Europ. J. Agronomy 53 (2014) 1–9

Contents lists available at ScienceDirect

European Journal of Agronomy

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

Effects of controlled irrigation and drainage on growth, grain yield and water use in paddy rice

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ARTICLE INFO

Article history:
Received 27 November 2012
Received in revised form 10 October 2013
Accepted 16 October 2013

Keywords:
Rice
Growth
Water use
Yield
Controlled irrigation and drainage

ABSTRACT

Rice is subjected to excessive waterlogging and flash-flooding on large areas in south China. A study on water use, growth and yield effects of controlled irrigation and drainage (CID) of paddy rice at four stages was conducted in specially designed experimental tanks. The treatments were (1) CID during Stage I of tillering stage (CID-Stage I), (2) CID during Stage II of booting stage (CID-Stage II), (3) CID during Stage III of heading to flowering stage (CID-Stage III), (4) CID during Stage IV of milky stage (CID-Stage IV), (5) alternate wetting and drying irrigation during the whole stage (CK). Compared with CK, CID reduced drainage volume with 15.8–31.3% in 2008, and 13.5–28.3% in 2009, and increased the efficiency of available rainfall and irrigation by 1.98–3.46% in both years. Irrigation water application during the whole growing season across the 2 years, on average, was only 81.8%, 91.1%, 93.9%, and 94.5%, respectively, of that applied to CK. A strong reduction in root length, root weight, root-shoot ratio and harvest index were observed, however, shoot weight and total dry mass is increased from the treatments of CID-Stage II, CID-Stage III and CID-Stage IV. The highest radiation use efficiency values were for CID-Stage IV. The responses of CID from vegetative plants at Stage I and Stage II were greater than in generative plants at the latter two stages. CID-Stage II had only a small effect on subsequent development and grain yield. This decrease in grain yield to less than 7.88% and 5.72% of CK was due to reduced number of spikelets per panicle in one trial, and reduced panicle number per unit area in another. The CID-Stage I treatment showed the lowest grain yield among the treatments and reduced it by 23.3% in 2008 and by 17.3% in 2009, due to the decreases in the percentage of filled grains and total number of panicles. The effect of stress was associated with low dry matter production during the flooding stress period as well as during the stress withdrawal period following the stress. With regards to irrigation water use efficiency, it was increased under the first two treatments, and by from a minimum of 101% to a maximum of 110%.
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1. Introduction

China is the most important rice (*Oryza sativa* L.) producing country in the world. Its planting area accounts for about 20% of the world total and 23% of all cultivated land in China (Frolking et al., 2002). Rice is a water intensive crop which requires large amount of freshwater under the flood-irrigated conditions, and water consumption by paddy fields accounts for approximately 50% of all diverted freshwater in China (Cai and Chen, 2000). 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; Edward and David, 2008). Traditionally rice is grown under a continuously flooded condition and hence most conventional water management practices aim to maintain a standing depth of water in the field throughout the season. Decreasing water availability for agriculture threatens the productivity of irrigated rice ecosystem, and ways must be sought to save irrigation water and maintain grain yield of rice (Belder et al., 2004; Bouman et al., 2007).

To solve the water shortage and improve the water use and water productivity, China has applied various water-saving irrigation technologies to achieve more water-efficient irrigation for agricultural systems, for rice, such as seasonal continuous flooding, flooding-midseason drainage-frequent flooding stress with intermittent irrigation (Huang et al., 2004), alternate wetting and

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http://dx.doi.org/10.1016/j.eja.2013.10.005

drying irrigation (Bouman et al., 2001; Belder et al., 2004), continuous soil saturation (Borrell et al., 1997), internal drainage (Ramasamy et al., 1997), rice cultivation on raised beds (Ockerby and Fukai, 2001), aerobic rice system (Bouman et al., 2006) and non-flooded mulching cultivation (Liu et al., 2005; Tao et al., 2006; Zhang et al., 2008; Lu et al., 2007). Alternate wetting and drying irrigation (AWD) is considered as a novel irrigation water-saving technique and has been practiced in many areas in China (Wu et al., 2006). In AWD, the field is allowed to be in disappearance of ponding water for a certain number of days. Irrigation water is applied when plants show visual symptoms of water shortage or when a certain threshold of soil water potential is reached during the whole rice growing season (Tuong et al., 2005; Bouman et al., 2007). Although positive implications were obtained by applying AWD technology in rice fields, the rainwater use in AWD has been reported to be less as the upper limit of ponding rain water is lower (Guo et al., 2009). Controlled drainage (CI) practices are a global phenomenon found in northeast Italy (Borin et al., 2001), southern Sweden (Wesstrom and Messing, 2007) and North Carolina, USA (Evans et al., 1995). Advantages of CI include reduced outflow velocity and outflow, stormwater mitigation and sedimentation, increased denitrification and saving irrigation water. Since the irrigation season of rice in south China was coincident with the summer wet season, and the annual average precipitation in south China is up to 1000 mm, taking into account the likely contribution of rainwater to irrigation water is, therefore, a prerequisite for sustainable paddy rice production in this region. Control irrigation and drainage (CID) aim to take advantage of AWD and CI, and maintain a higher depth of water and captured more drainage water than AWD in the field during some rainy days of the season. The frequency of irrigation and duration of CID approach can be determined by re-irrigating after a fixed number of non-flooded days, when a certain threshold of groundwater level is reached. In this system, more surface runoff is captured in paddy field for later use during moisture deficit periods and thus improves productivity of irrigation water in rice paddy.

