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Responses of rice yield and the fate of fertilizer nitrogen to soil organic carbon

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ABSTRACT

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Soil organic carbon (SOC) plays a critical role in rice production, but its feedback to the fate of fertilizer nitrogen (N) is not clear. In this study, a pot experiment was conducted to investigate the responses of rice yield and the fate of fertilizer N to different SOC levels using ^{15}N-labelled urea. The results showed that rice biomass, yield and the total N uptake increased significantly with increasing SOC content. Both rice N uptake from soil and urea increased significantly with increasing SOC content. The recovery rate and residual rate of fertilizer N improved significantly with increasing SOC content, leading to a reduced rate of not-specified fertilizer N. Therefore, it was concluded that high SOC could not only improve rice yield and fertilizer N recovery, but also could increase the retention of fertilizer N and decrease the not-specified N in the paddy soil.

Keywords: *Oryza sativa*; isotope tracing; soil fertility; fertilization; flooded rice system; macronutrient

Rice is the staple food crop for more than 50% of the world's population (Nachimuthu et al. 2015); therefore, increased rice production is needed to meet the food demands of the rapidly expanding population (Liu et al. 2016). However, the rice yield is stagnating in major rice-cropping systems, especially in China (Ray et al. 2012). Declining soil fertility may be one of the most important reasons for this yield stagnation (Bennett et al. 2012). Therefore, improving soil fertility, especially soil organic carbon (SOC) content (Pospíšilová et al. 2011), has an important role in maintaining a sustainable increase in rice yield (Liu et al. 2014, Espe et al. 2015, Murphy 2015, Zhao et al. 2016).

Although a large body of research has documented that increases in SOC content mainly through organic amendments (e.g., green manure, manure and crop residues) could improve soil fertility and crop yield (Liu et al. 2014, Tian et al. 2015, Zhang et al. 2016), relatively few studies have focused on the feedback of SOC content to the fate of fertilizer nitrogen (N) (i.e., N uptake by crops, residue in soil, or loss to the environment) (Liang et al. 2013, Oelofse et al. 2015, Plošek et al. 2017). To increase rice yield, excessive N fertilizer is applied in Chinese paddy fields, which has resulted in adverse impacts on environmental and human health (Gu et al. 2015, Zhang et al. 2015). The fate of fertilizer N plays a central role in crop production and environmental sustainability (Ju et al. 2009). Although several studies investigated the effects of SOC on the fate of fertilizer N, mixed results have been reported. Previous studies showed that increases in SOC may increase, decrease, or have no effect on the recovery efficiency of fertilizer N (Glendining et al. 1997, Liang et al. 2013, Oelofse

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et al. 2015). Furthermore, most of these studies were conducted in upland soils, while only few focused on the feedback of SOC to the fate of fertilizer N in flooded rice systems.

Because carbon (C) and N cycling is closely coupled in soil, it was hypothesized that higher SOC content could increase rice yield, N recovery efficiency and the retention of fertilizer N, thereby decreasing the loss of fertilizer N. Thus, a pot experiment was conducted using the ^{15}N-isotopic tracer method to determine the differences in rice yield and the fate of fertilizer N in soils with different organic C content.

MATERIAL AND METHODS

Soils. The soils used in this study were screened from 60 different fields in the Poyang County (28°55.5'N, 116°45.3'E), Jiangxi province, China, which have been used for rice cultivation for many decades. Three fields with different SOC contents were selected and soils were collected to a depth of 0–15 cm, air-dried and then sieved (2 mm mesh) for further treatment. The soils were silty clay and classified as Eutric Fluvisol. Their properties are listed in Table 1.

Experimental design. A pot experiment was conducted in the greenhouse of the Jiangxi Agricultural University in Nanchang, Jiangxi province, China from April to September 2016. Three different organic C soils (low, medium and high) with and without N fertilization (N and control) were combined into six treatments. Each treatment was replicated five times. Each pot (29 cm diameter and 21 cm height) contained four kg air-dried soil. Calcium-magnesium phosphate was thoroughly mixed with soil and urea and potassium chloride were dissolved in water and then added to the pots. All fertilizers were applied at basal at a rate of 150 mg N, 26.4 mg P and 83 mg K/kg dry soil. The ^{15}N-labelled urea (20.16% isotopic abundance) was provided by the Shanghai Institute of Chemical Industry, China. A hybrid rice cultivar, Y Liangyou 5867, was sown on April 21, 2016. The uniform seedlings were transplanted with two hills per pot and one seedling per hill on May 18. All pots were randomly arranged and kept flooded with a water depth of approximately 5 cm.

