rice and Red Rice Tiller Production

Tiller production by PI 312777 was prolific compared with the other two cultivars in both 1997 and 1998 (Table 1). Kaybonnet produced fewer tillers than Guichao in 1997, but the two were similar in 1998. In a greenhouse study, Estorninos et al. (2002) observed that PI 312777 produced twice as many tillers as Kaybonnet. McClung et al. (1998) also reported that *indica* rice produced more tillers than tropical *japonica* rice. Cultivars that produce tillers early tend to increase leaf numbers and leaf area and increase the competitive ability of grass crops against weeds (Johnson et al. 1998). Early rapid dry matter accumulation is very important in the suppression of weeds by a rice cultivar (Ni et al. 2000). However, in this study, the effect of higher tiller production by PI 312777 on red rice was undetectable as late as 70 DAE in 1997 (Table 1). It is also possible that, because it is a dominant competitor, red rice produced tillers faster than rice (Pantone and Baker 1991), especially in 1997 when the initial population was lower.

Rice tiller production increased with increased sowing rate in both years and tended to be lower in 1998 than in 1997 (Figure 2a). In 1997, increasing the rice sowing rate

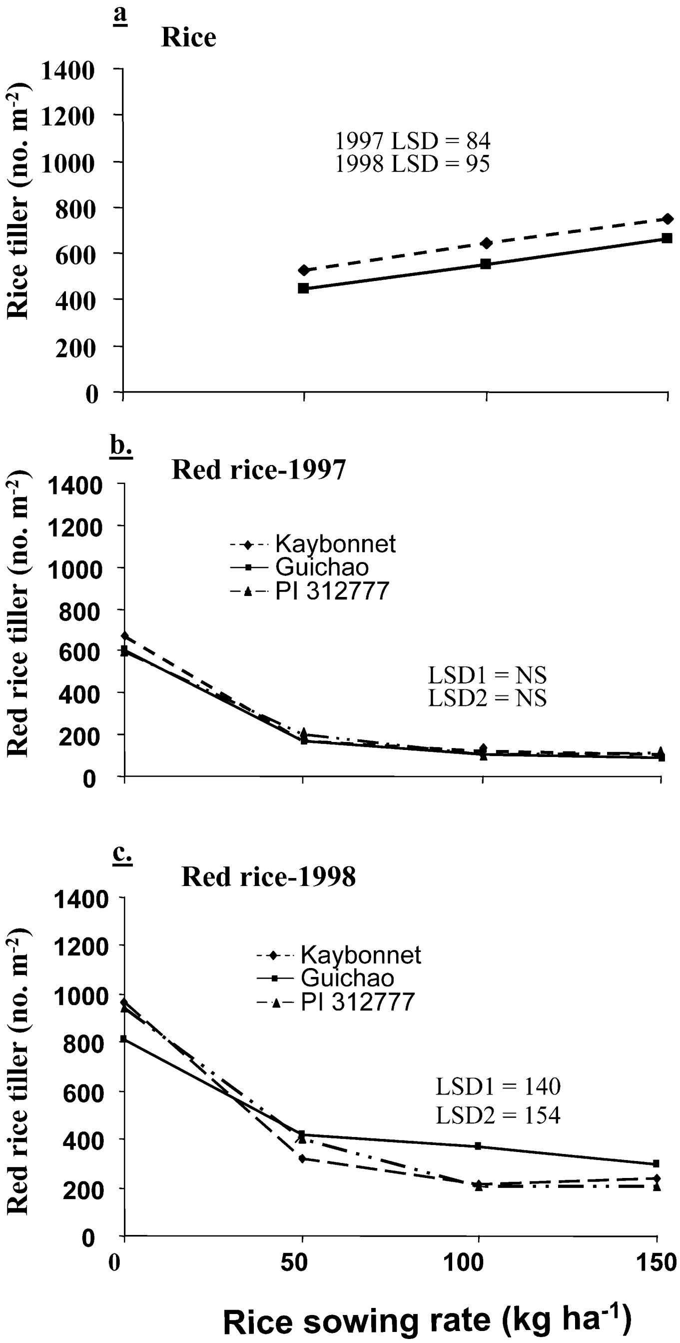

FIGURE 2. Tiller production as influenced by rice sowing rates: (a) rice tillers averaged over three rice cultivars in 1997 and 1998; (b and c) red rice tiller production in 1997 and 1998, respectively. Least significant difference (LSD) test (0.05): (a) compares sowing rate means in each year; (b and c) LSD1 compares sowing rate means for the same cultivar, and LSD2 compares cultivar means for the same or different rice sowing rate.

from 100 to 150 kg ha^{-1} did not affect red rice tiller density, despite the 14% increase in rice tiller production (Figure 2b). This indicates that rice competitiveness is not linked with tillering capacity, as was also reported by Ni et al. (2000). In 1998, red rice tiller production was dependent on rice cultivar and rice sowing rate (Table 1; Figure 2c). Red rice tillers were reduced when grown with rice, and the greatest reduction occurred between sowing rates of 0 and 50 kg ha^{-1}. Only PI 312777 further reduced the red rice tillers when the sowing rate was increased from 50 to 100 kg ha^{-1}. Red rice tillers did not differ among the three cultivars within each rice sowing rate except at 100 kg ha^{-1}, where PI 312777 affected tiller production more than Guichao.

