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ORIGINAL PAPER

# Changes of $CO_2$ emission and labile organic carbon as influenced by rice straw and different water regimes

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**Abstract** Crop residues under different water regimes can cause significant alterations in soil organic carbon fractions, and in turn, soil-atmospheric carbon dioxide ($CO_2$) emissions. To evaluate the effect of rice straw application on $CO_2$ emissions and labile organic carbon fractions under different water regimes, an incubation experiment was conducted for 90 days. Ten treatments were developed from the interaction between five water levels (100, 85, 70, 55, and 40 % of water-holding capacity (WHC)) with and without incorporation of rice straw. Peaks of $CO_2$ fluxes were observed after 13 days of rice straw incorporation, which decreased gradually till the end of the incubation period. The incorporation of rice straw caused significant increases in $CO_2$ fluxes by 2.77–2.83 times from the paddy soil. In the presence of rice straw, the highest $CO_2$ fluxes were generally observed at W3 (70 % of WHC), whereas the lowest fluxes were occurred at W1 (100 % of WHC). Addition of rice straw under a range of water regimes markedly improved the transformation of soil organic carbon and labile organic carbon pools such as dissolved organic carbon, microbial biomass carbon, light fraction organic carbon, particulate organic carbon, and permanganate oxidizable carbon. The significant correlations between all labile soil organic carbon fractions and $CO_2$ concentrations confirmed their important roles in the emission of $CO_2$ from the paddy soil. In summary, the results suggest that light fraction organic carbon, particulate organic carbon, and permanganate oxidizable carbon were more sensitive indicators for $CO_2$ emissions and organic matter alterations as compared to other carbon fractions.

**Keywords** Carbon dioxide emission · Labile organic carbon fractions · Water regimes · Rice straw

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## Introduction

Incorporation of crop residues in agricultural soils is considered as a good method for preserving and improving soil quality. In China, there are about 13 million hectares counted for rice–wheat cropping system, and most of these areas are located in four provinces (Anhui, Hubei, Jiangsu, and Sichuan) around the Yangtze River valley (Huke et al. 1993). This has led to high production and accumulation of rice straw (200 million tons) every year in China (Han et al. 2002). Thus, rice straw has become one of the main organic amendments in paddy soils, and its incorporation into these soils can lead to increases in soil organic matter contents and crop yields. The farmers have three different methods to return the rice straw to soils prior to crop cultivation. These ways are burning, mulching on soils, and incorporating into soils (Ma et al. 2010). The burning of rice straw is environmentally unacceptable and illegal, and has an extensive effect on global climate change and ecosystem properties through the release of some greenhouse gases (GHG) such as carbon dioxide ($CO_2$), methane ($CH_4$), and nitrous oxide ($N_2O$) to the atmosphere (Pathak et al. 2006; Ma et al. 2010).

Carbon dioxide ($CO_2$) is considered as one of the most important and abundant GHG in the atmosphere and contributes about 50 % to the global warming, and its concentration has been increasing at a rate of 0.5 % annually (Lal et al. 1995). The concentration of $CO_2$ in the atmosphere is predicted to reach high level (440–660 ppm) in 2050 (Bouwman 1990; Oechel and Vourlitis 1994). Increases in $CO_2$ emissions are mainly resulting from the use of fuel combustion, industrial activities, and intensive agricultural practices (Mestdagh et al. 2002).

Organic matter (OM) has an essential role in improving physical, chemical, and biological properties of soils, and it is considered as one of the most important indicators in evaluating soil quality and health (Brahim et al. 2011;Vaughan et al. 2011; Ghosh et al. 2012). The addition of organic amendments in rice agro-ecosystems (paddy soils) can be responsible for large accumulations in soil organic carbon and enhancements in crop productivity. This in turn results in high increases in $CO_2$ emissions from rice-soil systems (Zou et al. 2004; Lou et al. 2007; Iqbal et al. 2009; Bhattacharyya et al. 2012; Wu et al. 2013). The increase of soil organic carbon levels are directly related to the amount and quality of OM added to soils (Lemke et al. 2010). So, the soils can be one of the basic sources of $CO_2$ productions. It was reported that soils can contribute about 20–25 % to the total $CO_2$ emissions (Duxbury et al. 1993) and account for 68–75 peta gram (Pg) $CO_2$-C year$^{-1}$, which mainly results from the respiration of plant roots, soil microflora, and fauna, and also from the decomposition of OM (Lou et al. 2007). The exchange process of $CO_2$ between the atmosphere and the soil is a vital part of the carbon cycle, and controlling this process can affect its concentration in the environment (Ussiri and Lal 2009). The small variations of soil organic carbon pools may potentially cause critical changes in $CO_2$ concentrations in the atmosphere (Eswaran et al. 1995; Falloon et al. 1998; Davidson et al. 2000). The emissions of $CO_2$ from soils depend on many factors, including the quantity and quality of organic materials, availability of nutrients, soil moisture (aerobic and anaerobic conditions), temperature, pH, fertilization, land use, and management practices (Mosier 1998; Lou et al. 2003; Majumdar et al. 2006).

Labile fractions of organic carbon such as microbial biomass carbon (MBC), dissolved organic C (DOC), particulate organic carbon (POC), and easily oxidizable carbon (EOC) have been used as indicators for soil quality (Cambardella and Elliott 1992; Blair et al. 1995; Bolinder et al. 1999). It was mentioned that MBC consists of 1–5 % of total organic carbon (TOC), and it can be used as a receptive marker to evaluate the environmental impacts such as increasing concentrations of GHG in paddy soils (Hoque et al. 2001). The DOC is a complex mixture of organic compounds, which plays a key task in terrestrial ecosystems and acts as a major energy source for soil biota (Thurman 1985; Stevenson 1994). Although the concentration of DOC usually represents about 2 % of total organic carbon in agricultural soils, it is often considered as the most dynamic and available C fractions (Marschner and Kalbitz 2003). Particulate organic carbon (POC) accounts for 10 % of the soil C and consists mainly of semi-decomposed organic materials with a recognizable structure smaller than 2 mm and greater than 50 µm in size (sand-sized particles) (Carter et al. 1994; Gregorich et al. 1994). The POC is more sensitive to management practices as compared to total soil organic carbon and has an important role in nutrient release and microbial activities due to its readily decomposition by microorganisms (Cambardella and Elliott 1992; Gale and Cambardella 2000; Stella-Koutika et al. 2008). The easily oxidizable carbon (EOC) accounts for 5–30 % of TOC and includes organic components, which can be speedily oxidized by potassium permanganate ($KMnO_4$) (Blair et al. 1995). There have been a lot of investigations pointed out that MBC, DOC, EOC, and POC were sensitive and rapid indicators for changes in soil organic carbon (Bolinder et al. 1999; Gregorich and Carter 1997; Wander and Bidart 2000; Stella-Koutika et al. 2008).

