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Impacts of controlled irrigation and drainage on the yield and physiological attributes of rice

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ABSTRACT

Taking into account the likely contribution of rainwater to crop water requirements, is an alternative option for increasing the productivity of water in irrigated agriculture. We evaluated the response of yield and physiological characters to controlled irrigation and drainage (CID) at different growth stages of rice (*Oryza sativa* L.). Submergence at different stages was imposed in specially designed experimental tanks in 2009 and 2010 based on alternate wetting and drying technology (AWD, the control). Treatments include CID treatment at tiller stage (CID-Stage I), jointing–booting (CID-Stage II), panicle initiation (CID-Stage III), and milky stage (CID-Stage IV). Compared to the control, we observe a strong reduction in root length, root weight and root–shoot ratio were observed in the CID treatments. Under CID-Stage I and CID-Stage II, rice was characterized by faster shoot elongation, larger single leaf area extension, and more total dry mass, as a higher photosynthetic rate was maintained during and after submergence. The CID-Stage I and CID-Stage II treatments increased photosynthesis rate (P_N) and transpiration (T_r) significantly compared to the control, but decreased average leaf water use efficiency (WUE_L, defined as the ratio of P_N to T_r) by 3.3% (2009) and 5% (2010). The P_N and T_r also demonstrated close linear and quadratic relationships with stomatal conductance. Cultivation of rice under CID-Stage II resulted in 6% and 3% yield reduction over the control. This insignificant decrease in grain yield was due largely to the reduced percentage of filled gain. The lowest yields were obtained under CID-Stage I in 2009 and CID-Stage III treatments in 2010, respectively. The submergence-induced decrease in the number of panicles per unit area and number of spikelets per panicle were responsible for the lower yields obtained from those two stages. CID-Stage II had an average irrigation water productivity of 1.77 kg m^{-3} for the two years, an increase of about 9% from the control.

1. Introduction

Rice (*Oryza sativa* L.) plays an important role in feeding more than 3 billion people, including most of the world's 1 billion poor people (IRRI, 2010). According to the Chinese Ministry of Agriculture's statistics on rice production from 1990 to 2011, China's average annual rice planting area and total production had reached 30.1 million ha and 18.6 billion t, respectively. Both the planting area and total production are ranked first in the world (MOA, 2012). Decreasing water availability for agriculture threatens irrigated rice productivity, and ways must be sought to reduce irrigation water demands while maintaining grain yield of rice (Belder et al., 2004; Bouman, 2007a; Bouman et al., 2007b). Several water-saving technologies such as alternate wetting and drying (AWD) and aerobic rice are being developed to lower the water requirements of rice crop (Bouman, 2007a). Although positive results were obtained by applying AWD technology in rice fields, the rainwater use efficiency in AWD has been reported to be less since the upper limit of ponding rain water is lower (Guo et al., 2009; Yu et al., 2010). The rice season in Southern China coincides with the summer wet season and the annual average precipitation is more than 1000 mm. Plentiful rainfall in the southern region of China allows successful rice cultivation in rainy season with less irrigation. Judicious management of rainwater in existing farm infrastructure, taking into account the likely contribution of rainwater to irrigation water, is an alternative

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option for increasing productivity of water in irrigated agriculture (Mdemu et al., 2004).

Attempts to reduce nutrient losses in drainage water have led to the development of controlled drainage. The water table can be kept higher than that in conventional drainage at periods of low drainage demand. It has been used in northeast Italy (Borin et al., 2001), North Carolina, USA (Evans et al., 1995) and southern Sweden (Wesstrom and Messing, 2007). Advantages of controlled drainage include reduced outflow velocity and volume, stormwater mitigation, less sedimentation, increased denitrification, and less irrigation water. Under field conditions, however, it is unusual for soil moisture condition to remain constant throughout a cropping season; the soils are exposed to frequent episodes of alternate wet and dry conditions to various degrees. Controlled irrigation and drainage (CID) aims to take advantage of both AWD and controlled drainage. Under CID, a higher water depth is maintained and more drainage water is captured during rain events than with AWD. Under this water management practice, more surface runoff is captured in paddy field for later use during moisture deficit periods. Thus, the productivity and efficiency of irrigation water in rice field may be improved. However, ponding more rain water has the potential to cause decreased yields as a result of less oxygen available to be absorbed than under normal water level.

