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Do water-saving ground cover rice production systems increase grain yields at regional scales?

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ABSTRACT

"Ground cover rice production system" (GCRPS) is an innovative production technique that uses significantly less water than traditional paddy cultivation (Paddy). Consequently, this system may allow for expansion of rice crops to regions with limited water availability. Earlier studies have reported contradictory grain yields and yield performances of GCRPS versus Paddy systems in experimental plots. However, the actual effects of using GCRPS on yields under real farming practices on heterogeneous environments are still unknown. In this study, we compared grain yields and yield components between GCRPS and Paddy systems by sampling paired adjacent farmer fields at 36 representative sites in the region of Shiyan, central China, which is typical for many mountainous areas across China. Furthermore, we characterized soil physico-chemical properties, soil redox potential, stable carbon isotopic composition of plant leaves, and monitored soil temperature during the growing season.

Our study revealed the following findings: (1) Across all sites GCRPS significantly increased grain yield by on average 18%. Statistical analysis allowed us to classify three different groups of yield performance within the 36 paired sites: (a) group of significant increase (SI; $n = 22$) with increases in yields on average 32%, (b) group showing no significant increase (NI; $n = 9$), here yields increased on average 6%, and (c) sites with grain yields showing a small (−8%), but non significant decrease (ND; $n = 5$). (2) Shoot dry biomass, number of productive tillers, spikelets per square meter and percentage of filled grains were significantly larger for GCRPS as compared to Paddy systems. (3) No significant differences in soil physical and chemical properties were found for the 0–20 cm layer between GCRPS and Paddy systems. (4) Significantly higher soil temperatures observed in GCRPS during the first month after transplanting were only found in the SI sites, which showed that higher temperature during this critical period was the decisive factor for GCRPS-induced yield enhancement. (5) The average $\delta^{13}C$ of plant leaves and soil redox potential were significantly higher in GCRPS than Paddy for the SI group only. In-detail analyses of the 5 pairs showing decreases in yields (ND) between GCRPS and Paddy systems revealed the lack of significant effects observed in some key parameters such as soil temperatures during the first month, $\delta^{13}C$ of plant leaves and soil redox potential. These facts strongly suggested that unnecessary excess water was used, thus hampering GCRPS-induced increases in soil temperature and grain yields, and unequivocally signaling that appropriate water management by farmers is crucial for the successful implementation of GCRPS. Our study demonstrates the large potential of GCRPS to increase grain yields in regions where rice growth is both limited by low temperatures and water scarcity.

1. Introduction

Rice is arguably the most important staple food for almost half the world's population, representing about 20% of its overall energy intake (IRRI, 2007). Recent estimates calculate that 79 million hectares of irrigated lowland rice fields produce about 75% of the world's rice (Maclean et al., 2002; Qin et al., 2006), which

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represents 24–30% of the world's freshwater resources used for irrigation (Bouman et al., 2006). It is estimated that an annual increase in rice production by 8–10 million t is needed over the next 20 years in order to meet forecasted needs (IRRI, 2011). Furthermore, it is anticipated that 15–20 million ha of irrigated rice will suffer from water scarcity by 2025 due to increasing population growth and associated water demands for urban and industrial use (Tuong and Bouman, 2003; Belder et al., 2005; Bouman, 2007).

China is the world's largest rice producer with 197 million t of paddy rice, a figure that accounts for 35% of global rice production. To meet current national demands, an area of 29 million ha is currently under rice cultivation, consuming about 70% of its total agricultural water resources (FAOSTAT, 2011). Increasing water scarcity has the potential to further exacerbate conflicts on water resources over the coming decades, especially in the middle and northern part of China (Abdulai et al., 2005; Yong, 2009). At current levels of water usage, the total water shortage is estimated to be 30–40 billion m^3 $year^{-1}$ and may be even larger in dry years (MWR, 2007). By 2050, China's total water deficit could reach 400 billion m^3, which roughly represents 80% of the current annual capacity (Tso, 2004). Moreover, both the poor quantity and quality of water resources threatens not only economic development and quality of life, but it is also exerting a negative impact on food security (Yong, 2009).

