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Organic carbon and its fractions in paddy soil as affected by different nutrient and water regimes

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Abstract

As an essential indicator of soil quality, soil organic carbon (SOC) and its fractions play an important role in many soil chemical, physical, and biological properties. A 4-year field experiment was conducted to determine the effects of different nutrient and water regimes on paddy soil organic carbon quality by measuring the major SOC fractions. Four nutrient regimes were compared: (i) control; (ii) chemical fertilizers only (CF), (iii) combined application of chemical fertilizers with farmyard manure (FYM) (CM), and (iv) combined application of chemical fertilizers and wheat straw (CS). Two soil water regimes included continuous waterlogging (CWL) and alternate wetting and drying (AWD). The total organic carbon (TOC) and total nitrogen (TN) in paddy soil were 40–60% and 37–67% higher in the combined organic sources and chemical fertilizers treatment against the sole chemical fertilizers treatment (CF), especially under continuous waterlogging (CWL). By fractionalizing SOC, it was observed that, under the water regimes of CWL, easily oxidizable carbon (EOC), particulate organic carbon (POC), light fraction organic carbon (LFOC), microbial biomass carbon (MBC), and mineralizable organic carbon (MNC) in the organically treated paddy soil were significantly ($P<0.05$) lower, as compared with alternate wetting and drying (AWD). Especially for CM treatment, EOC, POC, LFOC, MBC, and MNC in the paddy soils under the regime of CWL were 23.5%, 32.7%, 16.3%, 56.8% and 25.1% lower than those by AWD, respectively. The proportions of EOC, POC, LFOC, MBC and MNC as a percent of TOC in the CWL were lower than those in the AWD, especially for the CM treatment. In the water regime of CWL, no significant differences were seen in the corresponding proportion of all the investigated organic fractions to soil total organic carbon (TOC) among the three fertilization treatments, whereas in the AWD, the corresponding proportions of different carbon fractions to TOC in the organic fertilizer treatments were significantly ($P<0.05$) higher than those in the chemical fertilizer treatment. Under continuous waterlogging, the proportion of soil water stable aggregate >250 μm (WSA) decreased by 42–45% and clay dispersion ratio (R_{CD}) increased by 12–38%, as compared to the water regimes of AWD, when FYM or wheat straw was incorporated into paddy soil. Correlation analysis showed that, under the water regimes of AWD, WSA was significantly and positively related to EOC, LFOC and POC with the coefficients (r) of 0.822, 0.889, 0.912 ($P<0.01$), respectively. R_{CD} was negatively correlated to EOC, LFOC and POC with the $r = -0.796$, -0.854, and -0.897 ($P<0.01$), respectively, under AWD. Under the water regimes of

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CWL, there were no significant ($P<0.05$) correlations between WSA as well as R_{CD} and any organic carbon fraction except POC.

Keywords: Alternate wetting and drying; Anthropogenic soil; Farmyard manure; Microbial biomass C; Organic carbon fractions; Water stable aggregation

1. Introduction

Soil organic matter (SOM) or organic carbon (SOC) is considered to be a key attribute of soil fertility and productivity because of its importance to soil physical, chemical as well as biological properties (Stevenson, 1986; Johnston, 1986; Reeves, 1997). However, soil total organic carbon (TOC) might not be sensitive to changes in soil quality resulting from soil management practices changes after a relatively short time. As soil organic carbon is a heterogeneous mixture of organic substances, the different forms or fractions of SOC might have different effects on soil fertility and quality. Accumulating evidence suggests that certain fractions of soil organic carbon are more important in maintaining soil fertility and are, therefore, more sensitive indicators of the effects of management practices compared with the soil TOC (Cambardella and Elliott, 1992; Von Lutzow et al., 2000; Carter et al., 1998; Freixo et al., 2002). Soil easily oxidizable organic carbon (EOC) and light fraction organic C (LFOC) responded more rapidly under different tillage and stubble treatments. Hence, potentially they are more sensitive indicators of agricultural management-induced changes than soil TOC (Campell et al., 1996; Campbell et al., 1999; Carter et al., 1998; Haynes, 1999; Chan et al., 2002). Microbial biomass C (MBC) is recognized as a sensitive indicator of cultivation-induced changes in both SOC and biological properties of soil quality and soil health (Anderson and Domesch, 1989; Powlson et al., 1987; Franzliebbers and Zuberer, 1995; Karlen et al., 1997). Based on soil organic carbon fractions, measurement of smaller and more active fractions of soil organic carbon is essential to identify changes in soil organic carbon quality as influenced by soil management practices.

Paddy soil, as an important soil resource in China, is an anthropogenic soil, and its evolvement and formation are affected greatly by tillage, irrigation, and fertilization. Taihu Lake region is the major distribution area of Chinese paddy soil resources. However, due to long-term submerging and application of mineral fertilizers, paddy soil in the region is undergoing degradation of soil quality such as breakdown of stable aggregation and deterioration of SOM, which badly affect the local agricultural sustainable development. The effects of tillage and stubble on arid and forested soil organic carbon and its fractions were well documented (Chan et al., 2002; Carter et al., 1998; Haynes, 1999; Freixo et al., 2002). However, there has been very little research on the relative effectiveness of nutrient and water management on the levels of different forms organic carbon of paddy soil. The objective of this study was to determine and evaluate the effects of different nutrient and water regimes on paddy soil organic carbon fraction and quality and soil structural stability. The information will be useful to supply groundwork and knowledge for establishing appropriate and sustainable paddy soil management systems. Relationships between soil organic carbon fractions and soil water stable aggregation as well as clay dispersion and were also examined.

