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Transpiration efficiency of rice (*Oryza sativa* L.)

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ABSTRACT

Transpiration efficiency (TE), defined as the total dry matter produced per unit of water transpired, is an important crop characteristic, especially when water resources are becoming scarcer in many regions. But, in contrast to other major food crops, very little is known about the TE of rice (*Oryza sativa* L.) and its dynamics in relation to climatic conditions in typical rice environments. To close this knowledge gap, we characterized rice TE in several experiments with varying experimental and climatic conditions. All six experiments were pot studies conducted between 1994 and 2006 at the International Rice Research Institute, Los Baños, Philippines. Between experiments, arithmetic means of TE varied from 1.8 to 4.7 g dry matter per liter transpired, whereas linear regressions showed TE means between 2.2 and 4.0 g dry matter per liter transpired. Actual TE values were estimated to be about 10% higher because root biomass was not determined. The corresponding *k*-factor ranged from 1.4 to 5.1 Pa (arithmetic mean) and 1.3 to 5.0 Pa (linear regression slope), indicating a considerable effect of climatic conditions on CO_2 and water vapor diffusion processes at the leaf surface. The analysis of different experimental treatments could not show a significant effect of drought treatments or variety on TE, but significant effects of soil type and water by nutrient interactions were observed. We concluded that the TE of rice is in the lower range of other small grain cereals, possibly comparable to oat. The results of this analysis can serve as a reference for further work on the TE of rice but they need to be verified in studies covering a wider range of climatic conditions and in field experiments.

1. Introduction

Rainfed lowland rice (*Oryza sativa* L.) in Asia covers about 45 million hectares or about 34% of the total rice area in that region (Haefele and Hijmans, 2007). In this environment, drought stress is the most important limitation to production and is estimated to frequently affect about 19–23 million hectares (Garrity et al., 1986). In addition, pressure is increasing to reduce water use in irrigated agriculture as a consequence of the global water crisis (Tuong and Bouman, 2002). A resulting major challenge is the development of technologies allowing maintained or even increased rice production with less water in irrigated systems and increased production with the available water resources in rainfed systems (Zeigler and Puckridge, 1995). To achieve this goal, unproductive water uses (evaporation, percolation, seepage, transpiration from weeds) must be reduced, and the quantity and/or efficiency of productive water use (transpiration) need to be increased. Considerable research on management options that reduce unproductive water uses in rice cultivation has been conducted (e.g., Bhuiyan, 1992; Tuong, 1999; Bouman and Tuong, 2001), but knowledge on options increasing productive water use and efficiency in rice is limited and the transpiration efficiency of rice was rarely studied.

Transpiration efficiency (TE) is defined as the ratio of biomass produced per unit of water transpired, and it is well established that the cumulative transpiration of a crop is linearly related to total dry matter production at a given site and season (de Wit, 1958; Bierhuizen and Slatyer, 1965; Tanner and Sinclair, 1983). Across sites, TE mostly depends on the crop species and air vapor pressure deficit; small or no effects are attributed to variety, soil water status, and plant nutrition (Briggs and Shantz, 1917; de Wit, 1958; Bierhuizen and Slatyer, 1965; Yoshida and Coronel, 1976; Fischer and Turner, 1978; Tanner and Sinclair, 1983; Ehlers and Goss, 2003). Frequently reported TE values for other small grain crops vary from 3.1 to 6.7 g kg^{-1} for wheat (Kemanian et al., 2005), 3.2 to 5.7 g kg^{-1} for barley (Kemanian et al., 2005), and 2.9 to 4.5 g kg^{-1} for oat (Ehlers and Goss, 2003; Ehlers, 1989). For rice, an early study of Yoshida (1975) reported transpiration ratios (TR; the reciprocal of TE) corresponding to TE values of 2.3–5.9 g kg^{-1} but details on varieties used (*O. sativa* japonica versus *O. sativa* indica), sampling, and climatic conditions were not provided. More

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recently, Impa et al. (2005) investigated varietal differences of TE in rice and reported TE values ranging from 2.5 to 5.4 g kg^{-1}, but the study most probably underestimated transpiration. Dingkuhn et al. (1991) and Peng et al. (1998) reported measurements of "water use efficiency" and "transpiration efficiency" in rice, but they determined the ratio of photosynthesis and transpiration at the leaf level only.

Thus, very little is known about the TE of rice and its dynamics in relation to climatic conditions in typical rice environments. The objective of this study was to determine and analyze the variability of TE in a number of experiments and to relate the observed TE values to the experimental and climatic conditions. The results could then serve as a baseline for further work on transpiration efficiency in rice.

2. Materials and methods

For the analysis of TE in rice, we pooled data from six experiments conducted for various purposes. All experiments were carried out at the International Rice Research Institute, Los Baños, Philippines (14°11′N, 121°15′E, 23 m altitude), but in various years, locations, and seasons. The institute is located in the warm humid tropics with annual means of 2027 mm rainfall, 16.1 MJ m^{-2} d^{-1} solar radiation, and 26.8 °C temperature. The climate is characterized by a distinct wet and dry season (WS and DS). The WS usually lasts from late May to December. The DS with higher solar radiation, more extreme daily temperatures, and a higher air vapor pressure deficit extends from January to May (Fig. 1). Table 1 gives an overview and a brief description of all experiments included in the analysis. The experiments had different treatments according to their original purpose and differed also in various other factors as described below. Locations distinguished were a screenhouse (SH; no temperature and light control, wire mesh walls and glass roof), glasshouse (GH; phytotron, partial temperature control, glass walls and roof), and growth chamber (GCh; phytotron, full temperature and light control, closed box).

