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Organic carbon stratification and size distribution of three typical paddy soils from Taihu Lake region, China

PAN Genxing[1,*], WU Laosheng[2], LI Lianqing[1], ZHANG Xuhui[1],
GONG Wei[1], WOOD Yvonne[2]

1. Institute of Resource, Ecosystem and Environment of Agriculture, Nanjing Agricultural University, Nanjing 210095, China.
E-mail: pangenxing@yahoo.com.cn
2. Department of Environmental Sciences, University of California Riverside, CA 92521, USA

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Abstract

Developing realistic soil carbon (C) sequestration strategies for China's sustainable agriculture relies on accurate estimates of the amount, retention and turnover rates of C stored in paddy soils. Available C estimates to date are predominantly for the tilled and flood-irrigated surface topsoil (ca. 30 cm). Such estimates cannot be used to extrapolate to soil depths of 100 cm since soil organic carbon (SOC) generally shows a sharp decrease with depth. In this research, composite soil samples were collected at several depths to 100 cm from three representative paddy soils in the Taihu Lake region, China. Soil organic carbon distribution in the profiles and in aggregate-size fractions was determined. Results showed that while SOC decreased exponentially with depth to 100 cm, a substantial proportion of the total SOC (30%–40%) is stored below the 30 cm depth. In the carbon-enriched paddy topsoils, SOC was found to accumulate preferentially in the 2–0.25 and 0.25–0.02 mm aggregate size fractions. ∂^{13}C analysis of the coarse micro-aggregate fraction showed that the high degree of C stratification in the paddy topsoil was in agreement with the occurrence of lighter ∂^{13}13C in the upper 30 cm depth. These results suggest that SOC stratification within profiles varies with different pedogenetical types of paddy soils with regards to clay and iron oxyhydrates distributions. Sand-sized fractions of aggregates in paddy soil systems may play a very important role in carbon sequestration and turnover, dissimilar to other studied agricultural systems.

Key words: profile stratification; organic carbon; paddy soils; size fractions; soil aggregates; carbon storage

Introduction

Destabilization of soil carbon through agricultural tillage is considered to represent a profound threat to worldwide efforts to slow the rate of carbon dioxide (CO_2) additions to the atmosphere (Lal, 1999; Amundson, 2001). Determining the amount of carbon sequestration in worldwide soils on a national scale is crucial for designing realistic strategies to fulfill the commitments to the Kyoto Protocol (Smith *et al*., 2000). National soil survey data have proven valuable in developing such estimates for several countries (Arrouys and Balesdent, 2002; Bernoux *et al*., 2002; Tate *et al*., 1997; Wang *et al*., 2002). However, estimates derived from such surveys rely primarily on soil organic carbon (SOC) data measured in the uppermost 20- to 30-cm soil depths. Thus they may miss important stores of SOC found at greater depths (Schwager and Mikhailova, 2002), which would be overestimated if calculated based on the SOC stored in the topsoil.

The mechanisms responsible for incorporating organic matter into soils are not fully understood. Recently, research has been directed at elucidating an observed link between the sequestration and decomposition rates of organic matter and soil aggregates and their destabilization. Soil carbon dynamics are often described by the distribution and partitioning of SOC into size fractions of soil aggregates < 2 mm (Schulten and Leinweber, 2000). The distribution of SOC within different aggregate size fractions changes over time as soil develops (Carter *et al*., 2003), and this natural process is disrupted by agricultural tillage practices (Franzluebbers, 2002; Wairiu and Lal, 2003). Under these anthropogenic conditions, recently sequestered "young" carbon is most often associated with the coarse micro-aggregates (0.25–0.02 mm) (Bossuyt *et al*., 2002; Puget *et al*., 1995; Six *et al*., 2000). The SOC turnover time can be evaluated by the $^{13}C/^{12}C$ isotope ratios (Yamashita *et al*., 2006).

Conceptual models have been proposed to describe the formation and decomposition of the complex chemical structure of soil organic matter, which is currently only vaguely defined (Carter *et al*., 2003). Most models recognize two to three soil organic carbon pools that are kinetically defined by their different turnover rates. These include a small pool with a rapid turnover rate and one (or more) larger pool(s) with slow turnover rate(s)

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[*] Corresponding author. E-mail: pangenxing@yahoo.com.cn.

(Kirschbaum, 1993; Davidson *et al.*, 2000). These pools have been linked to different sizes of soil aggregates (Tisdall and Oades, 1982; Carter *et al.*, 2002). Thus, understanding the processes responsible for soil aggregation will increase our understanding of the ability of the soil to sequester carbon (Six *et al.*, 2000).

China has a long history of both irrigated and non-irrigated agriculture, which has significantly altered the SOC pool (Wu *et al.*, 2003). Paddy soils are important to China's food production, and they account for 27.3% of Asia's arable lands (FAOSTAT, 2005). Paddy soils belong to a unique soil order of Hydragric Anthrosols within the Chinese Soil Taxonomy System (Gong, 1986; Gong *et al.*, 1999). They are a special group of anthropogenic soils with a long history–up to thousands of years of surface flooded irrigation during rice production.

