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Rice Parameters Describing Crop Performance of Four U.S. Cultivars

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ABSTRACT

Parameters describing processes of crop growth and yield production provide modelers with the means to simulate crops and provide breeders with a system of comparing cultivars. Such values for rice (*Oryza sativa* L.) are especially important for some regions in the southern USA. Accordingly, the objective of this study was to quantify key biomass and yield production processes of four rice cultivars common in this region. We measured the leaf area index (LAI), the light extinction coefficient (*k*) for Beer's law, N concentrations, and the harvest index (HI) for the main and ratoon crops in 1999 and 2000 at Eagle Lake, TX. Dry matter was linearly related to intercepted photosynthetically active radiation (IPAR) for all of the data sets. The mean radiation use efficiency (RUE) was 2.39 g aboveground biomass MJ^{-1} IPAR. Maximum LAI values ranged from 9.8 to 12.7, and the mean *k* value for the main crop was 0.37. The highest main crop yields were 7.04 Mg ha^{-1} for Cocodrie in 1999 and 7.22 Mg ha^{-1} for Jefferson in 2000. Yield differences among cultivars were due to HI differences and were not related to RUE values. The mean HI was 0.32 for all four cultivars over the two harvests in each of the 2 yr. Consistency in values of RUE, *k*, N concentrations, and HI among the cultivars in this study and between this study and values reported in the literature will aid modelers simulating rice development and yield and aid breeders in identifying key traits critical to rice grain yield improvement.

REALISTIC DESCRIPTION OF KEY PROCESSES in crops provides a means of quantifying how cultivars differ and helps provide a system of simulating grain yield production using crop models. Crops grow leaf area [as described with the leaf area index (LAI)], intercept light [as described with the light extinction coefficient (*k*) in Beer's law; Monsi and Saeki, 1953], and produce biomass as a function of intercepted light [radiation use efficiency (RUE)]. Biomass is partitioned into grain, as reflected by the harvest index (HI), and biomass production can be reduced by N deficiency, as described by plant concentrations less than values determined with adequate available N. Quantification of these processes for common cultivars of a crop is valuable for identifying key traits for selecting higher yielding cultivars in the future. Such is also important for simulating common cultivars under variable climatic conditions. As discussed by Amthor and Loomis (1996), mechanistic models simulating cropping systems at one level are best described by processes at a lower level. Likewise, Sinclair and Seligman (2000) discussed how crop-level simulation models should simulate processes at the whole-plant level and whole-plant simulation should be simulated at the organ level.

Description of these processes in rice is needed for simulating how changes in production acreage in the USA influence regional environmental quality. Reductions in areas used for rice production can change watershed hydrology, water quality downstream, and plant cover throughout the year. Accurate simulation of rice

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Abbreviations: AB, aboveground biomass; HI, harvest index; *k*, light extinction coefficient for Beer's law; IPAR, photosynthetically active radiation intercepted by plants; LAI, leaf area index; PAR, photosynthetically active radiation; RUE, radiation use efficiency.

LAI, biomass, and nutrient uptake is critical to evaluating environmental impacts of large-scale changes in areas traditionally used for rice production. Likewise, accurate measurements of critical parameters for processes involved in rice development and yield can be useful for comparing productivity of different cultivars. While rice is a dominant crop species in southeastern Arkansas, southern Louisiana, and the Coastal Plain of Texas, there is a paucity of information from these regions to allow its simulation by process-based models such as ALMANAC (Agricultural Land Management Alternatives with Numerical Assessment Criteria; Kiniry et al., 1992) and SWAT (Soil and Water Assessment Tool; Arnold et al., 1998). Especially needed are seasonal values for LAI, light extinction coefficient *k*, RUE, HI, and N concentrations.

Values for LAI of rice have been reported as great as 6 to 10. Campbell (2000), using only leaf laminae, reported maximums of 5.6 in 1998 and 6.2 in 1999 for cultivar Cypress in Texas. Maximum values were 5.7 to 8.2 at a Philippine site and 6.7 to 10.4 at a Chinese site (Ying et al., 1998a). Hasegawa and Horie (1996) found maximum LAI values of 6 and 7 in 2 yr at Kyoto, Japan. In Australia, maximum values were >7 for cultivar Lemont (Borrell et al., 1997) and 5.8 for a tall upland cultivar and 3.0 for a semidwarf lowland cultivar under high N application (Prasertsak and Fukai, 1997). In Arkansas, Grigg et al. (2000) reported maximum values >7 in 1989 and >6 in 1990. Maximum values in Cote d'Ivoire were 5.3 for improved lowland rice, 6.8 for improved upland rice (*Oryza sativa* L. subsp. *japonica*), and 8.1 for traditional upland rice (*O. glaberrima* Steud.) (Dingkuhn et al., 1999).

In addition to values for LAI, accurate values for *k* are vital for simulating light interception and RUE. While Monteith (1969) reported a rice *k* value of 0.65, recent values have been lower. Mitchell et al. (1998) reported a *k* value of 0.35 before panicle initiation. When Dingkuhn et al. (1999) included both stem area and leaf area, their mean *k* value over several rice cultivars was 0.47. Their mean *k* at 31 d after sowing ranged from 0.30 to 0.38, and the mean was 0.36.

