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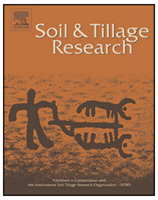

Effects of rice straw incorporation on active soil organic carbon pools in a subtropical paddy field

W. Wang [a,b,*], D.Y.F. Lai [c,**], C. Wang [a,b], T. Pan [a], C. Zeng [a,b]

[a] Institute of Geography, Fujian Normal University, Fuzhou 350007, China
[b] Key Laboratory of Humid Subtropical Eco-geographical Process, Ministry of Education, Fujian Normal University, Fuzhou 350007, China
[c] Department of Geography and Resource Management, and Centre for Environmental Policy and Resource Management, The Chinese University of Hong Kong, Hong Kong SAR, China

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ABSTRACT

Understanding the dynamics of soil organic carbon (SOC) in response to changing environment and management practices is crucial for minimizing the climatic impacts of rice agriculture. This study examined the effects of rice straw incorporation on total SOC, active SOC fractions, and carbon pool management index (CPMI) in a subtropical paddy field in China. The straw collected after harvesting the early and late paddy was incorporated immediately into the top 10 cm soil at a rate of 3.3 Mg ha^{-1} and the top 40 cm soil samples in the triplicate treatment, control and reference plots were analyzed for the concentrations of total SOC and four other active SOC fractions at the end of the early and late seasons. The concentrations of total soil organic carbon (SOC), light fraction organic carbon (LFOC), dissolved organic carbon (DOC), and microbial biomass carbon (MBC) were significantly ($P < 0.05$) higher in the straw application plots than in the controls by 7.1–128.6% for both the early and late paddy season. In general, significant and positive correlations were observed between SOC, DOC, LFOC, MBC and labile organic carbon (LOC) in the treatment and control plots for both early and late paddy ($r = 0.60$–0.96, $P < 0.05$). Moreover, there were significant and positive correlations of total SOC and active SOC fractions with both soil water content ($r = 0.69$–0.94, $P < 0.01$) as well as total soil nitrogen content ($r = 0.69$–0.99, $P < 0.05$). Straw incorporation significantly increased CPMI and other active soil organic carbon pools in the early paddy field ($P < 0.05$), but had no significant effects on CPMI in the late paddy field. It is therefore better to incorporate straw residues in the aerobic condition during the early paddy season in order for rice to benefit from an increased CPMI.

1. Introduction

Climate change has been one of the major global environmental problems of the 21st century, with increasing anthropogenic greenhouse gas (GHG) emissions being the main cause. Agriculture alone is reported to contribute to about 20% of the present atmospheric GHG concentrations (Hütsch, 2001), with methane (CH_4) and carbon dioxide (CO_2) being the two most potent carbon-containing GHGs released from agricultural activities (Myhre et al., 2013). Enhancing carbon (C) sequestration and minimizing GHG emissions has become one of the important tasks worldwide to successfully combat future climate change. Recently, there is a call to enhance the storage of soil organic carbon (SOC) in farmlands as a means to offset the anthropogenic GHG emissions.

Being the largest C reserve in the terrestrial ecosystems, global soils contain three times more C than that in the atmosphere (Lal, 2004). In view of the large magnitude of soil C stock, even a small change in this reserve can exert a considerable influence on gaseous C emissions and atmospheric CH_4 and CO_2 concentrations, thereby affecting global climate change (Cox et al., 2013). Under active human intervention and cultivation, the soils in paddy fields generally have a greater C sequestration potential than natural wetland soils (Pan et al., 2004). At present, the total C storage in the paddy soil of China is 1.3 Pg (Pan et al., 2004), which is lower than the reported range of 21.0 Pg in the forest (Zhou et al., 2000) and 41.0 Pg in grassland soils (Ni, 2002). As the rice plant residues are removed after each harvest, there is a little input of organic matter from litter or plant residues to soils in the paddy field, leading to lower soil C concentration in paddy fields compared with the natural ecosystem (Wang et al., 2014a). Since C saturation is more likely in a highly structured and organic-matter-rich soil

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[*] Corresponding author at: Institute of Geography, Fujian Normal University, Fuzhou 350007, China. Tel.: +86 591 83465214.
[**] Corresponding author. Tel.: +852 3943 6528.
E-mail addresses: wangweiqi15@163.com (W. Wang), dyflai@cuhk.edu.hk (D.Y.F. Lai).