It has been estimated that the top 30 cm of China's paddy soils contain a pool of 1.3 Pg (10^{12} kg) of SOC (Pan *et al.*, 2003). Of this pool, about 0.1 Pg was estimated to be within the top 30 cm of paddy soils in the Jiangsu Province, approximately a quarter of which is stored in the topsoils of the fertile Taihu Lake region (Pan *et al.*, 2005). However, without accurately determining the SOC content of the profile below the 30 cm depth, the total stock of SOC contained within Asia's paddy soils will probably be overestimated. While it is clear that agricultural management has induced changes in the storage of SOC in China's topsoils (Pan *et al.*, 2003, 2004; Wu *et al.*, 2003), the lack of consistent methods for estimating the total SOC pool with depths to 100 cm in China's soils limits the accurate estimation of this change (Pan *et al.*, 2003; Wang and Zhou, 1999). Specifically, reliable assessments of SOC stored in China's paddy soils are not available due to the lack of data for the deeper horizons from the last national soil survey completed in mid-1980s (SSSSC, 1996a, 1996b, 1997a, 1997b).

Few studies have focused on the depth distributions of C below the uppermost 30 cm, or on the distribution of SOC within different aggregate-size fractions of Asia's large extent of paddy soils. The goals of this study were (1) to examine the effects of agricultural land-use practices on SOC stratification within paddy soils to 100 cm, and (2) to evaluate the carbon turnover rates associated with different paddy soil aggregate sizes. The specific objectives were (1) to characterize, by pedogenic horizon, the depth distribution of SOC in three representative paddy soil profiles to 100 cm, (2) to evaluate the accuracy of estimates of SOC content for these profiles using data to 30 cm depths compared to 100 cm depths, and (3) to determine the SOC distribution in various aggregate-size fractions from these three soils.

1 Material and methods

1.1 Representative paddy pedons

Three paddy soil series from the Taihu Lake region (a large alluvial plain with little relief), Jiangsu Province, China were chosen for this study. This region has a long history of high yield rice farming and its paddy soils are well-developed and relatively uniform. Typical crop rotation in the region includes two rice crops plus a winter wheat or a winter green manure (alfalfa) per year in 1980's. The three studied types of paddy soils were chosen to represent the predominant paddy soils in this region (Xu *et al.*, 1980). Huangnitu (representative of Fe-accumulic Stagnic Anthrosols, AS soil), Baitu (representative of Fe-bleached Stagnic Anthrosols, BS soil), and Wunitu (representative of Gleyic Stagnic Anthrosols, GS soil), cover 224, 153, and 88 kha, respectively, of the rice production area in the Taihu Lake region in late 1980's (SSSJ, 1995).

1.2 Soil sampling

Soil samples from the representative pedons of the three paddy soil types were collected in Wu Xian County, Jiangsu Province, China in winter 1999 when there was no rice production and no waterlogging. Three pedons (one primary pit plus two auxiliary pits) were opened to take horizon soil samples for soil analysis for each of the three types. To observe and identify the pedogenic horizons, the primary pit was dug to about 1 m wide by 2 m long at the surface, but the length decreases to about 1 m as depth increases to 1 m. Disturbed samples were taken at each of the pedogenic horizons (5 horizons in each of the soil types, Table 1) by a stainless-steel hand shovel and described (SSSC, 2000). Triplicated soil samples were taken according to the horizon depths observed in the typical pedon of each soil type also by soil auger as composite samples used for SOC measurements. Bulk density samples were collected for each of the horizons of the typical pedon observed using stainless steel rings of 5 cm in diameter by 5 cm in height at each pedon.

For checking the SOC depth distribution, sampling at depth intervals to 1 m was done by a soil auger in two different locations for AS. The purpose of this more extensive depth sampling was to provide more detailed information on SOC distribution in the soil profiles, and use this information to verify the accuracy of the visual delineation of the pedogenic horizons.

Table 1 Basic properties of the typical pedon of the three studied types of paddy soils

Soil	Horizon	Depth (cm)	pH (H_2O)	Clay content (%)	Fe_d (g/kg)	Fe_{ox} (g/kg)
AS	A	0–15	6.3	31.0	18.0	8.7
	Ap	15–31	6.7	31.9	18.9	7.2
	Bw1	31–43	7.0	32.9	17.3	5.4
	Bw2	43–65	7.3	33.8	20.6	3.4
	Bg/C	65–100	7.3	34.3	–	2.9
GS	A	0–13	7.3	33.4	18.1	8.8
	Ap	13–26	7.1	31.9	17.3	11.3
	Bg1	26–60	7.1	40.2	18.7	4.5
	Bg2	60–80	7.0	40.3	19.7	3.6
	BCg	80–100	6.9	24.4	5.7	2.3
BS	A	0–13	5.5	22.3	15.2	7.1
	Ap	13–27	6.5	20.7	14.1	5.2
	W	27–46	6.9	32.5	12.7	2.3
	Bw	46–80	7.0	48.7	13.8	2.7
	Bg	80–100	6.6	32.1	11.6	–

1.3 Separation and preparation of soil aggregate-size fractions

Separating aggregates into different size fractions is a time-consuming process. Thus composite samples (Kempthorne and Allmaras, 1986) of the same soil series and horizon but different pits were used for soil aggregate analysis.

All the collected soil samples were air-dried. Large clods were split into smaller units of no greater than 10 mm by hand, and any root and crop residues were carefully removed (SSSC, 2000). Low energy ultrasonic dispersion was performed to obtain the aggregate-size fractions of the test soils. Fifty grams of bulk soil were dispersed in 500 ml distilled water by a tank disaggregator (using approximately 80 J/ml), following a similar procedure described by Tarchitzky *et al.* (2000). The macro-aggregate size fraction (2–0.25 mm, sand-sized) was obtained by wet sieving, while that < 0.002 mm was obtained by centrifuging. Intermediate size fractions (0.25–0.02 mm, fine sand-sized, and 0.02–0.002 mm, silt-sized) were separated by sedimentation. Finally, all the soil aggregate-size fractions were dried at 60°C using infrared radiation.

