Field Crops Research 175 (2015) 47–55

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Root and shoot traits for rice varieties with higher grain yield and higher nitrogen use efficiency at lower nitrogen rates application

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ARTICLE INFO

Article history:
Received 9 January 2015
Received in revised form 8 February 2015
Accepted 8 February 2015

Keywords:
Rice (*Oryza sativa* L.)
Nitrogen-efficient varieties
Nitrogen use efficiency (NUE)
Photosynthetic NUE
Root length density
Root oxidation activity

ABSTRACT

Understanding plant traits that are associated with high grain yield and high nitrogen use efficiency (NUE) is very important in breeding program to develop N-efficient varieties. However, such traits are yet to be identified in rice. We investigated this issue using rice varieties differing in response to N rates. Four *japonica* rice varieties, Huaidao 5 (HD-5), Lianjing 7 (LJ-7), Ninjing 1 (NJ-1) and Yangjing 4038 (YJ-4) were grown in the field, and four N rates, 0, 100, 200 and 300 kg ha^{-1}, were applied during the growing season. Results show that both HD-5 and LJ-7 produced higher grain yield, took up higher amount of N from the soil, and exhibited higher NUE than NJ-7 or YJ-4 at lower N rates (0, 100 or 200 kg ha^{-1}). Grain yield and NUE were comparable among the four varieties at the N rate of 300 kg ha^{-1}. When compared with NJ-1 or YJ-4, both HD-5 and LJ-7 had greater root and shoot biomass, deeper root distribution, longer root length, greater root length density, root oxidation activity and crop growth rate, higher photosynthetic NUE, and more remobilization of nonstructural carbohydrate from stems during grain filling at lower N rates. Our results suggest that HD-5 and LJ-7 can maintain grain yield at lower N rates as N-efficient varieties. The shoot and root traits, especially the deeper roots, greater root oxidation activity and higher photosynthetic NUE at lower N rates, could be used in selection for N-efficient rice varieties.

1. Introduction

Rice (*Oryza sativa* L.) is one of the most important crops in the world, and the foremost staple food in Asia, providing 35–60% of the dietary calories consumed by more than 3 billion people (Fageria, 2007). In the last 50 years, rice yield in the world has continuously increased, partly because of the increase in fertilizer nutrient input, especially nitrogen (N) fertilizer (Cassman et al., 2003; Peng et al., 2010). However, the use of N fertilizer is generally inefficient, and the apparent recovery efficiency of N fertilizer (RE$_N$, the percentage of fertilizer N recovered in aboveground plant biomass at the end of the cropping season) is only 33%, on average (Raun and Johnson, 1999; Garnett et al., 2009). The remaining N is lost as either surface runoff, leached nitrate in groundwater, volatilization to the atmosphere or by microbial denitrification (Vitousek et al., 1997; Ju et al., 2009). The problem of low N use efficiency (NUE) is more aggravated in China. To maximize grain yield, farmers often apply a higher amount of N fertilizer than the minimum required for maximum crop growth (Peng et al., 2006, 2010). Today, the national average rice yield is 6.40 tons per hectare and the average N rate applied in rice is 180 kg per hectare in China, which are about 50% and 75%, respectively, higher than the world average (Peng et al., 2010; Fan et al., 2012). In the high yielding area of Taihu Lake, the average N input is 300 kg per hectare, which is 67% higher than N application in the single rice cropping system in China. The average agronomic N use efficiency (increase in grain yield per kg N applied) is only 12 kg kg^{-1} N, less than half of that in the developed countries (Xue et al., 2013; Zhang et al., 2013). The high N input and low NUE could not only increase the production cost, but also result in severe environmental pollution (Ju et al., 2009; Peng et al., 2009;

Abbreviations: AE$_N$, agronomic N use efficiency; CGR, crop growth rate; DAT, days after transplanting; DW, dry weight; HI$_N$, N harvest index; IE$_N$, internal N use efficiency; NEVs, N-efficient varieties; NIVs, N-inefficient varieties; NSC, nonstructural carbohydrate; NUE, nitrogen use efficiency; PE$_N$, N physiological efficiency; PFP$_N$, N partial factor productivity; PNUE, photosynthetic nitrogen use efficiency; RE$_N$, apparent recovery efficiency of N fertilizer; ROA, root oxidation activity.

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http://dx.doi.org/10.1016/j.fcr.2015.02.007
0378-4290/

Guo et al., 2010; X.P. Chen et al., 2014). Ways must be sought to increase both grain yield and NUE so that the demand of the growing population could be met and environmental costs be mitigated (Peng and Bouman, 2007; X.P. Chen et al., 2014).

It is generally believed that development of genetic varieties with improved NUE is essential for sustainable agriculture (Kant et al., 2011; Haegele et al., 2013; Y.L. Chen et al., 2014). Although genetic differences in N upatake and/or grain yield per unit of N applied have been reported in different crops including wheat, rice, maize, sorgum and barley (see the review by Kant et al., 2011), plant traits that are associated with high grain yield and high NUE in rice are yet to be identified (Peng and Bouman, 2007).

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., 2004; Wu and Cheng, 2014). Root morphology and physiology are closely associated with soil resource acquisition and the growth and development of aboveground plants (Samejima et al., 2004; Yang et al., 2008; Garnett et al., 2009; Zhang et al., 2009; Lynch, 2013). The hypothesis was tested in maize that an ideotype root architecture for efficient N acquisition should have deeper roots with high activity, vigorous lateral root growth under high N conditions, and strong responses of lateral root growth to localizaed N supply (Mi et al., 2010). There are reports showing that some plant shoot traits could also contribute to high NUE (Bingham et al., 2012; Y.L. Chen et al., 2014; Pang et al., 2014). It is observed that NUE is positively correlated with post-anthesis dry mater accumulation and N uptake in barley (Bingham et al., 2012). An increase in photosynthesitic NUE (PNUE) of the leaves could maintain whole-plant photosynthesis and dry matter accumulation in maize (Y.L. Chen et al., 2014). Wheat genotypes with high early vigor accumulate more N and have higher PNUE during early growth in wheat (Pang et al., 2014). However, information on root and shoot traits in relation with high NUE in rice is very limited.

