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Grain yield and phosphorus uptake of rainfed lowland rice under unsubmerged soil stress

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ABSTRACT

Rainfed lowland rice often grows in unsubmerged soil conditions during dry spells. Even if the drought effect is negligible, nutrient uptake and rice yield may decrease because of chronic unsubmerged soil stress on coarse-textured soil. The objective of this study was to evaluate the effect of unsubmerged soil conditions on N and P uptake, biomass accumulation and grain yield of 20 diverse rice genotypes. Unsubmerged and submerged field trials were conducted at the Ubon Ratchathani Rice Research Center in northeast Thailand in the wet seasons of 2010 and 2011. In the unsubmerged trial, rice was grown aerobically by draining the perched water; soil moisture at 20-cm depth fluctuated between −10 and −30 kPa. On average, the yield decline in unsubmerged soil conditions was 47% compared with submerged soil conditions (3.75 vs. 1.99 t ha^{-1}), which was attributable to reduced biomass accumulation and N and P uptake. Unsubmerged soil stress had minimal effect on harvest index, days to heading and N concentration. In unsubmerged soil conditions, N and P uptake and N-use efficiency (biomass/N uptake) positively correlated with biomass accumulation at heading stage. Rice plants showed severe P deficiency because of unsubmerged soil stress, which limited the contribution of P-use efficiency to biomass accumulation. Our results showed that the physiological traits improving P uptake and plant P nutrition under unsubmerged soil stress would be important targets for future research. We suggest that genotype screening under unsubmerged soil stress on coarse-textured soil may further improve rainfed lowland rice for the drought-prone plains.

1. Introduction

Rainfed lowland rice ecosystems cover around 47 million ha of rice land in South Asia and Southeast Asia, where insufficient irrigation and drainage facilities limit options for water management (GRiSP, 2013). This ecosystem covers more than 70% of the total rice area in northeast Thailand, southern Laos and Cambodia. The climatic and edaphic conditions are proximate in these areas and the average rice yield is still around 2.5 t ha^{-1}. The rainfall pattern is erratic, flash floods may occur, and standing water may disappear at any time in the growing season. Approximately 66–86% of this area is estimated to be prone to drought or both drought and submergence (Bell and Seng, 2004). Rice farmers throughout Cambodia and the central and southern provinces of Laos regard drought as their most serious constraint (Fukai et al., 1998). These areas also commonly have additional soil problems, such as acidity or low cation-exchange capacity, with the extent of these problems depending upon the soil type and topographic position within mini-watersheds (Homma et al., 2007; Linquist and Sengxua, 2001). In Cambodia, 39% of the rice-growing soils are sandy and nutrient-poor and the rice yield in unfertilized fields is only 0.6–2.6 t ha^{-1} (Ouk et al., 2001; White et al., 1997).

A number of rice studies have been conducted in the drought-prone plains of the Mekong River basin (see Fukai and Ouk, 2012 for a review). One of the major achievements for the last two decades is the improvement of the rainfed lowland rice breeding program with innovative drought screening and phenotyping techniques (Jongdee et al., 2006; Ouk et al., 2006), resulting in the

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identification of promising rice genotypes adapted to drought conditions and preferred by farmers (Mitchell and Sipaseuth Fukai, 2014). This progress was based on better understanding of drought-prone environments and the physiological mechanisms of drought resistance of rainfed lowland rice (Fischer et al., 2012). For example, for late-season drought, genotypes with earlier heading and less photoperiod sensitivity were advantageous, whereas for intermittent drought during the reproductive stage, integrated drought-tolerant traits were needed, such as a high drought response index, low spikelet sterility, minimal delay in heading and high leaf water potential (Pantuwan et al., 2002b). The main research focus has been to boost rice yield under moderate or severe drought by screening under artificially-stressed conditions managed by withdrawing irrigation in the dry season or using a rainout shelter to exclude rainfall (Fischer et al., 2012).

However, several field investigations reported that rainfed lowland rice yield decreases significantly, even without visible drought symptoms (Fukai et al., 1999; Haefele et al., 2006). In wet years, the soil often becomes unsaturated but not too dry (Ouk et al., 2006; Pantuwan et al., 2002a), and the seasonal dynamics of soil moisture are similar to those in alternate wetting and drying culture (Bouman et al., 2007). Especially on sandy soils in the Mekong River basin, the standing water quickly disappears and aerobic conditions occur during short dry spells (Fukai and Ouk, 2012). Rice response to the anaerobic-aerobic transition is obviously different from the drought response (Kato and Katsura, 2014), and we need to consider chronic unsubmerged soil stress as one of the important rainfed lowland conditions. The highly weathered and coarse-textured soil in the region is inherently infertile, N- and P-deficiency are considered the main yield-limiting factors when water is sufficient to avoid drought stress (Haefele et al., 2006). Nutrient uptake under fluctuating soil water regimes remains poorly understood (Wade et al., 1998; Fukai and Ouk, 2012). The loss of yield during chronic periods of unsubmerged soil conditions may be caused by limited nutrient availability rather than drought (Fukai et al., 1999). Soil acidity often occurs together with Al toxicity, which might be additional factors limiting root growth and nutrient uptake during periods of unsubmerged soil conditions (Bell and Seng, 2004; Haefele et al., 2006).

