Agriculture, Ecosystems and Environment 219 (2016) 93–100

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Lower C sequestration and N use efficiency by straw incorporation than manure amendment on paddy soils

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ARTICLE INFO

Article history:
Received 5 September 2015
Received in revised form 3 December 2015
Accepted 10 December 2015
Available online xxx

Keywords:
Soil organic C
Chemical fertilizer
Organic materials
Rice yield
Cropping system
Long-term fertilization

ABSTRACT

Understanding the effects of external organic and inorganic components on soil organic C (SOC) and fertilizer N use efficiency (NUE, in kg of grain per kg of N applied) is essential for better stewardship of domesticated soils. We collected 106 paired-treatment data points from 28 long-term field fertilization trials of subtropical paddy soils with double-rice cropping systems in China. The effects of chemical fertilizer (NPK), NPK plus straw (NPK + s), and NPK plus manure (NPK + m) on rice yield, SOC density, and NUE were assessed. The greatest SOC sequestration rate was found with the use of NPK + m (0.67 Mg ha^{-1} $year^{-1}$), whereas this value was lower with NPK + s (0.48 Mg ha^{-1} $year^{-1}$) and NPK (0.30 Mg ha^{-1} $year^{-1}$). The soil C sequestration rate decreased with the experimental time, leading to a sequestration period of 43, 65, and 55 years to reach a new equilibrium value of SOC for NPK, NPK + s and NPK + m, respectively. Under the same N input condition, the treatment with N fertilizer proportionally replaced by manure (NPK + m) could enhance both rice yield and NUE by 28% and 27%, respectively, whereas the *in situ* rice straw incorporation (NPK + s) showed no distinct effect. Additional manure amendment on the basis of existing N fertilizer application rate did not have an effect on both rice yield and NUE. In contrast, additional rice straw incorporation decreased NUE by 24%, even though no distinct change of rice yield was found. Our results indicate that application of chemical fertilizer plus manure, rather than rice straw, to paddy fields is a promising practice to enhance SOC accumulation and improve rice yield, as well as the crop N use efficiency in subtropical rice production of China.

1. Introduction

Domesticated soil has a capacity to capture atmospheric CO_2 and enhance nutrient use efficiency by adoption of improved management (Chen et al., 2014; Amundson et al., 2015). The use of improved management in cultivated soil can sequestrate SOC by 0.36 Gt $year^{-1}$ and increase N use efficiency (NUE, kg of grain per kg of N applied) by 32–57% (Smith et al., 2008; Chen et al., 2014), which provide opportunities in regards to maintaining the role of domesticated soil in food, climate, and human security (Amundson et al., 2015). In the case of rice production, improved practice can improve the sequestration of SOC by 0.5 Mg ha^{-1} $year^{-1}$ and increase NUE by 32–39% (Niles et al., 2002; Chen et al., 2014). Among all the improved managements, straw incorporation and manure amendment have been suggested as the most promising practices in domesticated soil (Lu et al., 2009; Maillard and Angers, 2014).

In China, paddy soil covers an area of 33 million hectares, accounting for approximately 23% of the worldwide paddy area of 153 million hectares (FAO, 2007; Liu et al., 2014a). Approximately 60% of paddy soil in China is in the subtropical region, where the dominant cultivation pattern is double-rice cropping. Over the last three decades, a large body of research has shown that paddy soil in China has sequestered a significant amount of SOC, largely because of the increased use of N fertilizers and the application of organic materials, including rice straw and manure (Wu, 2011; Yan et al., 2011; Tian et al., 2015). However, the magnitude of SOC

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http://dx.doi.org/10.1016/j.agee.2015.12.012
0167-8809/

sequestration in paddy soil varies depending on geographic regions which differ in climate, rotation system, soil background condition, and custom management (Rui and Zhang, 2010; Huang et al., 2012; Luo et al., 2013; Tian et al., 2015). For this reason, the effects of improved managements on SOC sequestration should be reconsidered in different paddy regions of China (Tian et al., 2015).

The recent use of N fertilizer, straw incorporation, and organic manure amendment on rice paddies has led to high grain yields and increased food security in China. These practices may also potentially provide prospective opportunities for soil C sequestration in China's cultivated soils (Lu et al., 2009; Wu, 2011). However, the increasing rate of N fertilizer use by farmers has already resulted in a high N surplus, low NUE, serious surface water eutrophication, and accelerated greenhouse gas emission (Zheng et al., 2007; Chen et al., 2014). In subtropical China alone, the recent N fertilizer application rate was at an alarmingly high level of 300 kg N ha^{-1} $year^{-1}$, which was much higher than that in other regions of China (Lu et al., 2009). This large-scale use of N fertilizer has led to a low NUE, and whether the amendment of straw and manure can improve NUE is still unknown. In addition, the practice of *in situ* rice straw incorporation can increase CO_2 and CH_4 emissions, which may partly offset the benefits of C inputs from straw incorporation (Liu et al., 2014a, 2014b). Consequently, understanding the integrated effects of N fertilization, straw incorporation, and manure amendment on SOC sequestration and NUE is very necessary in subtropical paddy soils with double–rice cropping system.

