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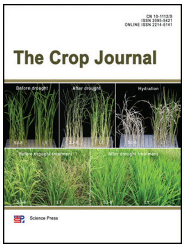

Agronomic performance of drought-resistance rice cultivars grown under alternate wetting and drying irrigation management in southeast China

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ABSTRACT

Compared to drought-susceptible rice cultivars (DSRs), drought-resistance rice cultivars (DRRs) could drastically reduce the amount of irrigation water input and simultaneously result in higher grain yield under water-saving irrigation conditions. However, the mechanisms underlying these properties are unclear. We investigated how improved agronomic traits contribute to higher yield and higher water use efficiency (WUE) in DRRs than in DSRs under alternate wetting and drying (AWD). Two DRRs and two DSRs were field-grown in 2015 and 2016 using two different irrigation regimes: continuous flooding (CF) and AWD. Under CF, no statistical differences in grain yield and WUE were observed between DRRs and DSRs. Irrigation water under the AWD regime was 275–349 mm, an amount 49.8%–56.2% of that (552–620 mm) applied under the CF regime. Compared to CF, AWD significantly decreased grain yield in both DRRs and DSRs, with a more significant reduction in DSRs, and WUE was increased in DRRs, but not in DSRs, by 9.9%–23.0% under AWD. Under AWD, DRRs showed a 20.2%–26.2% increase in grain yield and an 18.6%–24.5% increase in WUE compared to DSRs. Compared to DSRs, DRRs showed less redundant vegetative growth, greater sink capacity, higher grain filling efficiency, larger root biomass, and deeper root distribution under AWD. We conclude that these improved agronomic traits exert positive influences on WUE in DRRs under AWD.

1. Introduction

Global agriculture is currently facing two major challenges: an increase in food demand to feed the rapidly growing world population and a decline in global water resource availability [1]. Rice (*Oryza sativa* L.) is a major food staple for >50% of the global population [2]. It has been estimated that rice yield must increase by at least 1% annually to meet the challenge of food security for a rapidly growing population [3]. However, with industrial development, rapid population growth, and

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Abbreviations: AWD, alternate wetting and drying; CF, continuous flooding; CGR, crop growth rate; DRR, drought-resistance rice cultivar; DSR, drought-susceptible rice cultivar; HI, harvest index; LAD, leaf area duration; LAI, leaf area index; NAR, net assimilation rate; NPS, non-structural carbohydrates per spikelet; NSC, non-structural carbohydrates; NUE, nitrogen use efficiency; WUE, water use efficiency

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urbanization, irrigation water is becoming increasingly scarce in China [1, 4], and the scarcity of freshwater resources threatens rice production [5]. To help meet the food demand under limited water resources, researchers at Shanghai Agrobiological Gene Center (Shanghai, China) bred a new type of rice cultivar characterized by having a yield potential similar to that of the main irrigated lowland rice cultivars in use but with increased drought resistance [6]. The development of drought-resistant rices (DRRs) to reduce irrigation water input during rice production has become a critical area of agricultural research in China [6]. Although several field studies have demonstrated that DRRs are drought-resistance [7–10], the mechanisms underlying this trait are unclear.

AWD is an effective water-saving irrigation technology [11, 12] that has been applied on >12 Mha of agricultural land in China each year and is being adopted in Asian countries such as Bangladesh, India, The Philippines, and Vietnam [13, 14]. There is no doubt that AWD can reduce irrigation water input, but it remains debatable whether this technology can increase or maintain grain yield [10, 15–18]. A meta-analysis of 56 studies with 528 side-by-side comparisons of AWD with CF found that AWD decreased rice grain yield by 5.4%; however, when soil water potential was higher than −20 kPa or field water level did not drop below 15 cm from the soil surface, yields were not significantly reduced [15]. Lampayan et al. [16] found in the Philippines, Vietnam, and Bangladesh that AWD could reduce irrigation water input by up to 38% with no yield reduction, and increase farmers' income by 17%–38%. Norton et al. [17] found that safe AWD could increase rice grain production compared to CF. In our previous studies, a moderate AWD (soil water potential = −15 kPa) could maintain or even increase grain yield in DRRs or newly bred "super" rice cultivars [10, 18]. Crops are irrigated 13–15 times under the moderate AWD regime during the entire growth period [19, 20]. However, in many areas in the lower reaches of Yangtze River, rice receives fewer than 10 irrigations during the entire growth period, owing to an incomplete irrigation system and an expensive irrigation cost (unpublished data). Further investigation into how DRRs perform in relation to grain yield and WUE under water-saving irrigation is thus warranted, particularly under AWD.