Paddy soils in China occupy 25 % of total arable lands. The use of different water regimes in these soils can have a significant impact on soil organic carbon fractions, and in turn, soil-atmosphere $CO_2$ emissions. Although many experiments have been conducted to study the effect of water regimes or organic amendments such as rice straw on fluxes of $CO_2$ (Lou et al. 2003; Dong et al. 2009; Iqbal et al. 2009; Bhattacharyya et al. 2012), no attention has been paid to examine the combination effect of water regimes and rice straw on $CO_2$ emissions and labile organic carbon fractions in paddy soils. Accordingly, the study of $CO_2$ fluxes in response to labile organic carbon fractions is very important in these soils. So, the main objectives of this study are to (1) determine the emission of $CO_2$ and the transformation of labile soil organic carbon fractions in a paddy soil treated with rice straw under different water regimes, and (2) to signify the effect of labile organic carbon fractions on $CO_2$ emissions from Chinese paddy soils. To perform this study, the soil samples were incubated during March–June 2012 in a climatic cabinet at Huazhong Agricultural University, Wuhan City, Hubei Province, P.R. China.

## Materials and methods

### Site description

Soil samples were collected from the surface layer (0–15 cm) of a paddy soil (anthrosol, derived from Quaternary yellow sediment) at Wuxue City, Hubei Province, China (29°51′N, 115°33′E; 20 m above sea level). This region is characterized by a humid mid-subtropical monsoon climate with an average annual temperature of 16.8 °C. The mean annual precipitation is 1,360 mm, which mostly occurs between April and August.

### Soil and rice straw

The soil samples were air-dried for 7 days and ground to pass through 2-mm sieve prior to start of the experiment. The texture of the investigated soil was silty clay loam with 5.45 % sand, 38.19 % clay, and 56.36 % silt. Rice straw (RS) was obtained from an experimental farm after the harvest of rice plants. The RS was oven-dried at 50–60 °C and then crushed to small pieces by grinder milling machine. The used RS was characterized by 9.23 % moisture, 69.47 % organic matter, 0.79 % N, 0.18 % P, and 0.94 % K.

### Experimental design

An incubation experiment was laid in a completely randomized block design with three replicates. Air-dried soil samples (900 g) were put in plastic pots (17 cm width × 8 cm height), and the RS was mixed thoroughly at a dose of 1.5 % (W/W) and wetted by five water levels (40, 55, 70, 85, and 100 % of water-holding capacity (WHC)) using the distilled water. Ten treatments were developed from the combination of water regimes (W) with rice straw (RS): W1(100 % WHC), W2 (85 % WHC), W3 (70 % WHC), W4 (55 % WHC), W5 (40 % WHC), W1RS (100 % WHC + 1.5 % RS), W2RS (85 % WHC + 1.5 % RS), W3RS (70 % WHC + 1.5 % RS), W4RS (55 % WHC + 1.5 % RS), and W5RS (40 % WHC + 1.5 % RS). All experimental pots were covered with a fine polyethylene with small holes to allow gaseous exchange and minimize the moisture loss. The pots were incubated at a constant temperature of 25 °C and weighted every 2 days to adjust the moisture at used levels. The soil samples were collected four times after 15, 30, 60, and 90 days, and separated into two subsamples. The first subsample was kept in a refrigerator at 4 °C in order to determine dissolved and microbial biomass carbon, while the second subsample was air-dried and kept in polyethylene bags to measure other organic carbon fractions (total organic carbon, permanganate oxidizable carbon and light fraction, and particulate organic carbon).

### Basic soil and rice straw analyses

Dried soil samples were ground and sieved through 2.00 and 0.15 mm sieves to determine the following properties. Soil pH was measured in a suspension of 1:2.5 (w/v) soil/water ratio after shaking for 1 h, using pH meter. The international pipette method was used to evaluate the soil particle-size distribution (Sheldrick and Wang 1993). Total soil organic carbon was determined by potassium dichromate ($K_2Cr_2O_7$) oxidation at 170–180 °C followed by titration with 0.5 mol $l^{-1}$ ferrous sulfate (Walkley and Black 1934). The organic matter content of rice straw was determined by the combustion method in a muffle furnace at 600 °C for 6 h (Goldin 1987). The organic matter content was determined through the mass difference before and after the combustion process. The total nitrogen (N) and phosphorus (P) contents of soil and straw were examined by the FIA-star 5000 analyzer method after $H_2SO_4$/$HClO_4$ (2:1 ratio) digestion. The total potassium (K) of soil and straw were analyzed using the flame photometer apparatus. Soil available N was measured by Kjeldahl method after its extraction by KCl (2 mol $l^{-1}$), while the available K content was estimated by the flame photometer after its extraction by $NH_4COO–CH_3$ (1 mol $l^{-1}$, pH 7) (Jackson 1973). Available soil P was extracted by $NaHCO_3$ (0.5 mol $l^{-1}$, pH 8.5) and analyzed using the spectrophotometer (Olsen and Sommers 1982). Results of some chemical and physical properties of soil are presented in Table 1.