1.4 Soil analysis and determination of SOC

Soil pH was measured by a Mettler Toledo pH meter in a suspension of 1:1 (V/V) soil to water; Fed and Feox measurements was done using DCB reagent and Tamm reagent respectively with the protocol described by Lu (2000). Clay (< 2 μm) content was determined by sedimentation with hydrometer (SSSC, 2000). Contents of SOC in both the bulk soils and the soil aggregate-size fractions were determined by wet combustion with potassium pyrochromate (SSSC, 2000). All analyses were done using duplicate samples and the results are reported as the means of the duplicate samples.

Stable carbon ratio (∂^{13}C) of selected samples of the coarse micro-aggregate size fractions were analyzed by combustion and then by a Finnigan Mass Spectroscopy MAT-252 (Bird *et al.*, 2002; Roscoe *et al.*, 2000). The CO_2 from combustion was trapped in liquid N at –80°C. A reference sample (GBW04405) from the National Standard and Reference Sample Service was used to provide the relative Pee Dee Belemnite (PDB) value.

1.5 Calculations of carbon stratification

Carbon stratification in soil profiles can be used to describe the effect of soil formation processes and management practices on SOC accumulation patterns with depth (Franzluebbers, 2002). In this study, the SOC stratification ratio was calculated in two ways. First, to infer the effect of paddy management on the topsoil, the carbon stratification within the upper 30 cm (CSRt) was calculated from dividing the SOC content measured in the plow layer by the amount measured in the plowpan ($CSR_t = C_{\text{storage of plow layer}}/C_{\text{storage of plowpan}}$). To evaluate SOC partition to in the 100 cm profile of the three study soils, the carbon stratification within the whole profile (CSR_w) was also calculated from dividing the SOC content within the top 30 cm soil by the amount found in the lower soil (30–100 cm), i.e., $CSR_W = C_{\text{storage of topsoil}}/C_{\text{storage of the lower solum}}$.

The basic soil properties of the studied three representative pedons were given in Table 1.

2 Results and discussion

2.1 Profile depth distributions of SOC

The depth distributions of the measured carbon within the two satellite pits of AS (Fig.1) show that the presence of SOC within the intensively farmed paddy soil (typically two rice crops plus a wheat or alfalfa crop in winter) is strongly dependent on soil horizons. There are two distinct zones within the profiles of differing SOC accumulation: the upper profile, at depths of 25–30 cm, where SOC content is high; and the lower profile, composed of W and G horizons, where SOC content is low. The measured decrease of SOC content with depth fits very well (R^2 = 0.934, $P > 0.001$) in a first order decay equation:

$$SOC_d = SOC_0 \times e^{-\lambda d} \qquad (1)$$

where, SOC_0 and SOC_d represent SOC content (g/kg) at the soil surface and at depth within the soil (cm), respectively. λ is a constant that ranges from 0.026–0.028. Similar to the trends of the two auxiliary pits, the SOC content of all three soils (AS, BS, and GS) decreased exponentially with depth (Table 2). High SOC contents of 13.30–20.74 g/kg were found in the plow layer (A horizon), while SOC contents were lower (in the range of 7.05–16.00 g/kg) in the plowpan (Ap horizon).

The data from the present study show that the pattern of the SOC distribution was similar among the cultivated paddy topsoils, but the SOC content and storage varied with soil type, even though the agricultural practices such as crop rotation, fertilization, and water logging were generally the same. All three soils have predominately elevated topsoil SOC contents, which may indicate that intensive and long-term rice farming on paddy soils in the

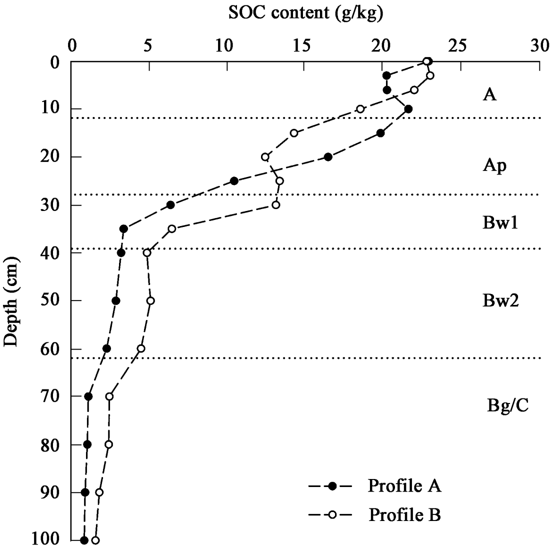

Fig. 1 Depth distribution of SOC inventories of the AS paddy soil as determined in two soil profiles.

