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Reprint of "Morphological and physiological traits of roots and their relationships with water productivity in water-saving and drought-resistant rice"☆

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ABSTRACT

Water-saving and drought-resistant rice (WDR) could substantially reduce irrigation water and meanwhile produce higher grain yield compared with paddy rice under water-saving irrigation. The mechanism underlain, however, is yet to be understood. We investigated if improved root traits would contribute to an increase in water productivity in WDR. Two rice varieties, each for WDR and paddy rice, were field-grown with two irrigation methods, continuous flooding (CF) and alternate wetting and drying (AWD) irrigation, which were imposed during the whole growing season. Under CF, grain yield, water productivity (grain yield over amount irrigation water and precipitation) and root morpho-physiological traits, such as root biomass and root oxidation activity (ROA), showed no significant difference between WDR and paddy rice. Under AWD, however, WDR exhibited greater root dry weight, root length density, ROA, total absorbing surface area and active absorbing surface area of roots, greater zeatin (Z) + zeatin riboside (ZR) contents in both roots and leaves, and higher activities of enzymes involved in sucrose-to-starch conversion in grains during grain filing, in relative to paddy rice. Grain yield under AWD was significantly decreased for paddy rice compared with that under CF, but showed no significant difference for WDR between the two irrigation treatments. The WDR variety increased grain yield by 9.2–13.4% and water productivity by 9.0–13.7% over the paddy rice variety under AWD. The root dry weight was significantly correlated with shoot dry weight, and ROA and root Z + ZR content were significantly correlated with leaf photosynthetic rate, Z + ZR content in leaves and activities of key enzymes involved in sucrose-to-starch conversion in grains. Collectively, the data suggest that improved morpho-physiological traits, as showing a greater root biomass, root length density, ROA and root Z + ZR content, contributes to higher grain yield and water productivity for WDR under water-saving irrigation.

1. Introduction

Rice (*Oryza sativa* L.) is one of the most important food crops in the world and consumed by more than 3 billion people (Fageria, 2007). It is estimated that, by the year 2025, it will be necessary to produce about 60% more rice than what is currently produced to meet the food needs of a growing world population (Fageria, 2007). Rice is also the greatest consumer of water among all crops and consumes about 80% of the total irrigated fresh water resources in Asia (Bouman and Tuong, 2001). Fresh water, however, is becoming increasingly scarce because of population growth, increasing urban and industrial development, and the decreasing availability resulting from pollution and resource depletion (Belder et al., 2004; Bouman, 2007). To meet the major challenge that rice production needs to increase to feed a growing population under increasing scarcity of water resources, water-saving and drought-resistant rice (WDR) varieties have been bred (Luo, 2010) and alternate wetting and drying (AWD) irrigation has been developed as a novel water-saving technique (Bouman and Tuong, 2001; Yang et al., 2007; Yao et al., 2012; Zhang et al., 2009).

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Abbreviations: AGPase, adenosine diphosphoglucose pyrophosphorylase; AWD, alternate wetting and drying; CF, continuous flooding; DAT, days after transplanting; DW, dry weight; ROA, root oxidation activity; StSase, starch synthase; SuSase, sucrose synthase; WDR, water-saving and drought-resistant rice; Z, zeatin; ZR, zeatin riboside.

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WDR is a new type of rice variety which has high yield potential and good quality as the current paddy rice, as well as the capacity of water-saving or drought resistance (Luo, 2010; Luo et al., 2011). There are reports showing that WDR could reduce water consumption by about 50% meanwhile could not markedly decease grain yield compared with paddy rice (Luo, 2010; Luo et al., 2011; Zhang et al., 2012a), although there is an observation that the super hybrid rice variety Yangliangyou 6 produced 21.5% higher grain yield than the WDR variety Hanyou 3 under AWD conditions (Yao et al., 2012). The mechanism that WDR has high yield potential and capacity of water-saving has yet to be understood.

In AWD, irrigation is applied a few days after water has disappeared from the surface so that periods of soil submergence alternate with periods of non-submergence during the whole growing season (Belder et al., 2004; Tuong et al., 2005; Yao et al., 2012). This technique could substantially reduce irrigation water and maintain or even increase grain yield because of the enhancement in nutrient uptake by rice plants, root growth, grain filling rate, and remobilization of carbon reserves from vegetative tissues to grains, in relative to continuous flooding (CF) irrigation (Belder et al., 2004; Liu et al., 2013; Tuong et al., 2005; Yao et al., 2012; Zhang et al., 2008, 2009, 2012b). Although the AWD technology has been researched extensively in countries such as China, India, and Philippines, the physiological mechanism involved in the effect of AWD on the yield and water productivity remains to be elucidated.

As an integral part of plant organs, roots are involved in acquisition of nutrients and water, synthesis of plant hormones, organic acids and amino acids, and anchorage of plants (Yang et al., 2004a,b). Root morphology and physiology are closely associated with the growth and development of aboveground plants (Osaki et al., 1997; Samejima et al., 2004; Yang et al., 2008; Zhang et al., 2009). However, information on root morphology and physiology and their relationship with grain yield and water productivity in WDR is unavalable.