### Carbon dioxide ($CO_2$) emission

The emission of $CO_2$ from the soil was estimated following the soil respiration method described by Parkinson (1981). Briefly, the experimental pot with 0.9 kg soil was put in

**Table 1** Chemical properties of the used paddy soil

| Properties | Values |
|---|---|
| pH | 5.95 |
| Total organic carbon (g $kg^{-1}$) | 19.45 |
| Light fraction of organic carbon (g $kg^{-1}$) | 0.91 |
| Particulate organic carbon (g $kg^{-1}$) | 2.50 |
| Easily oxidizable organic carbon (g $kg^{-1}$) | 1.14 |
| Dissolved organic carbon (mg $kg^{-1}$) | 770.9 |
| Microbial biomass carbon (mg $kg^{-1}$) | 68.49 |
| Total N (g $kg^{-1}$) | 1.25 |
| Total P (g $kg^{-1}$) | 0.84 |
| Total K (g $kg^{-1}$) | 17.79 |
| Available N (mg $kg^{-1}$) | 26.28 |
| Available P (mg $kg^{-1}$) | 7.39 |
| Available K (mg $kg^{-1}$) | 136.75 |

another plastic pot with a diameter of 40 cm which contained distilled water. Afterward, a plastic cylinder chamber of 20 cm in diameter was put around the experimental pot, and then, the flux of $CO_2$ was measured with a LI–8100-A portable infrared analyzer (LICOR Inc., Lincoln, NE, USA). The $CO_2$ fluxes were determined 16 times at 3, 6, 10, 13, 16, 22, 25, 28, 31, 35, 41, 50, 56, 65, 73, and 85 days from the experiment beginning (March 2012). Three readings of $CO_2$ emissions were recorded for each experimental pot at each sampling time. All the measurements were carried out in the morning (09:00–11:00 a.m.) to get representative daily soil $CO_2$ fluxes (Lou et al. 2003). The data of $CO_2$ fluxes were expressed as mg $CO_2$ $kg^{-1}$ soil $h^{-1}$. The $CO_2$ fluxes and cumulative emissions were calculated as described by Li et al. (2012a).

### Microbial biomass carbon

Microbial biomass carbon (MBC) was determined using the chloroform fumigation–extraction method (Vance et al. 1987). In brief, 10 g fresh soil sample was extracted by 40 ml of 0.5 $MK_2SO_4$ (non-fumigated). Another 10 g fresh soil sample was fumigated with chloroform for 24 h at 25 °C and then extracted by 0.5 $M{\cdot}K_2SO_4$ (fumigated). The non-fumigated and fumigated soil samples were shaken for 60 min at 200 rpm and then filtered using Whatman 42 paper. The concentrations of C in extracts were measured by a total organic carbon (TOC) analyzer (Multi N/C 2100, Jena, Germany). The values of MBC were calculated from the difference between the values of C in fumigated and non-fumigated samples and divided by 0.45 (Wu et al. 1990).

### Dissolved organic carbon

Dissolved organic carbon (DOC) was extracted from 10 g fresh soil using 40 ml distilled water according to the method of Zsolnay (2003). The soil samples were shaken for 30 min at a speed of 250 r $min^{-1}$. The supernatant was centrifuged for 10 min at 15,000 r $min^{-1}$ and filtered by 0.45-µm cellulose ester filters. The extracts were analyzed for C using a TOC analyzer (Multi N/C 2100, Jena, Germany).

### Light fraction and particulate organic carbon

Light fraction organic carbon (LFOC) was extracted from the soil using the method described by Gregorich and Ellert (1993). Dried soil subsamples (25 g) were placed into centrifuge tubes with 50 ml NaI solution and a density of 1.70 g $cm^{-3}$. The tube was shaken for 1 h at 200 rev $min^{-1}$and centrifuged at 1,000*g* for 15 min. The extraction process of LFOC was repeated three times. The floating material was transferred to a filter paper, washed every time with 0.01 $M{\cdot}CaCl_2$ and distilled water, and finally dried for 48 h at 60 °C.

Particulate organic carbon (POC) was examined by using the method of Cambardella and Elliott (1992). A portion of the dried soil sample (i.e., 10 g) was dispersed in 30 ml of sodium hexametaphosphate (5 g $l^{-1}$) and placed on a reciprocating shaker (90 r $min^{-1}$) for 18 h. The soil suspension was decanted over a 53-µm sieve under a flow of distilled water to ensure separation. The remaining soil on the sieve was transferred to a glass dish, dried at 55–60 °C for 48 h and ground to powder by a ball mill. The concentrations of organic carbon in LFOC and POC were estimated by the wet oxidation method using potassium dichromate (Walkley and Black 1934).

### Permanganate oxidizable carbon

The values of permanganate oxidizable carbon (PMOC) were determined using the method of Blair et al. (1995). Briefly, soil samples containing about 15 mg C were weighed and placed into plastic centrifuge tubes. The samples were shaken with 25 ml of 333 mM $KMnO_4$ for 1 h at 12 rpm. The blank sample was run under the same condition without any soil. The suspensions were centrifuged for 5 min at 2,000 rpm, and the filtrates diluted at 1:250 with deionized water. The concentrations of PMOC were measured by spectrophotometer at a wave length of 565 nm.

### Statistical analysis

The experimental data were organized in triplicate, and the mean values were considered for the statistical analysis. A one-way ANOVA was performed using the software of SPSS 12.0 (SPSS Inc., Chicago, USA) to estimate the effect of rice straw and water regimes on $CO_2$ emission and labile soil carbon fraction. A Pearson's correlation analysis was conducted to evaluate the relationships between $CO_2$ emission and labile soil carbon fractions. The Duncan's multiple range test based on least significant difference (LSD) values at level of $p < 0.05$ was used to analyze the significant variation between treatments.

## Results and discussion

### Effect of rice straw and water regimes on emissions of $CO_2$

Fluxes of $CO_2$ were significantly influenced by the addition of rice straw and water regimes (Fig. 1a,b). In general, the

