G Model
FIELD-6658; No. of Pages 16

ARTICLE IN PRESS

Field Crops Research xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Field Crops Research

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

Grain yield, water and nitrogen use efficiencies of rice as influenced by irrigation regimes and their interaction with nitrogen rates

Zhiqin Wang[a], Weiyang Zhang[a], Sarah S. Beebout[b], Hao Zhang[a], Lijun Liu[a], Jianchang Yang[a,*], Jianhua Zhang[c,*]

[a] Jiangsu Key Laboratory of Crop Genetics and Physiology/Co-Innovation Center for Modern Production Technology of Grain Crops, Yangzhou University, Yangzhou, Jiangsu, China
[b] Crop and Environmental Sciences Division, International Rice Research Institute (IRRI), DAPO Box 7777, Metro Manila, Philippines
[c] School of Life Sciences and State Key Laboratory of Agrobiotechnology, The Chinese University of Hong Kong, Hong Kong, China

ARTICLE INFO

Article history:
Received 5 February 2016
Received in revised form 10 March 2016
Accepted 10 March 2016
Available online xxx

Keywords:
Rice (*Oryza sativa* L.)
Alternate wetting and drying (AWD)
Nitrogen use efficiency (NUE)
Synergistic interaction
Water use efficiency (WUE)

ABSTRACT

A major challenge in rice production is to achieve the goal of increasing both food production and resource use efficiency. This study investigated if and how irrigation regimes could synergisticly interact with nitrogen (N) rates to increse grain yield, water use effciency (WUE) and N use effciency (NUE) in rice. A field experiment was conducted with three N rates, 100 (low amount, LN), 200 (normal amount, NN) and 300 kg ha^{-1} (high amount, HN), and three irrigation regimes, alternate wetting and moderate drying (AWMD), alternate wetting and severe drying (AWSD) and continuously flooded (CF). Among the three N rates, both grain yield and WUE were the lowest at LN in all the irrigation regimes, were the highest at NN in the CF regime and at HN in the AWSD regime, and showed no significant difference between NN and HN in the AWMD regime. Either internal N use efficiency or N partial factor productivity (PFP_N) decreased with the increase of N rates. At the same N rate, the AWMD regime showed the highest grain yield, WUE and PFP_N among the three irrigation regimes. Reduced unproductive tillers, enhanced root growth and increased harvest index contributed to a higher grain yield and higher resource use efficiency in the AWMD regime, especially at NN. The results indicate that adoption of an AWMD regime with an appropriate N rate can achieve a higher grian yield, WUE and NUE, and an increase in N rate can reduce the yield loss in an AWSD regime.

1. Introduction

Rice (*Oryza sativa* L.) is one of the most important crops in the world and is the foremost staple food in Asia, providing 35–60% of the dietary calories consumed by more than three billion people (Fageria, 2007; GRiSP (Global Rice Science Partnership), 2013). Rice is also the greatest consumer of water among all crops and consumes approximately 80% of the total irrigated fresh water resources in Asia (Bouman and Tuong, 2001). To meet the major challenge that rice production needs to increase to feed a growing population under increasing scarcity of water resources, many water-saving regimes have been introduced such as an aerobic rice system (Bouman et al., 2005; Singh et al., 2008; Lampayan et al., 2010), a system of rice intensification (Uphoff and Randriamiharisoa, 2002; Zhao et al., 2009), non-flooded mulching cultivation (Liu et al., 2005; Tao et al., 2006; Xu et al., 2007; Zhang et al., 2009b), and alternate wetting and drying (AWD) irrigation (Bouman and Tuong, 2001; Belder et al., 2004, 2007; Zhang et al., 2009a, 2012). Among water-saving technologies, AWD has been mostly applied in China with an area of more than 12 million hectares each year (Li, 2001; Yang et al., 2007; Zhang et al., 2008, 2010; Ye et al., 2013) and is being adopted in Asian countries such as Bangladesh, India, the Philippines, and Vietnam (Tabbal et al., 2002; Kukal et al., 2005; Tuong et al., 2005; Bouman, 2007). This technology, characterized by its alternation of periods of soil submergence with periods of non-submergence during the growing season, could substantially reduce irrigation water and lead to an