Rice and Red Rice Aboveground Biomass

The three rice cultivars produced similar aboveground biomass both years (Table 1). Rice biomass increased when the sowing rate increased from 50 to 100 kg ha^{-1} in 1997 and as the sowing rate increased in 1998 (Figure 3a). Red rice biomass in 1997 decreased significantly when grown with any of the cultivars and was also reduced when the rice sowing rate increased from 50 to 100 kg ha^{-1} (Figure 3b). The increase from 50 to 100 kg ha^{-1} resulted in a 42% reduction of red rice biomass by Kaybonnet and Guichao and a 52% reduction by PI 312777. However, red rice biomass was not significantly further reduced by increasing sowing rates to 150 kg ha^{-1}. In 1998, the rice cultivars did not differ in their effect on red rice biomass production, but the trend of decreasing biomass with increasing sowing rate was similar to that in 1997 (Figure 3c). Probably the lower initial red rice population in 1997 (24 plants m^{-2}) than in 1998 (40 plants m^{-2}) facilitated the potential for red rice to produce more tillers, greater growth, and increased interference capability per plant (Estorninos et al. 2002). Dunand (1988) reported that red rice growth decreased when the rice sowing density doubled from 100 to 200 kg ha^{-1}.

Rice and Red Rice Plant Height

Kaybonnet was taller than Guichao and PI 312777, but none of these cultivars was affected by either intraspecific interference with increased rice sowing density or by interspecific interference with red rice (data not shown). However, the shorter cultivars tended to reduce red rice growth more than did the taller Kaybonnet. PI 312777 was the only cultivar that consistently reduced red rice height until harvest. This result agrees with the greenhouse results of Estorninos et al. (2002) but is in contrast to other findings that taller red rice types compete for light more effectively than shorter types when compared with cultivated rice (Kwon et al. 1992). Red rice was taller when grown with 150 kg ha^{-1} rice than without rice, supporting other findings that red rice elongation is greater when in competition with rice (Fischer and Ramirez 1993). However, this difference may be of little biological significance, because 80 to 90% of the plants lodged at the hard dough stage, and most of the leaves were already dead at harvest. Noldin et al. (1999) reported that red rice is susceptible to lodging, especially at higher populations.