In this study, we targeted the rainfed lowland environment in the Mekong River basin where unsubmerged soil stress chronically occurs on coarse-textured soils. The objective of this study was to evaluate the effect of unsubmerged soil stress on N and P uptake, biomass accumulation and rice yield of 20 diverse locally-adapted rice genotypes for two years. It is important to understand the relative importance of N vs. P and of nutrient uptake vs. nutrient-use efficiency in order to prioritize traits in rainfed lowland rice breeding.

2. Materials and methods

Twenty rice (*Oryza sativa* L.) genotypes, including eight advanced backcross lines (IRUBN lines), seven doubled-haploid lines derived from CT9993-5-10-1-M × IR62266-42-6-2, Surin1, CT9993-5-10-1-M (upland rice), IR55423-01 (aerobic rice), IR72 (lowland rice) and RD6 (a mega-variety in northeast Thailand), were used (Fig. 1). The doubled-haploid population has previously been used for genetic studies on drought tolerance (Jongdee et al., 2006). One of the doubled-haploid lines (IR68586-F2-CA-143) was selected as a drought-tolerant donor and used to develop the advanced backcross lines (BC_3-derived lines) with Surin1 (a Thai high-yielding variety) (Fischer et al., 2012).

Field experiments were conducted at the Ubon Ratchathani Rice Research Center, northeast Thailand (15°20′N, 104°41′E, 110 masl) in the wet seasons (July–November) of 2010 and 2011. The set-up

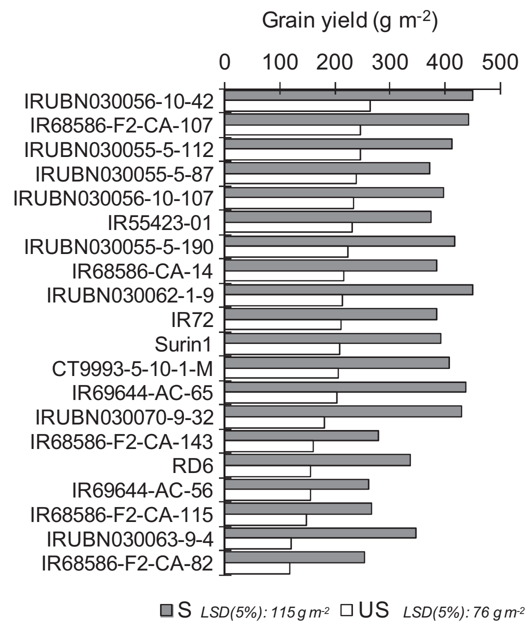

Fig. 1. Grain yield of 20 rice genotypes grown under submerged (S) and unsubmerged (US) soil conditions in Thailand (Ubon Ratchathani Rice Center). Average yields across the wet seasons of 2010 and 2011 were shown.

of the experiment and crop and water management were described elsewhere (Kato et al., 2013). The soil type was sandy loam or loamy sand (sand:silt:clay = 74–81%:9–15%:9–11%), and soil pH (a soil:water ratio of 1:5) was 4.8–5.3. The electrical conductivity (EC; a soil:water ratio of 1:5) of the topsoil (0–10 cm) was 5.2 and 2.6 mS/m in 2010 and 2011, respectively. The averages of daily maximum and minimum temperature and total rainfall in the wet season were 32.4 °C, 23.3 °C and 1189 mm in 2010, and 34.5 °C, 21.6 °C and 1358 mm in 2011, respectively. Two trials, submerged soil and unsubmerged, were set up, separate from each other by 100 m. In the submerged trial, the soil was puddled and kept submerged (3–5-cm water depth). The field was also puddled in the unsubmerged trial, and rice was grown aerobically from 2 weeks after transplanting by draining the surface water. For quick drainage, we created ditches around each plot. Flush irrigations were applied when the soil moisture at 20-cm depth reached −30 kPa. The soil moisture at 40-cm depth was maintained at field capacity (between −6 and −14 kPa). The soil moisture at 20-cm depth fluctuated between −6 and −49 kPa and reached below −20 kPa thrice (day-of-year 273–275, 300 and 308–312) in 2010, while it fluctuated between −6 and −24 kPa and reached below −20 kPa once (day-of-year 299) in 2011 (Kato et al., 2013).

Genotypes were arranged in a randomized complete block design with three replications in each trial. The size of each plot was 12.0 m^2 (3.0 × 4.0 m). A single 1-month-old seedling was transplanted into each hill (hill spacing was 20 × 20 cm) on 12 August 2010 and 30 July 2011. We applied N–P–K at the rate of 30–13–12 kg ha^{-1} in 2010 and at 60–26–24 kg ha^{-1} in 2011, by using compound fertilizer. Two-thirds of the amount was applied basally and the rest was applied at 30 days after transplanting in 2010, whereas the whole quantity was applied basally in 2011. Weeds were controlled by hand.

Above-ground biomass samples were collected at 50% heading date in each plot. In order to minimize the disturbance of the rice canopy, we selected four hills with an average number of tillers for destructive sampling after counting tiller number per hill for 1.0 m^2. Above-ground biomass was determined after the samples had been oven-dried at 80 °C for 72 h. At physiological maturity, all the plants from an untouched 1.0-m^2 area