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Effects of Long-Term Fertilization Management Practices on Soil Microbial Carbon and Microbial Biomass in Paddy Soil at Various Stages of Rice Growth

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ABSTRACT: Soil microbial biomass plays a significant role in soils, and it is often used as an early indicator of change in soil quality. Soil microbial biomass is affected by different fertilization management practices. Therefore, the impact of different long-term fertilization management practices on the soil organic carbon (SOC) content, soil microbial biomass carbon (SMBC), and soil microbial biomass nitrogen (SMBN), as well as the soil microbial quotient (SMQ) in the tilled layer (0.00-0.20 m) were studied in the present paper, together with grain yield, in a double-cropping rice (*Oryza sativa* L.) system. The experiment in NingXiang county of Hunan Province, China, begin in 1986, and the experiment included five fertilization treatments: without fertilizer input (CK), mineral fertilizer alone (MF), rice straw residues and mineral fertilizer (RF), 30 % organic matter and 70 % mineral fertilizer (LOM), and 60 % organic matter and 40 % mineral fertilizer (HOM). The results showed that there is no significant difference in effect on SOC, SMBC, and SMBN contents and on the SMQ in the paddy field with MF treatment compared with the CK treatment at the main growth stages of early and late rice. The SOC, SMBC, SMBN contents, and the SMQ in the paddy field were highest in the LOM and HOM treatments, followed by the RF treatment, at the main growth stages of early and late rice. The results indicated that grain yields of early and late rice with the LOM, HOM, and RF treatments were higher than the yields under the MF and CK treatments. As a result, combined application of organic matter or rice straw residues with mineral fertilizer is a practice available for increasing SOC and microbial biomass contents in double-cropping rice paddy soils.

Keywords: paddy field, fertilizer regime, double-cropping rice, soil organic carbon, grain yield.

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INTRODUCTION

Soil organic matter (SOM) is an important soil component that affects soil biological and soil physicochemical properties (Bhardwaj et al., 2011). In addition, SOM influences soil quality and nutrient processes, such as soil fertility, physical structure, and soil nutrient availability. In recent years, some research has indicated that SOM is an effective indicator for measuring greenhouse gas emissions because agricultural soils are an important source or storage area of carbon responsible for greenhouse gas emissions (Lal, 2002). Soil organic matter content is influenced by some agricultural measures, including soil tillage, cropping systems, and the fertilizer regime (Paustian et al., 1997; Rodríguez-Murillo, 2001; Bhardwaj et al., 2011).

Soil microbial biomass is frequently used as an early indicator of change in soil quality. Compared with SOM, soil microbial biomass is more susceptible to changes in the soil environment and soil management practices (Hargreaves et al., 2003; Liu et al., 2014). Although soil microbial biomass is a small portion of SOM, it plays a vital role in soil nutrient cycling because it can transform SOM and insoluble substances (Dou et al., 2016). At the same time, soil microbial biomass is closely related to N, P, and S cycling, and can usually be considered a pool of soil nutrients that affects plant growth by some nutrient elements (Wu et al., 1993). However, information regarding the effects of different long-term fertilizer regimes on soil microbial biomass should be obtained through further studies. Some studies have shown that mineral fertilizers increase soil microbial biomass carbon (SMBC) and soil microbial biomass nitrogen (SMBN) contents (Goyal et al., 1992; Li et al., 2008), but other studies have indicated that soil microbial biomass is not significantly affected by application of inorganic fertilizers and even that soil microbial populations and diversity were reduced by application of N fertilizer (Sarathchandra et al., 2001). Meanwhile, some studies have reported that the soil microbial community was affected by application of inorganic fertilizers and organic matter in different crop rotation systems (Zhen et al., 2014; Luo et al., 2015).

There is limited information about the dynamics of SOM, SMBC, and SMBN contents under different fertilization management practices in double-cropping paddy soils in southern China (Zhang and He, 2004). Organic matter is traditionally applied and constitutes an important source material in the process of rice (*Oryza sativa* L.) production in China. In recently years, it has generally been accepted that applications of mineral fertilizer along with the rice straw residues in upland and paddy field crop production systems enhance soil quality (Lal, 2002). The practice of returning rice straw residue to the field provides vital nutrients for rice production (Li, 1992). However, the fertilizer regime has changed in recent years; the application of inorganic fertilizer has increased and the application of organic fertilizer has decreased in rice production. Therefore, soil quality has decreased in this fertilizer regime through decreases in SOM content and the diversity of the soil microbial community (Xu, 2006). Compared to application of inorganic fertilizer alone, there are benefits in maintaining both soil quality and high grain yields of rice by combining application of mineral fertilizer with organic matter or straw in double-cropping production systems.

The double-cropping rice production system is the main crop rotation in southern China, and the fertilizer regime has a vital influence on factors for rice production and paddy agroecosystems; however, there is little information about the effects of different fertilization management practices on SOM, SMBC, and SMBN contents in double-cropping rice systems in southern China. Therefore, the main aims of this study were to investigate the impact of different long-term fertilizer regimes on SOM, SMBC, and SMBN contents at the main growth stages of early and late rice.

MATERIALS AND METHODS

Experimental site and cropping system

The long-term experiment began in 1986 in NingXiang County (28° 07' N, 112° 18' E) of Hunan Province, China. Under a continental monsoon climate, annual mean precipitation is 1,553 mm and potential evapotranspiration is 1,354 mm. The average monthly temperature is 17.2 °C. Soil texture in the tilled layer (0.00-0.20 m) consisted of silt clay loam with 13.71 % sand and 57.73 % silt. The climatic condition of the experimental paddy field, the surface soil (0.00-0.20 m) physicochemical properties at the beginning of this experiment, and the crop rotation systems are described by Tang et al. (2016).

