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Effects of Flooded Rice Cultivation on Soil Organic Carbon and Active Organic Carbon Content: A Microcosm Experiment

Bingjie Shen[1,2], Zhenke Zhu[2], Hongzhao Yuan[2], Jiurong Wang[2], Tida Ge[2], Mingli Chen[1], Xiaofu Wu[1] & Jinshui Wu[2]

[1] College of Environmental Science and Technology, Central South University of Forestry and Technology, Changsha, China

[2] Key Laboratory of Agro-ecological Processes in Subtropical Region, Institute of Subtropical Agriculture, Chinese Academy of Sciences, Changsha, China

Correspondence: Mingli Chen, College of Environmental Science and Technology, Central South University of Forestry and Technology, Changsha 410004, China. Tel: 86-731-8461-9736. E-mail: chml18@163.com

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Abstract

Information on carbon (C) dynamics and allocation in plant–soil system is essential to understand the terrestrial C cycle. Our aims were to determine the effects of rice growth on soil organic carbon (SOC), dissolved organic carbon (DOC) and microbial biomass carbon (MBC) content. For this a pot microcosm experiment in growth chamber was conducted with soils planted or unplanted with rice. The experiment lasted for 80 days. The SOC content increased both in unplanted and rice-planted soils over the incubation period. The increasing amount of SOC in rice-planted soil was larger than that of in unplanted soil, indicating that growing rice on bulk soil enhanced the function of soil as a carbon poo1. The DOC enhanced significantly ($P < 0.05$) compared to the zero time (Day 0 (CK)) both in planted soils and unplanted soils during 80 days of incubation. The DOC concentrations in planted soils were much larger than that of unplanted soils, suggesting the release of soluble root exudates from rice roots. However, MBC declined both in unplanted soil and rice-planted soil after incubation for 80 days, compared with the start of experiment. The results suggest that MBC dynamics in rice soil are largely controlled by organic substances released from rice roots.

Keywords: rice growth, soil organic carbon, dissolved organic carbon, microbial biomass carbon, carbon pool

1. Introduction

Organic carbon (C) sequestration of cropping soils provides a potential sink for atmospheric CO_2, with an annual rate of 0.4-0.8 Gt C globally (Lal, 2004). Understanding the interactions between plant roots, microorganisms and soil organic C pools provides a key to the processes controlling C fluxes between plant roots, microbial biomass, soil and atmosphere (Yevdokimov et al., 2006; Kumar et al., 2014). Almost 10% of the atmosphere's CO_2 passes through soils each year (Raich & Tufekcioglu, 2000), which has been driven by photosynthesis and respirations. Paddy soils globally cover a total area of about 1.5×10^6 km^2, which accounts for about 22% of the global cropping area (Knabner et al., 2010). Also, it is commonly accepted that paddy soils were possibly an important C sink (Lal, 2002). However, the capacity of plant-photosynthesized C, especially through root elution, entering into soil has, so far, not been quantified. Therefore, understanding the C cycle of the major paddies of the world is necessary for developing accurate and predictive global C cycle models.

The transportation of plant-photosynthesized C into the soil occurs rapidly and influences soil active organic C pools in the soil (Kaštovská & Šantrůčková, 2007; Rajesh et al., 2003). Root-derived materials are an important DOC source in soil (Lu et al., 2005). About 30 to 60% of the net photosynthesized C is allocated below ground parts, and as much as 40 to 90% of this fraction enters the soil in the forms of root exudates, mucilage, sloughed-off cells and decaying roots (Lynch & Whipps, 1990). Kuzyakov et al. (2006) have demonstrated that the majority of root-derived C of plant-photosynthesized C is represented by root exudates, which are dominated by low-molecular-weight compounds such as carbohydrates (e.g., glucose, sucrose), amino acids (e.g., glutamate, glycine), and organic acids (e.g., citrate, lactate). These compounds are an important DOC source and they are most available for soil microorganisms (Lu et al., 2002a; Chintala et al., 2014). The rhizodeposition occurs continuously in the form of root exudates, mucilage, sloughed-off cells and litter within the growing season of

plants. Witt et al. (2000) reported that MBC decreased with plant growth and there was no difference between planted and unplanted soils in flooded conditions. On the other hand, Reichardt et al. (1997) observed a decline of total microbial biomass but an increase in anaerobic populations toward the maturation stage of rice. However, the influence of plant growth on microbial dynamics, however, is complex and poorly understood in rice soils. Therefore, information of root-derived DOC and MBC is essential to understand the processes, such as microbial activity and soil respirations, which is important for further insight into C cycling in the plant-soil system.