The rate of conversion of intercepted light into biomass, or RUE, for rice is lower than for other common grain crops (Kiniry et al., 1989). Rice RUE generally ranges from 2.2 to 2.4 g of aboveground biomass (AB) per megajoule of intercepted photosynthetically active radiation (IPAR). The rice RUE from four studies outside the USA were described by Kiniry et al. (1989). The mean for three of these studies was 2.2 g AB MJ^{-1} IPAR. Rice RUE in the Philippines (Mitchell et al., 1998) was 2.34 g AB MJ^{-1} IPAR when photosynthetically active radiation (PAR) is assumed to be 45% of total solar radiation instead of 50%. Charles-Edwards (1982), using data from Japan (Vong and Murata, 1978), reported values with a mean of 2.37 g AB MJ^{-1} IPAR when mean temperatures were above 20°C. After deleting unusually large RUE values early in the season, Campbell (2000) reported values for cultivar Cypress in southern Texas with means of 2.55 in 1998 and 2.34 in 1999, for an average of 2.45. Horie et al. (1997) reported RUE values of 2.99, 2.94, and 2.96 g AB MJ^{-1} total solar radiation for Kyoto and Ina, Japan and Yanco, Australia. These were converted from the RUE in units of grams of AB per MJ of total solar radiation to grams per MJ of PAR by assuming 45% of total solar is PAR. Further refinement, using the correction factor of 1.449 for decreasing *k* of total solar radiation relative to *k* of PAR (the ratio for wheat and rye from Jovanovic and Annandale, 1998) and the technique described by Kiniry (1999) to correct for differences between PAR and total solar radiation in the fraction intercepted from LAI of 0.1 to 6.0, resulted in an RUE correction factor of 1.146. The Horie et al. mean RUE after this transformation, was 2.41.

Reduced *k* values (more upright leaves) are important for allowing better light penetration into leaf canopies, thus illuminating more leaf area at a lower intensity of PAR so that canopy C exchange rates should increase. This would be expected to increase the RUE. Such a trend was reported for diverse C_4 grasses (Kiniry et al., 1999). Alamo switchgrass (*Panicum virgatum* L.) had high LAI and low *k* values, resulting in high RUE. On the other hand, sideoats grama [*Bouteloua curtipendula* (Michaux) Torrey] had low LAI and high *k* values, resulting in much lower RUE.

Once biomass production is simulated, the partitioning of biomass into grain can be described with the HI. Rice HI values varied greatly among cultivars, locations, seasons, and ecosystems, ranging from 0.35 to 0.62, indicating the importance of this variable for yield simulation. Values were 0.35 to 0.50 (mean = 0.43) in the Philippines and 0.44 to 0.48 in China (mean = 0.46) (Ying et al., 1998a). Research by ten Berge et al. (1997) showed values ranging from 0.36 to 0.62 in China, 0.40 to 0.55 in India, 0.35 to 0.55 in the Philippines, and 0.42 to 0.57 in Australia. Cultivar Lemont in Australia had values of 0.49 in a dry season and 0.46 in a wet season (Borrell et al., 1997). Horie et al. (1997) reported mean values of 0.36 for Kyoto, Japan; 0.50 for Ina, Japan; and 0.43 for Yanco, Australia. In Australia, Prasertsak and Fukai (1997) reported values of 0.37 for a tall upland rice in the highest N application treatment and 0.53 for a semidwarf lowland cultivar.

Reductions in biomass due to N deficiency can also be important for rice modeling. Plant N concentrations in plots with adequate available N provide a system of describing nutrient demand for optimum biomass production. When available N is inadequate to meet demand, biomass will be reduced. Nitrogen concentrations for cultivar IR72 in the Philippines and China in 1996 were 38.2 and 40.7 g kg^{-1} at midtillering (mean = 39.4 g kg^{-1}), 14.1 and 12.7 at flowering (mean = 13.4), and 12.2 and 9.5 at maturity (mean = 10.8) (Ying et al., 1998b). In addition, reduced leaf N concentration has been described as a factor in plant biomass productivity and RUE, especially in N-deficient conditions (Sinclair and Horie, 1989).

The objective of the present study was to quantify LAI development, *k*, RUE, and HI of four common U.S. rice cultivars. Such quantification of these key parameters will enable their simulation by process-oriented crop models. In addition, this will offer a process-based system of comparing crop performance of rice cultivars.

MATERIALS AND METHODS

Four rice cultivars commonly grown in the southern USA were used in this study. All were grown at the Texas Agricultural Experiment Station near Eagle Lake, TX (29°37′ N, 96°20′ W; 54 m above sea level) on Nada fine sandy loam (fine-loamy, siliceous, active, hyperthermic Albaquic Hapludalfs) in 1999. The cultivars were Jefferson (Group 1 maturity), Cocodrie (Group 2 maturity), and Lemont and Cypress (Group 3 maturity). Cypress is grown in 50 to 60% of the rice acreage in Texas and Louisiana. Jefferson and Cocodrie are promising new cultivars. Jefferson matures 2 wk earlier than the Group 3 cultivars. There were four replications of each cultivar; each plot 10 rows wide and 4.88 m long, with 0.19 m between rows. Cultivars were grouped by maturity to allow the timing of flooding to match the maturity dates. We used a split-plot design, with maturity group as the main plots and cultivar as the subplot. Plots were planted on 29 Mar. 1999 and 13 Apr. 2000. Cultivars were planted to get plant stands of 200 to 260 plants m^{-2}. Actual stands in the 2 yr were 215 and 212 plants m^{-2} for Jefferson, 265 and 235 for Cocodrie, 258 and 195 for Lemont, and 230 and 202 for Cypress. Plots were flooded from the five-leaf stage until 2 wk before harvest. Plots received 188 kg N ha^{-1} as urea [$(NH_2)_2CO$], 42 kg P ha^{-1} as phosphoric oxide (P_2O_5), and 42 kg K ha^{-1}. All P and K and 30% of the N was incorporated preplant. The remaining N, as ammonium sulfate [$(NH_4)_2SO_4$], was split in two applications, at preflood and at panicle differentiation. The ratoon crops received 100 kg N ha^{-1}, as ammonium sulfate, 1 d after the first grain harvest and were flooded immediately thereafter. Ratoon crops were drained about 10 d before harvest.

