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More rice with less water – evaluation of yield and resource use efficiency in ground cover rice production system with transplanting

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ABSTRACT

Adoption of the innovative water-saving ground cover rice production system (GCRPS) based on transplanting of rice seedlings under high soil moisture conditions, resulted in an overall increase in grain yield compared to previous reports on GCRPS employing direct seeding. However, there is a lack of quantitative information on water and nitrogen use efficiency as affected by water and nitrogen management in GCRPS-transplanting. To close this knowledge gap, we conducted a two-year field experiment with traditional paddy rice (Paddy) and GCRPS-transplanting under two soil moisture conditions (GCRPS$_{\text{sat}}$ and GCRPS$_{80\%}$), combined with 3 nitrogen fertilizer management regimes (0, 150 kg urea-N/ha as basal fertilizer for Paddy and GCRPS, 150 kg urea-N/ha in 3 splits for Paddy or 75 kg urea-N/ha plus 75 kg N/ha as chicken manure for GCRPS). Grain yield, water and nitrogen use efficiency, stable isotope ^{13}C of plant shoots and yield components were evaluated.

The study showed: (1) compared to Paddy, both GCRPS$_{\text{sat}}$ and GCRPS$_{80\%}$ produced significantly more grain yield, while no significant difference in grain yield was found between both GCRPS treatments. (2) Irrigation water use efficiency was increased by 140% in GCRPS$_{\text{sat}}$ and >500% in GCRPS$_{80\%}$, while total water use efficiency was improved by 52–96% as compared to Paddy. (3) δ^{13}C of plant shoots was significantly higher in GCRPS than in Paddy, and showed significant positive correlations with total and irrigation water use efficiencies. (4) Compared to Paddy, agronomic N use efficiency was significantly higher in both forms of GCRPS. However, N recovery rates were only significantly higher in GCRPS than in Paddy when all urea nitrogen was applied as basal fertilizer before transplanting. With improved fertilizer N management, i.e., split N application in Paddy or combined application of urea and chicken manure in GCRPS, there were no significant differences. Overall, this quantitative evaluation of water use efficiency highlights that the use of GCRPS involving transplanting of seedlings has a great potential to reduce irrigation water input, increase grain yield and resource use efficiency.

1. Introduction

Rice is the major staple food for more than 3 billion people worldwide. The present and future of global rice production largely depends on irrigated rice production systems in Asia, which provide about 75% of the world's rice supply (Cantrell and Reeves, 2002; Qin et al., 2006). However, growing larger amounts of rice with less water is one of the major challenges for food security faced by humanity in the 21st century. Traditionally, irrigated rice grows under continuous flooding or submerged soil conditions, thus requiring much more water than other cereals. It was recently estimated that rice production consumes more than 45% of total freshwater resources in Asia and approximately 30% of the world's freshwater used for irrigation (Bouman and Tuong, 2001; Bouman et al., 2007). Nevertheless, the rapidly increasing population and associated water demands for urban and industrial use have put a strain on the fresh water resources worldwide (Bouman, 2007). It has been estimated that about 15–20 million hectares of Asia's irrigated rice will suffer from water scarcity by the year 2025 (Tuong and Bouman, 2003). In the light of diminishing water resources

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for agriculture and increasing demand for rice, water-saving rice production techniques have been sought for many years.

A promising water-saving technique for lowland rice production is the so called ground cover rice production system (GCRPS) which was firstly introduced in the mountainous region of Central China in 1990s to overcome both, seasonal water shortages and limitations imposed by lower temperatures at the beginning of the rice growing season. Since water and temperature limitations for growing rice can be found in many regions across China, the technique has the potential to be widely disseminated on more than 4 million hectare in northern China (Lin et al., 2002). GCRPS is an agricultural practice that is substantially different from traditional paddy rice systems. In GCRPS the soil surface is covered with a 5–7 μm thickness transparent plastic film, and there is no standing water during the entire growth period (Lin et al., 2002). Indeed, two different GCRPS techniques, namely direct seeding or transplanting of rice seedling, have been used on different soil types and different climatic conditions during the past two decades. For the practice of GCRPS-direct seeding, mainly used on sandy-loam soils with a low buffer and water holding capacity, lowland rice is grown across the entire growing season as directly-seeded upland crop at a soil moisture content of 70–90% maximum soil water holding capacity (Tao et al., 2006). Grain yield, agronomic performance, water and nitrogen use efficiency, and greenhouse gas emissions related to the implementation of this technique have been reported in previous research (Lin et al., 2002; Dittert et al., 2002; Sattelmacher et al., 2005; Tao et al., 2006, 2007; Kreye et al., 2007). Compared to traditional paddy rice production, GCRPS-direct seeding significantly reduced irrigation water consumption. However, under these conditions reductions in grain yield were also commonly observed (Lin et al., 2002; Tao et al., 2006). Moreover with GCRPS-direct seeding, a number of additional disadvantages were found. For example, the transition to more aerobic soil conditions in aerobic rice, which had considerable similarities with GCRPS-direct seeding, led to severe weed infestation, especially during the first weeks following seeding (Zhao et al., 2007). Furthermore, the increase in soil redox potential decreased the availability of micronutrients, which might result in potential deficiency of manganese for rice plants (Tao et al., 2007). Finally, continuous aerobic mono-cropping might increase the risk of soil-borne pathogen infestations leading to deterioration of soil health (Nie et al., 2009). Thus, there was much hesitation to adopt GCRPS-direct seeding in many regions of China.