Experimental design and soil sampling

The experiment included five fertilization treatments: control without fertilizer input (CK), mineral fertilizer alone (MF), rice straw residue and mineral fertilizer (RF), 30 % organic matter and 70 % mineral fertilizer (LOM), and 60 % organic matter and 40 % mineral fertilizer (HOM). A randomized block design was adopted in the plots, with three replications. The size of each plot was 66.7 m^2 (10 × 6.67 m). The total amount of N, phosphorus pentoxide (P_2O_5), and potassium oxide (K_2O) were adjusted to the same level in each fertilization treatment over the whole growth period for early and late rice (*Oryza sativa* L.). Detailed information about the fertilization management and farming practices is described by Tang et al. (2016).

Soil samples were collected in the tilled layer (0.00-0.20 m) at the main growth stages of early rice and late rice in 2016, including the seedling stage, tillering stage, jointing stage, heading stage, and mature stages. The methods of soil sample collection and treatment of samples is described by Hao et al. (2008).

Soil organic carbon and soil microbial biomass and other measurements

Soil organic carbon (SOC) content was measured in air-dried and ground samples with an elemental analyzer (Vario Max C/N). Soil microbial biomass carbon (SMBC) and soil microbial biomass nitrogen (SMBN) contents were measured by the fumigation-extraction method as described in Wu et al. (1990) and Jenkinson (1988). The soil microbial quotient (SMQ) was calculated from the equation: SMQ = SMBC/SOC.

Rice grain yield in each plot was measured at mature stages of early and late rice in 2016; three 1 m^2 areas of each plot were collected to calculate the dry weight of rice grain yield.

Statistical analysis

The results of every measured item were presented in mean values and standard error. The treatment means were compared by using one-way analysis of variance (Anova) following standard procedures at the 5 % probability level. All statistical analyses were calculated by using SPSS statistical software (version 3.11).

RESULTS

Soil organic carbon

The effects of different long-term fertilizer regimes on soil organic carbon (SOC) content in a paddy field after 30 years of cropping are shown in figure 1. At the main growth stages of early rice (*Oryza sativa* L.), the lowest SOC content in the paddy field was observed under the CK treatment, while the highest SOC contents in the paddy field were observed under the HOM, LOM, and RF treatments. The results indicated that SOC content in the paddy field was higher under the MF, RF, LOM, and HOM treatments than under the CK treatment.