We measured PAR interception during the season with a 0.8-m-long Sunfleck Ceptometer (Decagon, Pullman, WA). In each replication, we took three series of measurements in rapid succession. A series of measurements consisted of 10 PAR measurements above the canopy, 10 below the canopy, and 10 more above the canopy. The fraction of PAR intercepted was calculated with the mean of the measurements above and below the canopy. While taking the readings below the canopy, the light meter was moved across the plant rows. Measurements were taken between 1020 and 1200 h during times with relative stable incident solar radiation (without intermittent clouds). Daily incident PAR values were taken as 45% of the total solar radiation values reported for long-term measurements at the location (Monteith, 1965; Meek et al., 1984).

Whole plants were harvested for measuring LAI and dry weight on each day that light interception was measured. Samples consisted of a half meter of row per replication per cultivar. One-half meter of row from each plot was harvested after maturity for determining HI. Leaf areas of the samples were measured with a LI-COR LI-3100 leaf area meter (LI-COR, Lincoln, NE). Weights of the total aboveground plant and the panicle were measured after forced-air drying in an oven at 70°C until the weight stabilized. Grain was separated from a subsample of the panicles from each replication, and the fraction of the panicle that was grain was measured. Plant N concentrations were determined by the Soil, Water, and Forage Testing Laboratory at Texas A&M University using the total Kjeldahl digest procedure.

Regressions were fit with the treatment means of aboveground plant dry weight and summed IPAR for each replication. The RUE is the slope of the regression for this plant weight (g m^{-2}) as a function of the summed IPAR (MJ m^{-2}). In each year, using indicator variables for slopes and intercepts, we pooled all of the data and tested to see if regressions for Jefferson, Lemont, or Cypress differed significantly from Cocodrie at the 95% confidence level. Cocodrie was chosen due to it being in the intermediate maturity group. Each cultivar other than Cocodrie was assigned indicator variables for slope and intercept, their values being 1.0 for that cultivar and 0.0 for the other cultivars. Significance of the regression parameter corresponding to an indicator variable indicated that the slope or the intercept for the cultivar was different from that of Cocodrie (Neter et al., 1985).

The light extinction coefficient (k) for Beer's law (Monsi and Saeki, 1953) was calculated for each harvest date of each cultivar as:

$$k = [\text{logn}\ (1 - \text{FIPAR})]/\text{LAI} \qquad [1]$$

where logn = natural log of the number and FIPAR = fraction of IPAR. Using the measured values for each replication of each cultivar, means and standard deviation values were calculated for LAI, k, grain yield, and HI.

RESULTS

Leaf Area Index

The LAI values that we measured for the main crops were generally greater than those reported in the literature. Our values increased up to maximums of 11.2 to 12.7 in 1999 (Table 1) and 9.8 to 11.2 in 2000 (Table 2). In 1999, the greatest LAI on each harvest after the first was for one of the two later maturing cultivars. Lemont had the greatest value on three of these dates. In 2000, Lemont had the greatest LAI on the first three harvest dates. Thereafter, Cypress and Cocodrie had the greatest values.

For the main crop, the expected trend of later maturity cultivars reaching maximum LAI later did not always occur. In 1999, the two earliest cultivars had their maximum LAI values on 7 July, and LAI decreased by 22 July. Cypress LAI continued to increase until 22 July, and Lemont LAI changed very little between 7 and 22 July. In 2000, the earliest cultivar, Jefferson, had maximum LAI on 14 June. The medium-maturity Cocodrie and late-maturity Cypress had maximums later, on 27 June, as might be expected. Surprisingly, the late cultivar Lemont had its maximum LAI on 14 June.

For the ratoon crops in 2000, maximum LAI values were lower than for the main crops (Table 3). Because

Table 1. Main-crop leaf area indices (LAI) and light extinction coefficients (k) for Beer's law in 1999.

		Cultivar			
Date		Jefferson	Cocodrie	Cypress	Lemont
		Mean ± SD			
13 May	LAI	1.0 ± 0.0	0.1 ± 0.0	0.1 ± 0.0	0.1 ± 0.0
2 June	LAI	2.3 ± 0.4	1.6 ± 0.3	2.1 ± 0.5	2.6 ± 0.3
	k	0.42 ± 0.08	0.57 ± 0.11	0.60 ± 0.08	0.54 ± 0.06
23 June	LAI	9.0 ± 1.2	7.0 ± 0.6	9.5 ± 1.6	8.4 ± 0.9
	k	0.27 ± 0.02	0.37 ± 0.03	0.43 ± 0.04	0.42 ± 0.05
7 July	LAI	12.2 ± 1.2	11.2 ± 0.4	10.2 ± 0.5	12.7 ± 1.8
	k	0.28 ± 0.02	0.27 ± 0.02	0.35 ± 0.02	0.30 ± 0.05
22 July	LAI	8.1 ± 1.3	10.8 ± 2.7	11.8 ± 2.3	12.4 ± 2.7
	k	0.53 ± 0.14	0.40 ± 0.09	0.40 ± 0.06	0.34 ± 0.08
Mean k		0.38	0.40	0.45	0.40
Max. LAI		12.2	11.2	11.8	12.7

Table 2. Main-crop leaf area indices (LAI) and light extinction coefficients (*k*) for Beer's law in 2000.