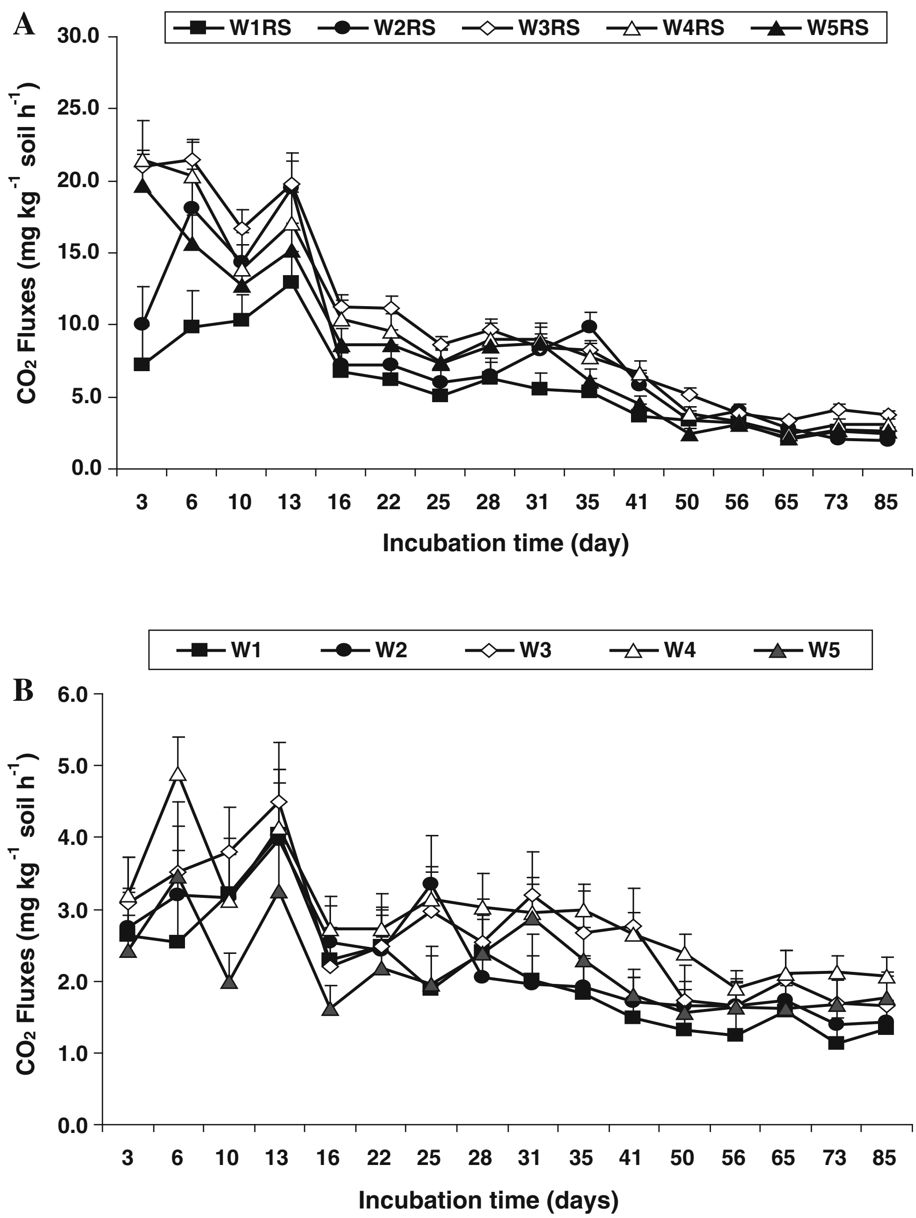


**Fig. 1** Emissions of $CO_2$ in a control paddy soil (**a**) and in a rice straw-treated soil (**b**) under different water regimes. The *error bars* represent the standard deviations of three replicates

decrease in soil water regimes led to noticeable increases in $CO_2$ release in the presence and absence of rice straw. Rice straw application caused higher emissions in $CO_2$ at all water regimes and incubation time as compared to control (no straw). The $CO_2$ emission rates reached their peaks after 13 days from the start of incubation and then gradually decreased to lower values till the end of incubation in both non-amended and rice straw-amended soils. In first 13 days of incubation, the concentration of $CO_2$ varied from 3.26 to 4.49 mg kg$^{-1}$ soil h$^{-1}$ in non-amended soil and from 12.98 to 19.74 mg kg$^{-1}$ soil h$^{-1}$ in rice straw treatments. Moreover, the highest values of $CO_2$ fluxes were 19.49 and 19.74 mg kg$^{-1}$ soil h$^{-1}$ at W2 (80 % WHC) and W3 (70 % WHC) when the soil received rice straw. However, in the case of no rice straw, the highest releases of $CO_2$ were 4.49 and 4.14 mg kg$^{-1}$ soil h$^{-1}$ at W3 (70 % WHC) and W4 (55 % WHC).

Similar results obtained by Lou et al. (2007) who observed that the addition of rice straw increased the emissions of $CO_2$ as compared with control in an incubation experiment were conducted on a paddy soil collected from Yingtan City, Jiangxi Province, China. They also found that soil $CO_2$ fluxes rapidly increased and reached their highest values within 10 days, and then gradually decreased to the lower values near to the control. This could be explained by the fast $CO_2$ emissions at the early stage might be produced due to the increase in carbon supply and other substrates, which might stimulate both microbial activities and communities after the incorporation of rice straw. In another study, the maximum $CO_2$

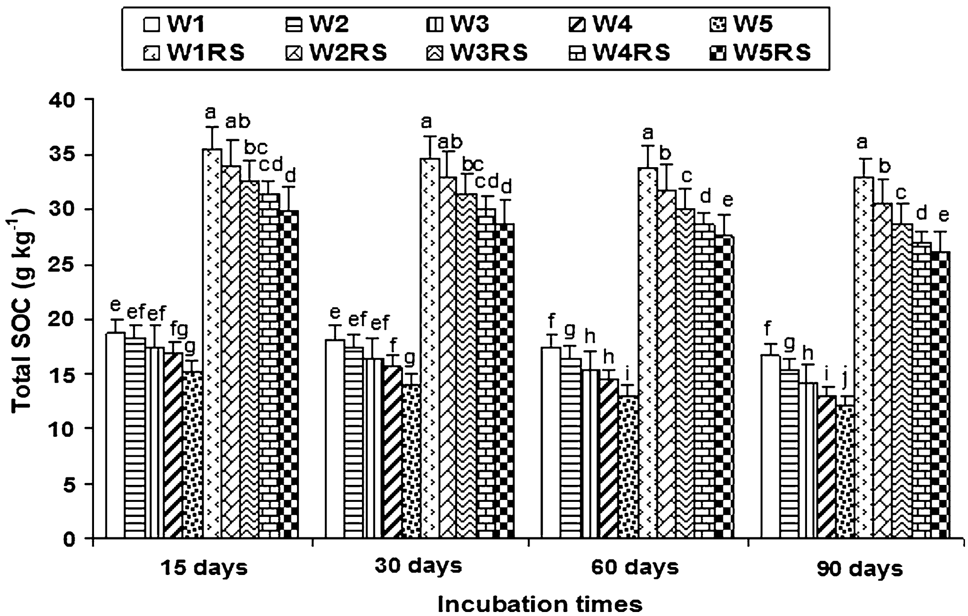


**Fig. 2** Effect of rice straw on soil total SOC at different water regimes. *SOC* soil organic carbon, *W* water regime, and *RS* rice straw. *Different letters* on *bars* indicate significant difference between treatments at $p < 0.05$. The *error bars* represent the standard deviations of three replicates

production occurred immediately after 1 day of the start of incubation with wheat straw at a dose of 2 % (w/w) in a sandy loam soil (red chromosol) of a natural bushland in Monarto, South Australia (Duong et al. 2009). These authors illustrated this phenomenon with the high respiration rates at the preliminary time due to the breakdown of easily available organic compounds when wheat straw residues were applied once. Furthermore, they mentioned that the respiration rates could have diminished after the exhaustion of easy mineralizable substrates. On the other hand, they reported that the increase in incubation periods caused low $CO_2$ release because of the hard decomposition process in the presence of recalcitrant compounds such as lignin cellulose and other macromolecules.