Table 2 Bulk density and SOC contents of the studied soils sampled in triplicates

Soil	Horizon	Bulk density (g/cm^3)	SOC content (g/kg)
AS	A	1.19	20.74 ± 1.12
	Ap	1.24	14.35 ± 2.03
	Bw1	1.34	4.22 ± 0.87
	Bw2	1.36	2.56 ± 1.46
	Bg/C	1.37	2.05 ± 1.24
Gs	A	1.20	17.03 ± 0.74
	Ap	1.21	16.00 ± 1.03
	Bg1	1.32	9.25 ± 0.69
	Bg2	1.33	6.34 ± 0.79
	BCg	1.36	2.70 ± 0.58
Bs	A	1.25	13.30± 2.32
	Ap	1.31	7.05 ± 0.81
	W	1.36	5.82 ± (0.48
	Bw	1.37	2.87 ± 0.34
	Bg	1.37	1.96 ± 0.22

Taihu Lake region has increased SOC storage. Measured SOC content in the plow layer (0–15 cm) of the paddy soils ranged from 13.33–18.93 g/kg and the SOC storage in the plow layer ranged from 21.67–33.85 Mg/ha (Table 3). These values are higher than the mean SOC storage in the A horizon (21.5 Mg/ha) of the agricultural soils in Jiangsu Province (Pan *et al*., 2003; Pan *et al*., 2005). Measured SOC content of the plowpan (generally 15–30 cm depth) ranged from 7.42–17.03 g/kg and the SOC storage in the plowpan ranged from 13.63–28.01 Mg/ha (Table 3).

Furthermore, SOC storage in the topsoils (including both the A and Ap horizons) of the two dominant paddy soils in this region (AS and GS) is higher (61.86 and 54.65 Mg/ha, respectively. Table 3) than the area-weighted mean of all China's paddy soils (44 Mg/ha, Pan *et al*., 2004). However, the SOC storage in topsoil of the BS is lower (35.29 Mg/ha) than the other two examined soils.

2.2 SOC stratification

Although the SOC of the topsoils is higher than the mean of the world's agricultural soils (Batjes, 1996) and of the French croplands in the top 30 cm (Arrouys and Balesdent, 2002), the SOC storage in the 100 cm profile of the three test soils, however, is lower than the world's mean of 106 Mg/ha (Batjes, 1996), which may indicates that rice cultivation with surface flooding irrigation enhances SOC sequestration predominantly in the top layer, not in the lower profile. Such enhancement will be reflected in the calculation of the soil carbon stratification ratio (CSR$_w$) for the 100 cm soil depth.

The calculated SOC storage of the 100 cm profile is 86.17, 89.73, and 58.20 Mg/ha, respectively, for AS, GS and BS paddy soils (Table 3). Except for the BS, which is considered a low SOC soil in the region, the other two paddy soils have higher SOC storage within the 100 cm depth than the overall mean of the total SOC in China's cultivated soils (80 Mg/ha, Wu *et al*., 2003) and their topsoils (35 Mg/ha, Song *et al*., 2005), respectively. For the examined paddy soils, approximately 63%–70% of the SOC is located in the top 30 cm of soil. For example, 70% of the total SOC is stored in the topsoil of the AS, while only 44% of SOC of the world soils was found in the 0–30 cm topsoil (Batjes, 1996), and only 20%–30% of the SOC of the central Canada soils was in the top 30 cm (Bhatti et al., 2002). The low SOC accumulation in the lower profile of paddy soils is attributed to the shallow roots of the rice crop as well as restriction of root growth by the compacted plowpan in paddy soils.

The calculated carbon stratification ratios (CSR$_t$) of the three soils were listed in Table 3. Significant difference in topsoil Cstratification was visible between the three types of paddy soils. Franzluebbers (2002) reported the finding that A higher CSRt value usually indicated a lower inherent SOC in the dry croplandsof USA. Here, a lower CSRt of topsoil represented weak SOC enhancement in the plowpan layer as SOC accumulation in the plowpan of BS could be inhibited by the lack of clay and oxyhydrates in the topsoil. However, a higher CSRw indicated stronger SOC accumulation due to hydroagric longterm managements with rice farming. Soil BS showed little C stratification in the topsoil with a ratio (CSRt) close to 1 when comparing to Soil AS and GS (Table 3). The AS soil, on the other hand, has a mean stratification ratio over 2, indicating very strong SOC enhancement in the topsoil. This is recently supported by a recent study by Hou *et al*. (2007) that most significant SOC sequestration had been observed in this soil of theses different soil seriesfrom the same region since 1980's. Compared to AS, the GS soil is significantly lower in whole pedon SOC stractification due its higher inherent SOC content as this soil had been developed from lucustrine material rich in organic matter.

2.3 Depth distributions of different size aggregates within the three paddy soils

The relative proportions of the aggregate-size fractions vary with depth within a specific profile as well as between different soils (Table 4). While there was no consistent difference in the percentage of the < 0.002 mm aggregate fraction between the depths and soils, the percentage of the larger size aggregates changed with horizons and soils. For example, within the plowpan layer, relative to the plow layer, aggregate size fraction > 2.0 mm of the three test

Table 3 Carbon storage of the topsoil, and lower solum and stratification ratios of topsoil (CSRt) and whole pedon (CSR$_w$)

Soil	Carbon storage (Mg/ha)			Carbon stratification ratio	
	Topsoil (0–30 cm)	Lower solum (30–100 cm)	Whole profile (0–100 cm)	CSR$_t$	CSR$_w$
AS	62.33±4.31 a	29.61±9.91 b	91.94±6.17 b	0.70±0.13 b	2.34±1.07 a
GS	62.43±3.28 a	50.01±6.91 a	112.44±3.64 a	0.53±0.01 c	1.27±0.24 b
BS	35.08±3.81 b	33.07±9.50 b	68.15±8.65 c	0.96±0.15 a	1.15±0.46 ab

Different lowercase letters in a same column indicates significance of difference between different soil types at $p < 0.10$.

soils decreased by 40% to 80%, while those of 0.02–0.002 mm for the AS soil increased due to compaction.