		Cultivar			
Date		**Jefferson**	**Cocodrie**	**Cypress**	**Lemont**
		Mean ± SD			
16 May	LAI	2.2 ± 0.5	2.4 ± 0.3	2.2 ± 0.2	2.9 ± 0.5
	k	0.31 ± 0.07	0.40 ± 0.02	0.36 ± 0.06	0.34 ± 0.02
5 June	LAI	7.8 ± 1.4	7.3 ± 0.9	6.3 ± 1.7	8.1 ± 0.9
	k	0.31 ± 0.07	0.29 ± 0.04	0.47 ± 0.15	0.29 ± 0.05
14 June	LAI	9.8 ± 1.2	9.5 ± 0.9	9.3 ± 1.4	10.0 ± 1.0
	k	0.29 ± 0.03	0.30 ± 0.04	0.36 ± 0.07	0.35 ± 0.03
27 June	LAI	8.6 ± 1.5	10.2 ± 1.3	11.2 ± 2.0	9.5 ± 1.1
	k	0.44 ± 0.08	0.42 ± 0.05	0.41 ± 0.06	0.48 ± 0.03
12 July	LAI	4.5 ± 2.5	8.5 ± 1.0	8.5 ± 1.0	6.1 ± 2.0
	k	–	0.57 ± 0.09	0.57 ± 0.13	0.81 ± 0.23
Mean *k*†		0.34	0.35	0.35	0.42
Max. LAI		9.8	10.2	11.2	10.0

† For the first four dates.

it was harvested and cut first, Jefferson had the advantage of earlier regrowth of leaf area. Jefferson had the greatest LAI values throughout the season and the greatest maximum LAI. All four cultivars had their greatest LAI values on the 21 September harvest date.

Light Extinction Coefficients

Values of *k* for the main crops were similar to values in the literature and generally did not show consistent trends of increasing or decreasing with increasing LAI (Tables 1 and 2). An exception to this was for the 12 July harvest in 2000 when light interception by senesced leaf material likely contributed to the increased *k*. Such was also apparent on the 22 July harvest of Jefferson in 1999. The mean main-crop *k* was lowest for Jefferson in both years (0.38 and 0.34) and greatest for Cypress in 1999 (0.45) and Lemont in 2000 (0.42). Jefferson's mean *k* in 1999 was 0.32 without the last harvest date.

The *k* values for the ratoon crops were greater than the main-crop values (Table 3). The means for the last five dates ranged from 0.65 to 1.03. On four of the last five harvest dates, Cocodrie had the greatest *k* value. Excluding the first two harvest dates, when LAI values were very low, there was not a consistent trend of *k* increasing or decreasing during the season.

Table 3. Ratoon crop leaf area indices (LAI) and light extinction coefficients (*k*) for Beer's law in 2000. Overall mean *k* for the last five dates was 0.85. Mean maximum LAI was 3.1.

		Cultivar			
Date		**Jefferson**	**Cocodrie**	**Cypress**	**Lemont**
		Mean ± SD			
18 Aug.	LAI	0.11 ± 0.05	0.02 ± 0.01	–	–
	k†	2.78	3.73	–	–
24 Aug.	LAI	0.8 ± 0.1	0.2 ± 0.1	0.2 ± 0.1	0.1 ± 0.1
	k	1.07 ± 0.20	2.16 ± 1.15	0.69 ± 0.23	2.10 ± 1.21
31 Aug.	LAI	1.6 ± 0.3	0.5 ± 0.1	0.3 ± 0.1	0.5 ± 0.2
	k	0.82 ± 0.30	1.10 ± 0.19	1.04 ± 0.30	0.97 ± 0.57
7 Sept.	LAI	2.8 ± 0.3	0.9 ± 0.2	0.6 ± 0.1	0.6 ± 0.3
	k	0.62 ± 0.07	1.41 ± 0.49	1.30 ± 0.25	1.63 ± 0.66
14 Sept.	LAI	3.2 ± 0.4	2.0 ± 0.5	2.4 ± 0.3	2.5 ± 0.9
	k	0.53 ± 0.09	0.87 ± 0.25	0.43 ± 0.09	0.44 ± 0.15
21 Sept.	LAI	4.4 ± 0.4	2.5 ± 0.2	2.8 ± 0.5	2.8 ± 0.6
	k	0.43 ± 0.08	0.65 ± 0.07	0.57 ± 0.18	0.46 ± 0.13
28 Sept.	LAI	2.4 ± 0.3	1.8 ± 0.5	1.7 ± 0.4	2.1 ± 1.3
	k	0.87 ± 0.10	1.10 ± 0.34	0.92 ± 0.26	0.88 ± 0.39
Mean *k*‡		0.65	1.03	0.85	0.88
Max. LAI		4.4	2.5	2.8	2.8

† Limited measurements of intercepted photosynthetically active radiation (PAR) on this date precluded calculation of SD values.