Under CID conditions, rice may experience fluctuating water level due to the intermittent nature of irrigation systems and rainfall patterns. Consequently, the plants are exposed to frequent episodes of alternate wet and dry conditions to various degrees. The desirable growth traits for adaptation to these fluctuating environments may be different from those under drought or flooding stress alone. In south China, flooding stress caused by abundant rainfall during the growing season reduces the crop establishment and adversely affects tiller and dry matter production (Pande and Reddy, 1984). The adverse effects of submergence are due to mechanical damage, silt deposition on leaves, reduced light, limited gas diffusion, leaching of solutes from plant tissues, and increased susceptibility to pests and diseases. Anbumozhi et al. (1998) studied the effects of change of ponding water depth on the growth and yield of rice and showed that an optimal ponding water depth for the rice crop may not cause a non-significant yield reduction under given climatic and agronomic conditions. Excessive standing water tend to increase oxygen deficiency on soil surface (IRRI, 1979), reduce photosynthetic leaf area (Yoshida, 1981), inhibit tiller (Williams et al., 1990), and decrease water use efficiency (Tuong, 1999). The simulation growth model without inclusion of water depth tends to overpredict rice shoot dry mass production (Caton et al., 1999). The morphological cause of yield reductions in rice crop under partial submergence has been attributed to impaired tillering (Yoshida, 1981). Study also showed that excessive standing water could reduce transpiration rate (Zhang et al., 2008). Usually, decrease in transpiration rate by reducing stomatal conductance will result in the loss of photosynthesis (Wong et al., 1985), leading to a reduction in biomass. In general, AWD increased water productivity with respect to total water input because the yield reduction was smaller than the amount of water saved. Several studies specifically examined the effect of the AWD irrigation approach on water use and rice yields by field experiments. Zhi (2001) found that irrigation water use was reduced by 7–25% with the AWD technique. Studies by Moya et al. (2004) and Cabangon et al. (2001) in China found similar results. In contrast, Bouman and Toung (2001) studied the impact of various forms of AWD and showed that 92% of the AWD treatments resulted in yield reductions ranging from zero to 70%, compared to the flooded control. In CID, flooding stress may be perceived as severe to plants when their roots were previously drought-stressed. Similarly, drought stress may be perceived as more severe to plants when their roots previously experienced flooding stress. Roots have to acquire both oxygen (O_2) and water level under such adverse conditions. The inability to acclimate to such changes in water regimes is assumed to affect root growth and functions, thus, biomass production. In addition, the effects of CID on paddy rice depend on duration of drought and flooding stress and the stage of development of the crop as well as other factors. However, understanding of the response of growth, grain yield and water use to this technology for paddy rice at various stages of the crop cycle is still limited.

Although many studies have investigated agronomic performance of rice individually under AWD and CI (Belder et al., 2004; Guo et al., 2009). Few studies have looked into the combined effect of AWD and CI for rice at different stages. Besides, CID whether to further take advantage of the interactive effect of AWD combined with CI and improve irrigation water use efficiency and grain yield should be confirmed and further studied. Moreover, rainfall management practices need to be developed to match the water-saving strategies. In this 2-year experiment, water balance and rice growth responses to CID were compared in 15 specially designed tanks with contrasting water level. It is hypothesized that the effects of AWD and CI may be additive and the magnitude of irrigation water saving in rice will be more with integration of these interventions, i.e. changing the threshold of irrigation and drainage compared to that by individual. For crop performance, we hypothesized that all environmentrial factors has the same effect on crops growth before CID treatments was imposed. We also hypothesized that plots have the same seepage and percolation rates when water table existed at soil surface and water table recession occurs evenly when floodwater recedes. Therefore, the objectives of this study were to analyze water use, the morphological and critical yield components response of rice plants at different stages to CID and to evaluate the CID as a useful technique to save irrigation water by increasing ponding rainfall depth while not significantly affecting the economic value of the plant in a clay soil in southern China under the climatic conditions. These were compared with a conventional planting treatment with AWD applied at four stages. All variables related to water balance, crop growth, grain yield and irrigation water productivity from each treatment were compared.

2. Materials and methods

2.1. Experimental conditions and plant material

The experiment was conducted in 15 concrete tanks, each of approximately 5 m^3 (surface area = 2.5 m × 2 m, depth = 2 m), Key Laboratory of Efficient Irrigation-Drainage and Agricultural Soil-Water Environment in Southern China, Ministry of Education (Nanjing, latitude 31°57′ N, longitude 118°50′ E, 144 m above sea level) during the rice growing season (May to October) of 2008, and repeated in 2009 (Shao et al., 2010a). Fig. 1 is the schematic diagram of a set-up for maintaining ponding water depth. Groundwater level was changed by raising or lowering the height of the finger of electromagnetic valve relative to the bottom of each tank. When ponding water depth lowered to lower limit of designed

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