We hypothesized that the dynamics of SOC, DOC and MBC in flooded rice soil were significantly influenced by plant growth. The objective of this study therefore was to evaluate the soil SOC and active organic C pools (DOC and MBC) during rice growth in a chamber.

2. Method

2.1 Soil Preparation

Three middle of subtropical red paddy soils (P1, P2, P3) developed from a quaternary red-earth parent material in China under double-cropping rice cultivation systems in Changsha City, Hunan Province, China were used in this study. All soil samples were collected from the plough layer (0-20 cm) using 5.5 cm diameter stainless steel corer after rice harvest. Bulk soil was immediately placed in a gas-permeable plastic box after removing coarse plant residues. The properties of the soil (a quaternary red-earth developing towards a typical Ultisol at all sites) are shown in Table 1. Soil pH was determined in 1:2.5 (w/v) soil to H_2O ratio extracts using pH meter. Soil texture (clay content) was determined using the pipette method (Müller & Höper, 2004). Contents of SOC and total N were measured by dry combustion in C/N (Vario MAX C/N, Elementar, Germany) auto-analyzers (Chintala et al., 2013). Cation exchange capacity (CEC) were measured by the procedure of Bruce and Rayment (Bruce & Rayment, 1982).

Table 1. Selected properties of the surface (0-20 cm) from three contrasting paddy soils used in this study

Soil	cultivation systems	Site/Position	SOC (g kg^{-1})	TN (g kg^{-1})	pH	C:N	Clay content (%)	CEC (c mol kg^{-1})
P1	double-cropping rice	E113°11′; N28°08′	22.7±0.09a	2.02±0.03a	5.98±0.06a	11.19±0.10a	41.6±0.1a	10.65±0.04b
P2	double-cropping rice	E113°11′; N28°08′	16.3±0.14b	1.74±0.02b	5.14±0.03b	9.36±0.05b	11.48±0.12b	12.24±0.04a
P3	double-cropping rice	E111°31′; N29°13′	15.6±0.03b	1.64±0.01b	4.74±0.01c	9.51±0.15b	11.32±1.28b	7.23±0.00c

Note. All values represent means ± SD (n = 3). All values are expressed on a soil dry weight basis and represent the mean of three determinations. In the same column, different letters are significantly different by Duncan test ($P < 0.05$), the same as below. SOC, TN, CEC indicates soil organic carbon, total nitrogen and cation exchange capacity, respectively.

2.2 Treatments

The experiment had two principal treatments, namely: (1) unplanted paddy soil with 12 h photoperiod; and (2) rice-planted paddy soil with 12 h photoperiod. The experiment was carried out with four replications and arranged in a completely randomized design, resulting 24 microcosms.

2.3 Rice Growth

Briefly, the soils were given an initial basal fertilizer application, consisting of NH_4SO_4, calcium super-phosphate and KCl at the rates of 40 mg N, 20 mg P and 80 mg K kg^{-1} soil for each treatment. One kilogram of the fertilized soil sample was filled into PVC tubes (10 cm inner diameter and 20 cm height). Three 25-day-old rice seedlings (*Oryza sativa* L. cv. Zhongyou 169 from Hunan Seedling Company, average dry weight of the rice seedling was 0.16 g $plant^{-1}$) were transplanted to each pot on 19 June 2009, just one day after the submergence of soil. Soil pots were irrigated with deionized water, with a 2-3 cm water layer maintained on the soil surface throughout the growing period.