‡ For the last five dates.

Table 4. Radiation use efficiency (RUE; mean ± SE) and light extinction coefficients (*k*) for Beer's law.

	Cultivar				
	Jefferson	**Cocodrie**	**Cypress**	**Lemont**	**Means**
	RUE, g AB MJ^{-1} IPAR†				
1999	2.32 ± 0.08	2.41 ± 0.16	2.09 ± 0.10	2.21 ± 0.11	2.26
2000	2.46 ± 0.17	2.77 ± 0.19	2.59 ± 0.14	2.24 ± 0.22	2.52
Ratoon 2000	2.10 ± 0.19	2.06 ± 0.14	2.21 ± 0.15	1.40 ± 0.19	1.94
Means‡	2.39	2.59	2.34	2.23	2.39
Ratoon rel.§	0.94	0.80	0.94	0.63	0.83
	k¶				
1999	0.38	0.40	0.44	0.40	0.40
2000	0.34	0.35	0.35	0.42	0.36

† AB, aboveground biomass; IPAR, intercepted photosynthetically active radiation.

‡ For main-crop values only.

§ Relative to main-crop means.

¶ Mean main-crop *k* for Beer's law.

Radiation Use Efficiency

For the RUE analysis, insufficient sampling precluded realistic results for the ratoon crop in 1999. Thus, only the main-crop results for 1999 and 2000 and ratoon crop results for 2000 will be presented.

For each main crop, the cultivar with the lowest RUE had the greatest mean *k* value (Table 4), in agreement with results on warm-season grass species as discussed above (Kiniry et al., 1999). In 1999, Cypress was the only cultivar that differed significantly from Cocodrie, and it only differed in slope. For the main and ratoon crops of 2000, Lemont was the only cultivar showing significant difference from Cocodrie, and similar to Cypress in 1999, it differed only in slope. In each season, we pooled data for the three similar cultivars and fit a new regression. The 1999 RUE for the three varieties pooled was 10% greater than for Cypress (Fig. 1). For the main crop of 2000, RUE of the three pooled varieties was 17% greater than the RUE of Lemont (Fig. 2). For the ratoon crop of 2000, the three pooled cultivars had an RUE that was 49% greater than that of Lemont (Fig. 3).

Some factors were reducing leaf area and biomass each year of the cultivar with the lowest RUE, but between years, it varied as to which cultivar this was. Relative to cultivars of similar maturity, for each year, the cultivar with the lowest main-crop RUE had lower LAI, accumulated similar amounts of IPAR, but had reduced biomass. In 1999, Cypress had the lowest LAI of all cultivars. In 2000, Lemont had a lower maximum LAI than Cocodrie or Cypress.

Differences among the two main-crop RUE values may be related to temperature (Table 5). The mean temperature from May to July was greater in 2000, primarily due to greater daily maximum temperatures. Especially important may be the nearly 5°C warmer mean for July in 2000 than in 1999.

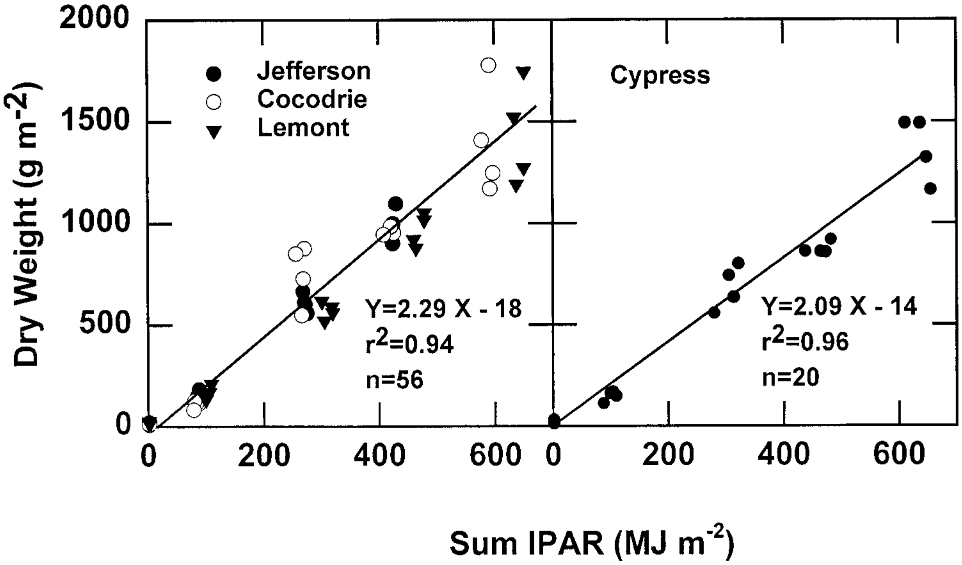

Fig. 1. For the main crop of 1999, rice dry weight as a function of summed intercepted photosynthetically active radiation (IPAR) for three cultivars pooled and cultivar Cypress at Eagle Lake, TX. The slope is the radiation use efficiency (RUE).

Grain Yield and Harvest Index

For each main and ratoon crop, the cultivar with the greatest yield (Table 6) also had the greatest values for HI (Table 7). In three of the four seasons, Jefferson was the highest yielding. The relatively low yield of Jefferson for the 1999 main crop was also evident in whole-plot yield estimates from adjacent plots, which had not been sampled during the growing season (data not shown).