2. Materials and methods

This field experiment was conducted at the Changshu Agro-ecological Experiment Station (CAES), Chinese Academy of Sciences, situated in Changshu City, Jiangsu province of China with latitude of 31°33′N and 120°42′E and altitude of 15 m from 1999 to 2002. Rice–wheat rotation is popular in the region. The soil under investigation belonged to gleyed paddy soil developed on lacustrine deposit. The selected soil physical and chemical properties are given in Table 1.

Table 1
Selected physical and chemical properties of the tested soil

Clay (%)	Sand (%)	CEC[a] (cmol kg^{-1})	pH H_2O 1:1	Organic C[b] (g kg^{-1})	Total N (g kg^{-1})	Available P[c] (mg kg^{-1})	Available K[d] (mg kg^{-1})
46.7	15.4	16.9	7.85	19.6	1.82	8.26	119.7

[a] 1 M NH_4 OAc method.
[b] Dry combustion method.
[c] 0.5 $MNaHCO_3$ extraction.
[d] 1 M NH_4 OAc extraction.

2.1. Experimental design and soil nutrient and moisture treatments

The experiment was laid out in a randomized complete block design using four replications. Plot size was 5×6 m^2 .The nutrient regimes were as follows: (i) control (CK), (ii) exclusively chemical fertilizers (CF), (iii) integration of chemical fertilizers with farmyard manure (FYM) (CM), and (iv) combined application of chemical fertilizers and wheat straw (CS). Each plot received an application at the equal levels of 150 kg N ha^{-1}, 45 kg P_2O_5 ha^{-1} and 60 kg K_2O ha^{-1}. Application rates of farmyard manure and wheat straw in the treatment CM and CS were 1500 and 2500 kg ha^{-1} each year, respectively. Farmyard manure and wheat straw were converted into the amount of N, P and K, and the rest was supplemented by chemical fertilizers. Total C, N, P, K of FYM were 356.4, 19.4, 7.45, 18.6 g kg^{-1}, respectively; wheat straw contained 401.2 C g kg^{-1}, 3.40 N g kg^{-1}, 0.89 P_2O_5 g kg^{-1}, 14.6 K_2O g kg^{-1}, respectively. P and K fertilizers were applied as superphosphate and potassium sulfate as basal when transplanting. Nitrogen was split into three applications: one half of total N fertilizers as NH_4HCO_3 at transplanting, one fifth and the other as urea at tillering and booting, respectively. Farmyard manure and wheat straw were chopped and incorporated into paddy soil 2 weeks before transplanting each year.

Two soil water regimes included: (i) continuous waterlogging (CWL): plots were flooded to a depth of 3–5 cm throughout the rice growth period, (ii) alternate wetting and drying (AWD): plots were allowed to dry up for 2 weeks before submerged (3–5 cm above the soil surface) for 3 weeks after transplanting, and then re-flooded to waterlogging for 2 weeks. Thus, soils were kept under alternating flooded and dried conditions until rice harvested.

2.2. Soil and plant samples collection and analyses

Soil samples were collected from 0- to 20-cm depth in each plot at the end of the experiment. The samples for biological and biochemical analysis were directly stored at 4 °C for 4–6 weeks prior to analysis. Part of sample was subsequently air-dried and finely ground (<2 mm). Soil organic carbon and total N were determined on air-dried samples while the other measurements were made on soils at the water content when sampled. Based on gravimetric water content, measurements were converted to a dry soil basis.

Soil organic C (TOC) was analyzed by means of dry combustion with an ANCA–MS (Automatic Nitrogen and Carbon Analyser–Mass Spectrometer). Kjeldahl N content as total nitrogen was determined by digestion in H_2SO_4 followed by colorimetric analysis with the indophenol blue method, using a spectrometer (Nelson and Sommers, 1980).

The easily oxidizable organic carbon (EOC) in each sample was determined as described by Blair and Lefory (1995). Briefly, a sample containing 15–30 mg of air-dried soil was reacted with 333 mmol l^{-1} $KMnO_4$ solution for 1 h, and the amount of EOC determined spectrophotometrically from the amount of $KMnO_4$ reduced. Light fraction organic C (LFOC) of the sampled soils, which represents a measure of the transitory pool of organic matter between fresh residue and stable organic matter, was isolated by flotation on NaI solution adjusted to a density of 1.8 g cm^{-1} using a hydrometer (Gregorich and Ellert, 1993; Gregorich and Janzen, 1996). Each sample was weighed (20 g, <2 mm) and placed in a 250-ml plastic centrifuge tube and 200 ml NaI solution gently added using a dispenser. After gently shaking for a few seconds, the particles which adhered to the tube and stopper were washed into the suspension using NaI solution. The suspension was centrifuged at $815 \times g$ for 30 min after standing for

30 min. The suspension with the floating particles was poured into a Bucher funnel fitted with a glass-filter paper and filtered under vacuum. After washing with deionized water to removed the remaining NaI solution, the floated material off the filter paper was dried at 65 °C for 12 h and then weighed and analysed for organic C content.