The purpose of this study was to identify root and shoot traits that are associated with higher grain yield and higher NUE in rice. Root biomass, root length, root length density and root oxidation activity (ROA) were used as root traits. Shoot traits were shoot biomass, photosynthetic rate and PNUE of leaves, crop growth rate, and nonstructural carbohydrate (NSC) in the stem at heading and its remobilization during grain filling. Such a study would give insight into understanding the mechanism underlying high grain yield and high NUE in rice, and provide breeders with information to develop N-efficient varieties without sacrificing grain yield potential (Peng and Bouman, 2007).

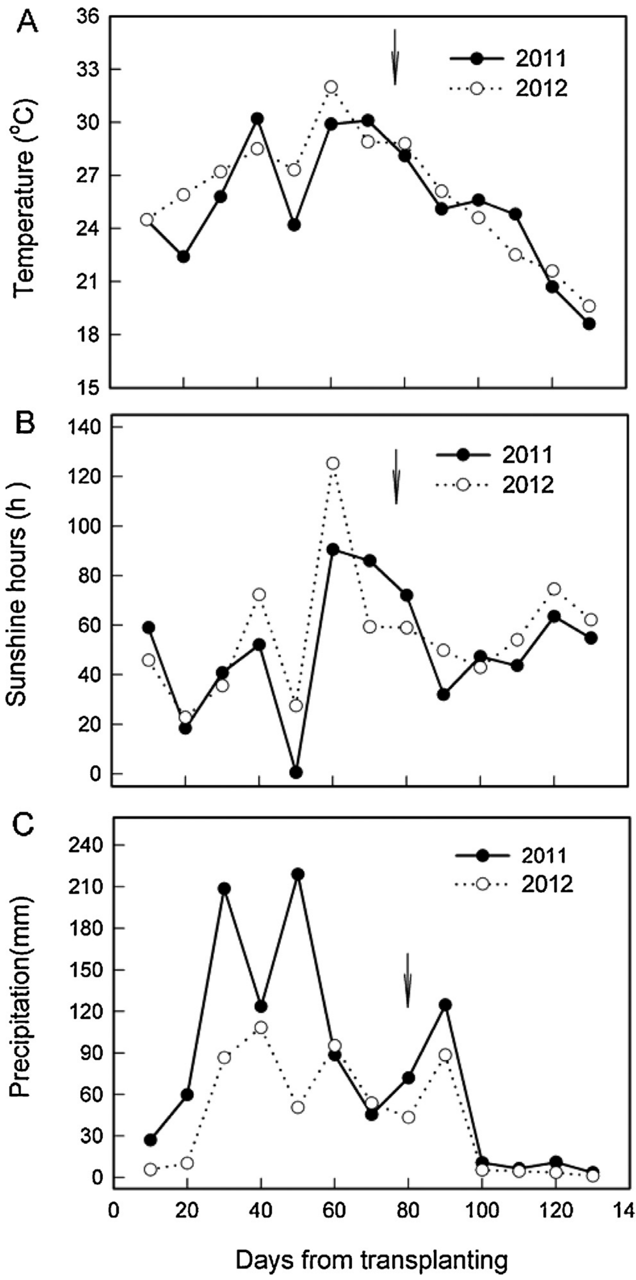

Fig. 1. The mean temperature (A), sunshine hours (B), and precipitation (C) during the growing season of rice in 2011 and 2012 at the experiment site of Yangzhou, Southeast China. Data are means of per 10 days from the transplanting of rice. Arrows indicate the heading time.

2. Materials and methods

2.1. Plant materials and growth conditions

The experiment was conducted at a farm belonging to Yangzhou University, Jiangsu Province, China (32°30′N, 119°25′E) during the rice growing season (May to October) of 2011, and repeated in 2012. The soil was a sandy loam [Typic Fluvaquents, Etisols (U.S. taxonomy)] with 24.5 g kg^{-1} organic matter, 102 mg kg^{-1} alkali hydrolysable N, 34.3 mg kg^{-1} Olsen-P, and 67.6 mg kg^{-1} exchangeable K. The field capacity soil moisture content was 0.189 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 Fig. 1.

Four high-yielding japonica rice (*O. sativa* L.) varieties currently used in local production, Huaidao 5 (HD-5), Lianjing 7 (LJ-7), Ninjing 1 (NJ-1) and Yangjing 4038 (YJ-4), were grown in the paddy field. Both HD-5 and LJ-7 could produce higher grain yield than NJ-1 and YJ-4 at lower N rates. The four varieties have a similar growth period ranging from 153 to 155 days from sowing to physiological maturity. Seeds of all the four varieties were obtained from Yangzhou Seed Company (Yangzhou, Jiangsu, China). Across the two years, seedlings were raised in the seedbed with sowing date on 15–16 May and transplanted on 9–10 June at a hill spacing of 0.16 m × 0.25 m with two seedlings per hill. Phosphorus (30 kg ha^{-1} as single superphosphate) and potassium (40 kg ha^{-1} as KCl) were applied and incorporated before transplanting. Water, weeds, insects, and diseases were controlled as required to avoid yield loss. The heading date (50% plants) of the four varieties was on 25–28 August, and plants were harvested on 15–17 October.