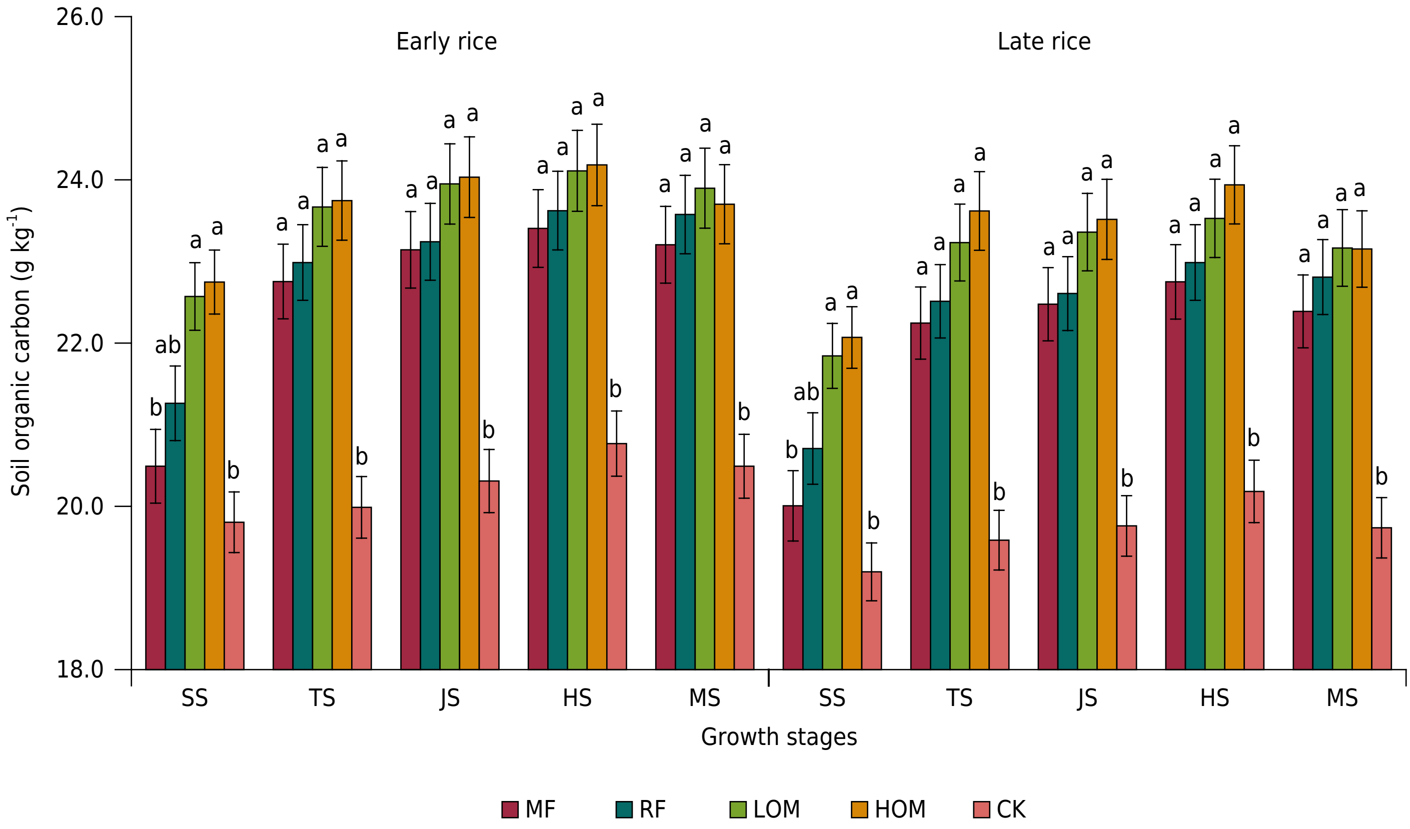

Figure 1. Effects of different long-term fertilization treatments on soil organic carbon content in a paddy field at main rice growth stages. MF = mineral fertilizer alone; RF = rice straw residues and mineral fertilizer; LOM = 30 % organic matter and 70 % mineral fertilizer; HOM = 60 % organic matter and 40 % mineral fertilizer; CK = without fertilizer input; SS = seedling stage; TS = tillering stage; JS = jointing stage; HS = heading stage; MS = mature stage. Bars represent standard deviation (SD) of three replicates. Different letters indicate significance at $p<0.05$ among the fertilization treatments at the same rice growth stage, according to the least significant difference test.

At the main growth stages of late rice, the SOC content in all fertilization treatments was similar to the main growth stages of early rice. Soil organic carbon content in the paddy field at late growth stages was higher than at early growth stages of late rice. The highest SOC content in the paddy field under all fertilization treatments was at the heading stage of late rice, which decreased at the mature stage of late rice. The SOC content in the paddy field under treatments with fertilizer application (MF, RF, LOM, and HOM) was higher ($p<0.05$) than under the treatment without fertilizer (CK) at the main growth stages of late rice.

Soil microbial biomass carbon

Soil microbial biomass carbon (SMBC) contents in the paddy field under the LOM and HOM treatments were higher ($p<0.05$) than under the MF, RF, and CK treatments at the main growth stages of early and late rice. The SMBC contents in the paddy field under the MF and RF treatments were higher ($p<0.05$) than under the CK treatment at the main growth stages of early and late rice (Figure 2). In early and late rice, the SMBC content in the paddy field at late growth stages was higher ($p<0.05$) than at early growth stages. The highest SMBC content in the paddy field with five fertilization treatments was at the heading stage, and it then decreased at the mature stage of early and late rice. At the heading stage, in comparison with the CK treatment, the SMBC content in the paddy field increased by 144.34, 190.61, 330.84, and 365.90 g kg^{-1} under the MF, RF, LOM, and HOM treatments, respectively, in early rice. It increased by 145.36, 191.60, 331.86, and 359.93 g kg^{-1} under the MF, RF, LOM, and HOM treatments, respectively, in late rice.