Abbreviations: AWD, alternate wetting and drying; AWMD, alternate wetting and moderate drying; AWSD, alternate wetting and severe drying; CF, continuously flooded; CGR, crop growth rate; DAT, days after transplanting; DW, dry weight; HI_N, N harvest index; HN, high amount of N; IE_N, internal N use efficiency; LAD, leaf area duration; LAI, leaf area index; LN, low amount of N; N, nitrogen; NN, normal amount of N; NSC, nonstructural carbohydrate; NUE, nitrogen use efficiency; PFP_N, N partial factor productivity; PNUE, photosynthetic nitrogen use efficiency; ROA, root oxidation activity; WUE, water use efficiency.

* Corresponding authors.
E-mail addresses: jcyang@yzu.edu.cn, jsyzyjc@126.com (J. Yang), jhzhang@cuhk.edu.hk (J. Zhang).

http://dx.doi.org/10.1016/j.fcr.2016.03.006
0378-4290/

improvement in water use efficiency (WUE) (Bouman and Tuong, 2001; Belder et al., 2004, 2005; Yang et al., 2007; Zhang et al., 2008, 2009a; Yao et al., 2012). However, it remains debatable if the technology could achieve the dual goal of increasing grain yield and saving water (Tabbal et al., 2002; Belder et al., 2004; Tuong et al., 2005; Yang et al., 2007; Zhang et al., 2008, 2009a; Yao et al., 2012; Liu et al., 2013).

Besides water, nitrogen (N) is another key factor determining crop yield, and it also consists of the main input in rice production (Ju et al., 2009). In the last 50 years, rice yield in the world has continuously increased, partly because of the increase in fertilizer nutrient input, especially N fertilizer (Cassman et al., 2003; Peng et al., 2009, 2010). However, the use of N fertilizer is generally inefficient, and the apparent recovery efficiency of N fertilizer (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). There are reports showing that the adoption of AWD-based technologies could reduce total cumulative plant N and N use efficiency (NUE) by stimulating N losses through increases in ammonia volatilization, nitrification and denitrification (Sah and Mikkelsen, 1983; Eriksen et al., 1985; Zou et al., 2007). But some studies have shown that AWD irrigation could not increase N loss due to the reduction in vertical NH_4^+-N and total N leaching, and accordingly, could not decrease NUE (Zhang et al., 2008, 2009a; Wang et al., 2011). It is hypothesized that there should be a synergistic interaction between soil moisture and N fertilizer on crop growth if both water and N are managed properly, and such a synergistic interaction can increase crop yield, WUE and NUE (Cao et al., 2007; Liu et al., 2013; Yang, 2015). However, the evidence is very scarce, and the way to realize the synergistic interaction between water and N on crop growth is yet to be understood.

The objectives of this study were to investigate if AWD-based irrigation regimes interacted with N application rates on rice yield, WUE and NUE, and to understand how irrigation regimes and N rates interacted on crop growth. Some agronomic and physiological traits that are closely associated with rice growth, percentage of productive tillers, leaf area duration (LAD), leaf photosynthetic rate, dry matter accumulation, nonstructural carbohydrate (NSC) in the stem at heading and its remobilization during grain filling, root biomass and root oxidation activity (ROA) (Yoshida, 1972; Fageria, 2003), were determined. Such a study would provide useful information to the rice production achieving higher grain yield and high resource use efficiency, and give insight into understanding the mechanism underlying the interaction between water and N on rice growth.