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(Chung et al., 2010), paddy soils with a lower SOC content than the natural soils present a higher potential of sequestering additional C when suitable management practices are adopted, such as application of organic fertilizers, return of plant residues, management of water regimes, etc. (Wissing et al., 2011).

Since changes in total SOC content occur over a long time scale, and are not easily discerned within a short time period (Wissing et al., 2011), it is important to distinguish the active C fraction from the total SOC pool for assessing the effect of paddy field management on soil C dynamics (Purakayastha et al., 2008; Gong et al., 2009; Xu et al., 2011a,b). Active carbon refers to the fraction of soil C that has a high activity, which means being strongly influenced by plants and microorganisms, as well as highly susceptible to oxidation and decomposition (Kimura et al., 2004; Chen et al., 2010). Based on different separation and extraction methods, active SOC can mainly be characterized as dissolved organic carbon (DOC), liable organic carbon (LOC), light fraction organic carbon (LFOC), and microbial biomass organic carbon (MBC) (Xu et al., 2011b). Although, different forms of active SOC have different sensitivities to environment change (Gu et al., 2004), few studies have actually examined the relationships between the different active SOC forms and changes in environmental parameters (Xu et al., 2011b; Zhao et al., 2014a), especially the soil properties. Since active SOC is a major source of CO_2 and CH_4 produced by microbes, properly managing this active C pool is important for mitigating global climate change (Knoblauch et al., 2011; Hanke et al., 2013). While previous studies have successfully applied the carbon pool management index (CPMI) in many crop fields (maize, wheat, millet, rice, etc.) to assess the response of SOC content to changes in environmental conditions and management practices (Blair et al., 2006; Verma and Sharma, 2007; Xu et al., 2011b; Zhao et al., 2014a), there is lack of similar studies on the flooded paddy fields.

Rice is the main cereal crop for over 50% of the world's population. It is estimated that a 40% increase in rice production is needed to meet the surging demand from the rapidly increasing population by the end of 2030 (FAO, 2009). Various strategies of agricultural management are currently being developed to improve rice productivity as well as soil C sequestration, including, for example, water management (Tian et al., 2013), cultivation methods (Xu et al., 2011a), fertilization management (Srinivasarao et al., 2012), development of new rice varieties (Inubushi et al., 2011), and application of exotic materials such as biochar (Xie et al., 2013) and rice straw (Liu et al., 2014a). Rice agriculture, in particular, contributes significantly to straw production globally, which totals at about 1000×10^9–2000×10^9 t year^{-1} (Lou et al., 2011). These agricultural residues are either removed from the field, burned in situ, piled or spread in the field, incorporated into the soil, or used as mulch for the following crop (Vibol and Towprayoon, 2010). In the past, straw was commonly removed from the field to be used as fuels or construction materials in many countries (Xu et al., 2011b). Yet agricultural lands around the world recently suffer from the problems of increasing pest attacks and hardening of soil agglomerates as a result of the excessive use of fertilizers. This has led to an increase in the practice of applying straw back to the field after harvesting, which has found to be able to improve soil fertility (Huang et al., 2012; Zhao et al., 2014b), ameliorate soil chemical and physical properties (Castillo et al., 2012), increase crop yield (Zhu et al., 2010; Krupnik et al., 2012; Dong et al., 2013; Su et al., 2014), enhance soil C sequestration (Lugato et al., 2006; Lu et al., 2009; Liu et al., 2014b), and mitigate greenhouse gas emissions (Bhattacharyya et al., 2012; Zhang et al., 2013). Unfortunately, little research has been done on the effects of straw application on the active SOC pool, which has significant implications to enhance the ability of paddy soil as a long-term C sink.

