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Potential to improve N uptake and grain yield in water saving Ground Cover Rice Production System

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A B S T R A C T

The Ground Cover Rice Production System (GCRPS) is a promising technology for water-saving lowland rice cultivation. However, excessive vegetative growth and potential N shortages during reproductive stages might limit the grain yield potential, because all N fertilizer has to be applied before transplanting due to technical difficulties with later applications. A 10-year experiment was conducted, covering two experimental series, to evaluate the effects of controlled-release urea fertilizer and a nitrification inhibitor, as well as effects of combining organic manure and mineral nitrogen fertilizer. In the first experimental period (2003–2006), field trials included four treatments: (1) zero-N; (2) urea alone; (3) urea + nitrification inhibitor; (4) controlled-release urea. In the second period (2007–2012), the first two treatments were continued as before, and treatments 3 and 4 were replaced by either application of chicken manure alone, or a combination of urea and chicken manure.

Compared to applying urea alone, controlled-release urea, or the combination of urea plus organic manure, significantly increased grain yield and nitrogen use efficiency, and enhanced the number of spikelets and the percentage of filled grains due to improved growth in the reproductive phase. Application of urea plus nitrification inhibitor did not enhance grain yield and nitrogen use efficiency because of high nitrogen uptake and biomass production in early growth stages and significantly lower N uptake at the later stages, which consequently also led to low spikelet numbers. Application of organic manure alone significantly decreased above-ground biomass production in early growth stages, and strongly reduced the number of productive tillers, indicating N shortages in the vegetative stage. Our results showed that, considering the present costs of controlled-release urea, the combination of organic manure with mineral N fertilizer is the most practical and most economical N fertilizer management for improving grain yield and nitrogen use efficiency, as well as the sustainability of water-saving GCRPS.

1. Introduction

Rice is the foremost staple food for more than 50% of the world's population. However, rice fields consume large amounts of water since most rice is grown in flooded fields. In Asia, 70% of all irrigation water is used in rice production (Bouman et al., 2007), and freshwater is becoming increasingly scarce because of the rising competition with other sectors like industry and urban consumption, which consequently threatens the sustainability of flood irrigated rice (Peng et al., 2009). Therefore, water-saving techniques for rice production are urgently needed in order to grow more rice with less water.

A promising water-saving rice production technique – the so-called Ground Cover Rice Production System (GCRPS) – was developed in China two decades ago (Shen et al., 1997). There are mainly two versions of cultivation method: (i) GCRPS – direct seeding with a soil humidity of 80–90% of water holding capacity; and (ii) GCRPS – transplanting with moist soil. However, the technique of GCRPS – direct seeding was not used as often in common practice due to several problems, including potential deficiency of the micronutrients manganese and iron, difficulty of weed control, and increased infestation under such conditions (Lin et al., 2002; Tao et al., 2006). The technique of GCRPS – transplanting is the most common and widely used technique in the region, implemented so far on >200,000 ha (Qu et al., 2012; Liu et al., 2013). In this paper,

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we exclusively refer to GCRPS-transplanting. Here, the soil surface is covered with a 5 μm transparent polyethylene plastic film, and young rice seedlings are transplanted into pre-punched holes. The soil water tension is kept close to saturation and there is no standing water layer during the entire growing period. Therefore substantial water savings are achieved by reduced water losses through seepage, percolation and evaporation (Peng et al., 1999). In addition, soil coverage by thin polyethylene sheeting leads to increased soil temperatures in early growth phases, preserves soil moisture and inhibits the growth of weeds, which results in improved grain yield (Shen et al., 1997; Qu et al., 2012). Therefore, in suitable regions, especially in mountainous areas with low spring temperatures and seasonal drought, GCRPS is seen as a very promising new technique to ensure food security and preserve freshwater resources. Typically in GCRPS, traditional lowland rice varieties are used (Liu et al., 2013).

While crop management practices are quite advanced, nitrogen (N) fertilizer management is still challenging (Deng et al., 2006). Since the plastic film covers the soil surface, topdressing cannot be applied for GCRPS. Until recently, all N fertilizer was given in a single basal application, which causes unwanted N loss and contributes to low fertilizer-N use efficiency (Liu et al., 2005). Also in consequence of the high basal N dressing, rice plants show excessive vegetative growth in early spring, resulting in high numbers of tillers and high vegetative biomass production, while during reproductive growth stages growth performance is poor (Qu et al., 2012). Correspondingly, late yield components that develop during the reproductive stage, such as spikelet number and spikelet fertility, showed poor performance (Kamiji et al., 2011). Lower spikelet numbers per panicle and reduced spikelet fertility in GCRPS as compared to conventionally irrigated lowland rice are indicative of N deficiency at later growth stages, which seems to be one of the major restrictions in attaining higher grain yields with this water-saving rice production system (Qu et al., 2012). In traditional flood-irrigated rice, N fertilizer split dressings at panicle initiation or at anthesis are recommended to increase productivity and fertilizer-N recovery efficiency (Zhang et al., 2013).