Rice and Red Rice Yield

Yields of rice and red rice were not affected by the interactions between cultivars and sowing rates. In 1997, PI 312777 produced greater yields and reduced red rice yield 29% more than did Kaybonnet (Table 1). This difference could be related to the combination of an increased LAI and tiller density in PI 312777 compared with Kaybonnet. Eleftherohorinos et al. (2002) reported that a strong rice competitor produced greater grain yields than did a weak competitor when grown with red rice. Guichao yielded 39%

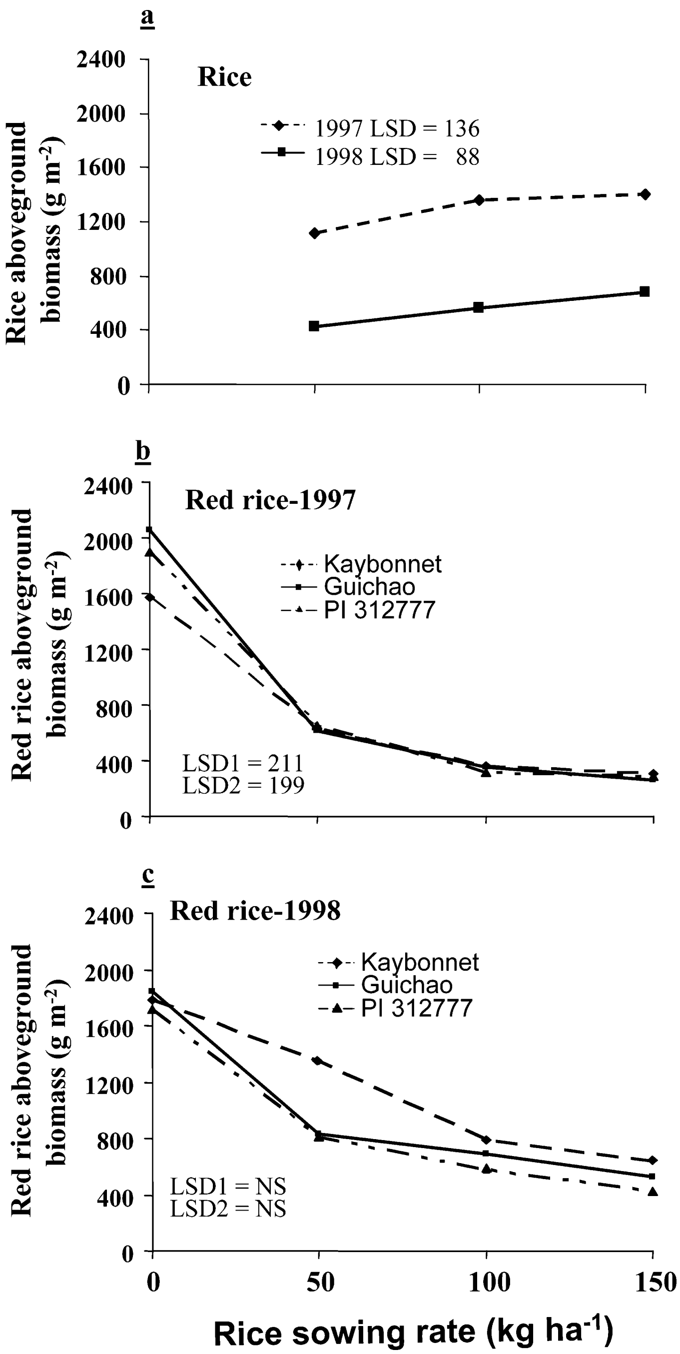

FIGURE 3. Aboveground biomass production as influenced by rice sowing rates: (a) rice biomass averaged over three rice cultivars in 1997 and 1998; (b and c) red rice biomass production in 1997 and 1998, respectively. Least significant difference (LSD) test (0.05): (a) compares sowing rate means in each year; (b and c) LSD1 compares sowing rate means for the same cultivar, and LSD2 compares cultivar means for the same or different rice sowing rate.

