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Differential responses of crop yields and soil organic carbon stock to fertilization and rice straw incorporation in three cropping systems in the subtropics

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ABSTRACT

Because the *in situ* incorporation of rice straw into paddy fields enhances CH_4 emissions, the *ex situ* (or shifted) incorporation of rice straw into uplands may provide an alternative way of mitigating CH_4 emissions and increasing crop productivity and soil organic carbon (SOC) accumulation. To evaluate the efficiency of this practice, three field trials were conducted in flooded paddies (FP), paddy-upland rotation (PU), and upland (UL) cropping systems in Taoyuan county, a subtropical region of China. All trials had three fertilization treatments: no fertilizer (Nil), chemical fertilizer only (NPK) and combined application of chemical fertilizer and rice straw (NPK + R in FP and NP + R in PU and UL). Results showed that the responses of crop yields to NPK in the UL trial (yields increased 2.4 to 4.1-folds relative to Nil) were greater than those of rice (increased 1.65 to 1.80-folds) in the FP and PU trial. Compared with NPK treatment, NPK + R constantly increased the grain yields of rice in the FP trial by 10% averagely, but not in PU trials. The effects of NP + R treatment on crop yields in the UL trial were significant ($p < 0.05$) during the first 5–6 years. NPK treatments increased the SOC accumulation at a rate of 0.48 Mg ha^{-1} yr^{-1} in the FP trial and 0.35 Mg ha^{-1} yr^{-1} in the UL trial, but not in the PU trial. NPK + R treatments resulted in SOC accumulation rates of 1.00, 0.68, and 0.24 t ha^{-1} yr^{-1}, and 9.11%, 6.56%, and 6.45% of the total straw C input was converted to SOC in the FP, UL, and PU trials, respectively. The results suggested that the incorporation of rice straw was highly efficient on SOC accumulation and crop productivity in the uplands (as shown in the UL trial). We therefore recommend the *ex situ* incorporation of rice straw in the upland neighboring paddy fields as a way of utilizing excessive rice straw in the hilly area of subtropical China.

1. Introduction

Soil organic carbon (SOC) sequestration attracts great attention as one of the key measures to mitigate the continuous rise in atmospheric carbon dioxide (CO_2), which has been concerned as the major trace gas attributed to global warming (IPCC, 2001; Lal, 2007). The incorporation of crop residues has been recommended as an essential practice of maintaining soil productivity (Wild, 1988; Kushwaha et al., 2001; Singh et al., 2007) and enhancing the ability of farmlands to sequester SOC (Pan et al., 2003; Lackner, 2003; Powlson et al., 2008; Xu et al., 2011). It was estimated that, in developing countries, irrigated rice production can result in the accumulation of a maximum of 0.5 t C ha^{-1} yr^{-1} with the use of organic materials, fertilizers and plant-residue management (Niles et al., 2002). Lal (2004) stated that Chinese farming systems had the capacity to accumulate significant amounts of atmospheric CO_2 through effective management practices such as crop residue incorporation.

In China, there are approximately 33 million ha of paddy fields (data from the yearbook of Chinese agriculture) producing 197 million tons of rice grain annually and almost the same amount of rice straw (assuming a 1:1 ratio of rice grain to straw). Over the last 30 years, substantial accumulations of SOC in paddy soils in subtropical China have been reported, largely due to the *in situ* retention of rice residues (Pan et al., 2003; Wu, 2011). A meta-analysis of 26 long-term paddy field experiments showed that the retention of rice straw increased SOC by 0.41 Mg ha^{-1} yr^{-1} (Rui and Zhang, 2010). However, the incorporation of rice straw into the soil can also result in enhanced methane emissions from flooded paddy fields, thus contributing to global warming (IPCC, 2001). CH_4 has a greenhouse global warming potential (GWP) ~25 times that of CO_2 (25 CO_2 equivalents—CO_2e); it is estimated that 25–54 Tg (equivalent to 625–1242 Tg CO_2e in GWP) or 150–350 kg ha^{-1} (equivalent to 2.5–8.0 t CO_2e in GWP) of CH_4 are released globally from flooded

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Table 1
Locations and rotations of the flooded paddy (FP), paddy-upland rotated (PU), and upland (UL) trials and the general soil properties determined at the start year (1990 for FP, and 2000 for UL and PU).

Trials[a]	Location	Soil taxonomy[b]	Rotation	Clay (%)	pH	SOC ($g\,kg^{-1}$)	Bulk density ($g\,cm^{-3}$)
FP	111°30′E, 28°55′N	Hydragric Anthrosol	Rice–rice	32.5	5.7	15.00	1.25
PU	111°31′E 29°14′N	Ultisol	Rice–maize	34.5	5.5	8.16	1.50
UL	111°31′E 29°14′N	Ultisol	Sweet potato-rape	36.4	5.2	6.09	1.21

[a] FP, PU, and UL refer to the flooded paddy, paddy-upland and upland trials.
[b] FAO/UNESCO taxonomy.

paddy fields per year (Cao et al., 1998; Mosier et al., 1998; IPCC, 2001). CH_4 emissions from flooded paddy fields are closely associated with straw incorporation, as emissions mainly occur when freshly incorporated straw is rapidly decomposed (Huang et al., 2006; Malhi & Lemke, 2007; Zhang et al., 2012a). Thus, it is still unclear on the overall GWP caused by the *in situ* incorporation rice straw in flooded paddy fields. This addresses a several question that how rice straw can be treated in a way to keep its merit in increasing SOC stock meanwhile avoiding CH_4 emission.