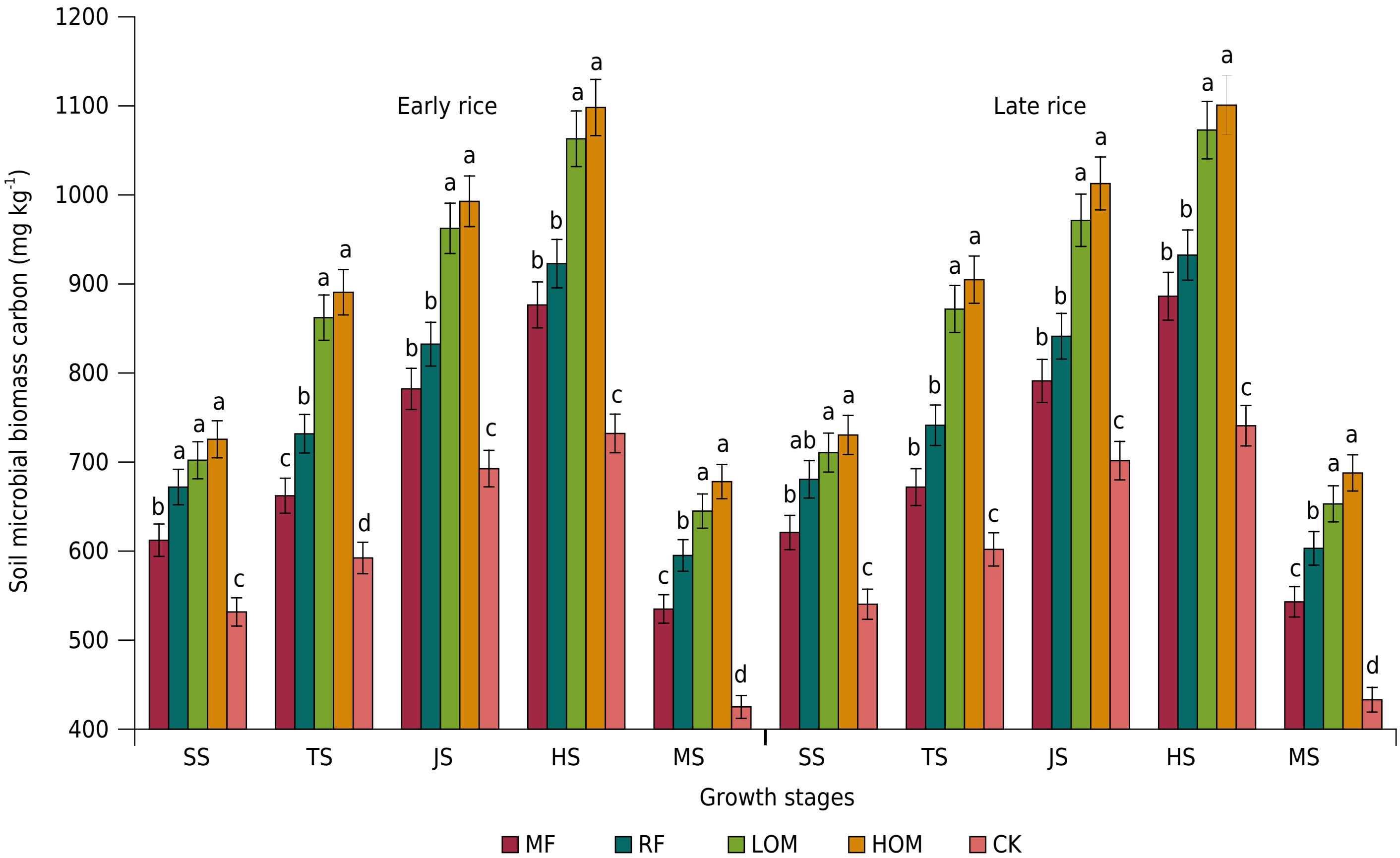

Figure 2. Effects of different long-term fertilization treatments on soil microbial biomass carbon in a paddy field at main rice growth stages. MF = mineral fertilizer alone; RF = rice straw residues and mineral fertilizer; LOM = 30 % organic matter and 70 % mineral fertilizer; HOM = 60 % organic matter and 40 % mineral fertilizer; CK = without fertilizer input; SS = seedling stage; TS = tillering stage; JS = jointing stage; HS = heading stage; MS = mature stage. Bars represent standard deviation (SD) of three replicates. Different letters indicate significance at $p<0.05$ among the fertilization treatments at the same rice growth stage, according to the least significant difference test.

Soil microbial biomass nitrogen

The SMBN contents in the paddy field under the LOM and HOM treatments were higher ($p<0.05$) than under the MF, RF, and CK treatments at the main growth stages of early and late rice. The SMBN content in the paddy field under the RF treatment was higher ($p<0.05$) than under the CK treatment at the main growth stages of early and late rice. The SMBN content in the paddy field under the MF, RF, LOM, and HOM treatments was higher ($p<0.05$) than under the CK treatment at the main growth stages of early and late rice (Figure 3). In early and late rice, the SMBN content in the paddy field under five fertilization treatments was higher ($p<0.05$) at the heading stage than at the other stages.

Soil microbial biomass carbon and nitrogen ratio

The value of the SMBC:SMBN ratio under different fertilization treatments throughout the growth stages of early and late rice are shown in figure 4. Throughout the growth stages of early rice, the value of the SMBC:SMBN ratio under the HOM treatment was higher ($p<0.05$) than under the MF and CK treatments, and the value of the SMBC:SMBN ratio under the RF, LOM, and HOM treatments was also significantly higher ($p<0.05$) than under the CK treatment (Figure 4). There is not a significant difference ($p>0.05$) in the value of the SMBC:SMBN ratio between the MF and CK treatments at the main growth stages of early rice. Over the growth stages of early rice, the mean value of the SMBC:SMBN ratio was 13.58, 14.16, 15.15, 15.37, and 12.42 under the MF, RF, LOM, HOM, and CK treatments, respectively.

