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REGULAR ARTICLE

Rapid decrease of soil carbon after abandonment of subtropical paddy fields

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Abstract
Background and aims Paddy field abandonment has become a major concern in China, particularly among traditional rice-cultivation regions. Abandonment results in the alteration of many processes affecting C sequestration and turnover, but the final effects on C stocks remain unknown.
Methods To examine the effects of paddy abandonment on topsoil organic C (SOC) content and stocks, a long-term experiment was performed in subtropical China, examining an abandoned paddy field with different pre-abandonment fertilization history (from 1991 to 2006 years) and SOC gradients (from 19.2 to 22.0 g C kg^{-1}).
Results Paddy field abandonment significantly reduced the topsoil SOC content and stock (0–20 cm). Eight years after cultivation ceased, SOC content and C stock had decreased by 9.9–20.9% and 10.2–20.8%, respectively, yielding a mean annual loss rate of 0.30–0.60 g C $kg^{-1}\cdot yr.^{-1}$ and 0.50–1.15 t C $ha^{-1}\cdot yr.^{-1}$, respectively. Soils with higher initial SOC content were more sensitive to abandonment than soils with low SOC levels. Dissolved organic C (DOC) was more sensitive to abandonment, as evidenced by the faster decrease of DOC than SOC. The rapid reduction of SOC content, combined with a strong decrease in DOC, indicates that post-abandonment C inputs into the soil were far lower than the concurrent SOC mineralization. The SOC content decreases was likely because of the shift from anaerobic to aerobic conditions. This change leads to faster litter decomposition and SOC mineralization, accompanied with decreasing SOC retention or stabilization by soil aggregates, mineral or Fe redox processes.
Conclusion Abandonment of paddy soils leads to switch from a C sink to a C source, resulting in high C losses. The succession of grasses in abandoned fields did not compensate for the losses of soil C stocks.

Keywords Abandonment of paddy field · Soil organic carbon · Soil carbon stock · Weeds · Subtropical humid region

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Introduction

Land use change has strongly affected C cycles both regionally and globally (Lal 2008; Poeplau and Don 2013). Two reversible processes—conversion of natural vegetation to cropland and cropland abandonment leading to succession of natural vegetation—both change soil organic carbon (SOC) stocks and composition, exerting opposing effects on the SOC stocks (Guo and Gifford 2002). Numerous studies across climatic zones have shown that cropland abandonment and succession of natural vegetation results in C sequestration in soil (Guo and Gifford 2002; Christopher et al. 2011; Kurganova et al. 2015). Thus, cropland abandonment is an effective way to restore SOC and reduce CO_2 concentration in the atmosphere (Lal 2004; Zhang 2010; Kurganova et al. 2014). Given that the total abandoned land area worldwide is approximately 220 million ha (FAO 2013), these soils provide considerable potential for long-term C sequestration.

Paddy fields are artificial wetlands, with cultivation under surface irrigation during rice production (Gong 1999). Rice (*Oryza sativa* L.) is the most important cereal crop in China, representing 22.7% of the total area harvested in 2013 (FAO 2013). Paddy cultivation significantly alters the SOC pools (Pan et al. 2003; Huang and Sun 2006; Wu 2011). In paddy soils, SOC accumulation likely occurs because of intensive rice production, inputs of high level of plant residues, coupled with their slowed decomposition under anaerobic conditions (Kögel-Knabner et al. 2010). The mechanism underlying SOC stabilization is driven by occlusion into aggregates and phytoliths, as well as by interaction with clay minerals and iron oxides (Pan et al. 2008; Kögel-Knabner et al. 2010; Wissing et al. 2013).

Although the protection of agricultural land is a persistent priority in China, paddy field abandonment is becoming increasingly common (Shi and Li 2013). This issue also affects other parts of Asia, including Japan (Yagasaki and Shirato 2014; Li et al. 2016). The causes appear to be rapid urbanization, economic growth, and labor shortage resulting from rural-to-urban migration (Peng et al. 2009; Kong 2014; Xiong et al. 2014). For example, paddy field area has declined noticeably from 33 to 29 million ha during 1980–2010, with a reduction of around 0.5% per year (Xiong et al. 2014). Additionally, the country has seen a south-to-north shift of major rice-growing areas (Liu et al. 2013; Kong 2014). This predominantly involves abandoning traditional rice cultivation regions in subtropical China (Shi and Li 2013; Xie et al. 2014; Xiong et al. 2014). This abandonment is especially important in the low hilly regions, where paddy fields are sporadic and scattered among other fields and land use types. Here, abandoned paddy fields exist in patches, surrounded by cultivated paddy and non-paddy fields, which is different from the abandonment patterns in other regions of the world (Rey Benayas et al. 2007; Kurganova et al. 2015).

Paddy field abandonment alters the physical (aggregate formation/breakage), chemical (Fe redox), and biological (plant, microbial action) processes affecting C sequestration and turnover (Kögel-Knabner et al. 2010; Wissing et al. 2013). The alterations are due to large shifts in the environment: first, periodic flooding stops; second, management practices (tillage, fertilization, and cultivation) cease and natural vegetation succession occurs; third, the anaerobic environment of paddy field transforms into an aerobic environment. Because C input, SOM decomposition, and SOC stabilization mechanisms are all affected, the abandoned soil differs considerably from the original paddy soil. Importantly, paddy field abandonment is distinct from the abandonment of croplands that had been and remain under aerobic environments (Guo and Gifford 2002; Christopher et al. 2011; Kurganova et al. 2015). We hypothesized that these differences should also lead to differences in the mechanisms of soil C accumulation in the abandoned paddy fields.

