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Canopy microclimate and gas-exchange in response to irrigation system in lowland rice in the Sahel

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ABSTRACT

In lowland rice production, water-saving irrigation technologies have been developed, but it has rarely been considered that the absence of a ponded water layer could change the field's microclimate due to the different thermal characteristics of water compared to air. At a site in the Senegal River valley, canopy and soil temperature as well as temperature at meristem level and relative humidity inside the canopy were observed in the presence and absence of a ponded water layer in an irrigated rice field. Gas-exchange measurements were conducted at different development stages of three varieties (IR4630, IR64, and Sahel108) sown in bi-monthly intervals and the effects of climatic and microclimatic parameters on stomatal conductance, assimilation rate, and intrinsic water use efficiency were investigated. Minimum soil ($T_s$min) and meristem temperature ($T_M$min) were usually lower in the absence of a ponded water layer. Stomatal conductance depended mainly on $T_s$min, $T_M$min, and minimum relative humidity inside the canopy. Assimilation rate was positively correlated with solar radiation, $T_s$min and $T_M$min, but depended mainly on stomatal conductance. Without standing water, stomatal conductance was significantly lower, but reductions could be explained with lower $T_s$min and/or $T_M$min. Nevertheless, $T_s$min and/or $T_M$min were the major determinants of stomatal conductance and assimilation rate, which suggests a pivotal role of root zone temperature on plant growth probably via water uptake and, thus, overall plant water status. Varietal differences were found, with assimilation rate in IR4630 and Sahel108 having been less affected by low temperature than in IR64. When water-saving irrigation measures are applied in irrigated rice, the negative effects of lower soil and meristem temperature in the absence of a ponded water layer in the field on the productivity of rice need to be considered. In regions where night temperatures below 20 °C occur, varieties should be used that are less temperature-responsive, if the effect of cool nights on meristem temperature cannot be mitigated by a ponded water layer.

1. Introduction

The growing world population requires increased food production, while at the same time, water resources need to be preserved. Since about one-fourth to one-third of the world's developed freshwater resources are already used to irrigate rice (Bouman et al., 2007), and competition for water between agriculture and industry will increase, particularly in developing countries, more rice needs to be grown with proportionally less water. Whereas increasing the productivity of irrigated rice per transpired amount of water may require breakthroughs in breeding and genetics, alternative technologies may reduce water inputs at field level and thus increase field-level water productivity, though most of them at the cost of a yield penalty (Tuong et al., 2005). Yield reductions in rice have been observed even when grown in soils close to their water holding capacity (Tao et al., 2006) or in saturated soils in comparison to continuously flooded fields (Borrell et al., 1997; Bouman and Tuong, 2001). Recently, water-saving practices,

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such as alternate wetting and drying (AWD) and the System of Rice Intensification (SRI), which comprises AWD as irrigation management practice, have been tested in the Sahel. Whereas, SRI saved 16–48% of water without significant impact on yield in comparison to continuously flooded fields (Krupnik et al., 2012a,b), AWD saved 22–39% of irrigation water with no or little yield loss in the wet season and an average yield loss of 1.8 t ha^{-1} during the dry season (de Vries et al., 2010). Since irrigation water savings do not necessarily lead to yield reductions and differences between growing seasons have been described, other factors than soil water deficits should be considered to explain the observed results. With water having a heat capacity four times higher than air, a strong effect of a ponded water layer on the temperature a plant is subjected to can be expected. So far, the effect of changes in microclimate in the absence of a ponded water layer has rarely been investigated. Alberto et al. (2009) found changes in soil temperature (T_s) and in temperature and vapour pressure deficit (VPD) inside the canopy in aerobic (non-flooded) rice fields. But since plants encountered drought spells during their experiments and canopy's microclimate is highly influenced by transpiration, which is reduced under drought, the reported results on microclimate do not show the effect of the presence or absence of a ponded water layer alone, but include interactions between plants and their direct environment. Therefore, the effect of a ponded water layer on the relative air humidity inside the canopy (RH_c), is difficult to assess in a cropped field, since RH_c influences transpiration which in turn affects RH_c. However, the environmental factors a plant experiences are manifold with different temperatures prevailing in the soil, inside and above the canopy and considering flooded rice in the ponded water layer. Since plants exist in a soil-plant-atmosphere-continuum and metabolic processes are not only influenced by their proximate environment, soil temperature can influence photosynthesis and respiration (Cooper, 1973) and the growth and activity of roots are inseparably related to those of the aerial parts (Yoshida, 1976). An impressive body of research exists describing effects of single factors such as temperature (e.g. Nagai and Makino, 2009), relative humidity (e.g. Asch et al., 1995), VPD (e.g. Ohsumi et al., 2008), or radiation (e.g. Campbell et al., 2001), on stomatal conductance and assimilation, but the way plants integrate all these different climatic factors is complex (Shrestha et al., 2012) and to date still poorly understood. A broader understanding of this integrative process will help defining the growth limiting factors in a specific environment and, therefore, enable improvement of crop management and point the way to new breeding objectives. Exploration of integrative processes requires multi-dimensional experiments under controlled conditions or a large number of close observations in natural environments. Staggered sowing dates in a location having large intra-annual climatic variation allow studying the effects of complex natural environments on different development stages. The Sahelian region, with its climatic extremes, provides the opportunity to study the effects of heat, cold, high VPD and high and low solar radiation under natural conditions at one site. Since gas-exchange parameters respond quickly to climatic conditions, they are useful for the assessment of the relative influence of individual parameters on the crop's reaction to its direct environment. In the present study, leaf gas-exchange measurements were used to quantify crop responses to its environment and to identify climatic and microclimatic parameters having the largest influence on the rice crop. As we hypothesized that water-saving irrigation will influence the microclimate within a crop, measurements were conducted in rice fields under flooded and non-flooded conditions. If the presence or absence of a ponded water layer already influences the rice crop via changes in microclimate, mechanisms need to be understood in order to develop alternative management strategies and new varieties that can minimize the risk of yield reductions under water-saving irrigation.

