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Substitution of fertilizer-N by green manure improves the sustainability of yield in double-rice cropping system in south China

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ABSTRACT

Rice–rice rotation is the most important intensive cropping system for food security in China. So far, few studies have examined sustainability of double-rice cropping system using partial substitution of fertilizer N (FN) by green manure (GM). The effects of 100% FN (N_{100}) and different substitution rates of FN by GM (80%, 60%, 40% and 20% FN plus 20%, 40%, 60% and 80% N through GM, and represented respectively by $N_{80}M_{20}$, $N_{60}M_{40}$, $N_{40}M_{60}$ and $N_{20}M_{80}$) on the rice productivity and N-supplying capacity of paddy soil were evaluated in double-rice system from 2008 to 2013. Soil organic matter and total N content in the 0–15 cm layer and rice grain yield of early and late rice annually increased in $N_{80}M_{20}$ and $N_{60}M_{40}$ plots, but decreased in N_{100}, $N_{40}M_{60}$ and $N_{20}M_{80}$ plots. Compared with N_{100} plots, the NH_4^+-N content and agronomic efficiency of applied N significantly increased in $N_{80}M_{20}$ and $N_{60}M_{40}$ plots. The grain yield and sustainable yield index of rice crops were improved in $N_{80}M_{20}$ and $N_{60}M_{40}$ plots, while declined in $N_{40}M_{60}$ and $N_{20}M_{80}$. Soil NO_3^--N content decreased significantly under partial substitutions of GM for FN. It can be concluded that the appropriate substitution of GM for FN (e.g., 20–40%) is beneficial for improving the productivity and sustainability of paddy field under double-rice cropping system.

1. Introduction

China is one of the largest rice producers in the world, which occupied 18.7% of global rice growing area and contributed 8.7% of production in 2012 (FAOSTAT, 2013). As its population grows, China will need to produce ~20% more rice by 2030 in order to meet the domestic need, if rice consumption per capita stays at the current level (Peng et al., 2009). Although rice yield has been significantly increased during the past decades due to injudicious use of fertilizer N (FN), N-use efficiency has decreased which also led to greater soil NO_3^--N content over time. This over-fertilization of FN has not only resulted in wastage of a valuable chemical input but has also led to deteriorated soil, water and atmospheric quality (Melero et al., 2006; Liu et al., 2013a). The degraded soil quality due to increased soil acidification and structural damage, and decreased water table level, has thus already started negative effects on rice yield (Guo et al., 2010; Liu et al., 2013b).

Legumes as GMs can fix atmospheric N with rhizobia (Hargrove, 1986). Studies have shown that GM can effectively reduce the species, density and population of weeds in early season rice fields (Krishnan et al., 1998; Norsworthy et al., 2005). Likewise, GM improves soil physical and biological properties (e.g., urease activity and microbial biomass), enhances soil carbon and N cycling (Tejada et al., 2008; Lee et al., 2010; Piotrowska and Wilczewski, 2012). Growing legume as GM crop such as Chinese milk vetch (*Astragalus sinicus* L.) in paddy fields can fully exploit the natural resources (e.g., light, water and heat) during the winter period and also improve rice yield at a minimum environmental and economic cost (Crews and Peoples, 2004; Voisin et al., 2014).

A combination of FN and GM can not only increase soil organic matter (SOM) and total N contents (Bedadaa et al., 2014), but also improves the activity of arbuscular mycorrhizal fungi, the population and activity of extra-radical hyphae, and the structure,

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population and activity of soil microbial communities in the rhizosphere (Zhang et al., 2012; Bedini et al., 2013). Additionally, the proportion of water-stable macro-aggregates goes up in the topsoil, while the ability of soil microbes to mineralize organic N, thus can increase the N-supplying capacity and productivity of soil (Liu et al., 2013c; Mohanty et al., 2013; Kumar et al., 2014). However, it does not imply that the substitution rate of GM for FN could be as high as possible. Excessive or sole application of GM exhibits a negative impact on rice yield (Dawe et al., 2003; Thorup-Kristensen et al., 2012), and the optimum substitution rate of GM for FN varies depending on crop species, soil type and soil fertility (Yadav et al., 2000a).

Using GM as an alternative to FN can reduce rice production cost and environmental degradation (Tejada et al., 2008). Previous studies have mainly investigated the effects of GM on rice production in monoculture or over a short term (Ashraf et al., 2004; Zhao et al., 2015) however; the influence of GM on the sustainability of rice productivity is not fully understood. Especially, no continuous studies have evaluated the sustainability of N-supplying capacity and productivity of paddy soil in double-rice cropping system with partial substitution of GM for FN.

The present study was aimed at: 1) evaluating the effect of different substitution rates of GM for FN on the continuous status of soil N-supplying capacity in double-rice cropping system, and 2) exploring the sustainability of double-rice productivity under different substitution rates of GM for FN over six consecutive years. The results are of guiding significance in maintaining sustainability of soil productivity in double-rice cropping systems in south China, and the study also provides a reference for reducing N loss and the associated environmental risks in paddy fields.

