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Morphological and physiological traits of rice roots and their relationships to yield and nitrogen utilization as influenced by irrigation regime and nitrogen rate

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ABSTRACT

Soil moisture and nitrogen nutrient are the main factors affecting rice (*Oryza sativa* L.) production. This study investigated the effects of irrigation regime and nitrogen rate on root morphology and physiology, grain yield, and nitrogen use efficiency in rice. A soil-grown experiment was conducted with three nitrogen rates, namely, 0 (no nitrogen applied), 240 (normal amount, MN), and 360 kg ha^{-1} (high amount), and three irrigation regimes, namely, submerged irrigation (0 kPa), alternate wetting and moderate drying (−20 kPa), and alternate wetting and severe drying (−40 kPa) over 2 years. Our results revealed significant interaction between irrigation and nitrogen regimes. Grain yield was the highest in MN coupled with mild water stress due to improved seed filling rate and grain weight. At the same nitrogen level, the root length, root surface area, root dry weight, root activity, and active absorbing area at main growth stages were higher in alternate wetting and moderate drying than in submerged irrigation. Furthermore, the zeatin + zeatin riboside and indole-3-acetic acid contents in root bleeding were increased, but the root-to-shoot ratio was low after panicle initiation. MN coupled with moderate drying enhanced rice yield and nitrogen use efficiency; this treatment was the optimal water–nitrogen interaction management model in this study. Our correlation analysis showed that grain yield positively correlated with the above morphological and physiological indices at main growth stages but negatively correlated with root-to-shoot ratio after mid-tilling and abscisic acid (ABA) content at maturity. A significant negative correlation was also observed between root-to-shoot ratio and nitrogen efficiency. Meanwhile, a significant or extremely significant positive correlation existed between root active absorbing area, root activity, root bleeding, ABA content, and nitrogen efficiency. These results suggest that adopting the alternate wetting and moderate drying with an appropriate nitrogen rate promotes root morphology and improves root activity, thereby increasing grain yield and nitrogen use efficiency in rice.

1. Introduction

Rice (*Oryza sativa* L.) is an important grain crop worldwide, it possesses a considerably prominent status in grain production and is the main staple food in Asia (Fageria, 2007; Peng et al., 2009). Nitrogen fertilizer application is an important approach to increase grain yield in rice production (Ju et al., 2009; Spiertz, 2010). In the past years, grain yield of rice has steadily increased worldwide, partly owing to the enhancement in nutrient inputs from fertilizer, especially nitrogen application (Fageria, 2007; Peng et al., 2009; FAOSTAT, 2013). Nevertheless, excess nitrogen fertilizer application is often inefficiently used by the crop. The average recovery efficiency of nitrogen fertilizer at present is only 33% at field level (Peng et al., 2009; Ju et al., 2015). Inefficient use of fertilizer nitrogen can harm the environment through surface runoff losses, nitrate leaching into groundwater, and volatilization into the water bodies or atmosphere (Vitousek et al., 1997; Ju et al., 2009; Spiertz, 2010; Xu et al., 2012; Wang et al., 2016). Furthermore, it increases the susceptibility of the crop to lodging and disease (Fujinuma et al., 2009; Spiertz, 2010; Jat et al., 2012; Wang et al., 2016) and constrains opportunities to increase rice yield (Peng et al., 2011). Nitrogen utilization in China is more aggravated. According to the 2015 data, the amount of fertilizer applied for rice production in China has reached 60.22 million tons, including 23.62 million tons of nitrogen fertilizer; this amount has become the largest

Abbreviations: 0N, no nitrogen applied; MN, normal nitrogen practice; HN, higher nitrogen application; PI, panicle initiation; Z, Zeatin; ZR, Zeatin riboside; IAA, indole-3-acetic acid; ABA, abscisic acid; DAT, days after transplanting

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consumption worldwide (National data of China, 2015). Unreasonable nitrogen input not only decreases nitrogen use efficiency but also increases production costs and result in a series of eco-environment damage, so ways should be sought to coordinately achieve high grain yield and high nutrient use efficiency.

Rice is the maximum consumer of freshwater in agriculture, and rice production is reduced annually due to drought and water shortage (Bouman and Tuong, 2001; Ye et al., 2015; Pan et al., 2017). With the increase in population, rapid development of industry, aggravation of environmental pollution, and change in global climate, the freshwater resources used for irrigation become increasingly scarce, which severely threatens freshwater resources and rice production. Therefore, the water use efficiency of rice should be improved and the contradiction between the supply and demand of water resources should be alleviated to ensure food security. Many water-efficient technologies, such as nonflooded mulching cultivation, aerobic rice, semidry cultivation, intensified rice system, combined shallow water depth and wetting, and alternate wetting and drying irrigation, have been introduced to cope with the shortage in water resources (Zhao et al., 2009; Zhang et al., 2012; Ye et al., 2013; Lampayan et al., 2015; Liang et al., 2016; Pan et al., 2017). Alternate wetting and drying irrigation is an effective water-saving irrigation technique, which has provided ideal economic and ecological benefits (Tuong et al., 2005; Zhang et al., 2009; Dong et al., 2012; Nalley et al., 2015; Pan et al., 2017). It is widely applied in major rice-producing countries in Asia, such as China, Philippines, Vietnam, India, and Bangladesh (Kukal et al., 2005; Bouman, 2007; Rahman and Bulbul, 2014; Wang et al., 2016). The inefficient use of freshwater and nitrogen resources is a major problem in rice production in China. Thus, it is significant to improve the efficiency of water and fertilizer resources in agricultural production.

