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Ground cover rice production systems are more adaptable in cold regions with high content of soil organic matter

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ABSTRACT

Water-saving ground cover rice production systems (GCRPS) can increase grain yield in mountainous regions with seasonal water shortages and cold, stress-inducing temperatures. For GCRPS the soil surface is covered with a plastic film which can effectively alleviate low-temperature stress in the early growth stage due to thermal insulation. Since topdressing is not possible in GCRPS, farmers usually apply all fertilizer as basal dressing before transplanting; this can lead to excessive growth during the vegetative period and low crop growth during the reproductive stage. However, we hypothesized that the technique might be well suited for marginal rice growing regions in the Northeast of China. These areas are characterized by a short vegetation period and soils rich in organic matter, delivering the required amounts of nitrogen (N) over the course of the season due to N mineralization. Here we report on a two year experiment, conducted in the Northeast of China, that compared grain yields between GCRPS and conventional paddy rice production (paddy) at three N fertilizer rates (0, 90 and 135 kg N ha^{-1}). Furthermore, crop growth rate, apparent nitrogen recovery rate and nitrogen physiological use efficiency were calculated. Compared to paddy, GCRPS significantly increased grain yield by 31%, 14% and 10% at N fertilizer rate of 0, 90 and 135 kg N ha^{-1}, respectively. Grain yield at 135 kg N ha^{-1} was significantly higher than 90 kg N ha^{-1} in paddy, but no difference was found between N fertilizer rates in GCRPS. However, grain yield at 90 kg N ha^{-1} in GCRPS was still higher than that at 135 kg N ha^{-1} in paddy. The considerably higher number of filled grains in GCRPS indicates that crop growth rate during the reproductive stage was improved, likely due to the positive effect of higher mineralization of organic N on crops with a low rate of N fertilization. Our study demonstrates that GCRPS is a very promising and highly suitable technique for rice production in cold regions in the North of China that possess high content of soil organic matter. Moreover, it shows that N fertilization can be minimized due to the autochthonous N supply from soil rich in organic matter. In regards to the decomposition of SOM in GCRPS over time, mutual feedback mechanisms located both above and below ground revealed that the potential loss of SOM stocks can be compensated by a greater input of root biomass in GCRPS.

1. Introduction

Rice, the dominant staple food for more than 50% of the world's population (Qin et al., 2006), is grown on almost 155 million ha of a total world's arable land (http://beta.irri.org/index.php/). China is the world's largest rice producer, which accounts for 43.7% of the total national cereal grain production (Fan et al., 2010). However, the water used in rice production accounts for roughly 70% of China's total agricultural water resources (FAOSTAT, 2011). More than 80% of the irrigation water is lost through evaporation and leakage in traditional paddy rice production systems, revealing a critical need to develop water-saving technology for the future of rice production worldwide.

Ground cover rice production systems (GCRPS) are one of water-saving technology. First introduced and promoted in the mountainous region of Central China roughly two decades ago, (Shen et al., 1997; Lin et al., 2002), the water-saving technique of GCRPS has been demonstrated to increase grain yields and

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water-use efficiency in areas where seasonal water shortages and low temperatures during early growth stages have been limiting factors for rice production (Qu et al., 2012; Liu et al., 2013). The technique also proved successful for varying edaphic conditions under real farming conditions at a regional scale (Liu et al., 2013). However, since the plastic film covers the soil surface, topdressing cannot be applied for GCRPS. Consequently, farmers usually apply all the fertilizer as basal dressing before transplanting, which can lead to excessive growth during the vegetative period (Qu et al., 2012). Nitrogen deficiency can later occur during the reproductive stage due to insufficient N supply from nitrogen fertilizer or the soil mineralization, leading to plant senescence and low crop growth (Tao et al., 2006; Qu et al., 2012). The benefits of GCRPS on crop yield in areas with low temperatures and water shortages have been well documented in the past, but on soils with relatively low content of soil organic matter (SOM); there is limited information about the potential of GCRPS in cold regions with high SOM content. Reduced basal N fertilizer, combined with higher mineralization of SOM, may solve the problem of excessive growth during the vegetative stage followed by lower crop growth during the reproduction stage.

With approximately 70,000 km^2 of black, SOM-rich soil, Heilonjiang province is the most important, representative region of low-temperature, high quality rice production in China (Pan et al., 2003; Li et al., 2011). Currently, the area of conventionally flooded rice cultivation in Heilongjiang province is 2.3 million ha; it is anticipated that this area will increase by 1 million ha by the year 2020. Expansion of the rice growing area is likely due to changes in agricultural structure, e.g. rice farming replacing soybean cultivation (Wang et al., 2009). However, the amount of available water per capita of arable land in Heilongjiang is lower than the average national level National and Bureau of Statistics of China (NBS) (2005). In addition, rice production is adversely affected by cold spells which stunt rice growth during the start of the vegetation period. This often leads to production losses of 25% or more, occasionally resulting in the loss of the entire crop yield (Nie, 2007). Third, the soil organic matter content is approximately 6% on average which is four times higher than the average for all rice growing areas in China (Pan et al., 2003). Because of its increased soil temperatures, GCRPS technology could stimulate soil organic matter mineralization, alleviating N limitations during the reproductive stage.