Main-crop yields were greater than mean yields of Texas rice growers for 1997 and 1998 (Klosterboer and McClung, 1999), but the relative ranking of cultivar yields was similar. Mean dry-weight grain yield of Jefferson for the growers was 568 g m^{-2}. This was only 79% as great as our mean main-crop yields for Jefferson. Our mean main-crop yield of Cypress was 94% of Jefferson's, and the mean for growers' fields was 93% of Jefferson's. The main crop yield of Lemont was 96% of Jefferson's, and the mean for growers' fields was 95% of Jefferson's.

Earlier maturity, due to maturity type or N applications, appears to increase yield of ratoon rice. Our ratoon yields were 30 to 44% of the main-crop yields. The mean ratio was 37%. Ratoon yields of the earliest cultivar, Jefferson, were greater than those of the other cultivars. Klosterboer et al. (1999) stressed the importance of fast stimulation of ratoon crop regrowth. They recommended early application of N to a ratoon crop to stimulate regrowth, cause earlier maturity, and increase yield potential.

The mean HI of 0.32 for all varieties at all four har-

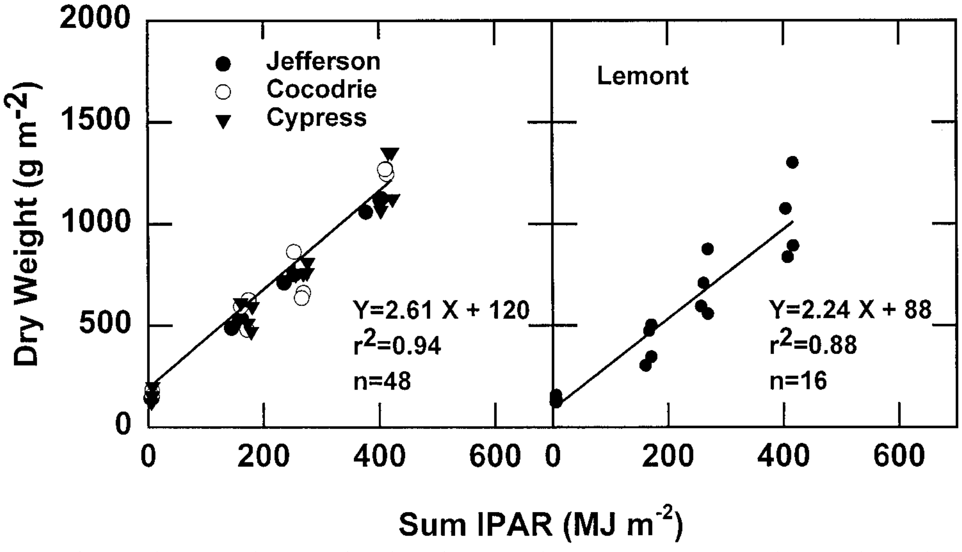

Fig. 2. For the main crop of 2000, rice dry weight as a function of summed intercepted photosynthetically active radiation (IPAR) for three cultivars pooled and cultivar Lemont at Eagle Lake, TX. The slope is the radiation use efficiency (RUE).

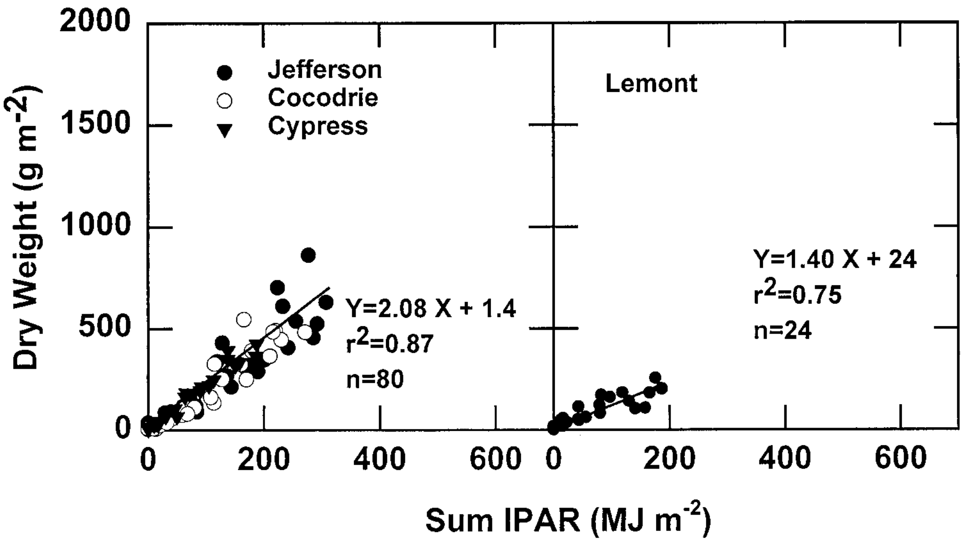

Fig. 3. For the ratoon crop in 2000, rice dry weight as a function of summed intercepted photosynthetically active radiation (IPAR) for three cultivars pooled and cultivar Lemont at Eagle Lake, TX. The slope is the radiation use efficiency (RUE).

vests was in the low end of the range of values reported by others (Table 7). Our mean main-crop HI values were 0.35 in 1999 and 0.36 in 2000.