The higher increase in organic carbon inputs due to the incorporation of rice straw (Fig. 2) might be used to elucidate the larger $CO_2$ fluxes in rice straw-amended soil than in the control (no straw). It was recorded that the high availability of C and N substrates, and microbial activities could be accountable for the large increase in $CO_2$ emissions after rice straw addition (Iqbal et al. 2009; Vaughan et al. 2011; Bhattacharyya et al. 2012).

The greater emissions of $CO_2$ from W3 and W4 treatments than from other treatments could be resulted from their larger DOC and MBC contents (Figs. 3 and 4), which could simulate the decomposition of rice straw and the release of $CO_2$. The role of soil moisture in $CO_2$ fluxes from soils might have resulted from its effect on microbial activity (Smith et al. 2003). It was recorded by Xu and Qi (2001) and Rey et al. (2002) that emissions of CO2 become more noticeable when the soil moisture was lower than 60 % of water-filled pore space (WFPS). Dong et al. (2009) found that the increase in soil water contents led to marked reductions in the release of $CO_2$ from a slit loam soil at Luancheng County, Hebei Province, China. Moreover, Iqbal et al. (2009) noticed that highest emissions of $CO_2$ were recorded at 60 % of WHC at 25 °C and 30 °C, whereas lowest emissions were recorded at 20 and 100 % of WHC in an incubation experiment on a paddy soil obtained from Xianning County, Hubei Province, Southern China. Ding et al. (2010) showed that $CO_2$ fluxes were extremely low when the soil moisture was at 85 % of WFPS, whereas the emission significantly linearly increased before reaching the soil moisture at 70 % of WFPS.

In the present study, the most wet (100 % of WHC) and dry (40 % of WHC) conditions had inhibition effects on $CO_2$ production when paddy soil did not receive rice straw. However, in the presence of rice straw, the highest wet (80 and 100 % of WHC) conditions only showed largest reductions in emissions of $CO_2$. This conformed that the incorporation of rice straw had low effect on $CO_2$ fluxes from paddy soils at wet conditions as compared with dry conditions.

### Organic carbon pools transformation

Rice straw additions significantly enhanced the total soil organic carbon (SOC) contents of the studied paddy soil under all water regimes (Fig. 2). The total SOC contents increased by 1.98 and 2.15 times after 90 days in W1 (100 % WHC) and W5 (40 % WHC), respectively. It was appeared that the application of rice straw at a rate of 4.5 Mg $ha^{-1}$ led to significant enhancement in SOC contents by 3.64 g $kg^{-1}$ in a paddy soil obtained from Jinjiaba Township, Jiangsu Province, China (Pan et al. 2009). Soil water regimes had significant effects on SOC and the

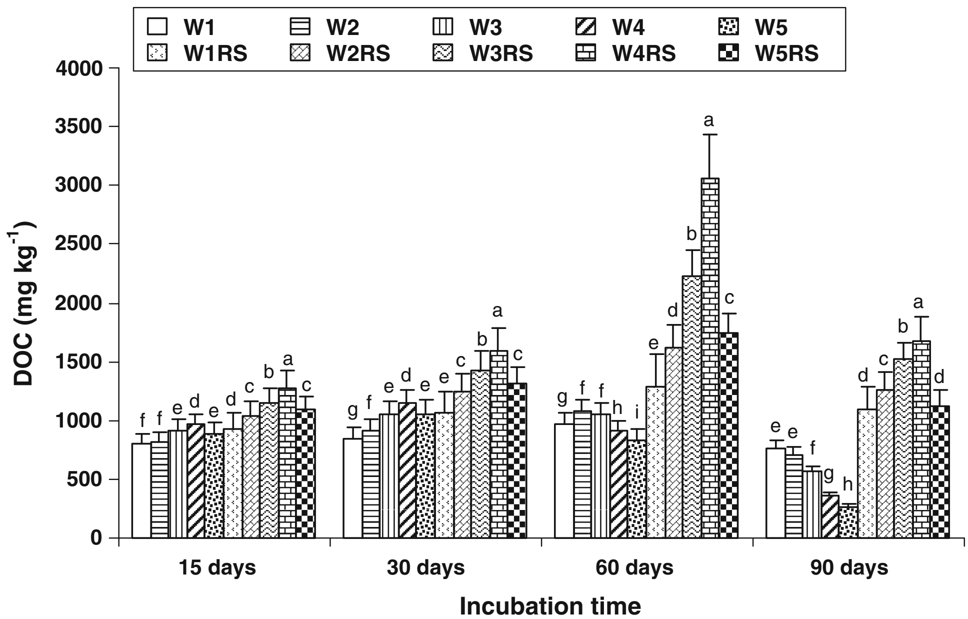


**Fig. 3** Effect of rice straw on soil DOC at different water regimes. *DOC* dissolved organic carbon, *W* water regime, and *RS* rice straw. *Different letters* on *bars* indicate significant difference between treatments at $p < 0.05$. The *error bars* represent the standard deviations of three replicates