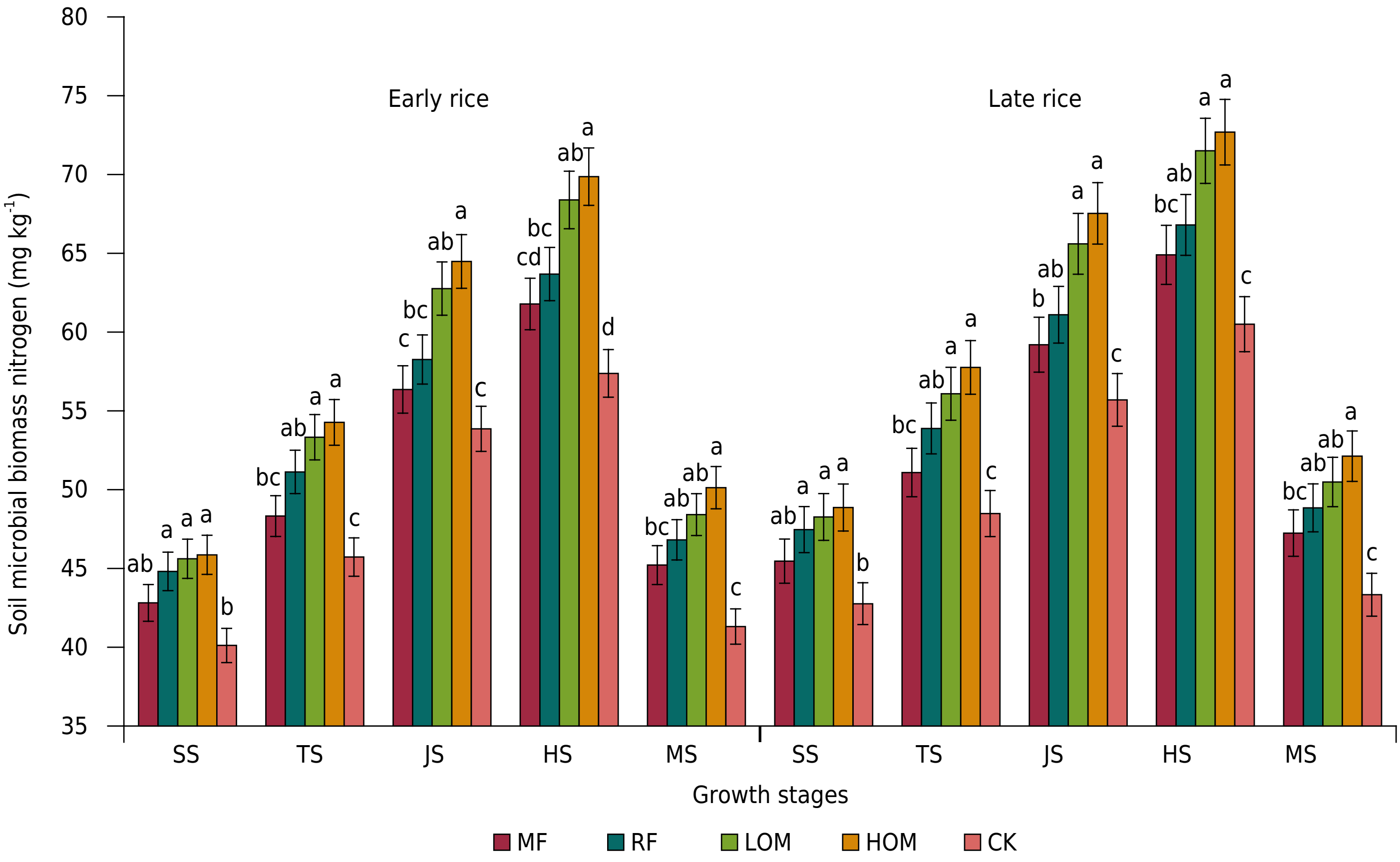

Figure 3. Effects of different long-term fertilization treatments on soil microbial biomass nitrogen in a paddy field at main rice growth stages. MF = mineral fertilizer alone; RF = rice straw residues and mineral fertilizer; LOM = 30 % organic matter and 70 % mineral fertilizer; HOM = 60 % organic matter and 40 % mineral fertilizer; CK = without fertilizer input; SS = seedling stage; TS = tillering stage; JS = jointing stage; HS = heading stage; MS = mature stage. Bars represent standard deviation (SD) of three replicates. Different letters indicate significance at p<0.05 among the fertilization treatments at the same rice growth stage, according to the least significant difference test.

The value of the SMBC:SMBN ratio under the HOM and LOM treatments was significantly higher ($p<0.05$) than under the CK treatment at the main growth stages of late rice. There is no significant difference ($p>0.05$) in this value between the MF and CK treatments from the seedling stage to the jointing stage, but this value under the MF treatment was significant higher ($p<0.05$) than under the CK treatment at the heading stage and mature stage of late rice (Figure 4). Over the growth stages of late rice, the mean value of the SMBC:SMBN ratio was 13.06, 13.63, 14.60, 14.79, and 11.98 under the MF, RF, LOM, HOM, and CK treatments, respectively.

Soil microbial quotient

The soil microbial quotient (SMQ, SMBC/SOC ratio) under the MF, RF, LOM, HOM, and CK treatments ranged from 2.07 to 4.54 % at the main growth stages of early rice. The SMQ under the HOM and LOM treatments was higher ($p<0.05$) than under the MF, RF, and CK treatments at the main growth stages of early rice. There is no significant difference ($p>0.05$) in the SMQ between the MF and CK treatments from the seedling stage to the heading stage of early rice. The mean value of the SMQ was 3.01, 3.23, 3.61, 3.76, and 2.93 under the MF, RF, LOM, HOM, and CK treatments at the growth stages of early rice, respectively (Figure 5).

The SMQ under the MF, RF, LOM, HOM, and CK treatments at the main growth stages of late rice was similar to the SMQ at the main growth stages of early rice. The SMQ under the MF, RF, LOM, HOM, and CK treatments ranged from 2.19 to 4.68 % at the main growth stages of late rice. At the main growth stages of late rice, there is no significant