Within the three test soils, the size fractions of 0.25–0.02 mm and 2–0.25 mm soil aggregates constitute ca. 70% of the total soil mass. For the AS soil, the larger of these two fractions (2.0–0.25 mm) increases in percentage towards the surface. This size fraction (2.0–0.25 mm) also increases in percentage towards the surface in the other two soils, and it overall represents the dominant size fraction, which agrees with the observations of Materechera and Mkhabela (2001) and Spaccini *et al.* (2001), who showed that cultivation can induce changes in the relative proportion of soil macro-aggregates (2.0–0.25 mm) in tropical ferralitic soils in Brazil.

2.4 Differential C partitioning within soil aggregate-size fractions

Generally, the SOC of all aggregate size fractions increased towards the soil surface (Table 4), which is consistent with the SOC profile distribution of the bulk soils (Table 2). Within the topsoil (plow layer and plowpan), high SOC contents are found in the fractions either > 0.25 mm or < 0.002 mm, while the SOC in the coarse micro-aggregate fraction of 0.25–0.02 mm tends to be depleted. Fig.2 shows the correlation between the SOC contents for different aggregate-size fractions and SOC contents of the bulk soils throughout all the soil depths. Generally, the SOC of the bulk soils has a higher correlation with the SOC content in the macro-aggregate size fraction (0.25–2 mm), which agrees with the findings of other investigators (Shang and Tiessen, 2003; Cayet and Lichtfouse, 2001; Jacinthe *et al.*, 2001; Carter *et al.*, 2002).

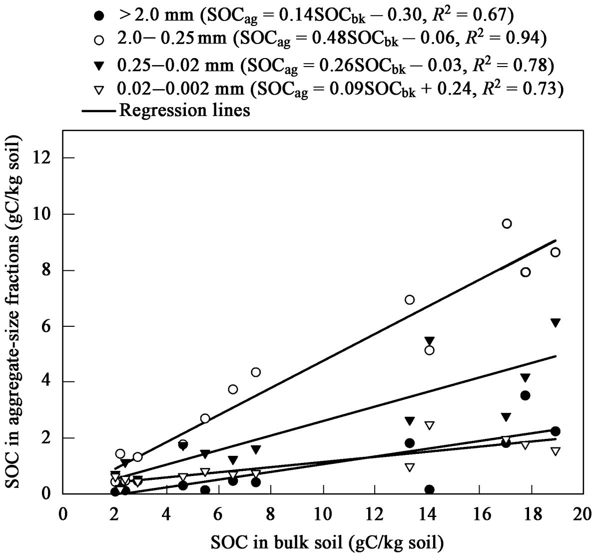

Fig. 2 SOC distribution in soil aggregate-size fractions (SOC_{ag}) versus bulk SOC (SOC_{bk}) of the three test soils (data pooled together).

Measured ∂^{13}C (‰ PDB) values generally reflect the isotopic equilibrium of SOC under the current vegetation and climatic condition. Since the studied paddy soils have been consistently cultivated with rice or wheat (C-3 crops), they are expected to be characterized by a light ∂^{13}C signature. The aggregate size fraction of 0.25–0.02 mm is usually considered to be the most stable micro-aggregate (Roscoe *et al.*, 2000) with a longer SOC residence time (Gerzabek *et al.*, 2001) than the other aggregate sizes. Two of the three studied soils (GS and BS) exhibit ∂^{13}C values in the range of –29‰~–21‰ (PDB) for this size fraction, with these values becoming heavier with increasing soil depth (Table 3). The α^{13}C of the coarse soil micro-aggregates of the topsoil, within and above the plowpan layer, is lighter than the lower-profile soil by –6‰ ~ –4‰.

The above observation supports a mechanism that younger carbon is preferentially incorporated in the topsoil while relatively stable carbon characterized by heavier ∂^{13}C being found in the lower part of the soil profiles. There is a high correlation between ∂^{13}C value of the 0.25–0.02 aggregate-size fraction and its SOC content, as well as the SOC content of the bulk soils (Fig.3), indicating that lighter ∂^{13}C tends to associate with higher SOC content within the topsoils. The accumulation of lighter ∂^{13}C and the increased SOC content in the topsoils

Table 4 Aggregate-size fractions (mass) and soil organic carbon content (SOC), δ^{13}C (‰ PDB) of SOC from the size fraction of 0.25–0.02 mm analyzed of the typical pedon of the three studied soils

Horizon	Depth (cm)	> 2 mm		2–0.25 mm		0.25–0.02 mm		0.02–0.002 mm		<0.002 mm		δ^{13}C (‰ PDB)
		Mass (%)	SOC (g/kg)	Mass (%)	SOC (g/kg)	Mass (%)	SOC (g/kg)	Mass (%)	SOC (g/kg)	Mass (%)	SOC (g/kg)	
Fe-accumulic Stagnic Anthrosol (AS)												
A	0–15	9.8	18.89	40.8	17.45	36.8	13.79	12.3	10.52	1.2	22.19	N.A.
AP	15–31	1.0	9.81	25.4	12.70	48.7	7.11	23.6	6.64	2.3	21.74	N.A.
W	31–43	13.0	2.83	34.2	6.24	36.6	5.74	13.9	5.52	2.3	7.67	N.A.
Bg	43–65	10.8	0.83	14.7	2.48	55.4	1.58	17.7	2.37	1.4	6.14	N.A.
Bg	65–100	6.7	0.58	19.0	1.21	49.5	0.76	22.7	1.46	2.1	3.86	N.A.
Gleyic Stagnic Anthrosol (GS)												
A	0–13	17.6	22.18	38.3	22.91	30.2	15.40	12.4	15.98	1.5	25.48	–28.7
AP	13–26	10.5	11.85	53.5	12.31	23.8	7.99	10.4	12.88	3.4	15.04	–27.4
Bg1	26–60	7.2	5.51	55.2	5.62	23.8	4.36	10.4	5.67	3.4	8.68	–24.3
Bg2	60–80	2.0	3.92	50.8	2.90	32.3	2.48	13.2	3.39	2.7	6.69	–23.4
Fe-bleached Stagnic Anthrosol (BS)												
A	0–13	13.1	17.06	49.9	17.06	24.1	13.49	8.5	14.36	4.4	25.94	–27.9
AP	13–27	6.2	7.04	52.5	8.52	30.4	5.50	9.1	8.45	2.1	13.11	–27.8
W	27–46	17.7	2.85	53.0	2.65	16.9	3.45	11.1	4.30	1.3	6.21	–22.8
Bw	46–80	19.3	1.75	60.9	2.86	12.3	2.11	5.7	3.94	1.8	5.86	–21.3