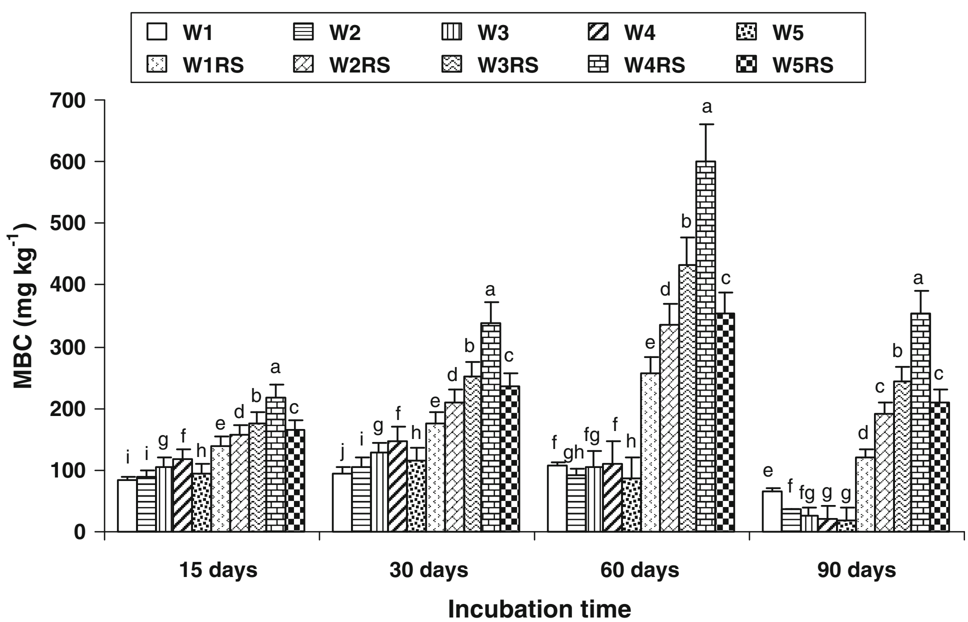


**Fig. 4** Effect of rice straw on soil MBC at different water regimes. *MBC* microbial biomass carbon, *W* water regime, and *RS* rice straw. *Different letters* on *bars* indicate significant difference between treatments at $p < 0.05$. The *error bars* represent the standard deviations of three replicates

decrease of water levels markedly diminished the SOC in the investigated soil. At all incubation times (15, 30, 60, and 90 days), the highest SOC values were recorded in W1 (100 % WHC), whereas the lowest were observed in W5 (40 % WHC). The change of soil water regime is one of the most important factors in controlling the process of SOC mineralization and transformation (Hao et al. 2011). Moreover, they mentioned that the daily mineralization of SOC contents under the aerobic condition (60 % WHC) was generally higher than under the submerged condition (soil/ water ratio of 1:1 w/w) during the whole incubation period in a paddy white soil collected from Changshu City, Jiangsu Province, China.

Data in Figs. 3 and 4 showed that the use of rice straw considerably increased the dissolved organic carbon (DOC) and microbial biomass carbon (MBC). In the presence of rice straw, the highest DOC and MBC concentrations (2,234.6 and 600.80 mg $kg^{-1}$, respectively) were recorded after 60 days at W4, whereas the lowest values (921.20 and 84.30 mg $kg^{-1}$, respectively) were noticed after 15 days at W1 (100 % WHC). In the absence of rice straw, the decease of soil water regimes generally improved the values of DOC and MBC at 15, 30, and 60 days only. However, after 90 days, the amounts of DOC and MBC sharply declined with the decrease in water regimes. The decrease in available substrates such as soluble carbon and nitrogen might have

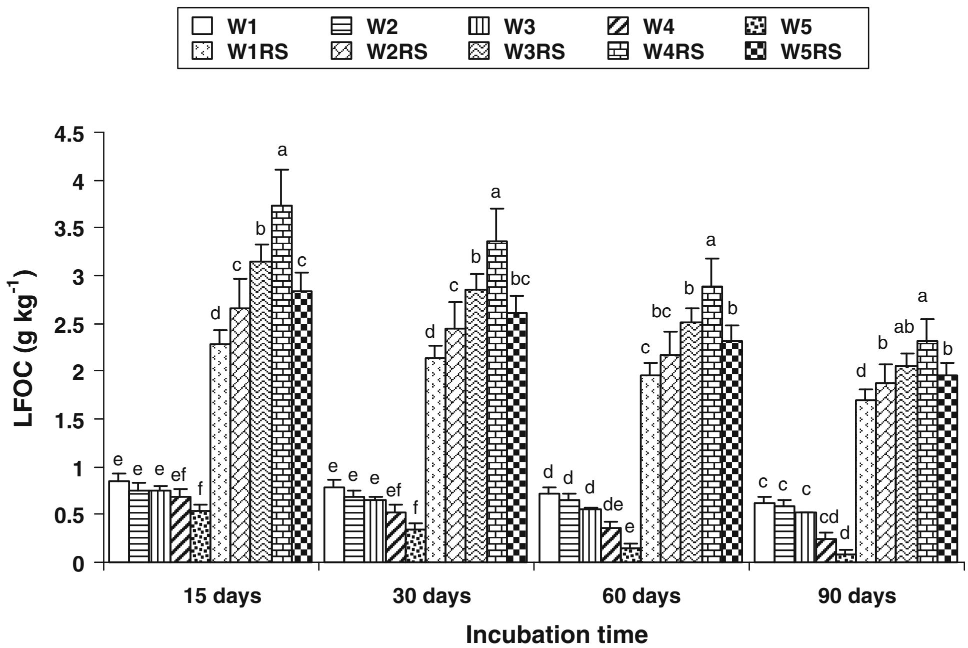


**Fig. 5** Effect of rice straw on soil LFOC at different water regimes. *LFOC* light fraction of organic carbon, *W* water regime, and *RS* rice straw. *Different letters* on *bars* indicate significant difference between treatments at $p < 0.05$. The *error bars* represent the standard deviations of three replicates