Understanding the agronomic traits of high-yielding and high-WUE rice cultivars could provide directions for future breeding and water-management efforts. Various agronomic traits are closely related to increased yield performance and high NUE or WUE in rice, including large sink capacity [21, 22], LAI and LAD [23], large shoot biomass, high CGR [24] and NAR [25], and large root biomass [26]. However, our understanding of the agronomic performance of DRRs under AWD is limited. The purposes of this study were to (1) compare yield performance and WUE between DRRs and drought-susceptible rice cultivars (DSRs) under an AWD irrigation regime, (2) compare agronomic traits including percentage of productive tillers, LAD, CGR, NAR, root dry weight and shoot biomass, and NSC accumulation in the stem at heading stage and its remobilization during ripening, between DRRs and DSRs under AWD. Such a study was expected to shed light on the ways in which DRRs cope with water-limited conditions, as well as provide helpful information for breeding new cultivars with drought tolerance and rice water-saving cultivation methods.

2. Materials and methods

2.1. Plant materials and cultivation

The field experiment was conducted at the Fuyang Agricultural Experimental Station of the China National Rice Research Institute (30.30′ N, 120.2′ E, 11 m above sea level) in 2015–2016. Fig. S1 shows the daily air temperature and precipitation during the rice seasons of 2015 and 2016. Soil of the experimental field is classified as a Fec-Stagnic Anthrosol (Etisols, US classification). The original soil fertility parameters in 0–20 cm soil layer were as follows: organic matter 38.7 g kg^{-1}, total N 2.02 g kg^{-1}, available N 324.6 mg kg^{-1}, available P 18.5 mg kg^{-1}, and available K 72.1 mg kg^{-1}, with pH 5.79. The gravimetric soil moisture content at field capacity was 0.187 kg kg^{-1}, and the soil bulk density was 1.12 g cm^{-3}.

Two newly bred DRRs and two DSRs were employed in the experiment. Hanyou-113 (HY-113, a three-line *indica* hybrid from Huhan-11A × Hanhui-3) and Hanyou-8 (HY-8, a three-line *japonica* hybrid from Huhan-2A × Xiangqing) were encoded as DRR-1 and DRR-2, respectively. Tianyouhuazhan (TYHZ, a three-line *indica* hybrid from Tianfeng-A × Huazhan) and Changyou-5 (CY-5, a three-line *japonica* hybrid from Chang-01-11A × CR-27) were encoded as DSR-1 and DSR-2, respectively. All the cultivars are planted over large areas in the lower reaches of the Yangtze River. Seeds of HY-113 and HY-8 were provided by the Shanghai Agrobiological Gene Center (Shanghai, China), and seeds of TYHZ and CY-5 were provided by the Fuyang Seed Company (Fuyang, Zhejiang, China).

Pre-germinated seeds of all the rice cultivars were raised in the field. Sowing dates were May 20 in both 2015 and 2016. Twenty-day-old seedlings were transplanted at a hill spacing of 25 cm × 16 cm with two seedlings per hill in both study years. Nitrogen (as urea) was applied at a total rate of 200 kg ha^{-1}, and split-applied with 50% before transplanting, 20% at mid-tillering, and 30% at panicle initiation. Phosphorus, as single superphosphate, was applied at a rate of 45 kg ha^{-1} before transplanting. Potassium, as potassium chloride, was applied at a total rate of 120 kg ha^{-1}, and split-applied with 50% before transplanting and 50% at panicle initiation. HY-113 and TYHZ headed (half of total panicles) on August 15–17 and were harvested on October 1, HY-8 and CY-5 headed on August 30–31 and were harvested on October 20.

2.2. Treatments

In both study years, the field experiment was laid out in a randomized complete block design with three replicates. Each plot was 30 m^2 (6 m × 5 m) in area and separated from the others by concrete walls (0.5 m in width and 1.0 m in depth). Two irrigation treatments, CF and AWD, were applied from the second week after transplanting until maturity. Field water was kept a depth of 2–3 cm under both irrigation regimes during the first week to allow the seedlings to recover and to control weeds. Under the AWD regime, plants were not

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