After an 8-year long field trial, Zhu et al. (2010) reported that transferring the incorporation of rice straw from paddy fields to uplands resulted in a significant increase in SOC in the upland soils. This put forward a new practice in the utilization of extra rice straw. To explorer the possibility and advantages of this practice in hilly area of subtropical China, the long-term effectiveness of rice straw incorporation on SOC stocks and crop yields in typical agricultural cropping systems in this area should be fully evaluated under similar climatic conditions and soil types. Thus, the aim of the present study was therefore to evaluate the effectiveness of the *in situ* incorporation of rice straw in paddy systems (usually double rice or rice–maize) and the *ex situ* incorporation of rice straw in upland systems (double crop rotations) in increasing crop productivity and soil carbon stock; data from three field trials in flooded paddy, paddy-upland rotation, and upland cropping systems in a hilly area in subtropical China were used. Such data can provide firsthand information and valuable knowledge on the practices needed to improve rice straw management (e.g., the transfer incorporation) in the subtropics.

2. Materials and methods

2.1. Field trials

Three typical cropping systems, including double rice, maize–rice–clover and sweet potato–oilseed rape rotations, in subtropical China were adopted in flooded paddy (FP), paddy-upland rotated (PU), and upland (UL) fields, respectively. The experimental sites were located on a hilly area (Taoyuan County, Hunan province) characterized by a typical subtropical climate with an annual mean temperature of 17.2 °C, a rainfall of 1450 mm between 1990 and 2010, and soils developed from quaternary red earth. The soil properties of this site are listed in Table 1. While the three trials had different cropping systems, similar treatments were applied in each trial, namely a control treatment (Nil), chemical fertilizer (N, P, and K) applied alone (NPK), and chemical fertilizer and rice straw (NPK + R in FP, NP + R in UL and PU). Chemical fertilizers were applied at the same rate in the NPK and NPK + R treatments of the FP trial (Table 2). For the NP + R treatment in the UL and PU trials, the total input rates of N and P from chemical fertilizers and rice straw were equal to that of the N and P applied to the NPK treatment, but not chemical K, because the straw applied to the NP + R treatment provided sufficient K as the NPK treatment.

The FP trial was established on a valley paddy field in 1990, and the PU and UL trials on a flat paddy field and a sloped upland field (with a gradient of approximately 8°), respectively, in 2000. A total of three, four and six replicates were used for each of the treatments in the FP, PU and UL trials, respectively. Treatments of the same replicate were randomly arranged in an individual block of plots of $4 \times 8\,m^2$ for the FP trial, $3.9 \times 6\,m^2$ for the UL trial, and $4 \times 5\,m^2$ for the PU trial. Harvested crop residues were removed from all plots of the three trials. In the plots of the NPK + R treatment in the FP trial, rice straw was returned at an annual rate of $14.5\,Mg\,ha^{-1}$ before the soil was ploughed in early rice season. For the PU and UL trials, the plots of the NP + R treatment were surface-mulched with rice straw (collected from the local paddy fields) at a rate of $12.7\,Mg\,ha^{-1}\,yr^{-1}$ after the soil was ploughed and after the maize was sown (in April) in the PU trial or after the sweet potato seedlings were transplanted (in May) in the UL trial. After the crops were harvested (in October), the straw on the soil surface was ploughed into the plough player. In addition, winter clover grown in the PU trial was ploughed into the plough player in April.

For the NPK treatments in all three trials, urea, super-phosphate and KCl were applied to all crops (early and late rice, maize, sweet potato, oilseed rape) except clover. The total amounts of applied N, P, and K are shown in Table 2. The same types of chemical fertilizer, also shown in Table 2, were applied in NPK + R, NP + R and NPK treatments. Because of the boron deficiency of oil-seed rape, all treatments in the UL trial were supplemented with solubor ($Na_2B_8O_{13}\cdot 4H_2O$, containing $110\,g\,B\,kg^{-1}$) at an annual rate of $4.27\,kg\,ha^{-1}$ along with the NPK fertilizers starting in 2006.

The early and late rice, maize, sweet potato, oilseed rape, and red clover used in the trials were local varieties. Three to ten centimeters of water were maintained above the soil surface in the plots of the FP trial, although occasional drainage was also performed for rice earring. Other aspects of crop cultivation (e.g., sowing or transplanting) and field management (e.g., fertilizing, irrigating and weed controlling) for the three trials were performed according to the local farming practices. The yields of all the crops were determined annually; the grain of rice and maize, the seed of oilseed rape, and the above-ground biomass of red clover were on a 65 °C oven dry basis, while the tube of sweet potato were fresh weight.

2.2. Soil sampling and analysis

Ten soil cores were bulked from the plough layer (0–20 cm) in each plot at harvest of late rice, maize or sweet potato in the FP,

Table 2
Mean annual fertilizer inputs of the long-term trials ($kg\,ha^{-1}$)[a]

Trial	Treatment	Chemical N	Chemical P	Chemical K	Straw
FP	Nil	0	0	0	0
	NPK	218	52	173	0
	NPK + R	218	52	173	14,500
UL	Nil	0	0	0	0
	NPK	224	52	174	0
	NP + R	137	36	0	12,700
PU	Nil	0	0	0	0
	NPK	405	108	200	0
	NP + R	310	95	0	12,700

[a] See Table 1 for FP, PU, and UL.