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Research paper

Yield differences get large with ascendant altitude between traditional paddy and water-saving ground cover rice production system

Lin Guo[a,c,1], Meiju Liu[b,1], Yanan Zhang[a], Yueyue Tao[a,c], Fan Zhang[a], Guoyuan Li[d], Klaus Dittert[c], Shan Lin[a,d,*]

[a] College of Resources and Environmental Sciences, China Agricultural University, Beijing 100193, China
[b] College of Resources and Environmental Sciences, Yunnan China Agricultural University, Kunming 650100, China
[c] Department of Crop Science, Section of Plant Nutrition and Crop Physiology, Faculty of Agriculture, University of Göettingen, 37075 Göettingen, Germany
[d] College of Life Science and Technology, Hubei Engineering University, Hubei 432000, China

A R T I C L E I N F O

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A B S T R A C T

In mountainous regions with high altitude, rice yield is mostly limited by low temperatures and insufficient irrigation facilities. The innovative ground cover rice production system (GCRPS) has a recognised potential to significantly increase rice grain yield where rice production is limited by water scarcity and low temperatures. We hypothesised that yield advantage of GCRPS over traditional Paddy might become larger at higher altitudes. We sampled 14 pairs of adjacent GCRPS and Paddy fields at altitudes of 900 m and 23 pairs at 500 m altitude with 3 replicates in central China.

The study revealed that Badano et al. (2005) grain and straw yield were 40% and 35% greater in GCRPS compared to Paddy at 900 m, while the difference was only 10% and 15% at 500 m Bennie et al. (2006). Compared to Paddy, increase in productive tiller numbers, spikelets per square metre and percentage of filled grains were significantly larger in GCRPS at high than at low altitude Bennie et al. (2008). Soil temperature differences between GCRPS and Paddy were significantly higher at 900 m than at 500 m during the first month after transplanting. Our findings demonstrate that GCRPS has a good potential to increase rice yield in mountain regions with high altitudes where rice production is limited by low temperature and seasonal water shortage.

1. Introduction

Rice, one of the most important crops in the world, feeds 50% of the world population and an annual increase of 8–10 million tons in rice production will be required to meet future needs (IRRI, 2011). However, in large regions, traditional paddy rice cultivation consumes 3–5 times more water than typical upland crops such as wheat and maize (Pimentel et al., 1997; Bouman et al., 2007). By 2025, it is predicted that 15–20 million ha of rice worldwide will likely suffer from drought stress due to water scarcity (Belder et al., 2005; Bouman, 2007). Water scarcity has become a serious problem especially in the intensive rice production area. Rice production and irrigation are challenged by the rapidly rising demand for rice due to the population growth, enhanced level of development, loss of cropping area for other types of land-use and the increase in competing demands for water by industries and the private sector. China is the world's largest rice producer, accounting for 35% of total world's rice production with a planting area of 29 million ha and at present, paddy rice consumes about 70% of its total agricultural water resources in China (Bouman et al., 2007; FAOSTAT, 2011). The water resource per capita is only one fourth of the world average level and its seasonal and spatial inhomogeneity in available water is also a great constraint to rice production in China (Tso, 2004). Therefore, China has reinforced its search for expanding and intensifying rice cultivation in regions which were formerly of only marginal importance with new innovative water-saving technologies of rice production (Lin et al., 2002; Tao et al., 2006).

Several alternatives of water-saving rice cultivation have been proposed worldwide. One of these, the so-called ground cover rice production system (GCRPS; Lin et al., 2002) can significantly save large amounts of irrigation water (Tao et al., 2015; Jin et al., 2016a,b), reduce greenhouse gas emission (Dittert et al., 2002; Yao et al., 2012; Yao et al., 2014) and increase soil organic carbon and nitrogen stocks at the regional scale (Liu et al., 2015). In addition, GCRPS saves herbicide usage and labor cost due to the remarkable efficiency in inhibiting weed growth under the polyethylene coverage (Shen et al., 1997). It has often been confirmed that GCRPS combined with rice seedling transplanting

* Corresponding author at: College of Resources and Environmental Sciences, China Agricultural University, Beijing 100193, China.
E-mail address: linshan@cau.edu.cn (S. Lin).
[1] These authors contributed equally to this work.