Understanding the array of responses of rice plant processes and mechanisms to CID is crucial and a fundamental part of crop stress tolerance (Reddy et al., 2004), and important to improve their agronomic performance. Yield of rice is a function of the production of assimilates by photosynthesis and translocation of assimilates to reproductive sinks. Any alteration of the photosynthetic rate (P_N) can also influence plant growth. Partial submergence conditions may result in the decoupling of photosynthetic rate and root absorption at different stages. In general, leaf photosynthesis decreases under submergence because of CO_2 depletion and low irradiation, resulting in decreased supply of carbohydrates following degradation of photosynthesizing tissues. Excessive standing water tends to increase oxygen deficiency on the soil surface (IRRI, 1979), reduce photosynthetic leaf area (Yoshida, 1981), inhibit tiller (Williams et al., 1990), and decrease water use efficiency (Tuong, 1999). Studies also showed that submergence could reduce transpiration rate (Zhang et al., 2008). Usually, a decrease in transpiration rate caused by reduced stomatal conductance will result in the loss of photosynthesis (Wong et al., 1985), leading to a reduction in biomass. However, partial submergence treatments in deepwater flooding-adapted rice had little effect on carbohydrate and sugar contents (Setter et al., 1987; Yamaguchi et al., 1989), with differences greatest in newly developed leaves under water. Submergence increases the source activity and photosynthetic rate in upper leaves above the water surface. Changes in physiological traits due to submergence depend on the plant developmental stage at which submergence occurs. However, little research has been done on direct effects of stress factors at different stages on the physiological processes affecting dry matter production.

Generally, several mechanisms can contribute to flooding tolerance of crop plants. These include morphological characteristics, such as rapid elongation of internodes and metabolic regulatory mechanism like osmotic adjustment. An important adverse effect of shoot elongation, which is the response frequently observed in rice plants under submergence, is an increase in carbohydrate consumption for cell division, cell elongation, and leaf elongation maintenance (Ito et al., 1999; Setter and Laureles, 1996; Voesenek et al., 2006). Submergence escape coupled with faster shoot elongation enables rice to resume functioning when aerobic conditions recur (Sakagami et al., 2009). In addition, distribution of the photoassimilated product or/and photosynthetic capacity in rice is altered by deepwater flooding (Hirano et al., 1995). Irrespective of the outcome, rapid shoot elongation involves the risk of depleting conserved plant carbohydrates during submergence (Sakagami and Kawano, 2011). Much of the work relating to submergence in crop species has involved the use of repeated or long (i.e. weeks or months) exposures to submergence (Orchard and Jessop, 1984; Musgrave, 1994). However, those studies have been limited to the effects on the final yield, with little attention to photosynthesis and dry mass accumulation.

Our goal is to determine how CID affects the photosynthesis and yield of rice at different growth periods in a clay soil under the climatic conditions of Southern China. We hypothesized that all environmental factors have the same effects on crop growth before the CID treatments were imposed. We also hypothesize that plots have the same seepage and percolation rates when a water table existed at the soil surface, and water table recession occurs evenly when floodwater recedes.

2. Materials and methods

2.1. Site description

The experiments were conducted in specially designed experimental tanks at the 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 masl) during the rice growing seasons (May to October) of 2009 and 2010. The experimental site has a subtropical, humid climate with an annual mean temperature of 15.3 °C. The mean annual precipitation at Nanjing city (located 20 km northeast of experimental site) from 1951 to 2009 is 1051 mm and the mean annual surface water evaporation is 900 mm. The air temperature, wind speed and direction, relative humidity, total solar radiation, and photosynthesis active radiation (PAR) were measured at the experimental site using an automated weather station. Precipitation was measured by a tipping bucket rain gauge. Soil temperatures were measured at 5, 15 and 30 cm depths near the instrumentation site, using a temperature probe. All meteorological parameters were stored in a datalogger and downloaded weekly via a computer.

2.2. Plant material and cultivated practices

Yangjing 4038, a high-yielding rice currently used in local production, was grown in the paddy tanks. Seedlings were raised in a seedbed and sowing dates were 11 May in 2009 and 15 May in 2010. Seedlings were transplanted on 14 June in 2009 and 29 June in 2010 at a hill spacing of 0.25 m × 0.20 m, with three seedlings per hill. A week before transplanting, the experimental plots were dry-ploughed and harrowed. The soil was soaked 1 day before transplanting and then flooded for about 1 week with a 2–3 cm water layer to promote good crop establishment. Applications of fertilizer (15:10:15) at the rate of 1200 kg ha^{-1} in the form of compound fertilizer were applied in three equal splits, i.e., 1/3rd as basal, 1/3rd at tillering, and 1/3rd at panicle initiation stage. Plants were harvested on 23 October in 2009 and 29 October in 2010. Two hand weeding were given at 30 and 50 days after transplanting. All other recommended cultivated practices for achieving maximum grain yield were followed.

2.3. Water regimes

The paddy tanks were 2 m wide 2.5 m long and 2 m high containers constructed from concrete block and sealed with a waterproof paint (Fig. 1). PVC pipe connected supply and drainage holes in the tanks to 3 m high bottles, which were connected with a tank that supplied water. The bottom of each tank was filled with a 20 cm layer of coarse gravel, separated from the soil by a water-permeable membrane to allow free supply and drainage. When