Combining water and nitrogen refers to an integration of two factors that mutually affect the growth and development of crops, the formation of yield and quality, and the nitrogen use efficiency. Montgomery (1911) studied the effects of different soil fertilizers of maize on water requirements. Leamer and Painten (1953) found that crop yield is high with high fertilizer application in high soil moisture. Numerous studies have quantified the effects of water and nitrogen interaction on yield formation, photosynthetic rate, physiology trait, nitrogen use efficiency, and water utilization (Begg and Turner, 1976; Lahiri, 1980; Prasertsak and Fuka, 1997; Cao et al., 2007; Paolo and Rinaldi, 2008; Sandhua et al., 2012; Sun et al., 2012; Ye et al., 2013; Wang et al., 2016; Pan et al., 2017). However, the root morphology and physiology under different water and nitrogen interaction and their relationship to shoots are not well understood.

Crop roots are the main organs that absorb nutrients and water; synthesize various organic acids, hormones, and amino acids; and provide anchorage to plants (Yang et al., 2004). Root morphology and physiological affect nitrogen absorption and utilization efficiency by keeping activity, thereby affecting the growth and development of rice, yield, and quality formation (Osaki et al., 1997; Samejima et al., 2004; Yang et al., 2012; Chu et al., 2014). Hormones play an important regulatory role in the growth of crops, which act as signal molecules to regulate crop physiological function by transporting tissues (Ha et al., 2012). However, evidence on root morphology, physiology and hormones content and their relationship to grain yield and nitrogen use efficiency under different irrigation regimes and nitrogen rates is considerably scarce.

The present study (1) investigated the yield performance and nitrogen use efficiency under different irrigation regimes and nitrogen rates, (2) investigated the root morphological and physiological traits under different irrigation regimes and nitrogen rates, and (3) analyzed the relationship between root characteristics and grain yield and nitrogen utilization.

Table 1
Monthly mean maximum temperature (*Tmax*), minimum temperature (*Tmin*), and rainfall during the rice growing season of 2015 and 2016 in Luoyang, Middle China. Rainfall are monthly totals. Maximum temperature and minimum temperature are the monthly averages.

Month	T_{max} (°C)		T_{min} (°C)		Rainfall (mm)	
	2015	2016	2015	2016	2015	2016
June	29.7	30.5	20.4	21.1	70	73
July	32.0	31.8	22.3	23.7	144	112
August	31.1	30.7	21.4	22.9	98	109
September	27.1	28.0	17.3	18.2	78	88
October	21.3	19.1	11.4	12.1	46	32

2. Materials and Methods

2.1. Plant materials

A pool experiment was conducted at a farm belonging to Henan University of Science and Technology, Henan Province, China (34°39/N, 112°26/E) during the rice-growing season (May to October) of 2015; the experiment was repeated in 2016. The field soil was clay loam [typic fluvaquent (USDA taxonomy)] with organic matter (21.2 g kg^{-1}), total nitrogen (1.23 g kg^{-1}), Olsen P (34.2 g kg^{-1}), and exchangeable K (120.9 g kg^{-1}). The field capacity soil moisture content, which was gravimetrically measured after constant drainage rate, was 0.188 g g^{-1}. The bulk density of the soil was 1.39 g cm^{-3}. The average air temperature and rainfall during the rice growing season across the two years measured are shown in Table 1.

A high-yielding rice (*Oryza sativa*. L) cultivar currently used in a local rice production, Lianjing 7 (Japonica cultivar), was grown in the pool soil. Crop duration from sowing to maturity for this cultivar are 153. During the 2 years, seedlings were raised in the seedbed on 10 May. These seedlings were transplanted on 8 June at a hill spacing of 0.2 m × 0.2 m with two seedlings per hill. The heading data (50% of plants) were obtained on 25–28 August, and plants were harvested on 13–15 October.

2.2. Treatments

The experiment was a 3 × 3 (three nitrogen rates and three irrigation regimes) one, which comprised nine treatments in a complete randomized block design. Each experiment was performed in three replicates with the plot area of 18 m^2 (9 m × 2 m). In order to prevent water and fertilizer flow between neighboring plots, the plots were separated by ridge that was 0.4 m wide and with a waterproof material to a depth of 40 cm to form a barrier (Sun et al., 2012). The experiment was conducted with three treatments of different nitrogen levels, including no nitrogen applied (0N), normal nitrogen practice (MN 240 kg ha^{-1}), and high nitrogen application (HN 360 kg ha^{-1}), and three irrigation regimes, including submerged irrigation (0 kPa; 2–2.5 cm water depth until one week before the final harvest as a recommended farming practice, except in the midseason), alternate wetting and moderate drying (−20 kPa; 7 days after transplanting (DAT) to maturity), and alternate wetting and severe drying (−40 kPa; 7 DAT to maturity). Soil water potential was monitored within the 15–20 cm soil depth. A tension meter consisting of a 5 cm-long sensor was installed in each pool for monitoring. Tension meter readings were recorded at 06:00–07:00, 11:00–12:00, and 16:00–17:00. When the soil water potential decreased to the designed value, a flood with 2.0–2.5 cm water depth was applied to the plots. The pool was sheltered from rain with a plastic canopy during all the growing season. In all treatments, nitrogen was applied as urea at pretransplanting (1 day before transplanting), early tillering stage (7 DAT), and panicle initiation (PI, 45 DAT); the proportion of nitrogen applied was 40%, 10%,