Sampling. All plants in each pot were harvested and separated into roots, straw and panicles at maturity in September 2016. The roots and straw were desiccated at 105°C for 30 min and then dried at 70°C to constant weight. All rice plants were weighed to determine the biomass, after which they were ground to determine the total N concentration and ^{15}N abundance.

Soil samples were collected from four randomly selected points in each pot with a 0.9 cm inner diameter auger. Samples were air-dried and sieved (0.149 mm) to determine the N concentration and ^{15}N abundance.

Analytical methods. The N in plants and soils was determined by the micro-Kjeldahl digestion. The ^{15}N abundance was determined using a Finnigan-MAT-251 mass spectrometer. The ^{15}N abundance of soils and plants in the control treatment was also determined and used as the ^{15}N background abundance.

Calculations and statistical analysis. Yield response to fertilizer N and the contribution of soil to yield were calculated as follows:

$$\text{Yield response to fertilizer N (\%)} = \frac{100 \times (Y_N - Y_{control})}{Y_{control}} \quad (1)$$

$$\text{Contribution rate of soil to yield (\%)} = \frac{100 \times Y_{control}}{Y_N} \quad (2)$$

Where: Y_N – rice yield in the N-applied; $Y_{control}$ – control treatment.

Plant N uptake derived from fertilizer (N_{dff}) and from soil (N_{dfs}) was calculated as follows (Zheng et al. 2016):

Table 1. Properties of selected soils with different organic carbon (C) content

Soil	Organic C	Total N	Alkaline N	Available K	Olsen P	CEC	pH
	(g/kg)		(mg/kg)			($cmol_+$/kg)	(1:2.5 H_2O)
Low	26.1	1.96	138	139	31.7	6.44	5.74
Medium	44.2	2.96	216	181	41.4	8.90	5.56
High	62.6	4.09	308	420	59.5	14.41	5.37

Low, medium and high – soils with low, medium, and high organic C content; CEC – cation exchange capacity

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$$N_{dff}(\text{mg/pot}) = \frac{\text{N uptake by plant} \times {}^{15}\text{N atom\% excess in plant}}{\text{urea } {}^{15}\text{N atom\% excess}} \quad (3)$$

$$N_{dfs}(\text{mg/pot}) = \text{total N uptake by plant} - N_{dff} \quad (4)$$

Fertilizer N residual rate in soil, N recovery rate and rate of not-specified N were calculated as follows:

$$\text{N residual rate in soil (\%)} = \frac{100 \times \text{total soil N} \times {}^{15}\text{N atom\% excess in soil}}{\text{urea } {}^{15}\text{N atom\% excess} \times \text{N application rate}} \quad (5)$$

$$\text{N recovery rate (\%)} = \frac{100 \times N_{dff}}{\text{N application rate}} \quad (6)$$

$$\text{Rate of N not-specified (\%)} = \frac{100 \times (\text{N application rate} - N_{dff} - N_{dfs})}{\text{N application rate}} \quad (7)$$

One-way ANOVA was conducted using the SAS 8.01 software package (SAS Institute Inc., Cary, USA). Significant differences of the measured variables between treatments were assessed by the least significant difference test at $P < 0.05$. All data shown are the averages of five replications.

RESULTS AND DISCUSSION

Rice yield and its components. Both high SOC and N fertilizer application could significantly increase rice yield and biomass (Table 2), but there was no significant interaction between SOC and N fertilization. Improving SOC significantly increased the panicle number and the grain number per panicle, but decreased the grain weight. N fertilization only significantly increased the grain number per panicle with no significant effect on other factors of yield components. Neither SOC content nor N fertilization had a significant effect on filled grain rate; however, there was an interactive effect between SOC content and N fertilization on the panicle number and the grain number per panicle.