On a global scale, increased SOM concentrations have been shown to be essential for enhancing the crop productivity of wheat (Bauer and Black, 1994; Kanchikerimath and Singh, 2001), maize (Kanchikerimath and Singh, 2001; Lal, 1981) and cowpea (Lal, 1981). Based on an analysis of data on yearly crop productivity and average SOM contents in mainland China from 1949 to 1998, it has been estimated that, on average, a 1% increase in soil organic matter would result in an increase boost total cereal productivity by 0.43 t ha^{-1} (Pan et al., 2009). Additionally, the mineralization of SOM significantly increases the amount of nutrients required for crop growth (Tiessen et al., 1994), thus helping to ensure greater food security. However, it is important to pay attention to the increased decomposition of soil organic matter in GCRPS fields, which may result in the mining of soil organic matter stocks and potentially contribute to a loss in soil fertility in the future.

Our hypotheses for this study are (1) in cold regions, where low temperatures and scarce water are limiting factors, the use of GCRPS will increase grain yield and efficient N use in soils with high content of SOM; (2) the application of reduced basal N fertilizer can alleviate excessive growth during the vegetative period, while increased mineralization with high SOM may enhance the rate of crop growth during the reproductive stage. To test these hypotheses two-year field experiments were carried out, each with two cultivation systems (GCRPS and paddy) at three rates of N fertilizer in a cold region of rice production that had a high content of SOM. The grain yield, yield components, rate of crop growth, and nitrogen use efficiency were analyzed.

2. Materials and methods

2.1. Site conditions

These experiments were carried out at the Agricultural Technology Extension Center of the 856th state farm (N45°38′, E132°41′, and 85 m a.s.l), located in the lower Muling River basin (Cai and Chen, 2008), Heilongjiang province, Northeast of China. The region has a temperate, continental monsoon climate. According to the 50 year climatic database (1959–2009), the average annual rainfall at this location was 535 mm. Approximately 80% (411 mm) of all annual rainfall occurs during the summer period, which covers the plant growing season from May to late September. The average total hour of sunshine per year is 2080 h, and the average frost-free period is 138 days. During an average year, the daily average temperature after May 10th is typically higher than 10 °C, and the average active accumulated temperature (i.e. if average daily temperature is >10 °C) is 2493 °C. The soil is classified as a meadow albic soil with high content of soil organic matter (Cai and Chen, 2008). The physiochemical properties of soil used in this experiment are summarized in Table 1.

2.2. Experiment design and field management

The experiments were laid out in a two-factorial, split-plot design with four replicates over two years. Water management functioned as differentiating variable between the main plots and nitrogen treatments varying across the subplots. The main plots represented two rice production systems: the traditional paddy rice production system (paddy) and the water-saving ground cover rice production system (GCRPS). Subplots represented nitrogen fertilization rates of 0, 90, and 135 kg N ha^{-1}. Each subplot was 7.5 m wide and 10 m long, and subplots were separated by dams 0.3 m wide and 0.3 m tall. For the convenience of irrigation and field management, each subplot was divided into four raised beds surrounded by ditches 0.3 m wide and 0.2 m deep. Each subplot received 30 kg ha^{-1} of phosphorus as Ca $(H_2PO4)_2$ and 55 kg ha^{-1} of potassium as K_2SO4. For the N90 and N135 treatments, 90 and 135 kg N ha^{-1} was applied as urea.

The field was flooded one week before transplanting; the day before transplanting, the field was ploughed, puddled and leveled. For the GCRPS fields, the soil surface was covered with a 5 μm thick transparent polyethylene plastic film, and holes were punched in the plastic film to allow transplanting of rice seedlings. In paddy, the fields were constantly flooded with about 3–5 cm of water until one month before harvesting. In GCRPS, irrigation ditches surrounding raised beds were filled with 10–15 cm of water to

Table 1
Soil texture (soil clay, silt and sand content), soil organic matter and total nitrogen content at soil depth of 0–20 and 20– 40 cm.

Soil depth	Clay (<0.002 mm)	Silt (0.002–0.05 mm)	Sand (0.05–2.0 mm)	Soil organic matter	Total N content
cm	%	%	%	g –kg^{-1}	g –kg^{-1}
0–20	7.09 ± 0.64	85.8 ± 1.59	7.13 ± 2.24	63.1 ± 1.08	2.99 ± 0.06
20–40	13.7 ± 3.33	78.5 ± 1.20	7.83 ± 2.13	59.0 ± 2.20	2.77 ± 0.03