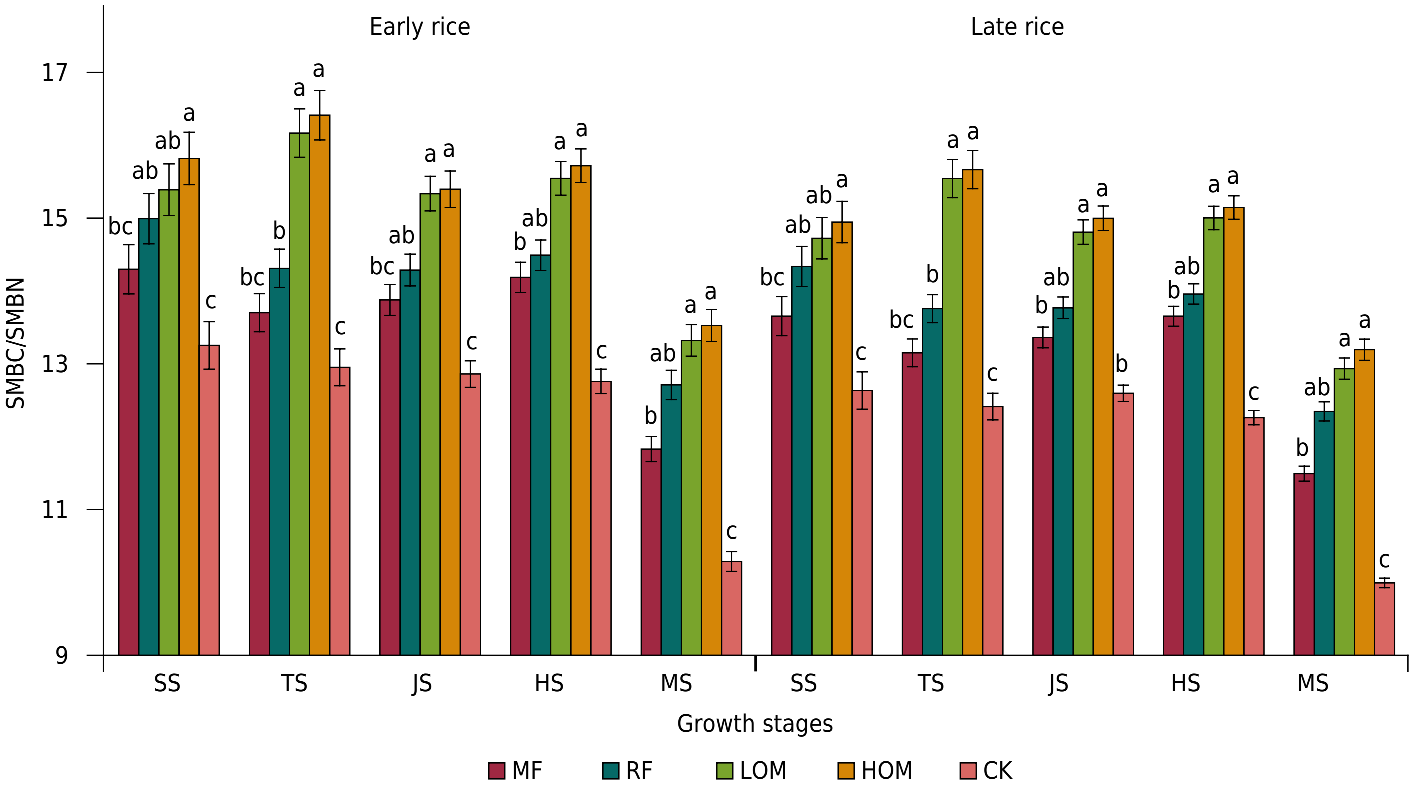

Figure 4. Effects of different long-term fertilization treatments on soil microbial biomass carbon and nitrogen ratio in a paddy field at main rice growth stages. MF = mineral fertilizer alone; RF = rice straw residues and mineral fertilizer; LOM = 30 % organic matter and 70 % mineral fertilizer; HOM = 60 % organic matter and 40 % mineral fertilizer; CK = without fertilizer input; SS = seedling stage; TS = tillering stage; JS = jointing stage; HS = heading stage; MS = mature stage. Bars represent standard deviation (SD) of three replicates. Different letters indicate significance at $p<0.05$ among the fertilization treatments at the same rice growth stage, according to the least significant difference test.