Nitrogen Concentrations

Nitrogen concentrations of Cypress in the main crops decreased from about 42 to 44 g kg^{-1} at early growth stages to about 16 g kg^{-1} at maturity (Tables 8 and 9). For the 2000 ratoon crop, Cypress N concentration decreased from 49 g kg^{-1} in August to 17 and 20 g kg^{-1} for stovers and seeds, respectively. Nitrogen concentration in the seeds was always greater than in the stover. Seed N concentration was 6 to 87% greater than in the stover.

The other three cultivars frequently had lower N concentrations than Cypress. With the exception of the ratoon crop of Jefferson and Cocodrie in 1999, the mean N concentrations of the three cultivars were 2 to 21% less than N concentrations of Cypress. However, in 1999, the only cases where N concentrations were significantly different from those of Cypress were the third harvest date of Jefferson for the main crop, the seed sample of Jefferson for the main crop, the stover sample of Jefferson in the ratoon, and all of the ratoon samples of Cocodrie. Statistical comparisons in 2000 were not possible because all of the samples from the replications of a cultivar were combined on each date.

Table 5. Temperatures during the growing seasons.

	Avg. daily max.	Avg. daily min.	Mean
	°C		
1999			
May	28.9	17.1	23.0
June	30.1	20.8	25.4
July	26.7	17.3	22.0
Aug.	35.0	21.8	28.4
Sept.	30.4	15.6	24.1
May–July	28.5	18.4	23.5
Aug.–Sept.	32.7	18.7	26.2
2000			
May	28.9	18.9	23.9
June	28.9	19.4	24.2
July	33.1	20.6	26.9
Aug.	34.4	20.6	27.5
Sept.	30.6	16.7	23.6
May–July	30.4	19.6	25.0
Aug.–Sept.	32.5	18.6	25.6

DISCUSSION

Rice, because of its importance as a human food crop, has been extensively studied in many countries. The transfer of research findings from international studies to U.S. rice production can benefit both modeling research and rice breeding. Results of the present study lend credence to the use of crop parameters similar to those reported elsewhere to simulate rice in the southern USA. An LAI value of 10 to 12 and a *k* value of 0.37 appear to be appropriate for the main crop of rice in this region. Likewise, an RUE value of 2.33 g AB MJ^{-1} IPAR is reasonable for such simulations. For ratoon crops, the maximum LAI should only be 3 to 4, and the *k* value can be 0.85. Harvest index values of 0.35 for a main crop and 0.30 for a ratoon should be realistic.

Our mean RUE of 2.33 g AB MJ^{-1} IPAR for the pooled three cultivars over the three seasons was similar to the Mitchell et al. (1998) RUE of 2.34, Charles-

Table 6. Rice grain yields (means ± SD) for 2 yr at Eagle Lake.

	Cultivar				
	Jefferson	Cocodrie	Cypress	Lemont	Means
	g m^{-2}				
1999	370 ± 80	704 ± 86	690 ± 100	670 ± 84	609
Ratoon 1999	434 ± 60	227 ± 36	232 ± 24	256 ± 36	287
2000	722 ± 114	701 ± 22	671 ± 36	712 ± 48	702
Ratoon 2000	317 ± 30	293 ± 22	177 ± 22	–	262
Means main crop†	722	703	681	692	656
Means ratoon crop	317	260	205	256	274
Ratoon/main crop†	0.44	0.37	0.30	0.37	0.37

† Mean for both years except only for 2000 for Jefferson's main and ratoon crops and only for 1999 for Lemont's ratoon crop.

Table 7. Harvest index (HI) results (mean ± SE) for 2 yr at Eagle Lake.

	Cultivar				
	Jefferson	Cocodrie	Cypress	Lemont	Means
1999	0.32 ± 0.02	0.38 ± 0.01	0.35 ± 0.01	0.35 ± 0.01	0.35
Ratoon 1999	0.33 ± 0.01	0.21 ± 0.01	0.22 ± 0.01	0.21 ± 0.02	0.24
2000	0.40 ± 0.01	0.36 ± 0.01	0.33 ± 0.01	0.37 ± 0.01	0.36
Ratoon 2000	0.35 ± 0.01	0.34 ± 0.02	0.25 ± 0.02	–	0.31
Means	0.35	0.32	0.29	0.31	0.32

Edwards' (1982) mean of 2.4, Campbell's (2000) mean of 2.45, and the mean of Horie et al. (1997) of 2.41. Pooling the four cultivars, our mean main-crop k value of 0.37 was similar to the 0.35 of Mitchell et al. (1998) before panicle initiation and the 0.36 of Dingkuhn et al. (1999) at 31 d after sowing.

Our mean value of RUE shows a realistic ranking relative to the maize (*Zea mays* L.) RUE reported by Kiniry et al. (1989). Using several sites in Japan, Murata and Togari (1975) reported a mean "solar energy utilization efficiency" of rice that was 66% of the maize value. Similarly, our mean rice RUE value of 2.33 g AB MJ^{-1} IPAR is 67% of the mean maize RUE of 3.5 g AB MJ^{-1} IPAR reported by Kiniry et al. (1989).

Our mean main-crop N concentrations were similar to those of Ying et al. (1998b) (Tables 8 and 9). Our means for 1999 and 2000 were 43.3 g kg^{-1} on the first date, 39.3 on the second, 15.3 at flowering, and 14.0 at maturity. Mean values of Ying et al., as discussed above, for IR72 in 1996 were 39.4 g kg^{-1} at midtillering, 13.4 at flowering, and 10.8 at maturity.