Particulate organic carbon (POC) (53–2000 μm) was determined with modifications to the method described by Cambardella and Elliott (1992). Twenty grams of air-dried soil < 2 mm was dispersed in 100 ml of sodium hexametaphosphate ($(NaPO_3)_6$) (5 g l^{-1}) with shaking by hand during the first 15 min and then on a reciprocating shaker (90 r min^{-1}) for 18 h. The soil suspension was poured over a 53-μm screen using a flow of distilled water. All material remaining on the screen, defined as the particulate organic fraction was washed into a dry dish, oven dried at 60 °C for 12 h, weighed and ground to < 0.5 mm for determination of organic C.

Soil microbial biomass C (MBC) was estimated on 20 g oven-dry equivalent of fresh soil sample by fumigation of the sample with ethanol free $CHCl_3$ and extraction with 0.5 M K_2SO_4 described by Vance et al. (1987). The concentration of organic C in the soil extractant was determined by oxidation with $K_2Cr_2O_7$ (Vance et al., 1987). Microbial biomass C was calculated by using a conversion factor (k_c) of 0.35.

Mineralizable soil C (MNC) was evaluated by incubating duplicate (25 g) field-moist soil samples wetted to field capacity at 25 °C for 30 days in a serum bottle and trapping evolved CO_2 in 10 mm of 1 M NaOH. The cumulative CO_2 was determined every 3 days during the incubation by titration with HCl (Anderson, 1982).

Soil water stable aggregate >250 μm (WSA) was determined by wet sieving procedure. About 20 g of the air-dried soil sub-sample (1–10-mm fraction) was weighed and wet sieved for 10 min using a sieve of 250-μm aperture in a 2-l cylindrical container. A stroke length of 38 mm at a frequency of 30 strokes per minute was used. Content of soil water stable aggregate >250 μm was calculated. All the measurements were duplicated.

Soil clay dispersion was evaluated with modifications to the method described by Burt et al. (1993). Aliquots of the prepared air-dried soils (1.5000 g) < 3 mm were transferred to 250-ml cylinders, and the total volume was brought to 250 ml with deionized water. The cylinders were then shaken in an end-over-end shaker at 90 cycles min^{-1}. After allowing an appropriate time (3 h) according to Stokes' law, the amount of dispersed clay (< 0.002 mm) was measured by turbidimetry, using calibration curves of turbidity vs. clay concentration prepared for each clay type. Soil clay dispersion ratio (R_{CD}) was expressed as a fraction of the total clay.

2.3. Data statistics and analysis

All analyses were carried out on the four replicates. Data were analyzed statistically by analysis of variance (ANOVA) procedure. Duncan's New Multiple Range Test (DMRT) was employed to assess differences between the treatment means. The effects of nutrient and water regime were declared as significant at 5% probability levels. Standard deviations were calculated for means values of all the determination. Correlations of soil water stable aggregation and clay dispersion to soil C fractions were carried out by regression analysis. The regression analysis was done separately for each water regime. All statistical analyses were performed with SAS procedure (Statistical Analysis System Institute, 1995).

3. Results

3.1. Effect of nutrient and water regimes on soil total organic carbon and total nitrogen

Significant differences in soil total organic carbon (TOC) between the sole chemical fertilizer treatment (CF) and the combination of chemical fertilizers with organic materials (CM or CS) could be observed after 4 years of field experiment (Table 2). The CM and CS treatments had significantly higher average content of TOC than the other nutrient treatments through the water regimes. The continuous waterlogging (CWL) showed a higher SOC, as compared with the alternative wetting and drying (AWD) in corresponding nutrient treatments. For organic treatments (CM or CS), the differences in TOC between water regimes were more pronounced ($P < 0.01$). For the same water regime, the effectiveness of farmyard and wheat straw to increase TOC did not differed significantly.

Table 2
Effect of soil nutrient and moisture regimes on paddy soil total organic carbon (TOC) and total nitrogen (TN) ($g\ kg^{-1}$)

Nutrient regimes[a]	TOC		TN	
	CWL[b]	AWD	CWL	AWD
CK	11.01(± 1.21)e[c]	10.32(± 0.87)e	0.98(± 0.12)d	0.83(± 0.09)d
CF	13.57(± 1.45)d	12.13(± 0.97)de	1.45(± 0.21)c	1.21(± 0.17)c
CM	19.43(± 2.72)ab	17.89(± 1.23)bc	2.31(± 0.18)a	2.02(± 0.31)ab
CS	21.73(± 1.87)a	17.10(± 1.92)c	1.98(± 0.14)b	1.91(± 0.25)b

[a] CK, CF, CM and CS indicate Control, chemical fertilizers, chemical fertilizers + farm yard manure and chemical fertilizers +wheat straw treatments, respectively.

[b] AWD and CWL indicate continuous waterlogging and alternative wetting and drying, respectively.

[c] The data in table were expressed as Means ± S.E.; means for the same measurement followed the same letter are not significantly different ($P<0.05$) by Duncan's multiple range test.

Soil total nitrogen (TN) followed a pattern similar to TOC, and was also significantly affected by nutrient and water treatment (Table 2). The combined water and nutrient management of CWL and CM had the highest soil TN, followed by the combinations of AWD and CM, CS and CWL, and CS and AWD. The combined CF and AWD treatment showed the lowest TN except the CK treatment.