In order to meet unprecedented challenges in rice production derived from severe deficits in water resources, a number of water-saving technologies have been proposed worldwide. One of these technologies is the ground cover rice production system (GCRPS, Shen et al., 1997; Lin et al., 2002). The GCRPS was developed in 1990 by the Agricultural Bureau of Shiyan (Central China) and it has been constantly expanding in the Shiyan region ever since (Shen et al., 1997). In this cultivation system, soil surface is covered with a 5–7 μm thick plastic film, traditional lowland rice cultivars are used and grown at soil water saturation with no standing water layer during the entire growth period (Qu et al., 2012). The proposed advantages provided this technique are numerous and include the following: (i) The adoption of GCRPS in water deficit and cool mountainous regions could preserve heat and effectively alleviate low-temperature stress on early growth stage after transplantation (Shen et al., 1997; Qu et al., 2012); (ii) GCRPS can save water through improved water use efficiency by means of reduced evaporation and seepage during the growing season. Previous research has reported that GCRPS water use efficiency yields up to 0.8–1.0 kg grain m^{-3} water (Tao et al., 2006), whereas in conventional Paddy systems water use efficiency is on average 0.4 kg grain m^{-3} (Tuong et al., 2005); (iii) This technique could minimize environmental pollution due to herbicide application because plastic film largely prevents weed germination and development (Peng et al., 1999; Wu et al., 1999).

While there are obvious advantages associated with the adoption of GCRPS, contradictory yield performances using GCRPS have been reported under different experimental settings (Shen et al., 1997; Tao et al., 2006; Yang and Zhang, 2010; Qu et al., 2012). GCRPS has shown similar or even reduced grain yields compared with the traditional flooded paddy system in areas where water and temperature were not limiting factors for crop growth (Liang et al., 1999; Wu et al., 1999) and also in a study conducted on markedly sandy soils (Tao et al., 2006). On the other hand, and compared to Paddy systems, grain yield increases have been observed using GCRPS in areas where seasonal water shortage and low-temperature during early growth stages were the main restricting factors (Shen et al., 1997; Jin et al., 2002; Liu et al., 2009; Qu et al., 2012). However, a better and more comprehensive understanding of the effects of GCRPS on yields and yield components is currently hampered by the limited experimental design of earlier work. These studies report findings from a small number of experimental fields that do not account for the impacts of GCRPS on yields under actual farming practices at regional scales. Therefore, the goals of this study were: (i) to evaluate the grain yield and yield components of GCRPS at the regional scale in Central China; (ii) to identify environmental and management factors determining the success of GCRPS application at regional scale under real farming practices.

2. Materials and methods

2.1. Sampling region characteristics

The study was situated in region of Shiyan, Hubei province, central China (32°02′ to 33°10′ N, 109°44′ to 111°04′ E, see Table A1), where GCRPS was introduced at the end of the last century (Shen et al., 1997; Liang et al., 1999). Shiyan is located in the QinBaShan Mountains with peaks reaching a maximum altitude of 2740 m a.s.l. According to Smit and Cai (1996) this area is in the northern subtropical agro-climatic zone of China's eastern monsoon region. In most of these mountainous regions rice growth is limited by both low temperatures at the start of the growing season, and severe seasonal and regional water scarcity (Shen et al., 1997). Specifically, spring drought periods can cause severe reductions in forecasted yields and may affect – as it was the case in the year 2011 – the date of rice transplanting and overall crop growth. The annual average temperature of the study region is 15.3 °C and total average annual rainfall is 829 mm (average calculated for the 1961–2009 period from seven meteorological stations located in the respective counties of Shiyan (Zhou et al., 2008). Annual rainfall shows a pronounced seasonality, with approximately 45% of the rainfall occurring during the summer period (June to August). The total sunshine hours per year are 1835. Given that GCRPS has only been introduced two decades ago and this growing technique has implications for farming activities, labor demand and costs, GCRPS and traditional lowland rice cultivation are often spatially interwoven, i.e. some farmers have adopted the technique while others have not (Zhou et al., 2008). However, in most cases the adoption of GCRPS by individual farmers is well documented by the local administration so that for the selected sites and fields it was possible to trace specific land management records.

2.2. Site and field selection

Site selection was performed by experienced staff members from the local Agricultural Bureau in Shiyan, with specific attention being paid to cover different rice growing areas at varying altitudes, on contrasting soil types and over a range of time spans since adoption of the GCRPS technique. The latter information, as well as data on fertilization regimes and soil and crop management, was obtained through interviews to farmers. A total of 49 sites with paired treatments consisting of GCRPS versus permanent flooding paddy fields (hereafter referred to as GCRPS and Paddy) were selected for soil-plant sampling and for in situ field measurements. The distance between the paired plots were in most cases less than 100 m with only 9 out of 49 sites being more than 250 m apart (Table A1). Geographical coordinates of the sites and fields were recorded by GPS (Garmin Colorado 300) and altitudes were obtained using the Global Digital Elevation Model (GDEM) provided by NASA and METI (2008).

2.3. Production management of Paddy and GCRPS

Traditional Paddy systems imply that rice seeds are sown and raised in external nurseries for one month before being transplanted to the fields. Fields get ploughed puddled and leveled while flooded. Based on the survey conducted to individual farmers,