N.A.: not analyzed.

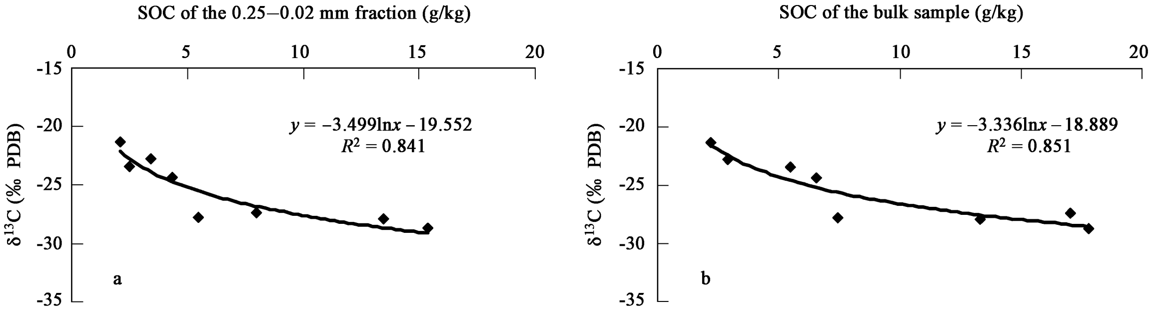

Fig. 3 Correlation of δ^{13}C (‰ PDB) of the size fraction of 0.25–0.02 mm with the SOC content of the fraction (a) and the bulk soil sample (b).

can be attributed to paddy soil cultivation practices, especially tillage operation under water logging conditions. In contrast, the lower SOC content in other size fractions of the test soils can be attributed to the loss of SOC with lighter ∂^{13}C. Thus, the degree of SOC enhancement in these soils is associated with the degree of protection of the labile C of the organic matter derived from rice and wheat plants during decomposition. The ∂^{13}C value of a given aggregate-size fraction in the paddy soils could be indicative of SOC enhancement in paddy soils if the soils have a consistent C-3 crop history.

Numerous studies have reported the SOC distribution in soil aggregate-size fractions under different tillage managements, conservation practices (Hernanz *et al.*, 2002), crop rotations (Zhang *et al.*, 2001), and vegetation covers (Li *et al.*, 2001). It is well recognized (Six *et al.*, 2000; Carter, 2002) that SOC in the coarse micro-aggregate fractions (0.02–0.25 mm) is the relatively young and active C that reflects the incorporation of fresh or less decomposed plant residues. It is expected that such SOC has a short turnover time, which is in the range of a couple of decades (Gerzabek *et al.*, 2001). Our previous work has also shown that the SOC in size fractions > 0.25 mm from paddy soils is very sensitive to agronomical management techniques (Li *et al.*, 2001; Zhang *et al.*, 2001).

Generally, the highest SOC content is found in the fraction of < 0.002 mm size, while the highest bulk SOC content is observed in the topsoil where paddy soil is subject to a repeated cycling of drying and wetting during flood-irrigation operations. Micro-aggregation during tillage operation under water logging condition (pudding) is a unique soil process in the paddy soils (Li, 1992) that results in the formation of abundant soil aggregates of size 0.02–2.0 mm, which can effectively protect the associated SOC in them. For the topsoil, SOC in the coarse micro-aggregate size fraction of 0.02–0.25 mm constitutes 32.5%, 23.6% and 19.9% of the total SOC, respectively, for the AS, GS, and BS soils. And the SOC in the macro-aggregate size fraction of 0.25–2 mm constitutes 45.6%, 44.6% and 52% of the total SOC. With depth in the soil below the zone of cultivation (the topsoils, A+Ap), the SOC content generally decreases as depth increases. Here, there were still observed differences in SOC storage patterns between the different aggregate size fractions, with the coarse micro-aggregates and the macro-aggregates combined accounting for between 57% and 75% of the total SOC at these depths.

However, the changes of C storage and SOC turnover rate within the paddy soils are primarily occurring in the topsoil, which is subjected to more frequent cultivation disturbance as compared to the lower soil layers. The enhanced SOC storage in topsoil involves the incorporation, retention, and protection of younger carbon by the micro-aggregates. The SOC in the coarse micro-aggregate fractions is isotopically lighter (Cayet and Lichtfouse, 2001), and hence, more bio-available (van den Pol-van Dasselaar and Oenema, 1999) than in other size fractions. Thus, SOC in the coarse fractions is the pool that enhances SOC storage upon vegetation recovery (Shang and Tiessen, 2003) and crop shift from C-4 plants to C-3 plants (Zhang *et al.*, 2001). However, the mechanism of SOC protection in soil aggregates of various size fractions in these paddy soils deserves further study.