3.2. Effect of nutrient and water regimes on paddy soil labial carbon, light fraction carbon and particulate organic carbon

Soil easily oxidizable carbon (EOC), light fraction organic carbon (LFOC) and particulate organic carbon (POC) were significantly influenced by both nutrient and water treatments (Table 3). Average content of EOC was 25–30% higher by the combination of chemical fertilizers with organic materials than that by the chemical fertilizer (CF) through water treatments. In the alternative wetting and drying (AWD), soil EOC, LFOC and POC were higher relative to the continuous waterlogging (CWL) ($P<0.05$ or $P<0.01$), especially for the organically fertilized soils (Table 3). The paddy soil EOC, LFOC and POC under the water regime of CWL decreased by 21.7%, 21.9% and16.3% for the CM treatment, and 30.6%, 8.3% and 10.6% for the CS treatment, respectively, as compared to the water regime of AWD. This demonstrated that the continuous waterlogging markedly weaken the effectiveness of organic treatments to increase soil EOC, LFOC and POC.

The proportions of EOC, POC, and LFOC as a percent of total soil organic carbon were also significantly influenced by nutrient and water managements (Table 3). For the different treatments, organic C in EOC, LFOC, and POC accounted for 19.01–34.97%, 31.19–44.56%, and 24.45–37.78% of soil total organic C (TOC), respectively. In continuous waterlogging (CWL), the proportions of the soil TOC in EOC, LFOC, and POC were generally lower, and especially for the combination of wheat straw with mineral

Table 3
Effect of soil nutrient and moisture regimes on paddy soil easily oxidizable organic carbon (EOC), particulate organic carbon (POC) and light fraction organic carbon (LFOC) ($g\ kg^{-1}$)

Nutrient regimes[a]	EOC		POC		LFOC	
	CWL[b]	AWD	CWL	AWD	CWL	AWD
CK	2.29c[c] (20.83)	2.47c (23.93)	3.09c (28.03)	3.01c (29.12)	3.93cd (35.71)	3.57d (34.56)
CF	2.91b (21.14)	2.63c (21.67)	3.72c (27.41)	3.69c (30.45)	4.65c (34.29)	4.42c (36.43)
CM	4.01b (20.63)	5.12a (28.62)	4.75b (24.45)	6.08a (34.02)	6.28b (32.34)	7.50a (41.74)
CS	4.13b (19.01)	5.95a (34.97)	5.82ab (26.78)	6.35a (37.78)	6.78ab (31.19)	7.58a (44.56)

[a] CK, CF, CM and CS indicate the control, chemical fertilizers, chemical fertilizers + farm yard manure and chemical fertilizers + wheat straw treatments, respectively.

[b] AWD and CWL indicate continuous waterlogging and alternative wetting and drying, respectively.

[c] Means for the same measurement followed the same letter are not significantly different ($P<0.05$) by Duncan's multiple range test. Value in parenthesis is proportions of SOC in EOC, POC and LFOC, respectively.

fertilizers (CS), the proportions were EOC = 19.01% of TOC, LFOC = 37.78% of TOC, and POC = 26.78% of TOC, respectively, as compared with the alternative wetting and drying (AWD) with corresponding values of 34.97%, 44.56%, and 37.78%, respectively.

3.3. Effect of nutrient and water regimes on soil microbial biomass carbon

Soil microbial biomass carbon (MBC), under different nutrient treatments ranked CS>CM>CF>CK in the continuous water-logged (CWL), while in the alternative wetting and drying (AWD), CM had the highest MBC, followed by the CS. For the same water treatments, there were no significant differences in soil MBC observed between CM and CS ($P < 0.05$). In the organic treatments, especially in the CM treatment, the water treatment of AWD showed significantly higher soil MBC than the CLW, while the reverse was observed in CF and CK, but the difference was not statistically significant ($P < 0.05$). The proportions of SOC in microbial biomass C also decreased in the continuous waterlogging (CWL) (Fig. 1).

3.4. Effect of nutrient and water regimes on soil mineralizable carbon

Fig. 2a and b shows that different nutrient and water regimes significantly influenced paddy soil mineralizable organic carbon (MNC). In the continuous waterlogging (CWL), soil evolution of CO_2 was significantly lower than that in the alternative wetting and drying (AWD), especially for the soils treated by the combination of chemical fertilizers with farmyard manure (CM) and wheat straw (CS). In the water regime of AWD, the average accumulative amount of soil carbon mineralization of by the CM and CS treatments was 60.49% and 58.02% higher than in the CWL, respectively. The effectiveness of water treatments on carbon mineralization of soil treated by the sole chemical fertilizers (CF) and control (CK) was not as strong, as compared with the CM and CS treatments. Low C mineralization in the CWL treatment indicated a change in the quantity and possibly availability of organic C to the soil microflora.

In both the CWL and AWD, evolution of CO_2 from soil for the combination of chemical fertilizers with farmyard manure (CM) and wheat straw (CS) was markedly higher than the sole chemical fertilizers

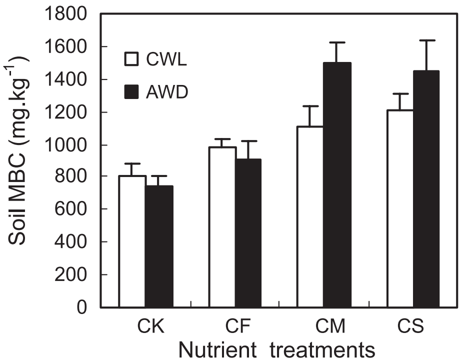

Fig. 1. Paddy soil microbial biomass carbon affected by nutrient and moisture regimes. CK, CF, CM and CS indicate the control, chemical fertilizers, chemical fertilizers + farm yard manure and chemical fertilizers + wheat straw treatments, respectively. CWL and AWD indicate the continuous waterlogging and alternative wetting and drying, respectively. Thin bars represent standard errors.

