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Soil water potential and recoverable water stress in drought tolerant and susceptible rice varieties

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ABSTRACT

We conducted a two-year field experiment to determine if water stress could be exploited to recover yield in one drought resistant (Vandana) and three susceptible (IR36, IR72 and Swarna) rice varieties. Stress was induced in active tillering, flowering and grain filling stages by suspending irrigation until the soil became sufficiently dry and plants began to show stress symptoms when irrigation was resumed, such that plants could recover from stress. We observed that terminal soil water potential (SWP) as low as −110 kPa in the active tillering stage was less detrimental to relative water content, proline content, and electrolyte leakage. A 27% rise in the level of stress led to ~8%, 44% and 21% increase in yield in IR36, Vandana and Swarna. The possible causes are 23%, 39% and 10% increase in the corresponding root biomass of the varieties, resulting in higher water uptake in the vegetative stage treatment plots. This was further supported by high correlations between yield and terminal SWP in this treatment. Critical limits of SWP may be identified to exploit the potential of rice varieties to sustain or improve yield under water stress. Results also suggest an opportunity to design a water saving strategy in lowland rice production.

1. Introduction

Lowland rice is grown on about 48 million ha (Raman et al., 2012), covering almost 25% of rice growing areas of the world (Wopereis et al., 1996). Many of these rice growing areas suffer from poor productivity due to drought. Drought recovery is an important adaptation by which water stress may be managed (Fukai and Cooper, 1995; Luo, 2010). Several studies have shown varying effects of drought recovery on crop performance. Higher tillering ability (Yoshida et al., 1982; Fukai and Cooper, 1995), stay green trait (Ingram et al., 1990; Lilley and Fukai, 1994c; Fukai and Cooper, 1995; Cattivelli et al., 2008), and crop stand-based drought recovery scores (De Datta et al., 1988; Kamoshita et al., 2004) are some of the common attributes used for assessing drought recovery. These measures do not explictly account for the avalaible soil water content, which is known to influence physiological changes in plants (Jones, 2007). In particular, studies have shown that physiological changes under similar soil water deficit may vary across rice varieties, due to differences in water extraction ability (Lilley and Fukai, 1994a,b) – a property that is closely associated with water availability in soil.

Water availability is expressed either in form of soil water content or soil water potential (SWP). While soil water content represents the amount of water present, SWP is a measure of the energy status of water in soil. Lilley and Fukai (1994b) emphasized the physiological response to soil water availability for differentiating drought resistance among varieties. Several researchers have estimated the threshold values of plant available soil water content during water stress to identify the divergence points of physiological processes, such as leaf and stem expansion, photosynthesis, transpiration, stomatal conductance, leaf turgor pressure and leaf water potential (Sadras and Milroy, 1996; Wopereis et al., 1996; Davatgar et al., 2009). These thresholds widely vary across different soils and atmospheric conditions, even for the same crop variety (Lilley and Fukai, 1994a; Davatgar et al., 2009). In contrast, there are several advantages for using SWP as a robust descriptor of soil water regime. First, the water available to plants at a given SWP remains similar across different soil textural classes (Wopereis et al., 1996). Second, SWP generally correlates well with leaf water potential and remains constant for varying water contents in different tissues of the same plant (Yang et al., 2007). Moreover, water uptake by plants is primarily controlled by the difference between SWP and root water potential (Bouman and Tuong, 2001). We propose

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that SWP should be used as a critical water stress recovery attribute instead of soil water content.

The upper limit of SWP measured by a tensiometer is only −100 kPa (although it is used to measure up to −90 kPa in practice). Because soils usually become much drier than −100 kPa during drought, the use of a tensiometer is limited in water stress studies. Consequently, water stress studies have been based on soil water content estimates involving misleading presumptions about the degree of water stress in soils. Several researchers used tensiometer in water stress studies (Yang et al., 2007; Luo, 2010; Zhao et al., 2010; Venuprasad et al., 2009, 2011; Chu et al., 2013). The maximum dryness in these studies is in the order of −60 kPa, which is relatively low. Consequently, the drying functions of soils were not fully exploited. Wopereis et al. (1996) derived a drying function beyond −100 kPa, but they converted volumetric water content to SWP based on soil water retention characteristic curves. Several other researchers have also related SWP derived from volumetric water content to physiological responses during stress (Turner et al., 1986; Lilley and Fukai, 1994b; Boonjung and Fukai, 1996; Wopereis et al., 1996; Yang et al., 2007; Chu et al., 2013; Xangsayasane et al., 2014). In this study, we estimated SWP using a combination of tensiometric measurements and the mechanistic water flow model given by the Richards equation to examine if the SWP attained just before irrigation is resumed (i.e. just before the stress is withdrawn) may be used as a criterion to characterize recoverable stress. The approach allowed us to estimate SWP values drier than −100 kPa. We correlated yield with the newly introduced concept of 'terminal SWP' defined as the SWP just before the stress is withdrawn, to propose a new drought recovery parameter for characterizing water stress in rice.