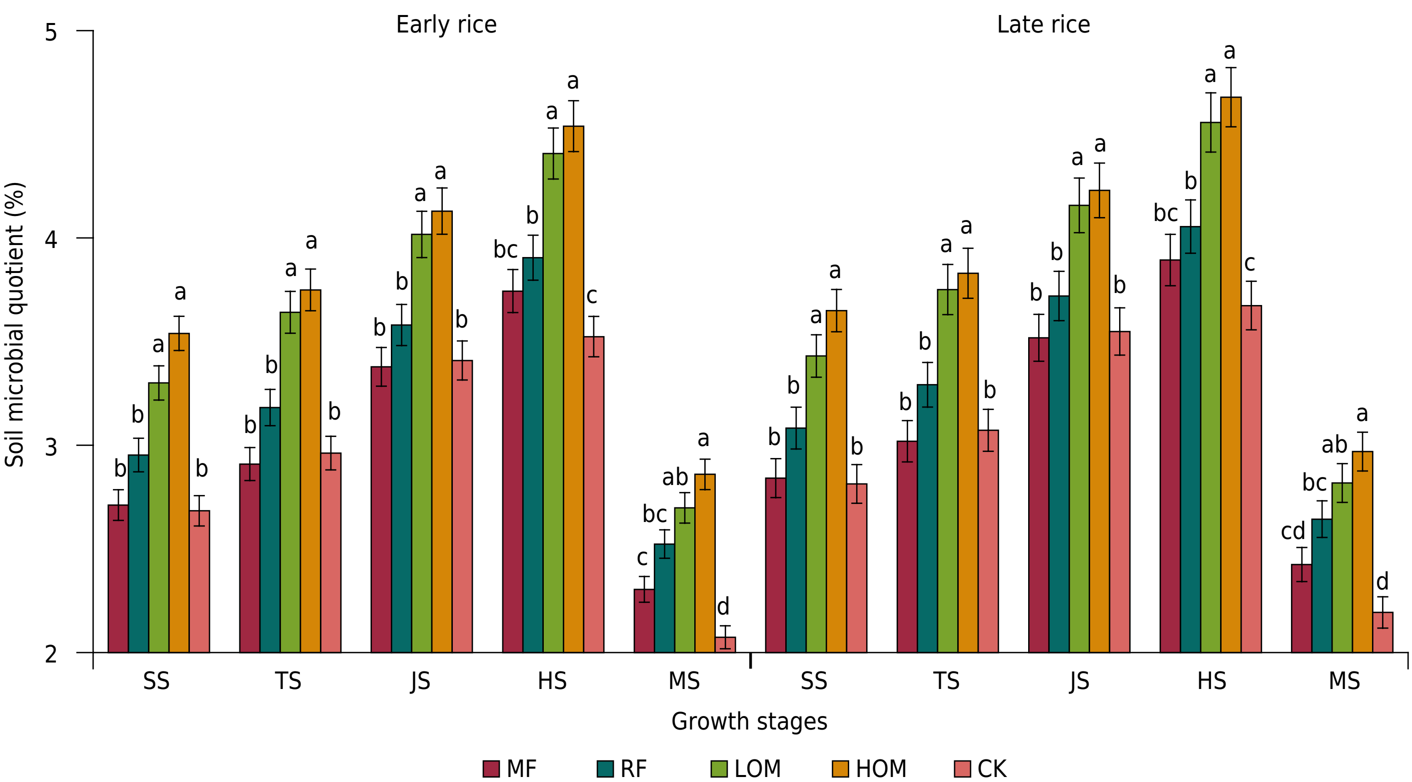

Figure 5. Effects of different long-term fertilization treatments on soil microbial quotient in a paddy field at main rice growth stages. MF = mineral fertilizer alone; RF = rice straw residues and mineral fertilizer; LOM = 30 % organic matter and 70 % mineral fertilizer; HOM = 60 % organic matter and 40 % mineral fertilizer; CK = without fertilizer input; SS = seedling stage; TS = tillering stage; JS = jointing stage; HS = heading stage; MS = mature stage. Bars represent standard deviation (SD) of three replicates. Different letters indicate significance at $p<0.05$ among the fertilization treatments at the same rice growth stage, according to the least significant difference test.

difference ($p>0.05$) in the SMQ between the MF and CK treatments, whereas the SMQ under the HOM and LOM treatments was higher ($p<0.05$) than under the MF, RF, and CK treatments. Furthermore, the mean value of the SMQ was 3.14, 3.36, 3.74, 3.87, and 3.06 % under the MF, RF, LOM, HOM, and CK treatments, respectively, at the different growth stages of late rice (Figure 5).

Grain yield of rice

The grain yield of rice after 30 years of cropping under different fertilizer regimes are shown in table 1. The grain yield of early rice under the LOM and HOM treatments was higher ($p<0.05$) than under the MF and CK treatments. Compared with the CK treatment, the grain yield of early rice under the LOM and HOM treatments increased by 2,641.5 and 2,569.5 kg ha^{-1}, respectively. Meanwhile, the results showed that the grain yield of late rice under the RF and LOM treatments was higher ($p<0.05$) than under the MF and CK treatments. Compared with the CK treatment, the grain yield of late rice under the RF and LOM treatments increased by 3,118.5 and 2,827.5 kg ha^{-1}, respectively. The grain yield of early and late rice under the LOM treatment was higher ($p<0.05$) than under the MF and CK treatments.

DISCUSSION

The SOC content was closely related to soil fertility and nutrient cycling, which affeted plant growth and crop yield. Aoyama and Kumakura (2001) reported that the SOC content was much higher with organic matter and chemical fertilizer than other fertilization treatments under long-term experimental conditions. In this study, the SOC content under all fertilization treatments ranged from 19.81 to 24.18 g kg^{-1} and 19.20 to 23.94 g kg^{-1} at the main growth stages of early and late rice, respectively. This was consistent with the results reported by some researchers (Regmi et al., 2002; Xu, 2006) and even higher than results of the paddy soils in the same area (Li, 1992). In the present study, the higher SOC content can be explained by the fact that paddy soils were submerged during the rice growth period, and anaerobic conditions inhibited decomposition of both endogenous and exogenous organic carbon in rice production (Guo and Lin, 2001). The results also showed that higher SOC content was a result of the organic matter input (chicken manure, rice straw residues), and rice plant root biomass increased (Kundu and Ladha, 1995).

The results demonstrated that the SOC and soil microbial biomass contents were influenced by combined application of organic matter or rice straw residues with chemical fertilizer, based on the long-term field experiment. The SOC and soil microbial biomass contents were higher with mineral fertilizer together with application of organic fertilizer (organic matter or rice straw residues) than with mineral fertilizer alone (Figures 1, 2, and 3). The SOC and soil microbial biomass contents were lower without the fertilizer input treatments than with application of fertilizer treatments at the main growth stages of rice. This corroborates what was reported by Kaur et al. (2005), who found that soil microbial biomass decreased

Table 1. Grain yield of early and late rice under different long-term fertilization treatments

Treatment	Grain yield of early rice	Grain yield of late rice	Grain yield of early and late rice
	kg ha^{-1}		
MF	4,810.5 ± 132.3 b	5,302.5 ± 153.1 b	10,113.0 ± 316.6 b
RF	4,867.5 ± 134.3 ab	6,127.5 ± 176.8 a	10,995.0 ± 317.4 ab
LOM	5,346.0 ± 138.9 a	5,836.5 ± 168.5 a	11,182.5 ± 291.9 a
HOM	5,274.0 ± 140.5 a	5,694.0 ± 164.4 ab	10,968.0 ± 322.8 ab
CK	2,704.5 ± 85.3 c	3,009.0 ± 86.9 c	5,713.5 ± 164.9 c

MF = mineral fertilizer alone; RF = rice straw residues and mineral fertilizer; LOM = 30 % organic matter and 70 % mineral fertilizer; HOM = 60 % organic matter and 40 % mineral fertilizer; CK = without fertilizer input. Different letters indicate significance at $p<0.05$ among the fertilization treatments, according to the least significant difference test.

