Catena 135 (2015) 283–289

Contents lists available at ScienceDirect

Catena

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

Short-term responses of soil organic carbon and carbon pool management index to different annual straw return rates in a rice–wheat cropping system

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ARTICLE INFO

Article history:
Received 26 March 2015
Received in revised form 29 July 2015
Accepted 13 August 2015
Available online 2 September 2015

Keywords:
Straw return
Soil organic carbon
Carbon pool management index
Crop yield

ABSTRACT

Crop straw return is recommended as an effective management practice to alter soil organic carbon (C) content. Understanding the effects of straw return rate on changes of soil organic C (SOC) is helpful for improving soil quality and sustaining crop productivity. To determine the short-term responses of SOC content and grain yield to different annual straw return rates, a 2-year field experiment with a random block design was carried out in a rice–wheat rotation system. Seven gradient rates of straw return, including 0%, 25%, 50%, 75% and 100% of total straw from previous crop returned in rice and wheat seasons, and 100% of straw returned only in rice or wheat season were set. Both rice and wheat yields were investigated and SOC pools and C pool management index (CPMI) were measured. The soil total organic C (TOC) and labile organic C fraction contents were higher under the straw return treatments compared to the no straw return treatment (0%S) at a 0–21 soil depth. The 50% annual straw return rate (50%S) had significantly higher soil TOC, dissolved organic C (DOC), easily oxidizable C (EOC), and microbial biomass C (MBC) contents than the 0%S treatment at a 0–21 cm depth. All of the straw return treatments had a significantly higher DOC content than the 0%S treatment at a 0–21 cm depth, except for the 100% only rice straw return treatment (100%RS). Compared to the 0%S, the 25%S and 50%S treatments had a significantly higher SOC lability (L), lability index (LI), C pool index (CPI) and CPMI at a 0–21 cm soil depth. With the increase of straw return rate, the crop yields first increased and then decreased, and the 50%S treatment had the highest crop yields. There were significant and positive correlations between the soil TOC and the annual crop yield. We concluded that the 50% annual straw return rate is the best option for improving SOC sequestration and crop productivity in the rice–wheat rotation system of China.

1. Introduction

Soil has two to three times the capacity to store more carbon (C) than exists in the atmosphere as CO_2, and the dynamics of soil C has an important influence on global climatic change (Davidson et al., 2000; Lal, 2004). Soil organic C (SOC) could serve as a potential sink for atmospheric C, and maintaining SOC is particularly important for sustaining the productivity of the agro-ecosystem since it plays an essential role in improving soil quality and crop production by affecting soil physical, chemical, and biological properties (Kundu et al., 2007; Rudrappa et al., 2006). Furthermore, an increase in SOC could involve C sequestration, which may contribute to mitigating the increase in atmospheric CO_2 (Lal, 2010). However, short- and medium-term changes in soil total organic C (TOC) are difficult to detect due to the high background C and temporal and spatial variabilities of recalcitrant C (Blair et al., 1995). Labile organic C fractions (i.e., microbial biomass C (MBC), dissolved organic C (DOC), and easily oxidizable C (EOC)), which respond relatively rapidly to land use and soil management practices, are thus suggested as early and sensitive indicators of SOC changes (Ghani et al., 2003; Haynes, 2000). Based on changes of EOC and TOC, the C pool management index (CPMI) was developed to assess the state and rate of change in agricultural soil C of agro-ecosystem, which is also a useful parameter to evaluate the capacity of management practices to improve soil quality (Blair et al., 1995; Diekow et al., 2005). Evidences have shown that SOC sequestration is influenced by many factors, such as regional climate, soil condition, root biomass, experimental duration and optimizing agricultural management practices, including fertilizer application, straw-return or conservation tillage, which can increase SOC through increasing C input and/or decreasing C output (Brar et al., 2013; Singh et al., 2007; Yan et al.,

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http://dx.doi.org/10.1016/j.catena.2015.08.008

2013). Therefore, it is very meaningful to determine a suitable agricultural management practice for increasing SOC sequestration and reducing greenhouse emission in cropland.

Crop straw return is recommended as an important management practice and is increasingly being adopted in the agricultural sector (Huang et al., 2012). Many studies have reported that the addition of crop straw to cultivated soils could help improve the soil quality and productivity via its favorable effects on soil properties (Choudhury et al., 2014; Sommer et al., 2011; Turmel et al., 2014). Liu et al. (2014) and Zheng et al. (2014) showed that straw return has highly efficient on SOC accumulation and grain yields in the cropland, and should be recommended as a long-term management practice to improve soil fertility and crop productivity. Lu et al. (2011) found that in semi-arid areas of China, the labile organic C, TOC, and CPMI were all higher in the moderate amount of straw return treatment (6000 kg ha^{-1} of millet straw and 9000 kg ha^{-1} of corn straw returned) than that of the low and high amounts of straw return treatments at 0–20 cm soil layer. Lou et al. (2011) also observed that C sequestration in topsoil was strongly affected by return rate of straw residue. Hence, the rate of crop straw return is one of the major factors causing the change of SOC.

A continuous rice–wheat rotation is the dominant cropping system in the middle–lower reaches of the Yangtze River of China (Ding et al., 2013). In the past several decades, many researchers have studied the effects of straw return on SOC and crop yields in this region (Hang et al., 2014; Rui and Zhang, 2010; Wang et al., 2015a,b). However, with the increase in crop yields, the quantity of crop straw is continuously increasing, especially in this intense cropping rotation. More attention should be paid on the quantity of straw returned to cropland in agroecosystems. To our knowledge, there is a paucity of literature on the effects of annual straw return rate on SOC and crop productivity in the rice–wheat rotation system of China (Lou et al., 2011). Therefore, the objectives of this study were to quantify the short-term responses of SOC pools, CPMI and grain yields to different annual straw-return rates in a rice–wheat rotation system in the middle–lower reaches of Yangtze River in China; and determine a suitable annual straw return rate for improvement of SOC and grain yields in the rice–wheat rotation system.