The yield response to N fertilization declined with increasing SOC content, while the contribution rate of soil to yield enhanced with increasing SOC content (Figure 1). High SOC could improve soil physical structure and increase the supply of soil indigenous N (Lal 2006, Xu et al. 2016, Zhao et al. 2016). Hence, increasing SOC enhanced soil productivity while offsetting the effects of N fertilization on rice production (Zhao et al. 2016).

Nitrogen uptake. Both high SOC and N fertilization significantly increased the total N uptake of rice (Table 3). Both rice N uptake from soil (N_{dfs}) and urea (N_{dff}) increased significantly with increasing SOC content (Table 3). In the present pot experiment, most of the N uptake in rice was derived from soil. As the SOC content increased, the percentage of N_{dfs} to the total N uptake increased, while the opposite was true for the percentage of N_{dff} to the total N uptake.

Nitrogen fertilization has been shown to stimulate increased N uptake from soil (Pan et al. 2012). When compared with the control, N fertilization increased N_{dfs} by 12.7, 4.5, and 4.6% in soils with

Table 2. Effects of soil organic carbon (SOC) content and nitrogen (N) fertilization on rice yield and its components

SOC	Fertilization	Grain yield (g/pot)	Panicles number/pot	No. of grains/ panicle	Filled grain rate (%)	1000-grain weight (g/pot)	Biomass (g/pot)
Low	control	37.3^{f}	13^{d}	119^{c}	84.7^{a}	26.3^{a}	104.7^{e}
	N	48.8^{e}	14^{d}	143^{b}	83.8^{a}	25.9^{a}	114.9^{d}
Medium	control	53.9^{d}	17^{c}	134^{bc}	85.5^{a}	25.3^{b}	130.8^{c}
	N	65.4^{c}	20^{b}	129^{bc}	84.4^{a}	25.3^{b}	146.4^{b}
High	control	72.9^{b}	24^{a}	130^{bc}	84.1^{a}	24.6^{c}	173.5^{a}
	N	83.1^{a}	22^{ab}	160^{a}	82.6^{a}	25.0^{bc}	180.4^{a}
ANOVA	SOC	**	**	*	ns	**	**
	N	**	ns	**	ns	ns	**
	SOC × N	ns	*	*	ns	ns	ns

Low, medium and high – soils with low, medium, and high organic carbon content; N and control – fertilization treatments with and without N fertilizer. The lowercase letters in the same column represent a statistical significance at $P < 0.05$ (*$P < 0.05$; **$P < 0.01$; ns – no significance)

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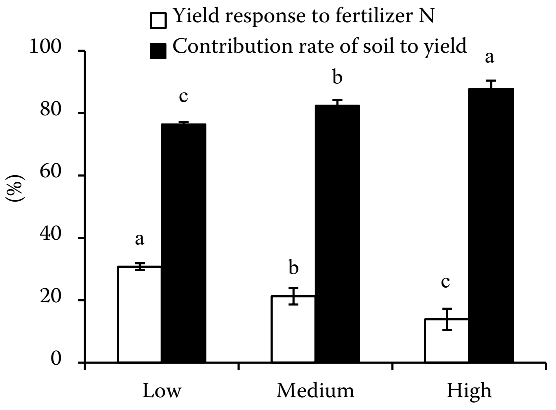

Figure 1. Yield response to fertilizer nitrogen (N) and the contribution rate of soil to yield as affected by soil organic carbon (SOC) content. Low, medium and high – soils with low, medium, and high organic carbon content. Error bars indicate the standard deviation of five replications. Different lowercase letters represent statistical significance among treatments at $P < 0.05$.

low, medium, and high SOC content, respectively (Table 3). Because N fertilization could improve rice growth and root development, the increase in root exudates could stimulate the growth and proliferation of soil microbes, thereby accelerating decomposition of SOC and mineralization of soil organic N (Ge et al. 2015).