with different fertilization treatments in the order organic fertilizer > mineral fertilizer > no fertilizer. The reason may be that the decomposed organic matter and rice straw residues contained large amounts of labile organic C, which could be not only readily decomposed, but may promote microbial activity and thus increase the mineralization of inherent SOC, therefore SOC content were increased by applications of organic matter or rice straw residues. The rice straw residues or organic matter provided substrate for soil microbial activities; therefore, the soil microbial biomass in the paddy field increased. This confirmed that applying rice straw residues and organic matter was beneficial in the sense of increasing SOC content under long-term fertilization conditions because they contain substantial organic carbon (Elzobair et al., 2016), and the conversion rate of carbon were increased under combined applications of organic matter or rice straw residues conditions. Some other study results also indicated that soil microbial biomass content under combined application of organic fertilizer (organic matter, straw residues) and chemical fertilizer was higher than soil microbial biomass content under application of inorganic fertilizer alone under long-term experimental conditions (Chu et al., 2007; Elzobair et al., 2016).

Soil microbial biomass is often used as an early indicator of soil quality changes (Liu et al., 2014). Some results have indicated that soil microbial biomass was greater with application of animal manure fertilizer than with application of rice straw residues. This is due to the wide range of C/N ratios in rice straw residues, and the rice straw residue decomposition rate is relatively slow (Paustian et al., 1997). In contrast, application of animal manure fertilizer promotes soil microorganism growth because it contains a large number of soluble available organic substrates. Therefore, incorporation of organic matter into paddy soils increases the supply of valuable soil nutrients, SOC, and soil microbial biomass contents. Data from this study revealed that throughout the rice growth period, the SMBC and SMBN contents increased along with the advance in rice growth stages. The SMBC and SMBN contents were higher under the MF, RF, LOM, and HOM treatments at the heading stage of rice. This could be due to organic matter decomposing and providing a large amount of available substrates for soil microbial growth. Compared with early growth stages, the SMBC and SMBN contents were lower at the mature stage of rice; the reason may be that plant root exudation decreased along with the soil drainage practiced at mature rice stages (Aulakh et al., 2001).

In our study, the range of the SMBC:SMBN ratio in paddy soils is similar to earlier reports under the same experimental conditions (Kushwaha et al., 2000; Chen and Xu, 2005). Nevertheless, compared to the treatment without fertilizer input, the value of the SMBC:SMBN ratio under the fertilized treatments (MF, RF, LOM, and HOM) increased throughout the growth stages of rice. The explanation of this change is closely related to changes in SOC content. The SOC content increased by the practice of long-term application of organic matter and rice straw residues. In agreement with previous studies, organic matter or rice straw residues and mineral fertilizer application could enhance SOC content and SMBC:SMBN ratio in soils due to large additional C inputs in the paddy fields (Dou et al., 2016; Han et al., 2016).

The soil microbial quotient (SMQ) ranged from 2.07 to 4.54 % and 2.19 to 4.68 % in all fertilization treatments at the main growth stages of early and late rice, respectively. The range of these values is similar to earlier reports under the same experimental conditions (Dalal, 1998; Dou et al., 2016). Furthermore, the same results were reported in paddy fields in other areas of China (Yang et al., 2005). The SMQ is often used as an early indicator of soil quality (e.g., SOC) changes and it is influenced by different field management measures that are taken (Hargreaves et al., 2003). There was the same trend of change in terms of the SMQ under different fertilization treatments at the main growth stages of rice. The mean value of SMQ was highest under the HOM and LOM treatments at the main growth stages of rice, which suggests that SMQ was positively influenced by application of organic matter (chicken manure). Furthermore, a higher value of SMQ implied that available organic substrates increased under application of organic matter, while a smaller value of SMQ implied that availability of basic substrates reduced under application of mineral fertilizer or without application of fertilizer (Anderson and Domsch, 1989).

A useful method of evaluating soil quality and crop yield is by monitoring the soil quality indicators (SOC, SMBC, and SMBN), which change based on long-term field experimental conditions (Bhardwaj et al., 2011). Liu et al. (2017) reported that combined application of chemical fertilizer and organic matter is the best way to increase SOC, SMBC, and SMBN contents, soil quality, and the grain yield of rice. In this study, results indicated that SOC content and soil microbial biomass (SMBC, SMBN, and SMQ) were affected by different fertilization management practices (Figures 1, 2, and 3). The grain yield of rice reflects changes in SOC content and soil microbial biomass (Table 1). The grain yield of rice (early rice and late rice) under the LOM and HOM treatments was higher than under the CK treatment. The SOC, SMBC, and SMBN contents and the SMQ were higher under the LOM and HOM treatments than under the CK treatment. Similar results reported that crop growth and crop yields and the soil physicochemical properties of the paddy field in rice production systems increased through the application of organic matter (manure or rice straw residues) and mineral fertilizer (Zhang et al., 2015).

CONCLUSIONS

Soil organic carbon and soil microbial biomass contents in the paddy field increased by combined application of organic matter with inorganic fertilizer. It is noteworthy that application of organic matter to maintain paddy soil fertility and grain yield achieve even higher grain yield in rice by combined application of organic matter and mineral fertilizer. That is, combined application of organic matter with mineral fertilizer is a benefit in sustaining or increasing SOC in a double-cropping rice region. Furthermore, the application of rice straw residues is another important way to increase SOC and soil microbial biomass contents in the paddy field; therefore, the significance of the practice of returning rice straw residues to the paddy field should be emphasized. Moreover, higher grain yield of rice was directly attributed to improvement in SOC and microbial biomass contents. Thus, cycling of organic matter and rice straw residues are effective ways to sustain grain yield and soil quality in a double-cropping paddy field.

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