Under these conditions of adequate applied N, cultivar differences in RUE were not related to plant N concentrations. Similar to results with different species of warm-season grasses with adequate soil N (Kiniry et al., 1999), the N concentration effect on RUE reported by Sinclair and Horie (1989) was not valid for comparing these rice cultivars under such conditions. Future research with differential N application rates will be valuable for identifying the critical concentrations to simulate N responses.

Table 8. Nitrogen concentration of aboveground (AB) biomass for 1999 (actual concentration of Cypress and the values of the other three cultivars relative to Cypress). Italic values were significantly different from Cypress with a *t*-test at the 95% confidence level.

	Cultivar			
Date	Cypress	Jefferson	Lemont	Cocodrie
	g kg^{-1}	—— Values relative to Cypress ——		
Main crop				
13 May	44.3	1.00	–	1.03
2 June	45.9	1.03	0.94	1.03
23 June	31.9	*0.90*	0.96	1.03
7 July	22.9	0.88	0.89	0.93
22 July	16.9	0.91	0.94	0.93
17 Aug. (stovers)	14.0	0.93	0.96	0.95
17 Aug. (seed)	18.1	*0.90*	0.93	0.95
Means†		0.94	0.94	0.98
Ratoon crop				
17 Sept.	24.8	0.93	1.00	*1.13*
4 Oct.	17.4	1.01	0.94	*1.34*
15 Nov. (stovers)	10.3	*1.42*	0.97	*1.44*
15 Nov. (seed)	19.3	1.22	0.80	*1.39*
Means†		1.15	0.93	1.32

† For all of the values except seed.

Table 9. Nitrogen concentration of aboveground (AB) biomass for 2000 (actual concentration of Cypress and the values of the other three cultivars relative to Cypress). Samples were combined for all replications, so we could not do *t*-tests.

	Cultivar			
Date	Cypress	Jefferson	Lemont	Cocodrie
	g kg^{-1}	—— Values relative to Cypress ——		
Main crop				
16 May	41.6	1.04	0.99	0.99
5 June	33.4	0.88	0.89	1.15
14 June	40.3	0.86	0.86	0.92
27 June	27.2	0.68	1.02	0.71
12 July	16.6	0.70	1.00	0.82
Maturity† (stovers)	16.0	0.60	0.75	0.83
Maturity† (seed)	17.0	0.88	0.94	0.87
Means‡		0.79	0.92	0.90
Ratoon crop				
24 Aug.	49.0	0.96	1.03	1.02
31 Aug.	38.9	1.10	1.13	1.03
7 Sept.	33.8	0.77	1.12	0.73
14 Sept.	34.9	0.76	1.05	0.65
21 Sept.	23.4	0.78	0.88	1.06
28 Sept.	19.5	0.75	0.87	1.08
Maturity† (stovers)	16.9	0.78	0.84	0.92
Maturity† (seed)	20.0	0.76	0.84	0.84
Means‡		0.84	0.99	0.93

† 26 July for Jefferson and Cocodrie and 2 August for Lemont and Cypress for the main crop and 10 Oct. for Jefferson and Cocodrie 19 Oct. for Lemont and Cypress in the ratoon crop.

‡ For all of the values except seed.

While this study described important aspects of rice biomass production, yield variability due to HI differences remains a fertile area for future research on yield assessment. Simulation of environmental aspects of rice production will rely heavily on such realistic description of plant biomass production and nutrient uptake. On the other hand, yield variability among cultivars is highly dependent on HI. In this study, the earliest cultivar, Jefferson, had the largest HI in three of the four seasons as well as the greatest yield in those seasons. Crop models need better description of why HI varies to improve the accuracy of rice yield simulation. Research on processes determining the number of panicles, the number of seeds per panicle, and the weight per seed should continue to be vigorously pursued to quantify the differences in HI observed among cultivars.

Future high-yielding cultivars will likely come from increases in yield components contributing to the aforementioned increased HI and not from increases in RUE. Cultivars showed large differences in grain yield while having similar RUE values. For the 1999 main crop, RUE of Jefferson was not significantly different from Cocodrie, but Jefferson had much smaller yield. For the ratoon crop of 2000, Jefferson and Cypress had similar RUE values, but Jefferson had 79% greater yield. These yield differences among cultivars were largely related to differences in HI.

In conclusion, some of the processes contributing to production of rice biomass and yield were surprisingly stable over a diverse set of locations and cultivars. As discussed above, rice k values, RUE, and optimum N concentrations showed little variability among many studies. Such consistency is desirable for researchers seeking to develop simulation models that are general over a wide range of conditions. However, rice breeders desire more variable plant traits that distinguish genotypes to select for improved cultivars. Such variability was evident in the HI and, thus, in the processes contributing to differences in HI among cultivars.

It is plausible that greater variability among all of these parameters will be evident with a different set of rice cultivars. The four cultivars in the present study were included because they were commonly used in recent production agriculture in the southern USA or they show promise as new cultivars. They may have a narrow genetic base that constrains their range of traits, as evidenced by their similar LAI, *k*, and RUE values. Similar evaluation of a more diverse set of genotypes, such as with more variable leaf angle, may give different results as to the stability of these values.

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