Fate of ^{15}N-urea. The SOC content had a significant effect on the fate of ^{15}N-urea (Figure 2). The recovery rate and residual rate of fertilizer N increased significantly with increasing SOC content, thus resulting in a significant decrease in the rate of not-specified fertilizer N.

The N recovery rate in the present study was much lower (16–25%) than that in previous results, while the percentage of not-specified N was much greater (Zheng et al. 2016). Several reasons may be given for the high percentage of not-specified N and low N recovery rate in this study. First, the environment in the pots used in our study may vary much greater than that in field experiments (Liang et al. 2013). Second, all of the N fertilizer was broadcasted as basal before transplanting, which may reduce the N uptake and increase N losses (Zhu et al. 1997). Third, the relatively high SOC content in the soil used for the present experiment inherently improves N supply from soil and thus leads to reduced N uptake from fertilizer (Peng et al. 2006). Last, the continuous flooding condition during the whole rice-growing period may intensify the N losses (McSwiney et al. 2010).

The present results demonstrated that high SOC improved the uptake and retention of fertilizer N and thus decreased the percentage of not-specified N, which supports the hypothesis of this study (Figure 2). First, higher SOC could improve soil structure and other physical properties, which supports greater root volumes and biomass for capturing fertilizer N (Lal 2006). Second, soils with high SOC have a great cation exchange capacity and nutrient retention capacity (Lal 2006). Third, higher SOC supports increased numbers of microbes, which act as a nutrient sink for improving N retention (Liang et al. 2013). The assimilated fertilizer N in soil microbial biomass could be reused by plants after death, thereby improving the synchrony between N supply and demand (Liang et al. 2013).

Table 3. Effects of soil organic carbon (SOC) content and nitrogen (N) fertilization on N uptake and its source

SOC	Fertilization	Total N uptake (mg/pot)	N_{dff} (mg/pot)	N_{dff}/total N uptake (%)	N_{dfs} (mg/pot)	N_{dfs}/total N uptake (%)
Low	control	919^{f}	–	–	919^{f}	–
	N	1135^{e}	98.7^{c}	8.7^{a}	1036^{e}	91.3^{b}
Medium	control	1463^{d}	–	–	1463^{d}	–
	N	1637^{c}	107.8^{b}	6.6^{b}	1529^{c}	93.4^{a}
High	control	1985^{b}	–	–	1985^{b}	–
	N	2225^{a}	148.4^{a}	6.7^{b}	2077^{a}	93.3^{a}

Low, medium and high – soils with low, medium, and high organic carbon content; control and N – fertilization treatments without and with N fertilizer; N_{dff} and N_{dfs} – N uptake derived from fertilizer and soil. The lowercase letters in the same column represent significance at $P < 0.05$ (– means no data are available)

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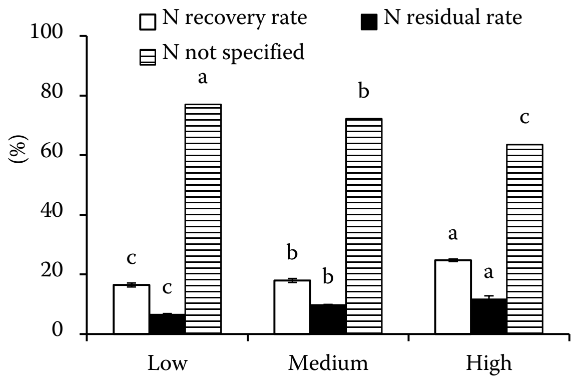

Figure 2. Effects of soil organic carbon (SOC) content on the fate of ^{15}N-urea. Low, medium and high – soils with low, medium, high organic carbon content. The error bars in each column indicate the standard deviation of five replications. Different lowercase letters on the error bar represent statistical significance among treatments at $P < 0.05$

In short, our results support the hypothesis that re-coupling of the C and N cycle through increasing SOC content could improve fertilizer N retention in the paddy soil and decrease the unspecified fertilizer N to the environment (Gardner and Drinkwater 2009, Liang et al. 2013). However, further research should be conducted to clarify the mechanism underlying the great retention capacity of fertilizer N in soils with high SOC such as separating different fractions of residual fertilizer ^{15}N and monitoring various pathways of N losses.

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