2. Materials and methods

2.1. Site specification

The field site (84 m × 20 m) is located at the experimental farm of Agricultural and Food Engineering Department, Indian Institute of Technology (IIT) Kharagpur, India (22°19′ N, 87°19′ E). There were 16 plots of size 5 m × 6 m. A 2 m wide bund (dyke around each plot) served as a buffer area to ensure no lateral mixing of water and nutrients among plots. The field site had been used for growing rice as a monocrop during the previous 50 years. Soil of the experimental site is acidic lateritic sandy loam and is classified as Typic Haplustalf. The local climate is humid subtropical with average rainfall of 140–160 cm, of which about 100 cm occurs from July to October.

2.2. Field experiment

Three drought susceptible (IR36, IR72 and Swarna) and one tolerant (Vandana) rice varieties were grown in the field experiment. IR36, IR72 and Swarna are generally grown in irrigated lowland condition (Lilley et al., 1996; Venuprasad et al., 2009, 2008) and Vandana (Venuprasad et al., 2008; Zhao et al., 2010) is an improved upland variety. The experiment was carried out in the winter (dry) seasons of 2011 and 2012 (December–May) using a split-plot design with four main plots and four subplots having three replications. Each of the 16 plots served as a main plot. Two extra plots were kept for Vandana and Swarna for applying stress treatments at flowering and grain filling stages separately. Two ropes fixed across the middle of each main plot served to demarcate subplots (3 m × 2.5 m) within main plots. The absence of physical boundary for subplots facilitated uniform water application to the main plots. Four water treatments: (a) fully irrigated condition as the control, (b) stress at active tillering stage, (c) stress at flowering stage and (d) stress at grain filling stage were allotted to the main plots, and the four rice varieties were allotted to sub-plots. Ponded conditions (maximum 5 cm ponded depth) were maintained throughout the growth period in all control plots by adding supplemental irrigation when ponded depth reduced to 1 cm. For stress treatment plots, irrigation was suspended to impose water stress coinciding with active tillering, flowering and grain filling stages. The decision to resume irrigation was based on tensiometer readings and observations of wilting and leaf rolling, which generally occurred about 5–7 days after tensiometers registered a SWP value of −90 kPa. This method of applying stress resulted in about 12–14 days of water stress during non-rainy periods and about 3 weeks of water stress when rain occurred during the stress treatment.

In 2011, traditional puddling was done within the plots without disturbing the bunds. Some of the plots showed higher seepage and percolation losses in 2011. Therefore, the bund plugging technique developed by Patil et al. (2011) was implemented in all the plots in 2012, which substantially reduced the seepage and percolation losses. Thirty day-old rice seedlings of IR36, IR72 and Swarna were transplanted with a spacing of 20 cm (row-to-row) × 15 cm (plant-to-plant) in puddled plots. Twenty-five days old seedlings were taken for Vandana. Recommended fertilizer dose of nitrogen (N), phosphate (P_2O_5) and potash (K_2O) at 120, 50 and 60 kg ha^{-1}, respectively, was applied in three splits: 50% N and full doses of P_2O_5 and K_2O as basal before transplanting, 25% N at mid-tillering and remaining 25% N at flowering stages. Insect pests were controlled using recommended doses of chemical pesticides.

2.3. Data collection

2.3.1. Physiological traits and yield components

Relative water content (RWC), proline content, and electrolyte leakage from the leaf tissues were estimated to characterize water stress. RWC measures the amount of water required by the plant to reach artificial full saturation (González and González-Vilar, 2001). Proline acts as an osmolyte to stabilize sub-cellular structures (e.g., membranes and proteins), scavenge free radicals, and buffer cellular redox potential under stress conditions (Ashraf and Foolad, 2007; Szabados and Savouré, 2010). Electrolyte leakage test reveals the membrane stability of the leaf cells under water stress. Three mature and fully expanded leaves were sampled from stress and control treatments before withholding and resuming irrigation. Flag leaf was collected during reproductive stages. For RWC, about 5 cm of leaf segment from the mid portion of leaves was taken. After taking fresh weight (FW), turgid weight (TW) was measured after immersing the leaf segments in distilled water for 4–6 h in a dark room. Dry weight (DW) was taken after drying leaf segments at 70 °C. The RWC was calculated as in Slayter (1967):

$$\mathrm{RWC}\ (\%) = \frac{\mathrm{FW} - \mathrm{DW}}{\mathrm{TW} - \mathrm{DW}} \times 100 \qquad (1)$$

Proline and membrane stability tests were conducted using 3 cm leaf segments. Proline content was analyzed following Bates (1973). To measure electrolyte leakage, cleaned, freshly collected leaf segments were put in 5 mL deionized water to measure initial electrical conductivity (EC_i). Leaf samples were then covered and kept in dark for 24 h to get the final electrical conductivity (EC_f). Test tubes containing leaf segments were autoclaved at 15 psi for 15 min to rupture cells for estimating total electrical conductivity (EC_t). The electrolyte leakage was calculated according to Bajji et al. (2002) as:

$$\text{Electrolyte leakage}\,(\%) = \frac{EC_f - EC_i}{EC_t - EC_i} \times 100 \qquad (2)$$