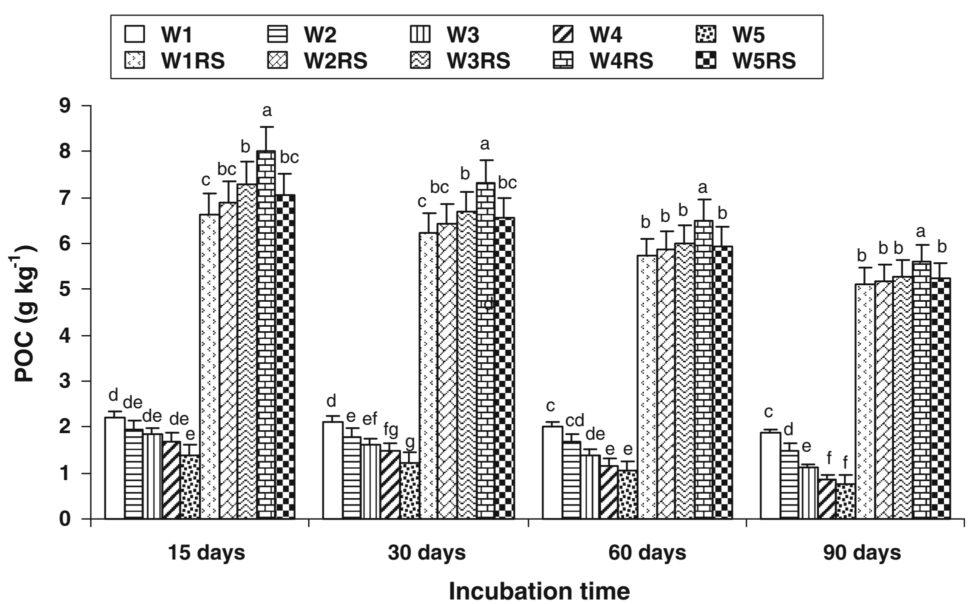


**Fig. 6** Effect of rice straw on soil POC at different water regimes. *POC* particulate organic carbon, *W* water regime, and *RS* rice straw. *Different letters* on *bars* indicate significant difference between treatments at $p < 0.05$. The *error bars* represent the standard deviations of three replicates

been used as a logical reason to explain the decline of DOC and MBC with increasing incubation time. Our results are compatible with the findings of Lou et al. (2007) who showed that the both DOC and MBC decreased significantly with the increase of incubation times from zero to 60 days in a paddy soil treated with rice straw (0.1 %) at 60 % WHC. They also found that the incorporation of rice straw led to higher DOC and MBC contents than in the absence of rice straw.

The addition of rice straw to the paddy soil under different water regimes resulted in higher concentrations of light fraction organic carbon (LFOC) and particulate organic carbon (POC) as compared with control (no straw) at all incubation periods (Figs. 5 and 6). Furthermore, when the soil was amended with rice straw, LFOC and POC contents markedly increased with the decrease of soil water regime. The highest values of LFOC and POC were noticed at W4 (55 % WHC), while being lowest at W1 (100 % WHC). In case of no straw addition, the decline of soil water content caused nonsignificant decreases in LFOC and POC values at the first four water regimes (W1, W2, W3, and W4). However, the decrease of LFOC and POC contents became more obvious at W5.

Under all water regimes and incubation periods, the permanganate oxidizable carbon (PMOC) fraction considerably

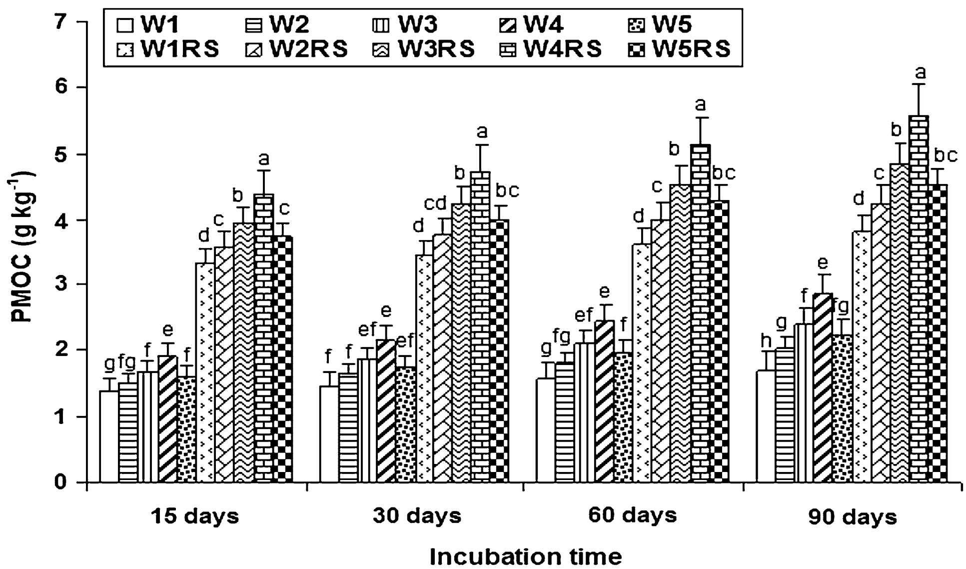


**Fig. 7** Effect of rice straw on soil PMOC at different water regimes. *PMOC* permanganate oxidizable carbon, *W* water regime, and *RS* rice straw. *Different letters* on *bars* indicate significant difference between treatments at $p < 0.05$. The *error bars* represent the standard deviations of three replicates

increased in rice straw treatments as compared to control (Fig. 7). Moreover, the decrease in soil water regimes led to marked increases in PMOC, the control and rice straw treatments. The highest values of PMOC (2.87 and 5.58 g $kg^{-1}$) were found at W4 (55 % WHC) after 90 days, whereas the lowest amounts (1.39 and 3.31 g $kg^{-1}$) were noticed at W1 (100 % WHC) after 15 days from the start of the experiment in the absence and presence of rice straw, respectively.

Our results were consistent with previous studies, which recorded that the input of organic materials into soils could increase LFOC and POC fractions. For example, Yan et al. (2007) showed that both POC and LFOC were increased from 4.88 and 1.44 to 5.28 and 1.96 g $kg^{-1}$ after the application of rice straw in a permeable paddy soil at Suzhou City, Jiangsu Province, China. In another study, Yang et al. (2012) showed that LFOC, POC, and PMOC were improved by 2.25, 1.84, and 2.15 times after the addition of wheat straw or maize stalk in a silt clay loam soil was located in Yangling district, Shaanxi Province, China. They also mentioned that PMOC was higher in wheat straw or maize stalk-amended soil than the control could be explained by the higher labile organic carbon inputs, which associated with the straw and stalk.

The higher concentrations of LFOC and POC in W4 (55 % WHC) as compared with other water regimes were possibly resulted from the greater microbial properties such as DOC and MBC (Figs. 3 and 4), which could simulate the decomposition of soil organic matter and then accumulate and distribute the organic carbon in LFOC and POC fractions under this water level. Moreover, the decomposition process of soil organic matter had a key role in enhancing soil PMOC values. It was found by Yang et al. (2005) that soil PMOC, LFOC, and POC under water regime of continuous waterlogging decreased by 30.6, 8.3, and 10.6 % in wheat straw treatment, respectively, as compared to the water regime of alternative wetting and drying. This confirmed that the adoption of soil water regimes is an important factor to improve the transformation of soil organic carbon pools after the addition of rice straw.