3 Conclusions

Estimation of carbon storage on a regional or even national level was often based on soil survey data. Using this methodology, however, carbon data for the lower layers of the soil profiles are often not available. Our study indicates that using the average topsoil SOC contents or SOC contents measured from natural soils to estimate the SOC pool of paddy soils to 100 cm can result in overestimation and uncertainty due to high SOC stratification ratios. It was shown that SOC contents in paddy decrease exponentially with depth. Approximately 63%–70% of SOC in the 100-cm profile is stored in the top 30-cm soil in the fertile Taihu Lake region, China. The SOC storage within the topsoils (A and Ap horizons) ranges from 35.29–61.86 Mg/ha, and within the 100-cm profile ranges from 58.20–89.73 Mg/ha. The three study soils have higher SOC storage than the average SOC storage of the China's cultivated soils, as well as higher than the mean of the China's paddy soils. Our C data measured from composite samples were close to the data obtained from a replicated study of the same three soils (Table 1).

A low SOC stratification ratio when comparing A horizons to Ap horizons, but a high SOC stratification ratio when comparing the topsoil (A and Ap horizons, 0–30 cm) to the lower soil (30–100 cm), and high percentages of soil aggregate-size fractions with lighter ∂^{13}C indicates SOC storage enhancement in the topsoil of these paddy systems.

The degree of this enhancement depends on the protection of labile carbon in the coarse micro-aggregates and the macro-aggregates. Incorporation of younger carbon in the top soil resulted in lighter ∂^{13}C in topsoil, and the lighter ∂^{13}C values of the coarse micro-aggregates is indicative of SOC enhancement in paddy soils with consistent C-3 crop history.

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References

Amundson R, 2001. The carbon budget in soils. *Annual Review of Earth and Planetary Sciences*, 29: 535–562.

Arrouys D, Balesdent J, 2002. Increasing Carbon Stocks in French Agricultural Soils. Scientific Assessment Unit for Expertise, INRA. http://www.inra.fr/actualites/ rapport - carbone.html.

Batjes N H, 1996. Carbon and nitrogen in the soils of the world. *European Journal of Soil Science*, 47: 151–163.

Bernoux M, Carvalho M D S, Volkoff B, Cerr C C, 2002. Brazil's soil carbon stocks. *Soil Science Society of America Journal*, 66: 888–896.

Bhatti J S, Apps M J, Tarnocai C, 2002. Estimates of soil organic carbon stocks in central Canada using three different approaches. *Canadian Journal of Forest Research*, 32: 805–812.

Bird M, Santruckova H, Lloyd J, Lawson E, 2002. The isotopic composition of soil organic carbon on a north-south transect in western Canada. *European Journal of Soil Science*, 53: 393–403.

Bossuyt H, Six J, Hendrix P F, 2002. Aggregate-protected carbon in no-tillage conventional tillage agroecosystems using Carbon-14 labeled plant residue. *Soil Science Society of America Journal*, 66: 1965–1973.

Carter M R, 2002. Soil quality for sustainable land management: organic matter and aggregation interactions that maintain soil functions. *Agronomy Journal*, 94: 38–47.

Carter M R, Angers D A, Gregorich E G, Bolinder M A, 2003. Characterizing organic matter retention for surface soils in eastern Canada using density and particle size fractions. *Canadian Journal of Soil Science*, 83: 11–23.

Carter M R, Skjemstad J O, MacEwan R J, 2002. Comparison of structural stability, carbon fractions and chemistry of krasnozem soils from adjacent forest and pasture areas in south-western Victoria. *Australian Journal of Soil Research*, 40: 283–298.

Cayet C, Lichtfouse E, 2001. Delta C-13 of plant-derived *n*-alkanes in soil particle-size fractions. *Organic Geochemistry*, 32: 253–258.

Davidson E A, Trumbore S E, Amundson R, 2000. Soil warming and organic carbon content. *Nature*, 408: 789–790.

FAOSTAT, 2005. Agricultural Data. http://apps.fao.org/faostat/collections/agriculture.

Franzluebbers A J, 2002. Soil organic matter stratification ration as an indicator of soil quality. *Soil and Tillage Research*, 66: 95–106.

Gerzabek M H, Haberhauer G, Kirchmann H, 2001. Soil organic matter pools and carbon-13 natural abundance in particle-size fractions of a long-term agricultural field experiment receiving organic amendments. *Soil Science Society of America Journal*, 65: 352–358.

Gong Z T, 1986. Origin, evolution and classification of paddy soils in China. *Advances in Soil Science*, 5: 174–200.

Gong Z T, Zhang G L, Wang J Z, Jia H Y, Shen H, Lu J C, 1999. Anthrosols. In: Chinese Soil Taxonomy–Theories, Practices and Methods (Gong Z. T., ed.). Beijing: Science Press. 109–200.

Hernanz J L, Lopez R, Navarrete L, Sanchez-Giron V, 2002. Long-term effects of tillage systems and rotations on soil structural stability and organic carbon stratification in semi-arid central Spain. *Soil and Tillage Research*, 66: 129–141.

Hou P C, Xu X D, Pan G X, 2007. Influence of land use change on topsoil organic carbon stock: a case study of Wujiang Municipality. *Journal of Nanjing Agricultural University*, 30(2): 68–72.