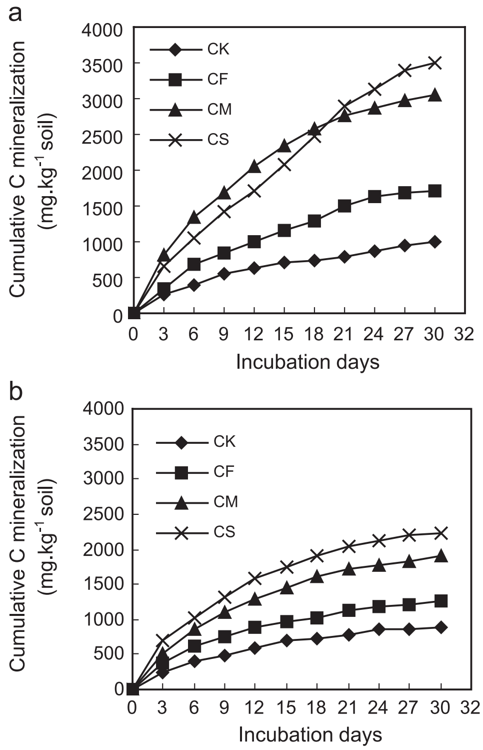

Fig. 2. Cumulative amount of paddy carbon mineralization for chemical fertilizers (CF), chemical fertilizers + farmyard manure (CM), chemical fertilizers + wheat straw (CS), and the control (CK) treatments in alternative wetting and drying (AWD) (a) and continuous waterlogging (CWL) (b), respectively.

(CF) and unfertilized control (CK), suggesting dissimilar C availability to the active microbial biomass. The difference in CO_2 evolution between nutrient treatments was more pronounced in AWD than that in CWL. CO_2 evolution rates of soil by different nutrient treatments were significantly different at any incubation sampling date. In the AWD, soil CO_2 evolution rates in 30-day incubation averaged 57.1, 101.7 and 117.1 mg CO_2–C kg^{-1} soil day^{-1} for the CF, CM, and CS treatments, respectively.

3.5. Effect of nutrient and water regimes on soil water stable aggregation and clay dispersion

The effects of nutrient and water regimes on soil water stable aggregation were shown in Fig. 3a. Soil water stable aggregate >250 μm content (WSA) in the alternative wetting and drying (AWD) was significantly higher than in the continuous waterlogging (CWL), despite nutrient treatments. The difference in WSA between water regimes was more pronounced for soil treated by the combination of organic material with chemical fertilizers, as compared with the sole chemical fertilizer (CF) and CK, with the order of CM>CS>CK>CF.

Soil clay dispersion ratio (R_{CD}) followed a pattern similar to WSA, and was also significantly affected by soil management treatments, especially soil nutrient regimes (Fig. 3b). Irrespective of water regimes, the combined application of chemical fertilizers and FYM or wheat straw showed lower soil clay dispersion ratio (R_{CD}) than the application of fertilizers alone. Especially, under the water regime of AWD, this R_{CD} for the CM and CS treatments decreased by 44.5% and 32.7%, respectively, compared to the exclusively chemical fertilization treatment, suggesting appropriate water management is essential in maintaining paddy clay structural stability as nutrient treatment.

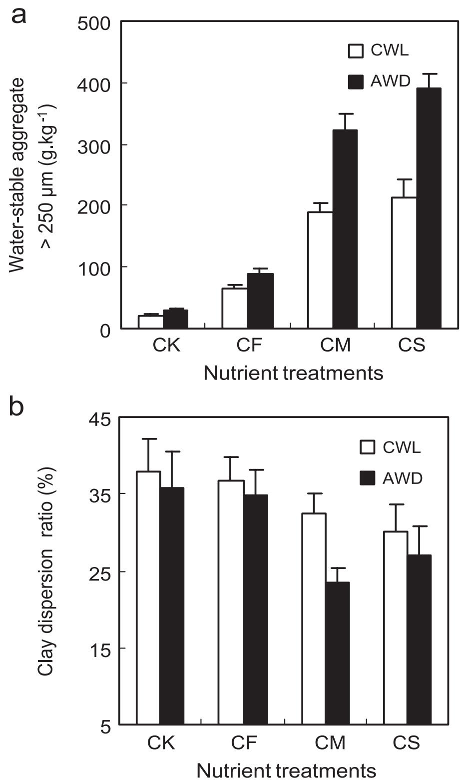

Fig. 3. Paddy soil water stable aggregate >250 μm content (a) and clay dispersion ratio (b) for chemical fertilizers (CF), chemical fertilizers + farmyard manure (CM), chemical fertilizers + wheat straw (CS), and the control (CK) treatments in alternative wetting and drying (AWD) and continuous waterlogging (CWL), respectively. Thin bars represent standard errors.