2.4 Sampling and Analyze

After 80-d growth, which included the vigorous growth period of the rice, including the entire tillering stage, the

microcosms were destructively harvested; the shoots were cut off at the stem base with a scissors, allowing for separation of the roots, shoots, and soil components. All roots, shoots, and a small soil sub-sample (about 20 g) were dried to a constant weight in an oven at 70 °C to analyze for total C. MBC was determined by the difference between K_2SO_4-extractable C in $CHCl_3$-fumigated and non-fumigated soil using k factor 0.45 (Wu et al., 1990). DOC was directly taken the values determined in the un-fumigated soil. Data were analyzed with SPSS 10.5 (SPSS Inc., Chicago, IL, USA) using the Post Hoc method.

3. Results

3.1 Rice Growth

At harvest time (after growth for 80 days), the amount of rice total plant biomass and shoot biomass C grown in P1 was 6.41 and 5.78 g pot^{-1}, respectively, which was 0.91, 0.90 and 0.58, 0.58 times larger than those of P2, P3, respectively (Table 2). In comparison to P3, rice root biomass C showed a significant increase ($P < 0.05$) when grown in P1 and P2. However, there was no significant difference ($P > 0.05$) in total biomass, shoot and root biomass C between which grown in P1 and P2. There was no significant difference ($P > 0.05$) in the shoot/root ratio growing in three tested paddy soils, illustrating little change in photosynthate partitioning between the aboveground and the belowground parts of plants during the growing periods (Table 2).

Table 2. Amounts of rice biomass C and the ratio of root to shoot obtained from three contrasting paddy soils after 80-d pot growth in a climate-controlled growth chamber

soil	Total biomass C (g $plot^{-1}$)	Shoot biomass C (g $plot^{-1}$)	Root biomass C (g $plot^{-1}$)	root/shoot
P_1	6.41±0.50 a	5.78±0.49 a	0.63±0.03 a	0.11 a
P_2	5.85±0.12 a	5.21±0.18 a	0.64±0.06 a	0.12 a
P_3	3.70±0.16 b	3.33±0.16 b	0.37±0.04 b	0.11 a

Note. Values represent mean ± SD (n = 4). Different lowercase letters in each column indicate significant difference among treatments at the 0.05 level.

3.2 SOC Change between Day 0 and Harvest

At the 80 days of incubation, the SOC amount in unplanted and rice-planted soils increased over the period between Day 0 and harvest (Table 3). ANOVA revealed that rice growth had no significant impact ($P > 0.05$) on the content of SOC although generally followed the series: rice planted soil > Unplanted soil. However, significant difference in SOC amount ($P < 0.05$) was observed among three tested soils, and generally followed the series: P1 > P2 > P3 (Table 3). This might be expected because of the different capacity of rice productivity and assimilation in different paddy soils.

Table 3. The change of soil organic carbon (SOC) between Day 0 and harvest (in rice planted and unplanted soil) from three contrasting paddy soils

SOC (g kg^{-1})	P1	P2	P3
Day 0 (CK)	22.65±0.09 a	16.30±0.35 b	15.63±0.22 b
Unplanted soil	22.78±0.14 a	17.07±0.47 a	16.13±0.36 ab
Rice-planted soil	23.20±0.03 a	17.40±0.47 a	16.35±0.20 a

3.3 DOC Change between Day 0 and Harvest

The dynamics of DOC differed significantly between planted soils and unplanted soils after 80 days of incubation (Figure 1). In planted soils, DOC concentrations ranged from 63.8 to 69.8 mg kg^{-1} at harvest in the studied soils, which was 2.2-3.4 times larger than those of the start of experiment (Day 0). In unplanted soils, DOC concentrations ranged from 40.1 to 56.6 mg kg^{-1} at harvest, which was 1.5-2.7 times higher than those of Day 0 (Figure 1). The mean DOC concentrations were 1.5 times higher in rice-planted soils than in unplanted soils. DOC content in P1 showed a significant higher ($P < 0.05$) than both in P2 and P3, however, there was no significant difference between in P2 and P3.