The objectives of this study were to (1) investigate the yield performance of WDR under both CF and AWD conditions, (2) make comparison between WDR and paddy rice in root morphological and physiological traits, and (3) analyze the relationship between root morpho-physiological traits and shoot growth and activity. Root biomass, root oxidation activity (ROA), root length density, root diameter, root total absorbing surface area, root active absorbing surface area and zeatin (Z) + zeatin riboside (ZR) contents in roots were defined as root morphological and physiological traits (Samejima et al., 2005; Yang et al., 2012; Zhang et al., 2009). Shoot biomass, leaf photosynthetic rate, Z + ZR content in leaves, and activities of some key enzymes involved in sucrose-to-starch conversion in grains, sucrose synthase (SuSase, EC 2.4.1.13), adenosine diphosphoglucose pyrophosphorylase (AGPase, EC 2.7.7.27), and starch synthase (StSase, EC 2.4.1.21), were used as indices of shoot growth and activity. The hypothesis is that improved root traits can benefit shoot growth, and consequently, contribute to an increase in water productivity in WDR under water-saving irrigation.

2. Materials and methods

2.1. Plant materials and growth conditions

Field experiments were conducted at a research farm of Yangzhou University, Jiangsu Province, China (32°30′N, 119°25′E, 21 m altitude) during the rice growing season (May–October) in 2011, and repeated in 2012. The soil was a sandy loam (Typic fluvaquents, Etisols, US classification) that contained 24.2 g kg^{-1} organic matter, 103 mg kg^{-1} alkali hydrolysable N, 34.5 mg kg^{-1} Olsen-P and 68.6 mg kg^{-1} exchangeable K in 0–20 cm soil depth. The field capacity soil moisture content, measured after constant drainage rate and made gravimetrically, was 0.188 g g^{-1}, and bulk density of the soil was 1.33 g cm^{-3}. The average air temperature, precipitation, and sunshine hours during the rice growing season across the two study years measured at a weather station close to the experimental site are shown in Table 1.

Table 1
Precipitation, sunshine hours, and mean temperature during the growing season of rice in 2011 and 2012 in Yangzhou, Southeast China.

	May	June	July	August	September	October
Precipitation (mm per month)						
2011	103	195	309	232	48.2	38.6
2012	38.2	32.2	195	213	60.6	27.2
Sunshine (h per month)						
2011	241	118	143	115	159	163
2012	202	101	173	122	172	171
Mean temperature (°C)						
2011	21.9	24.4	27.5	26.7	22.7	20.4
2012	22.1	25.3	29.3	27.9	22.2	19.5

Precipitation and sunshine hours are monthly totals. Temperatures are the monthly averages.

A WDR (*Oryza sativa* L.) variety Hanyou 8 (HY8, a japonica hybrid from the cross Huhan 2A × Huhan 2B) and a high-yielding paddy rice variety Lingxiangyou 18 (LXY18, a japonica hybrid from the cross Lingxiang A × YC418) were grown in the field. Both varieties are currently planted in local production. Except for drought resistance, both varieties have similar traits with plant height 105–110 cm, the whole growth period 152–155 days, 17 leaves in the main stem, thick culms and erect upper leaves, and are suitable for planting in the lower reaches of Yangtze River of China (Li et al., 2009; Yu et al., 2011). Seeds of HY8 were provided by Shanghai Agrobiological Gene Center (Shanghai, China) and those of LXY18 were obtained from College of Agriculture, Yangzhou University (Yangzhou, China). Seedlings were raised in the field with sowing date on 15 May and transplanted on 10 June at a hill spacing of 25 cm × 16 cm with two seedlings per hill. N (60 kg ha^{-1} as urea, P (45 kg ha^{-1} as single superphosphate) and K (60 kg ha^{-1} as KCl) were applied and incorporated before transplanting. N as urea was also applied at mid-tillering (40 kg ha^{-1}), panicle initiation (25 kg ha^{-1}) and at the initial of spikelet differentiation (25 kg ha^{-1}). Both varieties (50% of plants) headed on 25–26 August, and were harvested on 15–16 October.

2.2. Treatments

The experiment was laid out in a complete randomized block design with three replicates. Plot dimension was 8 m × 4.8 m and plots were separated by a 1-m wide alley using plastic film inserted into the soil to a depth of 50 cm. Two irrigation regimes (treatments), alternate wetting and soil drying (AWD) and continuous flooding (CF), were conducted from 10 days after transplanting (DAT), at which seedlings were recovered from transplanting injury, to maturity. In AWD, plants were not re-watered until the soil water potential reached −15 kPa (soil moisture content 0.172 g g^{-1}) at 15–20 cm depth. Except drainage at the mid-season, the CF regime was continuously flooded with 2–3 cm water level in the plot until one week before harvest in line with traditional farming practice. Soil water potential in the AWD plot was monitored at 15–20-cm soil depth with a tensionmeter consisting of a sensor of 5 cm length. Four tensionmeters were installed in each plot, and readings were recorded at 12:00 h each day. When the reading reached the threshold, a flood with 2–3 cm water depth was applied to the plots. The amount of irrigation water was monitored with a flow meter (LXSG-50 Flow meter, Shanghai Water Meter