3.6. Relationships between soil water stable aggregation and soil organic carbon fractions

Correlation analysis of the pooled data across soil nutrient treatments confirmed positive correlations between soil organic carbon fractions and water stable aggregation, for both soil water regimes (Table 4). In the alternative wetting and drying (AWD), there were significant ($P<0.01$ or $P<0.05$) positive relationships between soil water stable aggregate >250-μm content (WSA) and TOC and all the investigated soil labile organic carbon fractions, in particular easily oxidizable organic carbon (EOC), light fraction organic carbon (LFOC) and particulate organic carbon (POC) with the correlation coefficient (r) of 0.822, 0.899 and 0.912, respectively. However, in the continuous waterlogging (CWL), significant ($P<0.05$) correlation was found only between WSA and soil particulate organic carbon (POC).

Irrespective of water regimes, there were negative correlations between soil organic carbon fractions and clay dispersion ratio (R_{CD}) (Table 4). Higher coefficients between clay dispersion ratio (R_{CD}) and soil organic fractions were found in the alternative wetting and drying (AWD) than that in the continuous water-

Table 4
Linear correlation coefficients (r) of the relationship between soil organic carbon fractions and water stable aggregates >250 μm content (WSA) and clay dispersion ratio (R_{CD})

Water regimes[a]	Water stable aggregation	Organic carbon fraction					
		TOC	EOC	LFOC	MBC	MNC	POC
AWD	WSA	0.735*[b]	0.822**	0.889**	0.804**	0.712*	0.912**
	R_{CD}	− 0.632*	− 0.796**	− 0.854**	− 0.612*	− 0.647*	− 0.897**
CWL	WSA	0.431	0.512	0.572	0.398	0.501	0.743*
	R_{CD}	− 0.412	− 0.497	− 0.505	− 0.403	− 0.542	− 0.674*

[a] AWD and CWL indicate alternative wetting and drying and continuous waterlogging, respectively.
[b] *, ** denote significant level at $P<0.05$ and $P<0.01$.

logging (CWL). The negative correlations between R_{CD} and EOC, POC and LFOC were strongly significant at $P<0.01$ in the water regime of AWD with $r=-0.796$, -0.854, and -0.897, respectively. This demonstrated that more labile soil organic fractions, especially POC and LFOC were more effective in maintaining soil structure stability against clay dispersion in the alternative wetting and drying than in the continuous waterlogging.

4. Discussion

There is as yet not a well-defined universal methodology to characterize soil quality and to define a set of clear indicators due to the innate difficulty in defining soil itself and to the multifaceted nature. Doran and Parkin (1994) defined soil quality as the capacity to function within an ecosystem and sustain biological productivity, maintain environmental quality and promote plant, animal and human health. A criticism of recent developments in the soil quality concept has been aimed at more clearly defining the role of soil organic matter towards increasing agricultural productivity and environmental quality (Sojka and Upchurch, 1999). Though Sojka and Upchurch (1999) stress that the regions of the world with low soil organic matter are also highly productivity, the concept of 'soil quality' has well-recognized soil organic matter as a essential attribute that involved in and related to many soil chemical, physical, and biological properties (Stevenson, 1986; Johnston, 1986; Reeves, 1997). Maintenance and improvement in soil organic matter content in generally accepted as being an important objective for any sustainable system of agriculture. In conventional evaluation of soil quality, a number of soil physical, chemical, and biological indicators have to be measured and determined (Karlen et al., 1997). That makes it very difficult for many farmers to conduct practical and effective evaluation of soil quality. Soil organic carbon plays an important role in soil physio-chemical and biological properties (Stevenson, 1986; Reeves, 1997; Johnston, 1986). Currently, interest in the effects of soil organic carbon fractions on soil quality indicators of physical, chemical and properties in different soil management is increasing (Chan et al., 2002; Campbell et al., 1999). Haynes (1999) and Chan et al. (2001) reported that there are strong correlations between soil labile organic C and soil aggregate stability. In this study, significant relationships between soil EOC, LFOC, and POC and soil water stable aggregation and structural stability were observed only in alternate wetting and drying.

Light fraction organic matter made up largely of organic residues in various stages of decomposition but also containing appreciable amounts of microbial debris (Janzen et al., 1992; Gregorich and Janzen, 1996). It is characterized by rapid mineralization due to the labile nature of its constituents and to the lack of protection by soil colloids (Turchenek and Oades, 1979). Previous studies have found that soil labile fractions of organic C are more sensitive to changes of soil management and disturbance than total organic C (Bauhus, 1996; Bremer et al., 1994; Powelson et al., 1987; Conteh et al., 1997; Freixo et al., 2002). Haynes (2000) suggested that labile organic matter might act as an indicator of organic matter quality in arable and pastoral soils in New Zealand. Previous studies have shown that soil labile organic C could more reflect management impacts on soil quality than total organic C (Franzluebbers and Arshad, 1997; Campbell et al., 1999; Conteh et al., 1997; Freixo et al., 2002; Von Lutzow et al., 2000), which makes it possible that some soil organic C fractions are useful as indicators of soil quality. Particulate organic C (POC) has been recently shown to be a sensitive indicator of soil management effects on SOC (Elliott et al., 1994). The fraction is considered to represent the "slow" pool of SOC with an intermediate turnover time between the "active" and "passive" pools (Parton et al., 1987). Particulate organic C, therefore, may be of greater importance for defining SOC turnover. In our present study, more significant differences in soil organic C fractions of EOC, LFOC, as well as POC were observed than in soil total organic C among the different nutrient and water regimes. Greater differences in soil MBC and MNC were detected between different nutrient water treatments than those in TOC (Figs. 1 and 2), which may provide a very sensitive indicator reflecting influences of changes of soil management practices on soil quality.