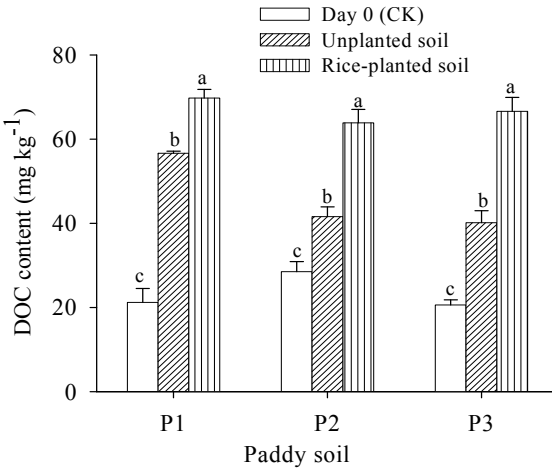

Figure 1. The change of dissolved organic carbon (DOC) between Day 0 and harvest (in rice planted and unplanted soil) from three contrasting paddy soils. Values represent mean ± SD (n = 4). Different letters indicate significant differences at the $P < 0.05$ level

3.4 MBC Change between Day 0 and Harvest

The mean of MBC decreased from 794±135 mg kg^{-1} soil at the start of experiment (Day 0 (CK)) to 555±51.3 in unplanted soil and 434±16.1 mg kg^{-1} soil in rice-planted soil, respectively, after incubation for 80 days (Figure 2). In planted soils, MBC concentrations ranged from 418.7 to 450.0 mg kg^{-1} throughout the period in three selected soils, which was 1.5-2.0 times lower than those of the start of experiment (Day 0). In unplanted soils, similarly, MBC concentrations ranged from 512.4 to 621.0 mg kg^{-1} throughout the experimental period, which was 1.2-1.7 times smaller than those of Day 0 (Figure 2). The mean MBC concentrations were 1.3 times lower in rice-planted soils than in unplanted soils. MBC content in P2 showed a significant higher ($P < 0.05$) than both in P1 and P3, however, there was no significant difference between in P1 and P3 incubated in planted and unplanted soils (Figure 2). During 80-d of incubation, MBC was positively correlated to DOC concentration (n = 6, $r^2 = 0.88$, $P < 0.01$).

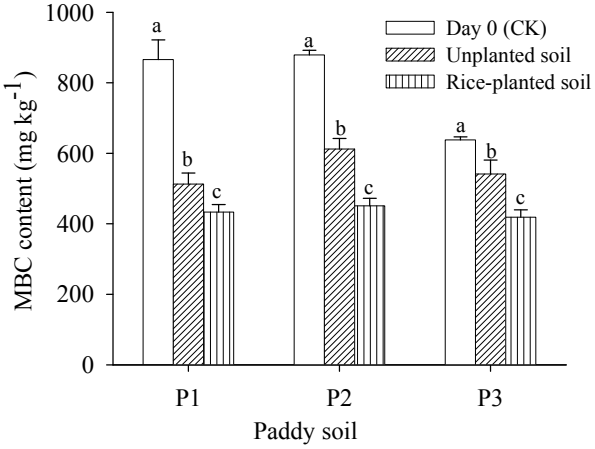

Figure 2. The change of microbial biomass carbon (MBC) between Day 0 and harvest (in rice planted and unplanted soil) from three contrasting paddy soils. Values represent mean ± SD (n = 4). Different letters indicate significant differences a t the $P < 0.05$ level

4. Discussion

The amount of SOC during incubation varied from 16.13-22.78 g kg^{-1} in unplanted soil and 16.35-23.20 g kg^{-1} in rice planted soil, a net increase of 0.57-4.72% in unplanted soil and 2.43-6.75% in rice-planted soil (Table 3).