## Effect of labile organic carbon fractions on the emission of $CO_2$

Interestingly, soil $CO_2$ fluxes positively correlated with all soil organic carbon fractions (SOC, MBC, DOC, LFOC, POC, and PMOC) in this study (Table 2). These correlations suggested that labile organic carbon fraction (LFOC, MBC, DOC, LFOC, POC, and PMOC) had more significant effects on $CO_2$ fluxes as compared with the total SOC in the paddy soil. Moreover, the highest correlations ($r = 0.97$ and 0.98 at $p < 0.01$) were found between $CO_2$ emissions and LFOC and POMC. Generally, our results were in agreement with Lou et al. (2007) who found that soil $CO_2$ fluxes positively correlated with DOC and MBC ($r = 0.764$ and 0.981 at $p < 0.05$ and 0.01, respectively) after 55 days from the experiment beginning. In another study, Iqbal et al. (2010) found positive relationships between $CO_2$ fluxes and DOC and MBC ($r = 0.799$ and 0.533 at $p < 0.05$) in a field experiment which was conducted on upland soil transferred from paddy at the experimental station of Zigui County, Three Gorges Reservoir Area, southern China. Bhattacharyya et al. (2012) also found significant correlations between SOC, MBC, readily mineralizable carbon (RMC), and $CO_2$ emissions ($r = 0.93$, 0.92, and 0.96 at $p < 0.01$, respectively) after the application of rice straw and green manure in a paddy sandy clay loam soil in Cuttack City at the eastern part of India.

**Table 2** Pearson's correlation coefficients ($r$) between means of $CO_2$ fluxes and organic carbon fractions ($n = 10$)

| | $CO_2$ | SOC | LFOC | POC | EOC | DOC | MBC |
|---|---|---|---|---|---|---|---|
| $CO_2$ | 1.00 | | | | | | |
| TOC | 0.87** | 1.00 | | | | | |
| LFOC | 0.97** | 0.91** | 1.00 | | | | |
| POC | 0.95** | 0.96** | 0.99** | 1.00 | | | |
| EOC | 0.98** | 0.87* | 0.97** | 0.95** | 1.00 | | |
| DOC | 0.93* | 0.74** | 0.94** | 0.88** | 0.94** | 1.00 | |
| MBC | 0.94** | 0.78** | 0.95** | 0.91** | 0.97** | 0.99** | 1.00 |

*SOC* soil organic carbon, *LFOC* light fraction of organic carbon, *POC* particulate organic carbon, *PMOC* permanganate oxidizable carbon, *DOC* dissolved organic carbon, and *MBC* microbial biomass carbon

** $p < 0.01$, respectively

In this study, LFOC compared to other carbon fractions appeared to be the most sensitive indicator of $CO_2$ emissions from the paddy soil ($r = 0.97$ at $p < 0.01$). The LFOC had higher effect on $CO_2$ fluxes as compared with POC because LFOC mostly consists of organic materials in a fresh case or in an early stage of the decomposition process for short period (Mueller et al. 1998), and also, it is more labile than POC (Gregorich and Janzen 1996). Overall, it is worthwhile to mention from our findings that the high efficient effects of rice straw on LFOC, POC, and PMOC (Figs. 5, 6, 7) could be used as an advanced illustration for the high emissions of $CO_2$ from the paddy soil.

### Relationships between soil organic carbon fractions

The correlations between all soil organic carbon fractions were significantly positive (Table 2). The total SOC had higher links with LFOC ($r = 0.91$) and POC ($r = 0.96$) than with PMOC ($r = 0.87$, DOC ($r = 0.74$) and MBC ($r = 0.78$) at $p < 0.01$. The correlations of DOC and MBC with LFOC ($r = 0.94$ and 0.95) and PMOC ($r = 0.94$ and 0.97) at $p < 0.01$ were higher than those with POC ($r = 0.88$ and 0.91) at $p < 0.01$. The largest correlations were found between LFOC and POC ($r = 0.99$), and DOC and MBC ($r = 0.99$) at $p < 0.01$. Similar results had been recorded by Yan et al. (2007), Dou et al. (2008), Chen et al. (2009), Lou et al. (2011), Li et al. (2012b), Wang et al. (2012), and Yang et al. (2012) who observed positive correlations between LFOC, POC, PMOC, MBC, DOC, and SOC. It was suggested by Yang et al. (2012) that the significant relationships between SOC and LFOC, POC, MBC, and PMOC confirmed the major role of SOC in the quantity and quality of labile organic carbon fractions.

The high correlations between DOC and MBC and other labile organic carbon fractions (LFOC, POC, and PMOC) might be used to show how LFOC, POC, and PMOC were significantly affected by the soil microbial properties. Moreover, the best correlations of SOC with LFOC and POC indicated their dynamic responsibility in the alteration rates of SOC in the investigated paddy soil.

## Conclusion

The changes of soil water regimes had an important effect on the emission of $CO_2$ with and without incorporation of rice straw into the paddy soil. The addition of rice straw resulted in higher $CO_2$ fluxes from the paddy soil as compared to control (no straw), especially in W3 (70 % WHC) and W4 (55 % WHC). The effect of water regimes on $CO_2$ fluxes from the paddy soil was more noticeable in the presence of rice straw than in the absence of rice straw. All evaluated labile organic carbon fractions, dissolved organic carbon (DOC), microbial biomass carbon (MBC), light fraction organic carbon (LFOC), particulate organic carbon (POC), and permanganate oxidizable carbon (PMOC) were significantly increased after the incorporation of rice straw in the paddy soil. Generally, the changes of soil water regimes had no marked effect on DOC, MBC, LFOC, POC, and POMC in the absence of rice straw. The results indicate that the emission of $CO_2$ from the studied paddy soil was highly affected by DOC, MBC, LFOC, POC, and PMOC. The higher positive correlations between total SOC and LFOC and POC as compared with other labile organic carbon fractions reflected their larger roles in soil organic matter alterations in the paddy soil. Further, short- and long-term studies are needed to improve our knowledge about the relationships between emissions of $CO_2$ or other greenhouse gases such as $CH_4$ and $N_2O$ from paddy soils and labile organic carbon fractions under field conditions as affected by different organic wastes.

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