Organic material could change composition of soil organic matter and markedly increase soil organic C and its labile fractions (Conteh et al., 1998; Liebig and Doran, 1999; Powelson et al., 1987; Leifeld et al., 2002). Kanchikerimath and Singh (2001) and Zinati et al. (2001) found that the combined application of chemical fertilizer and compost increased biological active soil organic carbon such as soil microbial biomass C, and mineralizable C. However, in this study, the effectiveness of organic material to increase soil labile organic carbon fractions was significantly different between the continuous waterlogging (CWL) and alternative wetting and drying (AWD) (Table 3). In the regimes of AWD, EOC, LFOC, MBC, and MNC in the soil under the combined application of fertilizers and organic material were significantly greater than those in the CWL. This demonstrates that adoption of appropriate water management is as important to improve soil organic carbon quality as organic amendments. Future study should focus on (i) reasons for the different effect of the different paddy soil treatments, in particular, soil water regimes, on soil organic carbon fractions and quality, (ii) sensitivity of different paddy soil organic C fractions to changes of agriculture management practices and correlations of soil organic C fractions to physical, chemical, and biological indicators of soil quality. It is desirable to understand the importance of soil organic carbon fractions on anthropogenic soil under different management impacts, as well as to acquire minimum data set (MDS) of soil organic C fractions as indicators of practical and effective evaluation of soil quality.

5. Conclusions

More labile organic carbon fractions of paddy soil are significantly influenced by both nutrient and water regimes. In the combined application of chemical fertilizers and farmyard manure or wheat straw, continuous waterlogging can markedly increase total soil organic carbon, but significantly reduce the labile paddy soil organic C fractions. In the alternative wetting and drying, incorporation of farmyard manure or wheat straw can increase the proportions of EOC, LFOC, POC, MBC, and MNC in TOC, but also improve soil water stable aggregation, compared to continuous waterlogging. The continuous waterlogging results in a lack of clear relationship between soil water stable aggregation and clay dispersion and soil organic C fractions.

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References

Anderson, J.P., 1982. Soil respiration. In: A.L. Page et al. (ed.), Methods of soil analysis. Part 2. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI, pp. 831–871.

Anderson, T.H., Domesch, K.H., 1989. Rations of microbial biomass carbon to total organic carbon in arable soils. Soil Biol. Biochem. 21, 471–479.

Bauhus, J., 1996. C and N mineralization in an acid forest soil at different locations along a gap-stand gradient. Soil Biol. Biochem. 28, 923–932.

Blair, G.J, Lefory, R.D., 1995. Soil C fractions based on their degree of oxidation and the development of a C management index for agricultural system. Aust. J. Agric. Resour. 46, 1459–1466.

Bremer, E., Janzen, H.H., Johnston, A.M., 1994. Sensitivity of total, light fraction and mineralizable organic matter to management practices in a lethbridge soil. Can. J. Soil Sci. 74, 131–138.

Burt, R., Reinsch, T.G., Miller, W.P., 1993. A micro-pipette method for water dispersible clay. Commun. Soil Sci. Plant Anal. 24, 2531–2544.

Cambardella, C.A., Elliott, E.T., 1992. Particulate soil organic matter changes across a grassland cultivation sequence. Soil Sci. Soc. Am. J. 56, 777–778.

Campbell, M.R., Biederbeck, V.O., McConkey, B.G., 1999. Soil quality-effect of tillage and fallow frequency. Soil organic matter quality as influenced by tillage and fallow frequency in a silt loam in southwestern Saskatchewan. Soil Biol. Biochem. 31, 1–7.

Campell, C.A., McConkey, B.G., Zentner, R.P., 1996. Long-term effects of tillage and crop rotation on soil organic C and total N in a clay soil in southwestern Saakatchewan. Can. J. Soil Sci. 76, 395–401.

Carter, M.R., Gregorich, E.G., Angers, D.A., Donald, R.G., Bolinder, M.A., 1998. Organic C and N storage, and organic C fractions, in adjacent cultivated and forested soils of eastern Canada. Soil Tillage Res. 47, 253–261.

Chan, K.Y., Bowman, A., Oates, A., 2001. Oxidizible organic carbon fractions and soil quality changes in an Oxic Paleustalf under different pasture leys. Soil Sci. 166, 61–67.

Chan, K.Y., Heenan, D.P., Oates, A., 2002. Soil carbon fractions and relationship to soil quality under different tillage and stubble management. Soil Tillage Res. 63, 133–139.

Conteh, A., Blair, G.J., Macleod, D.A., 1997. Soil organic carbon changes in cracking clay soils under cotton production as studied by carbon fractionation. Aust. J. Agric. Resour. 48, 1049–1058.

Conteh, A., Blair, G.J., Rochester, I.J., 1998. Soil organic carbon fractions in a Vertisol under irrigated cotton production as affected by burning and incorporating cotton stubble. Aust. J. Soil Res. 36, 655–667.