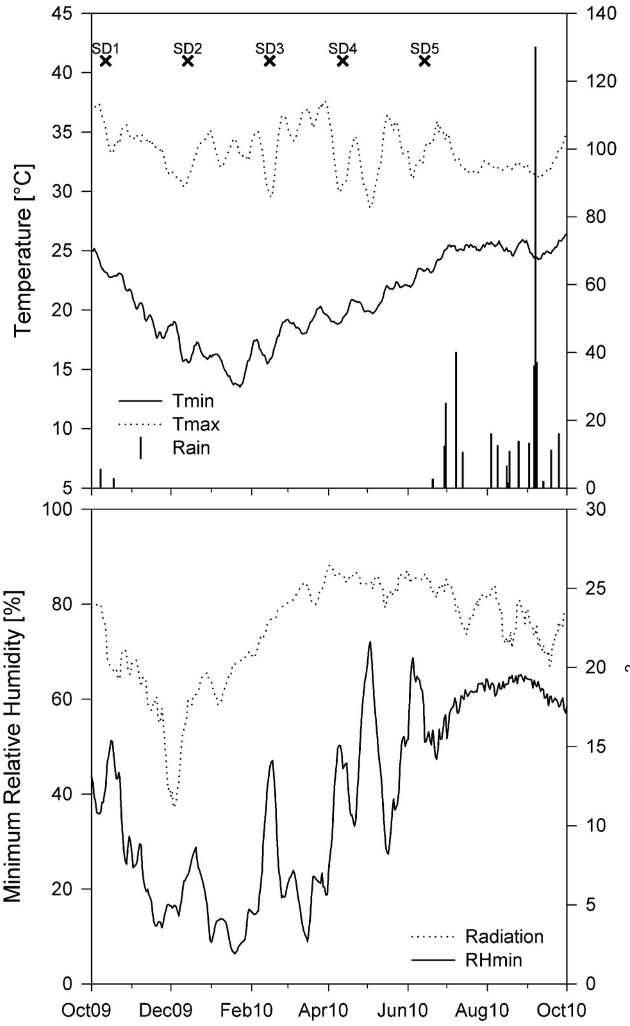

Fig. 1. Weather data for Ndiaye between October 2009 and October 2010. Crosses indicate sowing dates (SD1: October 12, 2009; SD2: December 14, 2009; SD3: February 15, 2010; SD4: April 12, 2010; SD5: June 14, 2010).

2. Materials and methods

2.1. Site description

Field trials were conducted between October 2009 and October 2010 in Ndiaye (16°11′N, 16°15′W), located in the Senegal River delta. The experimental site belongs to the Sahel station of the Africa Rice Center. It is characterized by a typical Sahelian climate with a short rainy season from July to early October. Temperature, relative humidity, solar radiation, and wind speed were recorded with an Onset Hobo© weather station every 20 min (Fig. 1). All sensors were installed close to the experiment, 2 m above a flooded rice field. Precipitation was measured at 300 m from the experiments at the Senegal River Development Agency (SAED). The soil is an orthothionic Gleysoil (following FAO classification, FAO, 2006), with a texture (0–20 cm) of 16-44-40% sand, silt and clay (Haefele et al., 2004). The experimental site has a shallow ground water table at 0.8–0.4 m below the soil surface (de Vries et al., 2010).

2.2. Experimental design and irrigation treatments

Three varieties (IR4630, IR64 and Sahel108) were sown on five regularly staggered dates (Fig. 1) and grown under flooded and non-flooded conditions. The first sowing date was in October 2009