Since 1986, a series of long-term agro-ecosystem experiments have been established to investigate the effect of fertilizers, including N fertilizer, rice straw, and manure on SOC change in subtropical paddy soil with a double-rice cropping system in China. In this study, after collecting published field experimental data on initial SOC, changes in SOC, rice yields, and N input rate with the application of chemical fertilizer, rice straw, and manure, we aimed to: (i) estimate the integrated effect and duration of fertilization on paddy soil C sequestration in a double-rice cropping system; (ii) quantify the effect of fertilizer N input on rice yield and NUE; and (iii) find the most promising practice to increase both SOC and rice yield, and to reduce N fertilizer input.

2. Materials and methods

2.1. Data sources

Data for SOC changes under different fertilization treatments in subtropical paddy soils of China were collected from all peer-reviewed research literature published before 2014, using Chinese electronic databases from www.cnki.net and www.cqvip.com. Field experiments on double-rice based cropping systems with an experimental period of more than 3 years were used as the selection criteria, in order to avoid the interaction of cropping system on SOC change (Rui and Zhang, 2010; Liu et al., 2014b). The analytical database for each field experiment needed to include complete details of the initial SOC content, change in SOC content, and rice yields in the control and fertilizer treatment groups. Experimental site information, including the experimental period, fertilization scheme, and N application rate were also considered in our database. Three fertilization schemes were selected: chemical fertilizer (NPK), NPK plus straw (NPK + s), and NPK plus manure (NPK + m). The manure was mainly fresh pig or cow manure, and straw was rice straw harvested during the season. Organic C and N contents of manure and straw were used as reported for each trial in literatures.

Twenty-eight long-term field experiments were chosen to for the database, including 104 paired trials. The details of the selected studies and associated references are presented in Table 1.

2.2. Data analysis

The SOC density was calculated using the following equation:

$$D = \mathrm{SOC} \times \rho \times H \times 10^{-1} \quad (1)$$

where D is the SOC density (Mg ha^{-1}); SOC is soil organic C content (g kg^{-1}); ρ is soil bulk density (g cm^{-3}); and H is the thickness of the sampling depth (20 cm).

In studies where only soil organic matter (SOM) concentrations were reported, a factor of 0.58 was multiplied to convert SOM to SOC content.

In studies where data for soil bulk density was not provided, the following empirical equation was used to estimate soil bulk density (Pan et al., 2003):

$$\rho = -0.220 \times \ln \mathrm{SOC} + 1.780 \quad (2)$$

The mean annual change in SOC stock for a single treatment was calculated as:

$$\Delta D = \frac{D_t - D_0}{t} \quad (3)$$

where ΔD is the mean annual change in SOC density (Mg ha^{-1} $year^{-1}$) during the experimental duration; D_t and D_0 are SOC density (Mg ha^{-1}) for the final and initial years of the experiment, respectively; and t is the experimental duration (year).

The relative influence of a particular fertilizer on annual SOC sequestration was calculated as:

$$\Delta D_{\mathrm{r}} = \frac{(D_t - D_0)_f - (D_t - D_0)_c}{t} \quad (4)$$

where ΔD_{r} is the relative change of SOC density (Mg ha^{-1} $year^{-1}$) with fertilization; and subscripts of f and c refer to data collected from the fertilization and control treatments, respectively.

The N input from fertilization was calculated as:

$$N_f = N_c + Y_{\mathrm{OM}} \times N_{\mathrm{OM}} \quad (5)$$

where N_f is the N input in each fertilization treatment (kg N ha^{-1} $year^{-1}$); N_c is the N input from chemical N fertilizers (kg N ha^{-1} $year^{-1}$); Y_{OM} is the amount of rice straw or manure applied (kg ha^{-1} $year^{-1}$); and N_{OM} is the N content (%) of rice straw or manure applied.

The fertilizer N use efficiency for rice (NUE, kg kg^{-1}) was calculated as:

$$\mathrm{NUE} = \frac{Y_f - Y_c}{N_f} \quad (6)$$

where Y_f and Y_c are the rice yields (kg ha^{-1}) of the fertilization and control treatments, respectively; and N_f is the fertilizer N input of each fertilization treatment (kg ha^{-1}). In our dataset, there were two schemes of N input for different fertilization treatments of each field experimental site: (i) an equal fertilizer N input rate for NPK, NPK + s, and NPK + m, in which organic fertilizer N proportionally replaced N fertilizer; and (ii) a non-equal fertilizer N input rate, in which rice straw and manure were added according to the application rate of N fertilizer, with 37% and 32% more N input for NPK + s and NPK + m than for NPK, respectively. Thus, NUE, as well as rice yield, will be calculated separately for these two schemes.

2.3. Statistical analysis

Statistical analysis was conducted using Microsoft Office (Excel 2003, Microsoft Corporation, Redmond, WA, USA) and SPSS software (SPSS 13.0 for Windows, SPSS Inc., Chicago, IL, USA). Each site that had the same type of fertilizer applied was considered a statistical unit, and data was replicated in preparation