In China, rice is predominantly grown in the subtropical areas, including Hunan, Jiangsu, Jiangxi, Hubei, Fujian and other provinces. We chose to conduct our study in a paddy field in Fujian province which was representative of the overall rice-producing areas in this country. The objectives of this study were to: (1) investigate the effects of straw incorporation on the total and active SOC concentrations in the paddy field, (2) examine the relationships between different active SOC fractions and other soil properties, and (3) apply the carbon pool management index to determine the sensitivity of SOC to straw application for two paddy crops.

2. Materials and methods

2.1. Study site

This study was conducted at the Wufeng Agronomy Field of Fujian Academy of Agricultural Sciences in Fujian province, southeast China (26.1°N, 119.3°E) (Fig. 1). There are two main crop seasons for paddy farming in Fujian province, namely the rainy season in which early paddy is cultivated in March–April and harvested in June–July, and the dry season in which late paddy is cultivated in July–August and harvested in November–December. The field experiments were carried out during the early paddy rainy season (5 April–25 July) and the late paddy dry season (1 August–6 November) in 2012. The soil of the paddy field was poorly drained, and the proportions of sand, silt, and clay particles in the top 15 cm soils were 280 g kg^{-1}, 600 g kg^{-1}, and 120 g kg^{-1}, respectively. Moreover, the top 15 cm soil at the onset of the experiment had a bulk density of 1.1 g cm^{-3}, pH value (1:5 with H_2O) of 6.5, and concentrations of organic carbon, total nitrogen (N) and total phosphorus (P) of 18.1, 1.2, and 1.1 g kg^{-1}, respectively (Wang et al., 2012). The water level was maintained at 5–7 cm above the soil surface throughout the rice growing period by an automatic water level controller, and the final drainage was done two weeks before the rice was harvested. In order to examine the effect of rice straws on active SOC pool, we immediately incorporated the straw collected after harvesting the late and early rice on November 6, 2011, and July 25, 2012, respectively, into the top 10 cm soils of triplicate plots at a rate of 3.3 Mg ha^{-1}, while another triplicate plots were treated as controls receiving no straw additions. The straw used in the early paddy was originated from the harvesting of late paddy in the previous year, while the straw incorporated in the late paddy field came from the previous crop of early rice that was harvested not more than 10 days prior to the cultivation of this late paddy.

The field was plowed to a depth of 15 cm with a moldboard plow and leveled 2 days before rice transplantation. Mineral fertilizers were applied in three splits as complete (N–P_2O_5–K_2O = 16–16–16%) and urea (46% N) fertilizers. The basal fertilizer was applied one day before transplanting at a rate of 42 kg N ha^{-1}, 40 kg P_2O_5 ha^{-1}, and 40 kg K_2O ha^{-1}. Twenty-one-day-old seedlings (3 seedlings per hill) of rice (cv. Hesheng 10, China) were transplanted manually at a depth of 3–4 cm at a spacing of 14 cm × 28 cm on 5th April (early paddy) and 1st August (late paddy) in 2012 to three replicate plots (24 m^2 each) at the study site. The second split of fertilizer was broadcasted during the tiller initiation stage (7 days after transplanting (DAT)) at a rate of 35 kg N ha^{-1}, 20 kg P_2O_5 ha^{-1}, and 20 kg K_2O ha^{-1}, and the third split was broadcasted during the panicle initiation stage (56 DAT) at a rate of 18 kg N ha^{-1}, 10 kg P_2O_5 ha^{-1}, and 10 kg K_2O ha^{-1}. Both the early and late paddy were managed in the same way as described above. The early and late paddy were harvested on July 25, and November 6, respectively.