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Incorporation of rice straw carbon into dissolved organic matter and microbial biomass along a 100-year paddy soil chronosequence

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ABSTRACT

Dissolved organic matter (DOM) and microbial biomass (MB) are small but reactive pools of soil organic matter (SOM). The incorporation of carbon (C) from rice residue into DOM and MB in paddy soils under aerobic condition when rice straw remains in the field is poorly understood. A one-year incubation experiment was conducted, in which ^{13}C-labelled rice straw was added to a cultivation chronosequence of paddy soils ranging from 0 to 100 years. Rice straw was rapidly decomposed during the first 30 days, after which 73% of the added straw C, on average, was retained in the soil and 46% of the straw C remained in the soil after one year. Throughout the entire incubation period, 0.2–0.9% of the added straw C was incorporated into DOM, and 2–5% was recovered in MB. The paddy cultivation age strongly affected the straw contribution to the organic C pools. In barren land (0 year), 32–60% of the DOM was derived from straw C, while 13–30% of the DOM was derived from straw C in 5–100-year paddy soils. On average, straw C contributed to 88% of the MB in barren land, 50% in 5-year soil, and 13% in 100-year soil. Consequently, over the duration of paddy cultivation, the contribution of rice straw C to the MB decreased, while the contribution of SOM increased. Our study has indicated that DOM in paddy soils mainly originates from SOM rather than from added plant residues but that plant residues are an important C source for microorganisms.

1. Introduction

Maintaining soil C stocks is important for sustainable agricultural development and the mitigation of global warming by sequestrating atmospheric CO_2 belowground (Lal, 2004; Li et al., 2005). The return and incorporation of crop residues into soil is a widely used technique to maintain the organic C content in cropland, thereby improving soil fertility through the enhancement of physical, chemical and biological properties (Hadas et al., 2004; Lian et al., 2016). Understanding the dynamics and fate of crop residue C in soil helps to clarify the mechanisms of C sequestration and soil fertility development.

Crop residues contain readily decomposable C, such as hemicelluloses and pectin, providing substrates for soil microbes (Lorenz and Lal, 2005). The crop residue C passes through the soil microbial biomass at least once, is transferred from one C pool to another, and is finally mineralized to CO_2 (Ryan and Aravena, 1994; Williams et al., 2006). Undecomposed crop residues will remain in the soil and contribute to the soil C stock (Lorenz and Lal, 2005, Majumder and Kuzyakov, 2010). Dissolved organic matter (DOM) and microbial biomass (MB) are small but reactive pools of soil organic matter (SOM) (Liang et al., 2011; Pabst et al., 2013). Dissolved organic C is usually < 1% of the soil organic C, while microbial biomass C composes 2–3% (Jenkinson and Ladd, 1981; McGill et al., 1986; Zhao et al., 2008). Both DOM and MB turn over more rapidly and respond more quickly to soil management than total SOM and most other C pools (Blagodatskaya et al., 2011a; Chen et al., 2009; Guillaume et al., 2016). Based on stable isotope ^{13}C data, the fate of crop residue-derived C in SOM pools can be exactly traced. In a Luvisol (FAO Classification), 0.01% of added maize C was detected in DOM, 2% was present in MB, 21% was retained in soil, and 73% was released as CO_2 after incubation for 240 days (De Troyer et al., 2011). Another study found that 0.19–0.34% of maize C was present in DOM, 2.4–3.7% was present in MB, and 28% was retained in soil one year later (An et al., 2015). These and nearly all other long-term laboratory and field investigations have

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focused solely on upland soils.

Paddy soil is one of the most important agricultural soils in Southeast Asia, most of which are distributed in tropical and subtropical areas (Huke and Huke, 1997). Large amounts of rice (*Oryza sativa* L.) residues are produced and remain in the field as the major organic C input. The incorporation of rice residues into soil is beneficial to the succeeding plant growth and organic C accumulation (Mandal et al., 2004). It has become increasingly common to leave rice residues in the paddy field directly after grain harvest using a combine harvester. Soils are usually aerobic after the rice harvest and during the winter fallow season. Except for some short-term incubation studies that traced rice residue C in submerged or anaerobic paddy soils (Katoh et al., 2005; Ye and Horwath, 2017), there is a dearth of information regarding the distribution of residue C during aerobic degradation.

Previous studies have focused on the dynamic changes in physical, chemical, and microbial characteristics during paddy soil development using chronosequences (Li et al., 2003; Li et al., 2005; Liu et al., 2016; Li et al., 2017). However, the decomposition dynamics, sequestration, and distribution of rice residues in the organic matter pools of paddy soil chronosequences are unclear. In this study, ^{13}C-enriched rice straw was added to a cultivation chronosequence of paddy soils and incubated for one year under aerobic condition. We hypothesized that the duration of paddy cultivation affects the decomposition and fate of added straw C. The objectives of the study were to (1) trace the decomposition of rice straw and quantify the amount of straw C incorporated into various C pools and (2) estimate the effects of paddy cultivation age on the incorporation of straw C into various organic C pools.