The conversion of paddy fields to vegetable fields, upland and other cropland, or forests leads to net losses in the SOC stock (Cui et al. 2012; Wang et al. 2014; Yagasaki and Shirato 2014; Li et al. 2016). Furthermore, the anaerobic to aerobic conversion accelerates SOC decomposition and reduces residue C inputs to the soil. However, such trends are not consistent across all the abandoned sites. For example, Folgarait et al. (2003) reported that surface SOC (0–20 cm) decreased by 38% within 2 years of abandonment, but others found a significant increase in soil C storage near the surface of former paddies (Zhang et al. 2007; Seiji and Nobuhisa 2013). The contradictory results may be attributable to the abandonment duration, pre-abandonment management, belowground productivity, climate, and pre-abandonment SOC (Zhang et al. 2007; Seiji and Nobuhisa 2013; Wang et al. 2014).

Chronosequence and pair approaches have typically been used to investigate the post-abandonment SOC changes. However, these two approaches are associated with uncertainties because details about historical land use and pre-abandonment SOC levels tend to be unknown, even with consistent land use, and specific agricultural practices have changed over time (Christopher et al. 2011; Spohn et al. 2015). Strict site selection and sampling design when applying the two techniques would enhance their accuracy in describing the post-abandonment SOC trends (Christopher et al.

2011). In particular, long-term field experiments are ideal for strict pair and chronosequence studies.

We, therefore, used a long-term field paddy experiment (1991–2014, abandoned since 2007) on subtropical paddy soil to examine the pre- and post-abandonment trends in topsoil SOC content and stocks. Three main questions and hypotheses to address them were as follows: (*i*) How paddy abandonment alters soil C content and stock? We hypothesized a swift reduction in mineral soil C content; (*ii*) How do pre-abandonment SOC levels and fertilizer history influence the subsequent C content? We hypothesized that soils with greater pre-abandonment C levels would be more sensitive to abandonment; (*iii*) What are the main factors driving the soil C response to abandonment?

Materials and methods

Site description

The experimental abandoned paddy field was located in the Taoyuan Agro-ecology Experimental Station of the Chinese Academy of Sciences, Taoyuan County, Hunan Province (28°55′N, 111°26′E). This region has a subtropical humid monsoon climate, with mean annual precipitation of 1450 mm, mean annual temperature of 16.5 °C, and frost-free period of 283 days. Paddy fields are the dominant cropland here.

Abandonment experiment

We modeled local abandonment from 1991 to 2014 in paddy fields that had been cultivated by farmers for over 100 years before the experiment began. The design involved two stages: double rice cultivation (common in a humid subtropical climate) from 1991 to 2006 and abandonment from 2007 to 2014 (Fig. 1). During the cultivation stage, each field was administered one of the following four treatments: Con (control with no fertilizers), NK (N + K fertilizers), NP (N + P fertilizers), or NPK (N, P, K fertilizers). The fertilizers were applied as urea for N (292.5 kg N $ha^{-1}·yr.^{-1}$), calcium superphosphate for P (50.4 kg P $ha^{-1}·yr.^{-1}$), and potassium chloride for K (132.8 kg K $ha^{-1}·yr.^{-1}$). Four replicates were established using a randomized block design. Each 30-m^2 plot was enclosed within cement ridges set up in 1991.

During cultivation, the order of one-year crop rotation was: 1) first rice, 2) second rice, and 3) fallow; the crop season lasted from the end of April to the end of October, with the remaining months left for fallowing. During the abandoned stage, no field management occurred except the occasional burning in a few plots (replications 1 and 4) during 2008 and 2010**.**

The lack of significant differences in the SOC content across replications ($p < 0.05$) indicated that burning did not affect this variable. Furthermore, the cement ridges prevented most of the soil erosion and the sealing of hole in the cement when ploughing the guard row annually also stopped any long-term flooding. The abandoned paddy fields were watered depending on the precipitation, and were characterized by frequent wetting and dry cycles during the wet season (from April to July), and by dryness during the dry season.

Weeds (*Paspalum paspaloides*, *Murdannia triquetra*, and *Bidens frondosa*) dominated the abandoned paddy fields. Their soil was derived from the quaternary red clay. Initial soil samples (0–20 cm, in 1991) contained 16.5 $g·kg^{-1}$ organic C, 1.79 $g·kg^{-1}$ total N, 0.45 $g·kg^{-1}$ total P, 12.6 $g·kg^{-1}$ total K, 4.88 $mg·kg^{-1}$

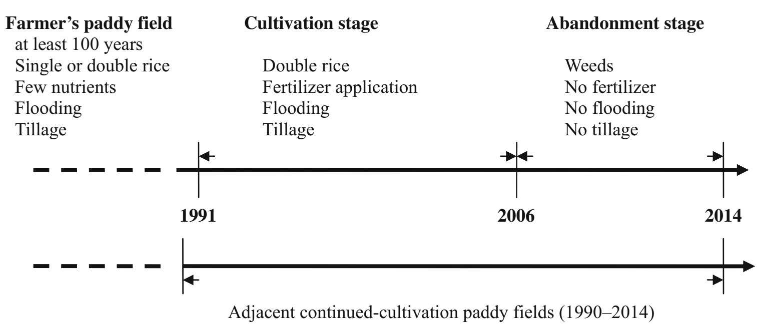

Fig. 1 Land use and management practices in experimental paddy fields (Taoyuan, Agro-ecology Experimental Station, CAS, China). The experimental site had been used as double-rice paddy fields by farmers for over 100 years before the experiment was established. The experiment included two stages: the double-rice cultivation stage (1991–2006) and the abandonment stage (2007–2014)

available P (Olsen P), and 59.7 mg·kg^{-1} available K (ammonium acetate extractable).