This enhancement of SOC was because of the input of rice roots, root exudates and the involvement of the process of the microbial assimilation of CO_2 by a wide range of autotrophic and phototrophic microorganisms. Through the use of isotopic techniques, i.e. continuous, pulse-chase ^{13}C or ^{14}C labeling and ^{13}C natural abundance, researchers have made considerable progress in determining the input and partitioning of plant-photosynthesized C into plant parts, below-ground C translocation and CO_2 emissions from soil (Kuzyakov & Schneckenberger, 2004). About 40% of plant-photosynthesized C input into the soil during the growing season is dependent on the plant species and environmental conditions (Lynch & Whipps, 1990). Hütsch et al. (2002) showed that the photosynthesized C input into the soil varied among plant species and that the maximum proportion was up to 20%, 64-86% of which was rapidly respired by soil microorganisms and only 2-5% of which was incorporated into SOC. Unfortunately, in our study, the contribution of rice-photosynthesized C and microbial assimilation of atmospheric CO_2 to SOC was unable to be quantified, because it was not labelled with ^{13}C or ^{14}C. Hence, quantifying the contribution of rice-photosynthesized C and soil assimilation C by microorganisms to SOC should also take into account by isotope-labelling technique in the future studies. It should be noted, in this work, use of plant pots and an enclosed growth chamber may both have decreased plant growth. Therefore, field-rice could be expected to input more C into the soil. The hypoxic and anoxic conditions in rice-paddy systems will absolutely effect the SOC and active carbon pool. The new SOC derived from roots in paddy soil is more stable because root-derived organic matter may form complexes with the active iron oxide in the soil. It would then become more stable and participate in the formation of soil aggregates (0.25-2 mm) that protect the newly root-derived SOC from decomposition.

Root-derived C dependence on photosynthesized C transformation contributes considerably to the soil C components, especially MBC and DOC, which are closely related to CO_2 and CH_4 emissions (Liang et al., 2002). In the present study, DOC in the rice-planted soil showed a significant increase (Figure 1), in comparison to that of the start of experiment (Day 0). Organic manure was not applied to soil in this experiment. This finding suggests that root-derived DOC is controlled by the release of organic materials originating from the roots. The increase in DOC with plant growth illustrated the increase in C substrates, which were readily available for microorganisms. Previous work has also shown that in rice cultivated paddy soil, the amount of DOC was higher than that in unplanted soil, increasing gradually with rice growth, and generally correlating with the root biomass increasing gradually with rice growth, and generally correlating with the root biomass (Lu et al., 2002b). This confirms our suggestion presented above. In addition, the increasing in DOC from unplanted soil indicate that phototrophic-derived DOC is controlled by the release of organic materials originating from the atmospheric CO2 assimilation by microorganisms. Previous work has shown that in rice-planted soil, the amount of DOC was higher than that in unplanted soil, increasing gradually with rice growth, and generally correlating with the root biomass (Lu et al., 2002a).

The decrease in MBC in rice-planted and unplanted soil during the 80-d incubation period, compared with the start of the experiment, was likely due to the change in the microbial community structure in the span of our experiment. This finding suggests that rice-photosynthesized C input into the soil has an effect on the dynamics of MBC, as supported by previous study (Witt et al., 2000). Lu et al. (2002b) observed a substantial decrease in MBC during the early periods and a slight increase during the late periods of rice growth. The level of decrease in rice-planted soil was higher than that of unplanted soil, suggested that plant competition for nutrition resources depressed microbial growth during the rice growth. Several studies have shown that most of the recently photosynthesized C directly allocated to the soil by the plant roots is more rapidly lost through soil respiration than through microbial respiration (Leake et al., 2006). The unplanted soil has also an effect the dynamics of MBC during the incubation revealed some anaerobic microbes with photosynthesis function, So far, it is unclear what the characteristic and ecological functions of these soil microbes are acted as in paddy soil.

4. Conclusions

The SOC content was increased both in unplanted and rice-planted soil over the incubation season indicating that growing rice and bulk soil enhanced the function of soil as a carbon poo1.

DOC concentrations in planted soils were much larger than that of unplanted soils, reflecting the release of soluble root exudates from rice roots.

MBC declined both in unplanted soil and rice-planted soil after incubation for 80 days, compared with the start of experiment.

However, the information on input, distribution and fate of photosynthesized carbon (C) in rice-soil system, such as the contribution of rice growth on the soil C pools by using C isotope labeling technique, the influence of photosynthesized C input on the decomposition of native soil organic carbon (SOC), is essential for

understanding their nutrient and C cycle and require further study. We believe that such work is important for an understanding of the role of the below-ground biomass in the storage and dynamics of SOC in flooded rice-soil systems.

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