2. Materials and methods

2.1. Plant materials and cultivation

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) of 2013 and 2014. The soil was a sandy loam (Typic fluvaquents, Etisols, US classification) that contained 24.4 g kg^{-1} organic matter, 102 mg kg^{-1} alkali hydrolysable N, 33.5 mg kg^{-1} Olsen-P, and 67.3 mg kg^{-1} exchangeable K. The field capacity soil moisture content was 0.189 g g^{-1}, and bulk density of the soil was 1.34 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.

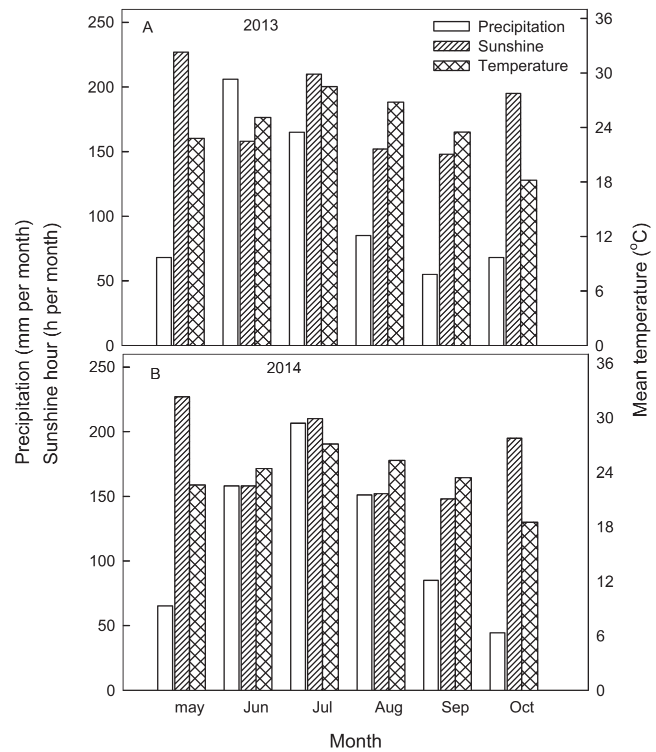

Fig. 1. Precipitation, sunshine hours, and mean temperature during the rice growing season of 2013 (A) and 2014 (B) in Yangzhou, Southeast China. Precipitation, sunshine hours are monthly totals. Temperatures are the monthly averages.

A *Japonica* rice (*Oryza sativa* L.) cultivar Wuyunjing 24 currently used in local production were grown in the field. Across the two years, seedlings were raised in the seedbed with sowing date on 15 May and transplanted on 10 June at a hill spacing of 0.25 m × 0.16 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. Weeds, insects, and diseases were controlled as required to avoid yield loss. The heading date (50% plants) of the cultivar was on 27–28 August, and plants were harvested on 15–16 October.

2.2. Irrigation and N treatments

The experiment was a 3 × 3 (three irrigation regimes and three N rates) factorial design with 9-treatment combinations. Each of the treatments had three plots as repetitions in a complete randomized block design. Plot dimension was in 5.5 m × 4.8 m and plots were separated by an alley of 1 m wide with plastic film inserted into the soil to a depth of 0.50 m to form a barrier. Nitrogen application treatments consisted of three N rates including 100, 200, and 300 kg ha^{-1}, and were represented low amount (LN), normal amount (NN), and high amount of N (HN), respectively. Nitrogen as urea was applied at pre-transplanting (1 day before transplanting), early tillering (7 days after transplanting, DAT), panicle initiation (the first appearance of differentiated apex) and the initial of spikelet differentiation (the appearance of glumous flower primordia at the tips of elongating primary rachis-branches). The proportion of N split was 40%, 10%, 25% and 25%, respectively, at the above four stages.

Irrigation treatments consisted of three irrigation regimes including alternate wetting and moderate soil drying (AWMD), alternate wetting and severe soil drying (AWSD), and continuously flooded (CF), and were applied from 10 days after transplanting (DAT) to maturity. In the AWMD regime, fields were not irrigated