2. Materials and methods

2.1. Site description and soil sampling

The study was conducted at the Yingtan National Agroecosystem Field Experimental Station of the Chinese Academy of Sciences in Yujiang County, Jiangxi Province, China (28°15′30″N, 116°55′30″E). This region has a typical subtropical monsoon climate, with a mean annual temperature of 17.6 °C and precipitation of 1795 mm. The paddy field study plots, which were no more than 1000 m apart, have been cultivated from barren land for double rice cropping (*Oryza sativa* L.) over time scales ranging from 5 to 100 years (Table 1). The implementation of agriculture management practices, such as flooding irrigation and fertilizer application, was almost the same in all fields. Straw residues were returned to the soil after rice harvesting in the last 30 years. The adjacent barren land was chosen as a control, with all paddy fields initially developed from this land, and this land represented 0 year of paddy field cultivation. All soils, classified as typical Ultisols (USDA Soil Taxonomy), were derived from Quaternary red clay. The paddy soil chronosequence was established according to the sampling records at the experimental station and a consultation from at least three local experts. Three field plots were selected within each paddy soil age class and the adjacent barren land.

Sampling was conducted in late November 2015, which was shortly after the late rice harvest when rice paddies were aerobic. Five random surface soil cores (0–20 cm) were collected from each field to compose one sample. The fresh soil samples were air-dried and sieved (2 mm) after visible crop roots were removed. Subsamples were stored in plastic bags at room temperature. The soil properties are presented in Table 1.

2.2. Incubation experiment

The ^{13}C-labelled rice straw used in this study was obtained using four rounds of $^{13}CO_2$ pulse-labeling across the rice growth stages in 2013 (see details in Liu et al., 2015). Sampled mature rice straw was dried to a constant weight at 70 °C, and then ground and sieved through a 0.5 mm sieve prior to laboratory incubation. The rice straw contained 387 g kg^{-1} organic C and 19.7 g kg^{-1} total nitrogen (N), with a δ^{13}C value of 797‰.

An air-dried equivalent of 120 g oven-dried soil and 1.2 g ^{13}C-enriched rice straw (corresponding to an addition of 3.87 mg C g^{-1} soil) were thoroughly mixed and placed in 500 mL plastic pots. The soil water content was adjusted to a 60% water holding capacity with deionized water. All pots were covered with sterile membranes that permits gaseous exchange to maintain aerobic conditions and then incubated in the dark at 25 °C. Control soils without rice straw were prepared at the same time. Each treatment had twelve replicates. Throughout the entire course of the incubation, deionized water was added every seven days to maintain a constant soil moisture content. On days 30, 90, 180 and 360 after incubation, three replicates were randomly and destructively sampled from each treatment. One portion of a fresh soil sample was analyzed to determine the DOM and MB contents and their δ^{13}C signatures within three days, and another portion was air-dried, ground, and sieved for total SOM content analysis.

2.3. Microbial biomass and dissolved organic matter

The soil MB was determined by the fumigation-extraction method (Vance et al., 1987). A moist soil equivalent of 15 g oven-dried soil was fumigated for 24 h at 25 °C with ethanol-free chloroform. After removal of the chloroform, the fumigated soil was extracted with 60 mL 0.05 M K_2SO_4. An equivalent amount of unfumigated soil was also extracted when fumigation commenced. The total organic C (TOC) content of the soil extracts was determined using an automatic analyzer (Multi N/C 3100 TOC/TN, Analytik Jena AG, Jena, Germany). According to previous studies, the organic C content in K_2SO_4 extracts of nonfumigated soils was used as the fraction of DOM (Domanski et al., 2001; Novara et al., 2014). Microbial biomass C was calculated as the difference in the amount of organic C between the fumigated and nonfumigated soils using a correction factor (k_{EC}) of 0.45 (Vance et al., 1987; Wu et al., 1990). The K_2SO_4-extract aliquots (20 mL) were freeze-dried for the determination of δ^{13}C signatures.

Table 1
Properties of the soils used for the paddy chronosequence.

Cultivation	pH	Organic C	Total N	δ^{13}C	Microbial biomass	Clay
Age		(g kg^{-1})	(g kg^{-1})	(‰)	(mg C kg^{-1})	(%)
0 y	4.94 ± 0.07c	2.01 ± 0.03 d	0.40 ± 0.01 d	−25.3 ± 0.3 a	25 ± 3 d	47.7 ± 1.5 a
5 y	5.25 ± 0.03 a	11.29 ± 1.70c	1.10 ± 0.11c	−25.5 ± 0.8 a	226 ± 34c	42.3 ± 2.2b
15 y	5.14 ± 0.05 ab	12.12 ± 0.36c	1.27 ± 0.01c	−25.8 ± 0.1 a	272 ± 13c	39.3 ± 0.4b
30 y	5.06 ± 0.04 bc	17.35 ± 0.88b	1.72 ± 0.08b	−26.3 ± 0.2 a	393 ± 17b	31.7 ± 0.7c
100 y	5.09 ± 0.02b	26.67 ± 0.65 a	2.66 ± 0.06 a	−28.4 ± 0.0b	1611 ± 90 a	25.7 ± 0.9 d

All values are the means ± standard errors, n = 3. Lowercase letters in the same column indicate significant differences ($p < 0.05$). The terms 5 y, 15 y, 30 y and 100 y represent the duration of paddy field cultivation, and 0 y refers to barren land.