Instead, GCRPS-transplanting has recently become a promising technology in water-saving rice production (Qu et al., 2012; Liu et al., 2013, 2014). GCRPS-transplanting can be readily adopted in areas with typical paddy soils, where transplanting is typically done when rice seedlings are approximately one month old. For this approach the soil moisture is kept close to saturation during the entire growing period (Qu et al., 2012). There have been reports about this technique having a remarkable efficiency by increasing soil temperature, preserving soil moisture and inhibiting weed growth under the thin polythene coverage (Shen et al., 1997). It has been showed that, in areas where either water or temperature were restricting factors for rice production, GCRPS-transplanting significantly increased grain yield by 10–18% in both, a long-term field experiment and at the regional scale where GCRPS-transplanting and paddy rice were compared under real farming conditions (Qu et al., 2012; Liu et al., 2013). Given the potential benefits of GCRPS-transplanting for many regions across China, there is an urgent need to quantify its effects on water and nitrogen use efficiency as compared to paddy systems. Furthermore, there is no sufficient information on water use efficiency and the yield performance of GCRPS-transplanting or, whether there is potential to further reduce water input after middle tillering stage, the period when rice plants are less vulnerable to reduced soil moisture. On the other hand, stable carbon isotope composition (δ^{13}C) of plant has been a useful indicator of water and carbon balance over longer periods (Farquhar and Richards, 1984). Previous research observed strong relationships between water use efficiency and δ^{13}C on wheat or barley and mostly applied in plant breeding program (Farquhar and Richards, 1984; Farquhar et al., 1982). However, the association between water use efficiency and δ^{13}C are not well documented in rice under different production systems.

Undoubtedly, there are a few aspects to consider when developing concepts for new fertilizer schemes in GCRPS-transplanting. Since the plastic film covers the soil surface, all N fertilizer has to be applied as a basal dressing before transplanting (Shen et al., 1997). Consequently during their juvenile phase, rice plants may show excessive vegetative growth while in the reproductive phase, growth may be limited by insufficient N availability, which may lead to pre-mature plant senescence and constrain grain yield (Qu et al., 2012). Combination of urea and organic manure, with improved N supply after panicle initiation, could enhance the N uptake during the reproductive phase and increase the grain yield as seen with GCRPS in saturated soil in a long-term experiment (Tao et al., 2014). However so far, there are no studies assessing the effect of combining mineral fertilizer such as urea – the most commonly used fertilizer in China – and manure for their effects on yield potential and nitrogen use efficiency in GCRPS-transplanting under different soil moisture conditions.

In response to these research needs, a two-year field experiment was conducted to investigate rice grain yield and yield components, water consumption and N uptake, and δ^{13}C of plant shoots as an indicator for water stress and soil temperature in the upper Han River basin of China for Paddy and GCRPS. The objectives of this work were: (i) to quantify the water and nitrogen use efficiency of GCRPS-transplanting as compared to traditional paddy rice; (ii) to identify whether irrigation water supply might be further reduced in GCRPS-transplanting after middle tillering stage without reduction in crop yield.

2. Materials and methods

2.1. Site descriptions

A field experiment was conducted at a farm (32°07′N, 110°43′E, and 440 m ASL) in Fangxian County of Hubei Province, China during the rice growing season (late April–September) in 2012 and 2013. The soil at the experimental site was a silt loam with a texture of 20.3% sand (0.05–2 mm), 60.0% silt (0.002–0.05 mm) and 19.8% clay (<0.002 mm) and in the 0–20 cm depth layer it had 21.3 g organic matter kg^{-1} and 1.31 g total N kg^{-1}. The mountainous region of Fangxian County is exposed to northern subtropical monsoon climate, with an annual mean air temperature of 14.2 °C and an annual average rainfall of 830 mm. The total annual sunshine hours are 1850 ± 150 h and the frost-free period lasts 225 ± 15 days. During the growth period, weather data were collected at a meteorological station (WeatherHawk 500, Campbell Scientific, USA) 30 m away from the center of experimental site. Weekly averages of air temperature and rainfall are shown in Fig. 1.

2.2. Experimental design and field management

This field experiment was composed of nine experimental treatments (consisting of three rice production systems combined with three N treatments) arranged in a randomized block design, and replicated thrice. The three production systems were: (1) Paddy, the traditional paddy rice production system, in which fields were flood-irrigated to maintain a 3-cm water layer from transplanting until two weeks before harvest. For water level control five graduated poles were fixed at each plot until two weeks before harvest.