Application of controlled-release urea, with improved N supply from flowering to maturity, could delay leaf senescence and photosynthesis function decline seen in paddy rice (Nie et al., 2005). The use of controlled-release urea might be a possible way to meet rice crops' N demand in the reproductive growing stage in GCRPS and thus improve its yield potential. However, due to the higher cost of controlled-release urea, its acceptance has so far been quite limited to large-scale promotion programs, especially in small-holder farming. Organic fertilizers, which mainly derive from crop residues, animal waste, or compost based on animal waste, are marked for their mineral nutrient slow-release properties and also for their beneficial effects with respect to soil structure (Naguib, 2011). Therefore, the combination of an organic fertilizer with synthetic urea might be an attractive strategy to be adopted by farmers to balance N supply for optimum rice production as well as decreasing N loss into the environment (Fageria and Baligar, 2003). In addition, the current massive increase in livestock production has brought a substantial increase in the generation of manures in China (Fischer et al., 2010). Therefore, concepts for appropriate use of organic fertilizers that recycle nutrients and organic matter and concepts that decrease their environmental hazards are highly needed as well (Topp et al., 2009).

Lowland rice has developed in flooded soils under anaerobic conditions, therefore it is well adapted to the predominance of ammonium nitrogen in soil rather than to nitrate. In hydroponic experiments, significantly higher shoot biomass was observed under ammonium-only than nitrate-only nutrition at seedling and tillering stages (Lin et al., 2005). Moreover, ammonium nutrition can increase photosynthesis rate, leaf area and water uptake in early growth stages under water-stressed conditions (Guo et al., 2007; Gao et al., 2010). However, it has also been reported that partial nitrate nutrition led to faster biomass accumulation at later growth stages because of higher Rubisco contents in rice leaves (Zhang et al., 2011). The shift from flooded conditions in traditional paddy cultivation to GCRPS without a standing water layer results in higher soil redox potential and influences the nutrient form and availability (Tao et al., 2007). With the increase in redox potential, ammonium that is present in flooded paddy soil is oxidized to nitrate, resulting in nitrate being abundant in high concentrations. The question of whether lowland rice variety plants are able to adapt to these changes in their growth environment is still open, and consequently, another important question is whether the yield performance of rice plants in GCRPS is better when ammonium nitrogen is stabilized by the use of a nitrification inhibitor.

Previous studies on GCRPS mostly focused on comparisons with traditional paddy rice. Until now, there are almost no studies in the optimization of nitrogen nutrition in GCRPS. To improve grain yield and increase resource use efficiency, appropriate nitrogen management is urgently needed. It was the aim of the present study to evaluate controlled-release urea, nitrification inhibitor-stabilized ammonium and/or organic fertilizer use in water-saving GCRPS in two experimental periods covering a total of 10 years. The objectives were: (1) to identify whether N deficiency during the reproductive growth stage is the limiting factor of grain yield by using urea alone in GCRPS; (2) evaluate whether improved N management could increase grain yield and N use efficiency in GCRPS, through balanced N uptake during the vegetative and reproductive stages, by using controlled-release urea or organic fertilizer plus urea.

Table 1
Chemical and physical properties of the soil (0–20 cm depth) at the experimental field site.

Properties		Mean	S.D.
Organic matter	$g\,kg^{-1}$	14.9	1.6
Total N	$g\,kg^{-1}$	0.83	0.01
Total P	$mg\,kg^{-1}$	271.8	20.4
Available P-Olsen	$mg\,kg^{-1}$	4.09	0.59
Available K	$mg\,kg^{-1}$	138.7	9.43
Sand, 2000–50 μm	%	38.9	2.7
Silt, 50–2 μm	%	59.5	2.7
Clay, <2 μm	%	1.6	0.2
pH	–	6.2	0.1

Soil samples were taken 2 days after harvest in 2004.

2. Materials and methods

A field experiment was conducted close to Shiyan (32°38′ N, 110°37′ E, and 234 m asl), Hubei province, China. The main physical and chemical soil properties are given in Table 1. In September 2004, soil samples were collected at the 0–20 cm depth with a soil auger (3.5 cm diameter) from five individual locations in each plot and then mixed together as one replicate. Soil organic C and total N content were determined by Walkley–Black and the Kjeldahl digestion methods, respectively (Keeney, 1982; Nelson and Sommers, 1982). Soil total P content was measured colorimetrically with Kjeldahl digests. Soil water-soluble P was determined by the Olsen method (Olsen et al., 1954). Soil available K was extracted with 1 M NH_4OAC (pH = 7) and analyzed by a flamed photometer. Soil texture was determined using the pipette method (Gee and Bauder, 1986). Soil pH was measured in 1:2.5 soil-water solution using a combined electrode pH meter (HI 98121, Hanna Instruments, Kehl am Rhein, Germany). The weather data during the growth period was collected at a meteorological station. Average monthly rainfall and daily temperature are summarized in Fig. 1.