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can significantly increase rice grain yield, especially in cold (Liu et al., 2014) or in mountainous regions (Qu et al., 2012; Liu et al., 2013; Tao et al., 2014) where grain yield is limited by seasonal water shortage and/or low temperature stress in early spring. GCRPS was shown to greatly increase tiller numbers due to higher soil temperatures before the maximum tillering stage (Tao et al., 2006; Liu et al., 2013; Tao et al., 2015). However on the contrary, GCRPS fails to increase grain yield or even results in yield reduction in tropical and subtropical regions where there is no obvious water shortage or temperature limitation for rice growth (Liang et al., 1999; Fan et al., 2002). Moreover, a regional assessment at the household level indicated that GCRPS did not significantly increase grain yield of all farmers, whose yield largely depends on inappropriate water management of individual farmers (Liu et al., 2013). The study implies that the effect of GCRPS on grain yield is greatly associated with local climate conditions, namely air temperature, precipitation and field management. However, little is known on whether GCRPS has positive effects on rice grain yield with ascendant altitudes in mountainous areas.

Rice production in mountainous area accounts for about 10% of the entire rice planting area in China, where the highest fields attain 2650 m (Tan et al., 2009; IRRI, http://irri.org). The average grain yield is lower in mountainous areas than the national level (Li et al., 2013) and the main limiting factor for rice grain yield is seasonal water scarcity caused by insufficient irrigation infrastructure and low temperatures. Meanwhile, low temperature stress is a more obvious and detrimental factor for rice production in high altitude regions (Liu et al., 2013; 2014), which seriously limits rice growth at initial rice growing stage (Shen et al., 1997). Altitude strongly influences microclimate, including air temperature, precipitation and evaporation (Bennie et al., 2008). A shift of 500 m in altitude has been reported to reduce the mean air temperature by about 3 °C (Bennie et al., 2006). Therefore, altitude greatly affects plant performance such photosynthesis and growth duration (Badano et al., 2005) but also soil properties (Casals et al., 1995; Kölbl et al., 2011). Low temperatures at high altitudes especially lead to greatly inhibited vegetative development in early growth stages and limit the translocation of assimilates into the grain during the reproductive stage (Yang and Zhang, 2010). Thus it has often been observed that the numbers of productive tillers and grain filling are reduced at high altitudes compared to lower regions (Tan et al., 2009; Li et al., 2013). However, only little information is available on how to improve rice yield in higher altitude regions which suffer from seasonal water shortage and low temperatures.

Our hypotheses are: 1) rice grain yield advantage of GCRPS over traditional Paddy gets greater at high altitude compared to lower altitude which can be explained by increase of yield determined components like productive tillers, spikelets and filled-grain percentage; 2) with GCRPS, soil temperature increase over Paddy is greater at high than at low altitude.

2. Materials and methods

GCRPS was first put into practice at the end of 20th century at this sampling sites (Shen et al., 1997; Liu et al., 2013). The county is located in Central China tropical monsoon climate zone with sufficient sunshine duration of less than 1500 h in the whole year. Even with averagely 1000 mm per year, it often results in severe seasonal water scarcity due to inhomogeneous rainfall and insufficient irrigation facility (Shen et al., 1997). The clear advantages of GCRPS as compared to conventional lowland rice production system have led to a further promotion of GCRPS. The air temperature is relatively low in early spring, which seriously limits rice growth at initial rice growing stage (Liu et al., 2013). The large altitude gap of this mountainous area made it possible to find available sampling sites at different altitudes since the maximum altitude is 2740 m a.s.l. in southwest and minimum is 276 m a.s.l. in northeast. However, most rice were cultivated at three altitudes levels, namely < 250 m, around 500 m and 1000 m. Due to the insufficient water supply and low temperature at 500 m and 1000 m, GCRPS technique was adopted by individual farmers. Nevertheless, not all farmers have introduced GCRPS since it adds field work as well as costs (e.g. buying of coverage foliage) so that both systems can be found in direct vicinity on fields owned by different farmers or even the same family.