2. Materials and methods

2.1. Study site

The experiment was conducted in Xiaohu Country, Huaisi Town, Yangzhou City, Jiangsu Province, China (119°01′–119°54′E, 32°15′–32°25′N), from June 2011 to June 2013. The experimental site had a subtropical monsoon climate with an average annual precipitation of 1020 mm, an average annual temperature of 14.8 °C, a mean duration of annual sunshine of 2140 h, a frost-free period of 220 d, and a plum rain season generally from mid-June to mid-July. The rice–wheat double-cropping system is the most important cropping system in the region. The soil of the experimental site is a sandy loam that is classified as an anthrosol (World Reference Base for Soil Resources, 2006). The main properties of the sampled soil (0–20 cm depth) as measured by the methods of Bao (2000) were as follows: soil organic matter 25.70 g kg^{-1}, total nitrogen 1.30 g kg^{-1}, available phosphorus 20.34 mg kg^{-1}, available potassium 58.52 mg kg^{-1}, pH 6.65 and bulk density 1.41 g cm^{-3}.

2.2. Experimental design and field managements

This experiment had a randomized block design with three replications. Each plot had a dimension of 5 m wide and 6 m long. There seven treatments were as follows: (1) no straw return (0%S: 0% wheat straw return in the rice season + 0% rice straw return in the wheat season); (2) 25% annual straw return (25%S: 25% wheat straw return in the rice season + 25% rice straw return in the wheat season); (3) 50% annual straw return (50%S: 50% wheat straw return in the rice season + 50% rice straw return in the wheat season); (4) 75% annual straw return (75%S: 75% wheat straw return in the rice season + 75% rice straw return in the wheat season); (5) 100% annual straw return (100%S: 100% wheat straw return in the rice season + 100% rice straw return in the wheat season); (6) only 100% rice straw return (100%RS: 0% wheat straw return in the rice season + 100% rice straw return in the wheat season); and (7) only 100% wheat straw return (100%WS: 100% wheat straw return rate in the rice season + 0% rice straw return in the wheat season). The amount of 100% wheat straw returned was 6000 kg ha^{-1}, while that of 100% rice straw returned to soils was 9000 kg ha^{-1} for the duration of the experiment.

The experimental site was cultivated with a rice–wheat rotation prior to June 2011, in which rice was transplanted from June to November, and wheat was planted from November to June. After the wheat and the rice were harvested, the plots were cultivated at a depth of 10–15 cm by rotary tillage. For straw returned plots, the wheat/rice straw was cut into 8–10 cm pieces after being air-dried and placed back on the surface of the soil in June/November of each year and was then incorporated into the soil by rotary tillage.

In this study, the rice variety Huaidao5 (*Oryza sativa* L.) was transplanted using machinery at approximately 3–4 seedlings per hole and 255,000 holes per hectare on June 13, 2011, and June 20, 2012, respectively. The same fertilization rates (300, 120, 120 kg ha^{-1} of N, P_2O_5, K_2O, respectively) were adopted for all the treatments according to local agronomic management practices during each rice growing period. The N fertilizer applied were 40% as a basal fertilizer before transplanting, another 40% at the tillering stage, and the remaining 20% at the earing stage (Table 1). The rice was harvested on November 7, 2011, and November 5, 2012, respectively. The wheat variety Zhengmai9023 (*Triticum aestivum* L.) was sown on November 11, 2011, and November 25, 2012, respectively. The wheat was directly drilled with a seed quantity of 150 kg ha^{-1}. The rates of fertilizer application were the same (270, 67.5, 67.5 kg ha^{-1} of N, P_2O_5, K_2O, respectively) for all the treatments according to the local agronomic management practices during each wheat growing period. The N fertilizer applied as basal fertilizers were 50% before sowing, and another 50% was at the elongation stage (Table 1). The wheat was harvested on June 10, 2012, and June 8, 2013, respectively. Pesticide management in both the rice and wheat seasons was in accordance with the conventional pest management practices. All other management procedures were identical in every treatment.

2.3. Soil sampling and analysis

Soil cores (5 cm diameter) were randomly collected on June 7, 2013 (immediately before the rice was harvested). Samples from each plot consisting of five composite soil cores were sectioned into 0–7, 7–14 and 14–21 cm depth according to the different amount of crop straw in soil layer. There were 21 composite samples in total, and the collected moist samples were ground and sieved through a 10-mesh (2 mm) screen. The sieved soil samples were divided into two sub-samples. One was air-dried and sieved through a 100-mesh (0.15 mm) screen to determine the soil TOC and EOC. The other was immediately stored

Table 1
Chemical fertilizer application rate and time over two annual cycles from 2011 rice season to 2013 wheat cropping season.

Crop	Chemical fertilizer application rate	Application time (dd-mm-yy)	
	($N:P_2O_5:K_2O$, kg ha^{-1})	2011–2012	2012–2013
Rice	120:120:120	13-Jun-11	20-Jun-12
	120:0:0	9-Jul-11	15-Jul-12
	60:0:0	15-Aug-11	20-Aug-12
Wheat	135:67.5:67.5	15-Nov-11	25-Nov-12
	135:0:0	20-Feb-12	2-Mar-13