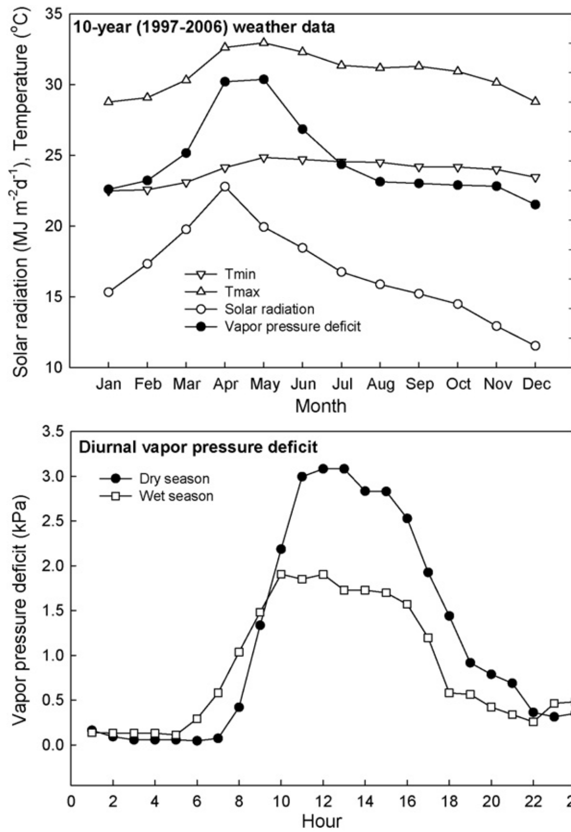

Fig. 1. Climatic characteristics at the International Rice Research Institute. The upper panel presents monthly averages of minimum and maximum temperature, solar radiation, and the vapor pressure deficit of the air for the period 1997–2006 (Climate Unit, IRRI). The lower panel shows the diurnal fluctuations of the vapor pressure deficit of the air for a day in the dry season (April) and the wet season (July), 2006.

2.1. Experiment 1

Experiment 1 was conducted in the 1994 DS in the screenhouse at IRRI as described in Boling et al. (1998). A randomized complete block design (RCBD) with four replicates was used. To minimize border effects, pots with plants were placed around the experiment. Treatments were based on the combination of three factors: variety, water availability, and establishment method. Varieties used were IR72 and PSBRc14. The three water treatments were T1-continuously flooded with a ponded water depth of 20–50 mm; T2-as T1 but drought stress at mid-tillering; T3-as T1 but drought stress at panicle initiation (PI). Water stress was imposed by withholding irrigation until 50% of the leaves died and the remaining green leaves registered a leaf rolling score of 5 (IRRI,

Table 1
Overview of characteristics and treatments for all experiments analyzed. All experiments were pot experiments and conducted at IRRI, Los Baños, Philippines.

Exp.	Duration[a]	Experimental factors					Location[b]
		Variety	Water treatments[c]	Establishment[d]	Soil texture	N–P–K–Zn applied[e]	
Exp. 1	18 January–10 May	IR72, PSBRc14	Flooded, drought at MT, drought at PI, drought at H	Dry DS, Wet DS, Transplanting	Clay loam	240–40–40–0	Screenhouse
Exp. 2a	16 July–19 November	PSBRc14	Flooded, drought at MT	Dry DS	Clay loam	240–40–40–0	Growth chamber
Exp. 2b	16 July–19 November	PSBRc14	Flooded, drought at PI	Dry DS	Clay loam	240–40–40–0	Glasshouse
Exp. 3a	2 February–25 June	PSBRc14	Flooded, drought at MT	Transplanting	Clay loam	240–40–40–0	Growth chamber;
Exp. 3b	2 February–25 June	PSBRc14	Flooded, drought at MT	Transplanting	Clay loam	240–40–40–0	Glasshouse
Exp. 4	26 January–6 May	Apo, IR43	Flooded, aerobic	Transplanting	Clay	180–60–40–5	Screenhouse
Exp. 5	25 June–25 September	Apo	Flooded, aerobic	Transplanting	Clay, silty clay loam	100–30–40–5	Screenhouse
Exp. 6	26 March–21 August	PSBRc82	Flooded, soil saturated, 1 irrigation per week	Wet DS	Clay loam	0–0–0–0, 40–20–20–0, 80–30–30–0, 120–40–40–0	Screenhouse

[a] Trial duration refers to the time from seeding to the last sampling.
[b] Locations used were screenhouse: open, no control; glasshouse: closed, partial temperature control; growth chamber: closed, full temperature and light control.
[c] Full details in the text; MT, mid-tillering; PI, panicle initiation; H, heading.
[d] Establishment methods: DS, direct seeding.
[e] Shown are corresponding fertilizer rates per hectare (kg NPKZn ha^{-1}).