2.1. Selection of study sites

To avoid spatial heterogeneity in soil types and precipitation, two criteria were defined for the selection of fields in various areas: i) relative large difference on altitudes with less space distance for assessment of altitude effects and ii) adjacent pairs of GCRPS and Paddy fields for assessment of cultivation system effects. Two sites with altitude of c. 900 m and c. 500 m were chosen along the same valley at the beginning of May 2014 at Zhuxi County (31°32′ to 32°31′N, 109°29′ to 110°08′E), Hubei Province in mountainous areas of central China. As preparation, information was collected on topography, geology, soil type and land use from Shiyan Agricultural Bureau. Experienced staff, who have been working with close interaction with the local farmers in the individual villages since more than 20 years, provided us with valuable information on land use history. Then, potentially suitable adjacent paired sites of GCRPS and Paddy managed by individual farmers were visited. Information on agronomic parametres (e. g., transplanting data, rice cultivar, fertilisation and irrigation scheme) provided by the local extension staff was compared with those collected from individual farmer interviews.

Based on the above-mentioned preparation, totally 23 adjacent paired of GCRPS and Paddy fields at 500 m in Zhongfeng Town (32°19′N, 109°41′E) and 14 pairs at 900 m in Quanxi Town (32°14′N, 109°43′E) were selected and identified (Table S1). The distance between adjacent GCRPS and Paddy fields was less than 500 m. Geological information, namely precise altitude, longitude and latitude were recorded by a GPS (Garmin Colorado 300). The main important information is available in supporting Table S1. Data on daily rainfall and air temperature was collected from metrological station located 2 km from the sampling sites.

2.2. Field management

The fields got ploughed and flooded 3–5 days, and then puddled and leveled before transplanting (Tao et al., 2015). Rice seeds were sown and raised in external nurseries in small plastic arch canopy. One month later, rice seedling with 4 leaves were transplanted to fields. The date of transplanting is 12nd May for both GCRPS and Paddy at altitude 500 m, while it is ten days later on 22th May 2014 at altitude 900 m. Two rice cultivars Yixiang 725 and 3728 were used with similar plant density for GCRPS (27 ± 0.3 cm * 23 ± 0.6 cm, n = 69) and Paddy (26 ± 0.5 cm * 25 ± 0.8 cm, n = 69) at altitude 500 m, while other cultivars Mingyou No.6 and Teyou806, which is of relatively short growth duration were used with similar plant density for both GCRPS (22 ± 0.1 cm * 17 ± 0.3 cm, n = 42) and Paddy (23 ± 0.9 cm * 19 ± 0.5 cm, n = 42) at altitude 900 m (Table S1). To avoid cultivar mix effect on our proposals, the paired GCRPS and Paddy must have the same cultivar. After transplanting, 74 calibrated temperature sensors with integrated logger (EBI-20T, Ebro Instruments, Germany) were installed at the soil depth of 5 cm for all selected GCRPS and Paddy fields. The hourly soil temperature was recorded during the whole growth season.

For GCRPS, 150 kg N ha^{-1} in which 100 kg N ha^{-1} as compound NPK (22-16-16) fertilizer and 50 kg N ha^{-1} as urea were applied one day before transplanting in single dose and incorporated into soil by plowing. Due to the difficulty for topdressing, all fertilizer was applied as basal fertilization for GCRPS (Qu et al., 2012; Liu et al., 2013). After leveling, GCRPS field was covered with transparent polyethylene film of 5–7 μm thickness and the holes were punched with special hole-