Doran, J.W., Parkin, T.B., 1994. Defining and assessing soil quality. Defining Soil Quality for a Sustainable Environment. Soil Science Society of America, Madison, Wisonsin, USA, pp. 3–21.

Elliott, E.T., Burke, I.C., Monz, C.A., 1994. Terrestrial carbon pools in grasslands and agricultural soils: Preliminary data from the Corn Belt and Great plains region. pp. 179–191.In Doran, J.W., et al. (ed.) Defining soil quality for a sustainable environment. SSSA Spec. Publ. 35. SSSA and ASA, Madison, WI.

Franzliebbers, A.J., Zuberer, D.A., 1995. Soil organic carbon, microbial biomass, and mineralizable carbon and nitrogen in sorghum. Soil Sci. Soc. Am. J. 59, 460–466.

Franzluebbers, A.J., Arshad, M.A., 1997. Particulate organic carbon content and potential mineralization as affected by tillage and texture. Soil Sci. Am. J. 61, 1382–1386.

Freixo, A.A., Machado, P.L., Santos, H.P., 2002. Soil organic carbon and fractions of a Rhodic Ferralsol under the influence of tillage and crop rotation systems in southern Brazil. Soil Tillage Res. 64, 221–230.

Gregorich, E.G., Ellert, B.H., 1993. Light fraction and macroorganic matter in mineral soil. In: Carter, M.R. (Ed.), Soil Sampling and Methods of Analysis. Lewis Publishers, Boca Raton, FL, USA, pp. 397–407.

Gregorich, E.G., Janzen, H.H., 1996. Storage of soil carbon in the light fraction and macro organic matter. In: Carter, M.R., Stewart, B.A. (Eds.), Advances in Soil Science. Structure and Organic Matter Storage in Agricultural Soils. CRC Lewis, Boca Raton, pp. 167–190.

Haynes, R.J., 1999. Labile organic matter fractions and aggregate stability under short-term, grass-based leys. Soil Biol. Biochem. 31, 1821–1830.

Haynes, R.J., 2000. Labile organic matter as an indicator of organic matter quality in arable and pastoral soils in New Zealand. Soil Biol. Biochem. 32, 211–219.

Janzen, H.H., Campbell, C.A., Brandt, S.A., 1992. Light fraction organic matter in soils from long-term crop rotations. Soil Sci. Soc. Am. J. 56, 1799–1808.

Johnston, A.E., 1986. Soil organic carbon, effects on soils and crops. Soil Use Mdmt. 2, 97–105.

Kanchikerimath, M., Singh, D., 2001. Soil organic matter and biological properties after 26 years of maize–wheat–cowpea cropping as affected by manure and fertilization in Cambisol in semiarid region of India. Agric. Ecosyst. Environ. 86, 155–162.

Karlen, D.L., Mausbach, M.J., Doran, J.W., Cline, R.G., 1997. Soil quality: a concept, definition, and framework for evaluation. Soil Sci. Soc. Am. J. 61, 4–10.

Leifeld, J., Siebert, S., Kogel-Knabner, I., 2002. Changes in the chemical composition of soil organic matter after application of compost. Eur. J. Soil Sci. 53, 299–309.

Liebig, M.A., Doran, J.W., 1999. Impact of organic production practices on soil quality indicators. J. Environ. Qual. 28, 1601–1609.

Nelson, D.W., Sommers, L.E., 1980. Total nitrogen analysis of soil and plant tissues. J. Assoc. Off. Anal. Chem. 63, 770–778.

Parton, W.J., Schimel, D.S., Cole, C.V., 1987. Analysis of factors controlling soil organic matter levels in Great Plains grassland. Soil Sci. Am. J. 51, 1173–1179.

Powelson, D.S., Brookes, P.C., Christensen, B.T., 1987. Measurement of soil microbial biomass provided an early indication of changes in total soil organic matter due to straw incorporation. Soil Biol. Biochem. 19, 159–164.

Reeves, D.W., 1997. The role of soil organic matter in maintaining soil quality in continuous cropping system. Soil Tillage Res. 43, 131–167.

SAS Institute, D.W., 1995. SAS/Stat User Guide. Version 6.1 SAS Inst. Cary NC, USA.

Sojka, R.D., Upchurch, D.R., 1999. Reservations regarding the soil quality concept. Soil Sci. Am. J. 63, 1039–1054.

Stevenson, F.J., 1986. Carbon balance of the soil and role of organic matter in soil fertility. Cycles of Soil–Carbon, Phosphorus, Sulphur, Micro-nutrients. Wiley, New York, pp. 45–77.

Turchenek, L.W., Oades, J.M., 1979. Fractionation of organo-mineral complexes by sedimentation and density techniques. Geoderma 21, 311–343.

Vance, E.D., Brookes, P.C., Jenkinson, D.S., 1987. An extraction method for measuring soil microbial C. Soil Biol. Biochem. 19, 703–707.

Von Lutzow, M., Leifeld, J., Kainz, M., Kogel-Knabner, I., Munch, J.C., 2000. Indications for soil organic matter quality in soils under different management. Geoderma 105, 243–258.

Zinati, G.M, Li, Y.C, Bryan, H.H., 2001. Utilization of compost increases organic carbon and its humin, humic and fulvic acid fractions in calcareous soil. Compost Sci. Util. 9, 156–162.