The abandoned paddy fields were compared with the adjacent, continuously cultivated paddy fields to eliminate the effects of year-to-year variation. These continued-cultivation fields cultivated the same rice varieties as the abandoned fields and included the same four fertilizer treatments (Con, NK, PK, and NPK), but rice was grown throughout the entire experimental period (1990–2014, and for more than 100 years previously). The SOC content (0–20 cm) was measured every four years from 1990 to 2014. The annual fertilizer application rates were 262.5 kg N ha^{-1} (1990–1996) or 182.3 kg N ha^{-1} (1997–2014), 39.3 kg P ha^{-1} (1990–2014), and 137.0 kg K ha^{-1} (1990–1996) or 197.2 kg K ha^{-1} (1997–2014).

Sampling and analysis

Sampling

Soil samples from the surface layer (0–20 cm) were collected in April 1991, before the spring plowing, and at every two years from 1998 to 2014. Each tested sample was a composite of six or nine subsamples taken at random points within a single plot. During the abandoned stage, organic litter was removed from the soil surface before sampling. Soil samples were air-dried and passed through a 2-mm sieve before analyzing the physical properties. The subsamples were ground through a 0.15-mm sieve for chemical analysis. The visible pieces of organic material were removed before and after grinding.

Three soil columns (20 cm × 20 cm area; 20 cm depth, or the depth of the pre- abandonment plow layer) were collected at random points in each plot to measure the vertical distribution of weed roots in July and August of 2012, 2013, and 2014. Litter was removed from the soil surface in the abandoned paddy fields before collection. Each column was split into 0–5 and 5–20 cm depths. Only total root biomass was measured due to the difficulty in separating dead and live roots. The visible weed roots were washed free of soil, dried at 75 °C, and weighed to calculate their dry mass.

Analyses

To determine the soil aggregate size, the soil samples were dispersed by soaking in $(NaPO_3)_6$ for 2 h and ultrasonic shaking for 15 min; the samples were then left to stand for 12 h. The aggregate size was determined with the Malvern MS2000 particle analyzer (Malvern Company, UK); volume percentages of macro-aggregates (50–2000 μm), small aggregates (2–50 μm), and micro-aggregates (< 2 μm) were calculated.

To determine the soil specific surface area (SSA), the root residues were carefully removed from the samples by passing through a 2-mm sieve (as described under "Sampling") and subjected to nitrogen adsorption at a liquid-nitrogen temperature of −196 °C in a Quadrasorb SI (Quantachrome Company, USA).

The dissolved organic carbon (DOC) was measured in air-dried soil samples, which were weighed and placed in 100-mL polypropylene centrifuge tubes. They were extracted in a 1:10 soil-to-water mixture for 5 h on an end-over-end shaker at an approximate shaking speed of 200 r/min, were subsequently centrifuged for 10 min at 8000 rpm, and then placed in a TOC-Vwp analyzer (Shimadzu Corporation, Japan).

The soil bulk density (BD) was measured using 100-cm^3 soil cores, collected from four random replicates in April 2014. Soil and plant organic C content was determined using the wet digestion method with potassium dichromate (Nelson and Sommers 1975). The C content of weed roots, rice stubble, and rice roots was 41.9, 43.0, and 36.8%, respectively.

Calculations

SOC sequestration or loss rate

The rate of change in the SOC content was calculated as the difference in the SOC content under a given treatment across the study years, divided by the duration (years), as follows:

$$\Delta C_{rate} = \Delta C_{cont}/(i_2 - i_1) \quad (1)$$

where ΔC_{rate} is the rate of change in SOC content (g C·kg·yr.$^{-1}$), and i is the time of measurements (years), and ΔC_{cont} is the difference in SOC content from year i_2 to year i_1.

Soil C storage and change rate

Surface soil C storage was calculated as follows:

$$C_s = \text{conc}i \times B_d \times H \quad (2)$$

where C_s is the surface soil C storage ($t{\cdot}ha^{-1}$), conc$i$ is the SOC content ($g{\cdot}kg^{-1}$), B_d is the soil bulk density ($t{\cdot}m^{-3}$), and H is the soil thickness (0.20 m). In this study, we assumed that the bulk density was stable throughout the abandonment stage because drastic soil disturbance did not occur during this time. Therefore, B_d measured during April 2014 (1.01 $t{\cdot}m^{-3}$) was used to calculate C storage in 2006.

$$\Delta C_{s\ rate} = \Delta C_s/(i_2 - i_1) \tag{3}$$

where $\Delta C_{s\ rate}$ is the rate of change in SOC storage ($t{\cdot}ha^{-1}{\cdot}yr.^{-1}$), i is the time of measurements (years), and ΔC_s is the difference in SOC storage from year i_2 to year i_1.

Total C stock of surface layer

Total C storage (C_{total}) of the surface layer (including plant root C and SOC) ($t{\cdot}ha^{-1}$) was calculated as follows:

$$C_{total} = C_s + C_{residue} \tag{4}$$

where C_s is the surface soil C storage ($t{\cdot}ha^{-1}$) and $C_{residue}$ is the plant biomass C ($t{\cdot}ha^{-1}$) remaining in the surface soil layer (0–20 cm). Before abandonment, $C_{residue}$ included C from rice roots and stubble (plowed into the soil yearly), but post-abandonment $C_{residue}$ only comprised weed root C. C from litter aboveground (except for DOC) was assumed not to have entered the soil because the decomposition was fast and no tillage occurred.