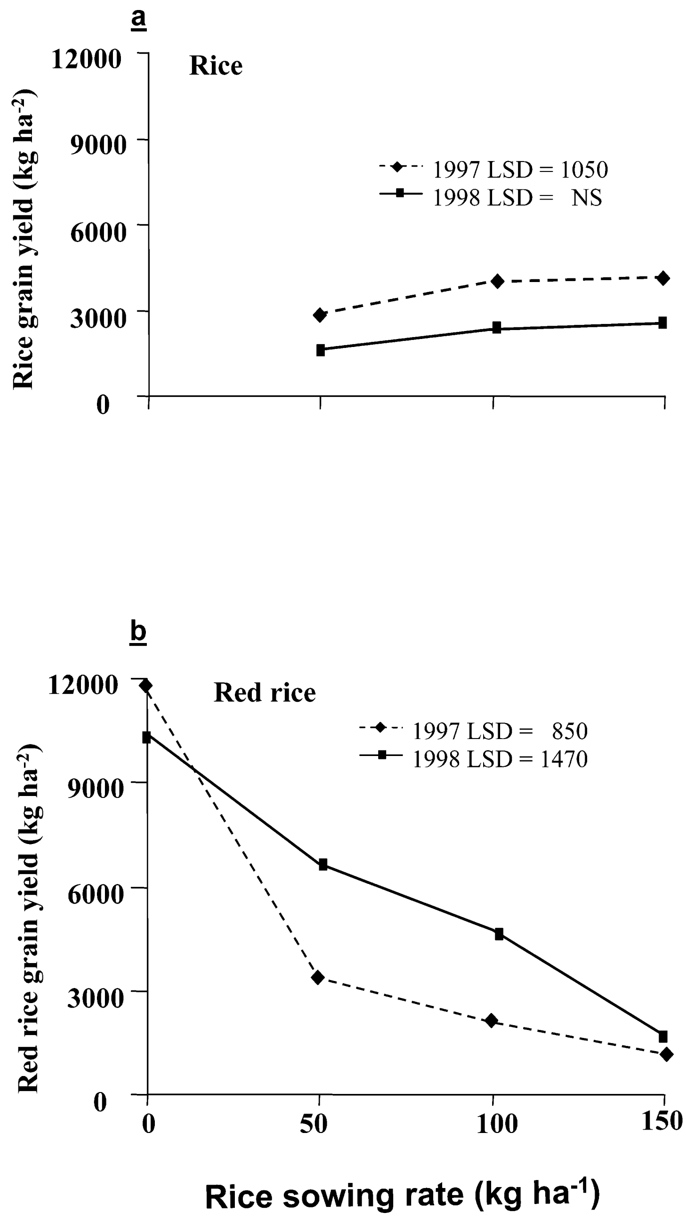

FIGURE 4. Grain yield in (a) rice and (b) red rice as influenced by rice sowing rates in 1997 and 1998. Data were averaged over three rice cultivars. Least significant difference (LSD) test (0.05) compares sowing rate means in each year.

more than Kaybonnet, but the two cultivars affected red rice yields similarly. In 1997, the yield of rice increased when the sowing rate was increased from 50 to 100 kg ha^{-1} but did not increase further at the sowing rate of 150 kg ha^{-1} (Figure 4a). The sowing rate did not affect yield for any cultivar in 1998. It is notable, though, that the yield of rice was relatively higher in 1997 when the red rice population was low than when the red rice initial population was nearly doubled in 1998. Sowing cultivated rice into the red rice plots greatly reduced red rice seed yields compared with the yield of red rice without rice present (Figure 4b). The profuse tiller production of red rice when planted alone resulted in seed yields of about 12,000 and 10,000 kg ha^{-1} in 1997 and 1998, respectively. These are much higher than the Kaybonnet grain yield of 7,500 kg ha^{-1} (Estorninos et al. 2005). In 1997, rice sowing rates of 100 and 150 kg ha^{-1} produced a greater rice yield and reduced the red rice yield at a rate of >50 kg ha^{-1} (Figure 4b). In 1998, the yield of PI 312777 was higher than Kaybonnet. These differences could be attributed to the greater interference effect of the higher red rice populations in 1998 than in 1997.