2. Materials and methods

2.1. Experimental site, soil and climate

The study was conducted at an experimental station managed by National Engineering and Technology Research Center for Red Soil Improvement in Fengcheng, Jiangxi Province, China (N28°07′, E115°56′ and altitude 25.4 m). The experimental site has a subtropical monsoon climate, characterized by heavy rain from April to June and seasonal drought from September to December. The average annual temperature is 17.7 °C and the accumulated temperature greater than 10 °C is 5581.9 °C. The average annual rainfall is 1552.1 mm. The annual sunshine is 1935.7 h, with an average total radiation of 4637.9 MJ m^{-2}. The average frost-free period lasts for 274 days. The average monthly temperature (°C) and total monthly precipitation (mm) at the experimental site from 2008 to 2013 are shown in Fig. 1.

The soil is silt–clay derived from quaternary red soil. The initial soil chemical properties of 0–15 cm soil layer are as follows: soil organic matter (SOM) 29.4 g kg^{-1}, total N (TN) 3.06 g kg^{-1}, total P 0.36 g kg^{-1}, total K 35.2 g kg^{-1}, available N 178.2 mg kg^{-1}, available P 5.4 mg kg^{-1}, available K 62.0 mg kg^{-1}, and pH 5.02 (1:1 soil/water).

2.2. Crop management and experimental design

The experiment was conducted for six consecutive years (2008–2013). Early rice (cv. Zhuliangyou 35 bred by China National Rice Research Institute) was transplanted in the first week of May and harvested in the mid-July. Late rice (cv. IIyou 305 bred by Jiangxi Seed Company, Longping High Tech.) was transplanted in the last week of July and harvested in the last week of October. Rice seedlings (25-days-old for early rice and 30-days-old for late rice) were transplanted at the spacing of 16.5 cm × 20.0 cm (early rice) or 22.0 cm × 15.5 cm (late rice).

The experiment included six treatments arranged in a randomized complete block design with three replications: control (no FN or GM); 100% FN (N_{100}); 80% FN plus 20% GM ($N_{80}M_{20}$); 60% FN plus 40% GM ($N_{60}M_{40}$); 40% FN plus 60% GM ($N_{40}M_{60}$); 20% FN plus 80% GM ($N_{20}M_{80}$). Experimental plots with an area of 20 m^2 (4 m × 5 m) each were separated by a ridge (0.5 m wide and 15 cm aboveground) to prevent the movement of water and nutrients between plots.

The recommended rates of chemical fertilizers to rice in Central China are: 150 kg ha^{-1} N (urea 46.4% N), 75 kg ha^{-1} P (super phosphate 12.0% P_2O_5) and 120 kg ha^{-1} K (potassium chloride 60% K_2O) for early rice; and 180 kg ha^{-1} N, 75 kg ha^{-1} P and 150 kg ha^{-1} K for late rice. For urea application, 40% urea was broadcasted as basal application, 30% top-dressed at the tillering stage, and another 30% was top-dressed at the panicle initiation stage. Basal P and K fertilizers were consistently applied at the recommended rates.

Chinese milk vetch (*A. sinicus* L. var. Fengchengqinggan, CMV) which contained 25.4 g N kg^{-1} and was having a moisture content of 90.5%, was directly seeded without tillage 20 days before the harvest of late rice from the experimental plots during the winter season (except the control and N_{100} treatments). Fresh vetch was harvested and measured sequentially every year at the full-bloom stage. The fresh vetch straw was applied at the rate of 12.4 × 10^3, 24.9 × 10^3, 37.3 × 10^3 and 49.7 × 10^3 kg ha^{-1} as equal substitutions of 20%, 40%, 60% and 80% FN for the following early rice respectively, 5 days prior to early rice transplanting, mixed mechanically within 15 cm depth of surface soil, and then flooded up to 5–7 cm depth. The applied amounts of CMV depended on the yields in each plot during every year. All N treatments were fertilized with the same amount of N which was either from FN alone or both from GM and FN. Rice straw was removed from the plots after harvesting a quarter of the rice field.

2.3. Sampling and chemical analysis

Each year composite soil samples from five randomly selected locations in each plot were collected from the upper horizon (0–15 cm) after late rice harvest. Samples were obtained using a soil auger (3.8 cm in diameter), air dried, crushed to pass through a 0.25-mm sieve, labeled and then stored in plastic bags. SOM was determined by wet digestion (120 °C, 2 h) using potassium dichromate along with a mixture of H_2SO_4 and 85% H_3PO_4 (3:2, v/v) (Snyder and Trofymow, 1984). Pre-treatment of soil with 3 ml of 1 N HCl g^{-1} was carried out to remove carbonate and bicarbonate. Mineral N (including ammonium, NH_4^+ and nitrate, NO_3^-) was extracted with 2 M KCl at a 5:1 ratio (KCl:soil, v/v) (Keeney and Nelson, 1982). Filtrate concentrations of NH_4^+ and NO_3^- were analyzed with a discrete auto analyzer (SmartChem TM200, USA). Total N was determined by sulfuric acid digestion and Kjeldahl distillation (Lu, 2000).

At physiological maturity, grains were separated from straw using a plot thresher for double rice crops in the whole plot every year. The grains were sun-dried and weighed separately to obtain the annual yield.

2.4. Statistical analysis

The minimum guaranteed yield that could be obtained relative to the maximum observed yield over the years of double-rice cropping system was quantified through the sustainable yield index (SYI). The SYI was calculated as follows (Singh et al., 1990):

$$\mathrm{SYI} = \frac{\overline{Y} - \sigma_{n-1}}{Y_{\max}} \quad (1)$$