The average annual rice yields (1991–2006) were 5318, 6387, 6690, and 8948 $kg{\cdot}ha^{-1}$ for Con, NK, NP, and NPK treatments, respectively. In the adjacent cultivated paddy fields, the average ratios of rice stubble and roots to rice yields were 27.6 and 23.3%, respectively. Because negligible variability exists in the relationship between rice yield and crop residue production (Evans and Fischer 1999), rice yields were used as the basis of calculating rice root and stubble C.

Statistical analysis

Data were tested with one-way analysis of variance (ANOVA) in SAS 6.1 (SAS Institute Inc. Cary, USA). Significant differences between the means were evaluated at the 95% confidence interval using Duncan's multiple range test ($p < 0.05$). Graphs were prepared in Origin 7.5 (Originlab, Northampton, USA). The relationships between the variables were evaluated using correlation analysis.

Results

Soil organic carbon dynamics before and after abandonment

During the period of cultivation from 1991 to 2006, SOC increased from the initial values by 16.3–33.0% in all the treatments (Fig. 2a). The paddy field abandonment led to a significant decrease in the SOC content ($p < 0.05$, Fig. 2a). From 2006 to 2014, the SOC content decreased by 10.2–20.8%.

The post-abandonment SOC loss rates were clearly faster than the accumulation rates during cultivation. The

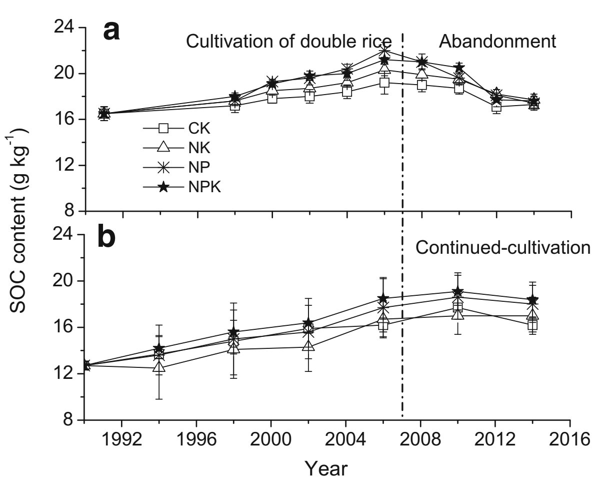

Fig. 2 Dynamics of SOC (± SE) content in experimental abandoned paddy fields (**a**) and continued-cultivation fields (**b**). The former contains two stages: the cultivation stage (1991–2006) and the abandonment stage (2007–2014). Con: no fertilizer; NK: N, K fertilizers; NP: N, P fertilizers; NPK: N, P, K fertilizers (all fertilization occurred during the cultivation stage). During abandonment, Con, NK, NP, and NPK represent the fertilization history during the cultivation stage

control soil (without fertilizer) increased the SOC contents (to 0.18 $g \cdot kg^{-1} \cdot yr.^{-1}$) during the 1991–2006 cultivation period, whereas fertilization additionally increased the sequestration rate (by 0.25–0.36 $g \cdot kg^{-1} \cdot yr.^{-1}$). During abandonment (2007–2014), the SOC content decreased sharply at rates of 0.33–0.57 $g \cdot kg^{-1} \cdot yr.^{-1}$. The highest SOC loss rate (0.63–1.41 $g \cdot kg^{-1} \cdot yr.^{-1}$) occurred 4–6 years post-abandonment in previously fertilized soil, and then the loss was reduced to 0.07–0.34 $g \cdot kg^{-1} \cdot yr.^{-1}$ after 6–8 years of abandonment. In unfertilized control soil, SOC accumulated at 0.11 $g \cdot kg^{-1} \cdot yr.^{-1}$ from 2012 to 2014 (Table 1).

Change in dissolved organic carbon

The paddy abandonment significantly decreased the DOC concentrations (Fig. 3) from 60.6–73.8 $mg \cdot kg^{-1}$ in the cultivated soil in 1998 and 2006 to 18.9–21.7 $mg \cdot kg^{-1}$ in the abandoned soil in 2014. In 2006 and 2014, the DOC concentration and the SOC content were significantly correlated ($p < 0.01$, Table 2). However, eight years post-abandonment, DOC decreased much faster (67.8–70.6%) than the total SOC. On average, the DOC proportions in SOC decreased post-abandonment, from 0.3% in 2006 to 0.1% in 2014.

Change of soil C stocks

The paddy soil abandonment significantly decreased the soil C stock (Fig. 4) by 10.2–20.8% in 2014 from the amount in 2006. In general, the post-abandonment rate of C storage loss ranged from 0.50 to 1.15 t C $ha^{-1} \cdot yr.^{-1}$.

We assumed that the soil bulk density would not change during abandonment. This assumption was supported by constant soil bulk density in the continued-