Although the red rice population was higher in 1998, its seed yield was slightly lower than in 1997, probably because the excessive vegetative growth produced lodging, which decreased the number of florets filled (2.1 vs. 1.2 g per panicle for 1997 and 1998, respectively). The resulting intraspecific interference probably reduced the grain production (Kwon et al. 1991). Results of this study demonstrate the effect of the different initial red rice populations present in 1997 and 1998. In a related study (Estorninos et al. 2005), the grain yield of Kaybonnet rice was reduced by 29 and 79% when initial red rice populations were 16 and 51 plants m^{-2}, respectively.

The results of this study were generally different from the previous results of Eleftherohorinos et al. (2002) in which 'Ariette', a medium-stature rice cultivar, reduced red rice growth more than did the shorter 'Thaibonnet' rice cultivar. Our results probably differed because of the greater LAI and tiller number of the semidwarf PI 312777 when compared with the taller Kaybonnet, which could have a compounding effect on the growth of the much taller Stgstraw red rice. PI 312777 was more competitive than Kaybonnet when compared with a very tall LA3 red rice ecotype (Estorninos et al. 2002), while Stgstraw was less competitive than a much taller LA3 ecotype when compared with Kaybonnet rice (Estorninos et al. 2005). Gealy et al. (2003b) reported that the Asian *indica* cultivars, PI 312777 and Guichao, produced greater yield and total biomass and were more suppressive than the tropical *japonica* Kaybonnet with respect to barnyardgrass. Fofana and Rauber (2000) observed that early tiller production in IG10 made it more competitive against weeds than IDSA6, Moroberekan, and other improved *Oryza sativa* cultivars. The ability to produce more tillers and aboveground biomass resulted in sustained competitiveness against red rice by PI 312777 compared with Kaybonnet. Ni et al. (2000) reported that the competitiveness against weeds of modern rice cultivars is best predicted by biomass at the tillering stage, as was reported by our data.

Some rice cultivars, including PI 312777, can produce phytotoxins and exhibit allelopathic activity against barnyardgrass or other target plants (Ebana et al. 2001a, 2001b; Jensen et al. 2001; Mattice et al. 2001; Olofsdotter 2001; Rimando et al. 2001). The extent to which allelopathic activity may have facilitated the suppression of red rice by PI 312777 or the other cultivars in this study was not addressed.

The introduction of high-yielding *indicas* into the southern United States appears to be promising (Gealy et al. 2003b; Rutger et al. 2003). Our work indicates that some of these cultivars (PI 312777 and Guichao) can suppress red rice moderately and can produce high yields. The effect of these cultivars on red rice was not as dramatic as with barnyardgrass, probably because of the competitiveness of red rice (Estorninos et al. 2002) and uneven development due to high dormancy (Annou et al. 2000). Although these *indicas* had poor quality attributes (Dilday et al. 2001b; Gealy et al. 2003b; Slaton et al. 2001), it may be feasible to combine their weed-suppressive traits with high grain quality germplasm to develop competitive cultivars for regions in the southern United States with problematic red rice infestation as well as for the water-seeded rice production systems in California (Gibson et al. 2003) and tropical regions (Ni et al. 2000). Early reports on commercial hybrid rice recently introduced into the United States suggest that these cultivars are especially competitive against weeds, including red rice. Although red rice must be completely controlled to optimize rice production, our results suggest an opportunity to develop reduced-cost management programs for red rice alone or in combination with other weed management strategies. The above characteristics of the *indicas* could improve the success of reduced herbicide rate application and reduce the perceived risks associated with the environmental effects of pesticides.

Sources of Materials

[1] Licor LI 3000A Portable Area Meter, LI3050A/4, Li-Cor Inc., 4308 Progressive Ave., Lincoln, NE 68504.

[2] PQ21B Delnet bag, Applied Extrusion Technologies Inc., 601 Industrial Drive, Middletown, DE 19709.

[3] Dickey-john Multi-grain Moisture Tester, Seedburo Equipment Co., 1022 W. Jackson Blvd., Chicago, IL 60607-2990.

[4] SAS Institute Inc. 1999. SAS OnlineDoc, Version 8, SAS Institute Inc., SAS Campus Drive, Cary, NC 27513.

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