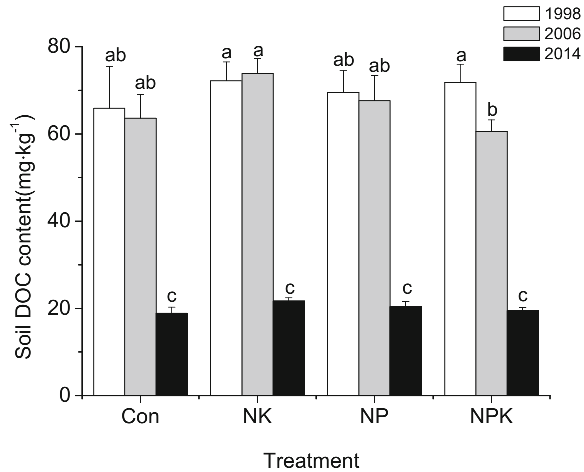

Fig. 3 Dynamics of soil DOC (dissolved organic C) content (± SE). Con: no fertilizer; NK: N, K fertilizers; NP: N, P fertilizers; NPK: N, P, K fertilizers (during the cultivation stage). During the abandonment stage, Con, NK, NP, and NPK represent the fertilization history. Lowercase letters indicate significant differences at $p < 0.05$ across all treatments in 1998, 2006, and 2014

cultivation paddy fields between the four treatments during 2006 and 2014 ($p > 0.05$; data not published). In these fields, the mean bulk density during 2006 was 1.04 $t \cdot m^{-3}$, nearly identical to the mean in the abandoned paddy fields during 2014. Therefore, C storage in the abandoned paddy fields underwent similar decreases as the SOC content (Table 1). The greatest losses occurred 4–6 years post-abandonment (2010–2012) with rates of 1.28–2.86 $t \cdot ha^{-1} \cdot yr.^{-1}$, which were much higher than the 2007–2010 (0.38–1.60 $t \cdot ha^{-1} \cdot yr.^{-1}$) and 2012–2014 rates (0.14–0.69 $t \cdot ha^{-1} \cdot yr.^{-1}$). Likewise, soil C storage in 2014 did not differ across fertilization histories ($p > 0.05$), despite long-term fertilization practices (NK, NP, or NPK, or Con) exerting an effect on pre-abandonment C storage amounts (Fig. 4).

Table 1 SOC content (± SE), accumulation, and loss rate. Con: no fertilizer; NK: N, K fertilizers; NP: N, P fertilizers; NPK: N, P, K fertilizers during cultivation of double rice; post-abandonment Con, NK, NP, NPK represent the fertilization history

Tre.	SOC content (g $C \cdot kg^{-1}$)			SOC sequestration rate (g C $kg^{-1} \cdot yr.^{-1}$)		Rate of SOC change after abandonment (g $C \cdot kg^{-1} \cdot yr.^{-1}$)			
	1998	2006	2014	1991–2006	2006–2014	2006–2008	2008–2010	2010–2012	2012–2014
Con	17.2 ± 0.6e	19.2 ± 0.7 cd	17.3 ± 0.3e	0.18	-0.25	-0.10	-0.18	-0.81	0.11
NK	17.6 ± 0.3e	20.3 ± 0.3bc	17.7 ± 0.5e	0.25	-0.33	-0.22	-0.20	-0.63	-0.26
NP	17.6 ± 0.4e	22.0 ± 0.5a	17.4 ± 0.6e	0.36	-0.57	-0.50	-0.69	-0.75	-0.34
NPK	18.0 ± 0.3de	21.2 ± 0.5ab	17.6 ± 0.4e	0.31	-0.46	-0.09	-0.25	-1.41	-0.07

Lower-case letters indicate significant differences in SOC at $p < 0.05$

Table 2 Correlations among macro-aggregate, small aggregate, micro-aggregate, SOC (soil organic C), and DOC (dissolved organic C) in 2006 and 2014

	DOC	Micro-aggregate	Small aggregate	Macro-aggregate
SOC	0.896**	-0.458	-0.941**	0.973**
DOC		-0.184	-0.981**	0.960**
Micro-aggregate			0.212	-0.385
Small aggregate				-0.983**

** indicate significant differences of at $p < 0.05$ and $p < 0.01$, respectively. Micro-aggregate: diameter < 2 μm; Small aggregate: diameter 2–50 μm; Macro-aggregate: diameter 50–2000 μm

Change in soil aggregate and soil specific surface area

During rice cultivation, the volume percentage of macro-aggregates or small aggregates in the total aggregates was generally stable across all the treatments and years (1998 and 2006) (Table 3). The volume percentage of micro-aggregates significantly decreased ($p < 0.05$) from 1998 to 2006 for all the treatments except control (Table 3). Paddy field abandonment significantly decreased the macro-aggregate percentage by 36.3%, 8 years post-abandonment, and the macro-aggregates were broken into small- and micro-aggregates, strongly increasing the percentage of small-aggregates ($p < 0.05$, Table 3). The proportion of macro-aggregates decreased similarly to the decrease in SOC content ($p < 0.01$, Table 2). Consequently, the percentage of small- and micro-aggregates increased with the decrease in SOC (Table 2).

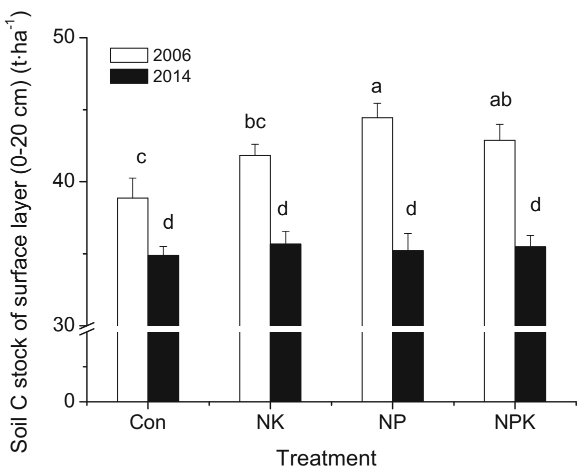

Fig. 4 C stock (± SE) of the surface soil layer (0–20 cm) pre- and post-abandonment. Con: no fertilizer; NK: N, K fertilizers; NP: N, P fertilizers; NPK: N, P, K fertilizers (during the cultivation stage). During the abandonment stage, Con, NK, NP, and NPK represent the fertilization history under cultivation. Lowercase letters indicate significant differences at $p < 0.05$ across all treatments before (in 2006) and after (2014) abandonment

The breakage of macro-aggregates into small- and micro-aggregates increased the soil specific surface area (SSA). The SSA in 2014 was 4.3–10.5% greater than in 2006, a significant change for soils with NP and NPK history ($p < 0.05$, Fig. 5). Significant positive correlations were found between SSA and micro-aggregate volume percentage ($r^2 = 0.347$, $p < 0.05$, $n = 12$). Additionally, significant negative correlations were present between the SSA change and volume percentage of small- and micro-aggregates ($p < 0.05$ and $p < 0.01$, respectively; data not shown). The decreasing SOC concentrations may have led to the weakening linkage across the aggregates, which in turn increased the volume percentage of smaller aggregates. Significant negative correlations were found between SSA and SOC ($r^2 = 0.379$, $p < 0.05$, $n = 12$).

Total C stocks

Comparing the total pre- and post-abandonment C stocks (including mineral and root C stock) indicates a post-abandonment conversion of the soil from a C sink to a C source, because grass succession in abandoned fields contributes to the roots C. During 2012–2014, the average root C in the abandoned paddy soil was clearly higher than before abandonment (Table 4). However, 8 years post-abandonment, weed root C did not compensate for the decreases in total C stocks, including the decrease in soil C stocks below the O (litter) horizon. Thus, the total C stocks in 2014 was 1.0–13.3% lower than the amount in 2006 (Table 4). Overall, the total C stock in the plow (Ah) horizon meant that the paddy soil switched from a C sink to a C source, post-abandonment. This was confirmed by the fact that even greater

Table 3 Volume percent (± SE) of soil aggregation. Con: no fertilizer; NK: N, K fertilizers; NP: N, P fertilizers; NPK: N, P, K fertilizers during cultivation of double rice. After abandonment Con, NK, NP, NPK represent the fertilization history

Tre.	Volume of micro-aggregate (%)			Volume of small-aggregate (%)			Volume of macro-aggregate (%)		
	1998	2006	2014	1998	2006	2014	1998	2006	2014
Con	13.8 ± 0.3ab	13.8 ± 0.8ab	12.3 ± 0.6bc	65.9 ± 1.6c	69.1 ± 0.7b	75.3 ± 0.3a	20.3 ± 1.7ab	17.2 ± 0.8b	12.5 ± 0.6c
NK	13.5 ± 0.7ab	11.5 ± 0.7c	12.1 ± 0.5bc	66.2 ± 1.2bc	68.3 ± 1.6bc	75.4 ± 1.6a	20.3 ± 1.7ab	20.2 ± 1.5ab	12.3 ± 1.3c
NP	14.2 ± 0.8a	11.4 ± 0.9c	12.3 ± 0.3bc	66.6 ± 1.0bc	67.6 ± 0.5bc	75.9 ± 0.6a	19.2 ± 1.7ab	21.0 ± 0.9a	11.8 ± 0.4c
NPK	14.1 ± 0.2a	11.7 ± 0.5c	12.3 ± 0.3bc	66.7 ± 0.2bc	68.2 ± 0.9bc	74.7 ± 0.5a	19.2 ± 0.3ab	20.1 ± 0.6ab	13.0 ± 0.7c

Different lowercase letters indicate significant differences at $p < 0.05$. Micro-aggregate: diameter < 2 μm; Small aggregate: diameter 2–50 μm; Macro-aggregate: diameter 50–2000 μm

losses of total C stocks were found in soils with larger pre-abandonment SOC (Table 4).

Discussion

SOC accumulation

SOC accumulation in paddies has been largely attributed to an increase in rice biomass production over the last few decades, which returns a greater amount of root and stubble residues to the soil (Huang and Sun 2006; Sun et al. 2009; Wu 2011). In the past four decades, rice yield in China has more than doubled: 3000 kg·ha^{-1} in 1970, 4300 kg·ha^{-1} in 1981, and 6500 kg·ha^{-1} in 2010 (Grassini et al. 2013; Xiong et al. 2014). The increased yield is likely due to the development of high-yield varieties and improved crop management practices, such as the use of mineral fertilizers, organic fertilizer (e.g. manure) application, and irrigation (Huang and Sun 2006; Sun et al. 2009; Wu 2011). Higher crop productivity results in greater organic C input into the soil, adding to the sequestrated C in paddy systems (Liu et al. 2014b). These factors could explain why C sequestration has steadily increased in subtropical China recently, even in paddy soils with long irrigation histories.

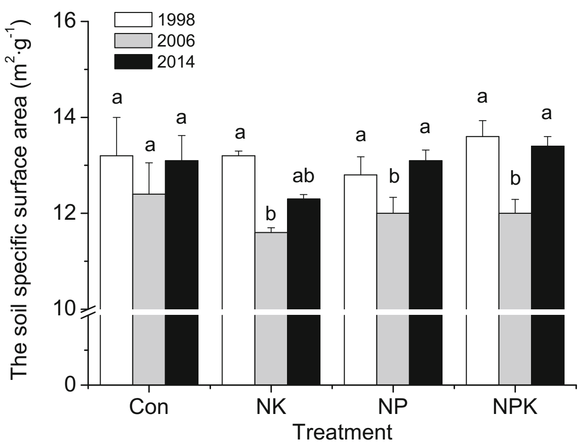

Fig. 5 Dynamics of soil specific surface area (± SE). Con: no fertilizer; NK: N, K fertilizers; NP: N, P fertilizers; NPK: N, P, K fertilizers during the cultivation. During the abandonment stage, Con, NK, NP, and NPK represent the fertilization history. Lowercase letters indicate significant differences at $p < 0.05$ across all treatments in 1998, 2006, and 2014

SOC increased after the paddy fields were converted to our experimental fields in 1991 (Fig. 2a), a pattern we also attributed to improvements in the local (Hunan province) rice varieties and crop management. Hunan's mean rice yield increased from 2300 kg·ha^{-1} during 1949–1960 to 3900 kg·ha^{-1} during 1971–1980. Fertilizer application also rose markedly during this period: whereas there was no application in 1949–1953, it was 13 kg·ha^{-1} in 1954 and 270 kg·ha^{-1} in 1983 (Yearbook of Hunan Statistics 1983). After our experimental setup, we changed the rice to an improved variety every two or three years from 1991 to 2006, in keeping with local farming practices. This procedure could explain the steady increased in C sequestration, despite a century-long history of the paddy fields.

Response of SOC content and stock to abandonment

Total SOC content decreased quickly after paddy field abandonment (Fig. 2a), in support of our first hypothesis. The pre-abandonment SOC level affected the rate of SOC loss in the abandoned paddy fields: the SOC response to abandonment was more pronounced for soils with higher initial SOC contents. Moreover, soils with different fertilizer histories did not significantly vary in their SOC eight years post-abandonment. Both

Table 4 C storage (± SE) in the surface soil layer (0–20 cm) before and after abandonment. Con: no fertilizer; NK: N, K fertilizers; NP: N, P fertilizers; NPK: N, P, K fertilizers during cultivation of double rice. After abandonment Con, NK, NP, NPK represent the fertilization history

Tre.	C storage in 2006($t \cdot ha^{-1}$)			C storage in 2014($t \cdot ha^{-1}$)				Difference from 2006 to 2014 (%)
	Residue C	Soil C	total	root C (0–5 cm)	Root C (5–20 cm)	Soil C	total	
Con	1.2 ± 0.0c	38.9 ± 1.4b	40.0 ± 1.4b	3.4 ± 0.5a	1.3 ± 0.3a	34.9 ± 0.6a	39.6 ± 0.2a	-1.0
NK	1.3 ± 0.0b	41.0 ± 0.9ab	42.3 ± 0.9ab	4.2 ± 1.0a	1.3 ± 0.4a	35.7 ± 0.9a	41.2 ± 1.9a	-2.6
NP	1.4 ± 0.0b	44.4 ± 1.0a	45.8 ± 1.0a	3.3 ± 0.7a	1.2 ± 0.7a	35.2 ± 1.2a	39.7 ± 0.7a	-13.3
NPK	1.8 ± 0.0a	42.9 ± 1.1a	44.7 ± 1.1a	4.0 ± 1.03a	1.6 ± 0.5a	35.5 ± 0.8a	41.1 ± 1.5a	-8.2

C storage of surface layer in 2006 included the mineral soil and rice residue (stubble and roots). In 2014, C storage included mineral soil and weed roots. Different lower-case letters indicate significant differences at $p < 0.05$

these results support our second hypothesis, stating that pre-abandonment SOC and fertilizer history would affect the C loss rates.

The rapid SOC reduction was primarily due to the paddy field abandonment, and not because of other factors, such as climate. Specifically, the continuously cultivated paddy fields exhibited similar SOC accumulation trends as the abandoned paddy fields during the rice cultivation stage in the latter. Moreover, SOC generally remained stable in continued-cultivation paddy fields even later in the experiment, contrasting the rapid decrease in the abandoned paddy fields.

Typically, SOC rapidly decreases when natural vegetation is converted to cropland, whereas cropland abandonment to natural vegetation enhances the SOC accumulation (Kurganova et al. 2015). However, this standard pattern is reversed under paddy field abandonment or conversion to other land use types. Both the present and previous studies (Cui et al. 2012; Wang et al. 2014) have found that paddy abandonment (or conversion) rapidly decreases the SOC content. This decrease may be attributable to the fact that paddy fields in the humid areas already contain SOC levels near the maximum as compared to the other land use in the same region (Wu 2011). Hence, the post-abandonment or post-conversion SOC in the paddy fields are expected to decrease in the humid regions. We note, however, that paddy management does not necessarily enhance the SOC sequestration due to the differences in residue management (OM inputs) between the paddy and non-paddy sites (Winkler et al. 2016). This observation suggests that SOC change after the paddy field abandonment might be diverse, mainly because of the variation in soil types, initial SOC level, abandonment duration, and local management under distinct climatic conditions.

Drivers of SOC reduction after paddy abandonment

Paddy abandonment was the main driver of soil C loss, which was caused by the anaerobic-to-aerobic conversion of soil and subsequent differences from paddy soil in physical, chemical, and biological processes (Kögel-Knabner et al. 2010).

Abandonment significantly altered the physical processes in the former paddy fields, specifically related to the shift from periodic anaerobic and aerobic conditions to the year-round aerobic conditions. Repeated puddling (tillage) over many years reduces the number of small coarse- and meso-pores in soil, while increasing the number of micropores (Eickhorst and Tippkötter 2009). After abandonment, the lack of flooding and tillage leads to the increase of soil O_2 density through macropore formation by dead roots, soil organism (e.g., earthworm) activities, and surface-layer cracking. Moreover, the anaerobic-to-aerobic conversion causes the destruction of macro-aggregates and increases in the specific surface area of soil, both of which may further enhance the oxidation potential. Thus, the reversal of physical processes after paddy abandonment favors SOC decomposition.

Post-abandonment physical processes also significantly affect the chemical processes, specific to the redox state (Thompson et al. 2006; Kögel-Knabner et al. 2010). Retention of dissolved organic matter (DOM) on mineral phase and subsequent stabilization against the microbial decay largely depend on the redox state. High concentrations of DOM in post-flooding paddy soils enhance the changes and the release of structural iron in clay minerals, and support the formation of ferrihydrite (Kögel-Knabner et al. 2010). DOM stabilization in paddy soils occurs when precipitated by ferrihydrite (Fe^{3+}). These Fe oxyhydroxides are less susceptible to anaerobic dissolution, maintaining their capacity to retain and stabilize the DOM (Kögel-Knabner et al. 2010). After paddy abandonment and increased aerobic conditions, the decrease in the release of structural iron in clay minerals and the formation of ferrihydrite, as well as dehydration of ferrihydrite weaken the DOM retention and stabilization. Because red soil in subtropical China is iron-rich, the post-abandonment anaerobic-to-aerobic conversion leads to Fe^{3+} becoming the most important element (after oxygen) in the former paddy soils for oxidizing the organic matter (Yao et al. 1999).

The final factor affecting C sequestration in the abandoned paddy soil was the change of biological processes. Most C inputs into the abandoned paddy soil were from weed roots; very little aboveground litter entered the soil due to the lack of tillage and fast decomposition caused by high temperature, humidity, and aerobic environment. The greater amounts of weed-root C and lower SOC content in the abandoned fields suggest that the conversion rate of weed-root C to SOC was far lower than the C decomposition rate, even taking into account the fact that weed-root C was higher than the rice residue C. Under similar climatic conditions and the same soil types, the conversion ratio of the total straw-C input to SOC was lower in an upland (6.6% of straw-C conversion to SOC) and a paddy-upland rotation trial (6.5%) than in a flooded paddy (9.1%) (Liu et al. 2014a). In the present study, over 75% of weed-root C was present in the top 5 cm of soil, allowing for accelerated decomposition of dead roots and maintenance of a low C conversion ratio. Additionally, the decreasing C/N ratio of litter input to soil, from 69 in the rice residue to 50 in the weeds roots (data not shown), also enhanced the SOC and OM decomposition.

In summary, changes to all the three process groups under aerobic conditions affected the balance between C input and output through dampening of the SOC stabilization and enhancement of the SOC decomposition. Comparing with the other land use types, the paddy SOC is more labile and vulnerable to release under aerobic conditions due to a high DOC content and microbial biomass (Cui et al. 2012). Generally, the increased oxidation potential, post-abandonment, enhances the SOC decomposition; in this study, we demonstrated that the labile SOC was indeed more sensitive to abandonment, given the faster decrease of DOC compared to SOC.

The greater aggregate stability and the enrichment of C in the macro-aggregates are also the major reasons for higher C sequestration capacity of the paddy soil (Pan et al. 2008; Wissing et al. 2013). Residue retention increases the aggregation, which depends on the residue quantity and quality (Chivenge et al. 2011). Under aerobic conditions, coupled with increased weed-root C litter, the macro-aggregates were destroyed and the aggregate stability was weakened. This pattern suggests that both the decreased SOC content and input could drive macro-aggregate destruction and the reduction of macro-aggregate formation. Because broken macro-aggregates form smaller aggregates, the destruction also accelerates the decomposition of encapsulated particulate organics by exposing the small aggregates to increased O_2 content (or partial pressure). This conclusion is demonstrated by post-conversion C decrease in paddy, which was mainly attributed to C loss from the breakdown of water-stable macro-aggregates (Wang et al. 2014). However, because macro-aggregate destruction lowers the SOC, and decreased SOC can lead to reduced macro-aggregate formation, it is still unclear which of these factors drive C loss and which is an outcome of C loss during both the interactions.

In general, increased decomposition—rather than decreasing organic C input—was the likely driver of SOC reduction in the abandoned paddy soils, aided by the decreasing SOC interaction with clay minerals and iron oxyhydroxides. These changes were due to the anaerobic-to-aerobic shift after the abandonment, which caused alterations in the major physical, chemical, and biological processes. In contrast, cropland abandonment in arid and semiarid regions are associated with SOC increase, a phenomenon driven by decreased SOC decomposition, reduction of soil erosion, increasing root C input, and enhanced SOC stabilization in aggregates (Guo and Gifford 2002; Christopher et al. 2011; Novara et al. 2014).

Conclusions

Paddy field abandonment in a humid subtropical climate rapidly decreased the SOC content by 10.2–20.8% of its initial content within eight years of ceasing the cultivation. The mean annual rate of SOC content and C stock losses were 0.30–0.60 g C $kg^{-1}\cdot yr.^{-1}$ and 0.50–1.15 t C $ha^{-1}\cdot yr.^{-1}$, respectively. The rate of SOC loss was 1.5–1.8 times higher than the C sequestration rate during cultivation. The DOC decreased much faster (67.8–70.6%) than the SOC.

The rapid decrease in C stock was mainly caused by the anaerobic-to-aerobic conversion, which increased the decomposition and reduced the SOC input. This change also reduced the interactions of SOC with clay minerals and iron oxyhydroxides, as well as decreased the SOC stabilization within the soil aggregates.

Paddy field abandonment carries a high risk of soil C loss, and soils with larger initial SOC content are more sensitive to abandonment. Weeds established on abandoned fields do not compensate for the decrease in SOC, resulting in paddy fields shifting from a C sink to a C source. Therefore, the continued cultivation of paddy fields with high soil C sequestration is critical for maintaining the SOC stocks.

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