Jacinthe P A, Lal R, Kimble J M, 2001. Organic carbon storage and dynamics in croplands and terrestrial deposits as influenced by subsurface tile drainage. *Soil Science*, 166: 322–335.

Kempthorne O, Allmaras R R, 1986. Error and variability of observations. In: Methods of Soil Analysis. Part 1. Physical and Mineralogical Methods (Klut A, ed.). 2nd ed. Madison, WI: ASA and SSSA. 1–32.

Kirschbaum M U F, 1993. A modeling study of the effects of changes in atmospheric CO_2 concentration, temperature and atmospheric nitrogen input on soil organic carbon storage. *Tellus B*, 45: 321–334.

Lal R, 1999. World soils and greenhouse effect. *IGBP Global Change Newsletter*, 37: 4–5.

Li L Q, Pan G X, Zhang X H, 2001. Vegetation recovery in degraded red earth: effect on organic carbon and Pb and Cd partitioning in soil particle size fractions. *Ecologica Sinica*, 21: 1669–1774.

Li Q K, 1992. Paddy Soils of China. Beijing: China Science Press. 232–248.

Lu R K, 2000. Methods of Soil and Agrochemical Analysis. Beijing: China Agricultural Science and Technology Press.

Materechera S A, Mkhabela T S, 2001. Influence of land-use on properties of a ferralitic soil under low external input farming in southeastern Swaziland. *Soil and Tillage Research*, 62: 15–25.

Pan G X, Li L Q, Wang X K, Sun X B, Xu X, Jiang D A, 2005. Organic carbon stock in topsoil of Jiangsu Province, China, and the recent trend of carbon sequestration. *Journal of Environment Sciences*, 17: 1–7.

Pan G X, Li L Q, Wu L S, Zhang X H, 2004. Storage and sequestration potential of topsoil organic carbon by paddy soils of China. *Global Change Biology*, 10: 79–92.

Pan G X, Li L, Zhang X H, Dai J Y, Zhou Y C, Zhang P J, 2003. Soil organic carbon storage of China and the sequestration dynamics in agricultural lands. *Advance in Earth Sciences*, 18: 609–618.

Puget P, Angers D A, Chenu C, 1995. Total and young organic matter distributions in aggregates of silty cultivated soils. *European Journal of Soil Science*, 46: 449–459.

Roscoe R, Buurman P, Velthorst E J, 2000. Disruption of soil aggregates by varied amounts of ultrasonic energy in fractionation of organic matter of a clay Latosol: carbon, nitrogen and delta C-13 distribution in particle-size fractions. *European Journal of Soil Science*, 51: 445–454.

Schulten H R, Leinweber P, 2000. New insights into organic-mineral particles: composition, properties and models of molecular structure. *Biology and Fertility of Soils*, 30: 399–432.

Schwager S J, Mikhailova E A, 2002. Estimating variability in soil organic carbon storage using the method of statistical differentials. *Soil Science*, 167: 194–200.

Shang C, Tiessen H, 2003. Soil organic C sequestration and stabilization in karstic soils of Yucatan. *Biogeochemistry*, 62: 177–196.

Six J, Elliott E T, Paustian K, 2000. Soil macroaggregate turnover and microaggregate formation: a mechanism for C sequestration under no-tillage agriculture. *Soil Biology and Biochemistry*, 32: 2099–2103.

Smith P, Powlson D S, Smith J U, Falloon P, Coleman K, 2000. Meeting Europe's climate change commitments: quantitative estimates of the potential for carbon mitigation by agriculture. *Global Change Biology*, 6: 525–539.

SSSC (Soil Science Society of China), 2000. Handbook of Soil and Agro-Chemistry Analysis. Beijing: China Agricultural Press. 5–200.

SSSJ (Soil Survey Service of Jiangsu Province,China), 1995. Soils of Jiangsu. Beijing: China Agriculture Press. 232–357.

Song G H, Pan G X, Zhang Q, 2005. Topsoil SOC storage of China agricultural soils and its loss by cultivation. *Biogeochemistry*, 74: 47–62.

Spaccini R, Zena A, Igwe C A, Mbagwu J S C, Piccolo A, 2001. Carbohydrates in water-stable aggregates and particle size fractions of forested and cultivated soils in two contrasting tropical ecosystems. *Biogeochemistry*, 53: 1–22.

SSSSC (State Soil Survey Service of China), 1996a. Soil Survey Technical Report. Beijing: China Agriculture Press. 50–135.

SSSSC (State Soil Survey Service of China), 1996b. Soil Survey Technical Report. Beijing: China Agriculture Press. 50–135.

SSSSC (State Soil Survey Service of China), 1997a. China Soil Survey Dataset. Beijing: China Agricultural Press.

SSSSC (State Soil Survey Service of China), 1997b. China Soil Survey Dataset. Beijing: China Agricultural Press. 35–65.

Tarchitzky J, HaMgCher P G, Chen Y, 2000. Properties and distribution of humic substances and inorganic structure-stabilizing components in particle-size fractions of cultivated Mediterranean soils. *Soil Science*, 165: 328–342.

Tate K R, Giltrap D J, Claydon J J, Newsome P F, Atkinson I A E, Taylor M D, Lee R, 1997. Organic carbon stocks in New Zealand's terrestrial ecosystems. *Journal of the Royal Society of New Zealand*, 27: 315–335.

Tisdall J M, Oades J M, 1982. Organic matter and water-stable aggregates in soils. *Journal of Soil Science*, 33: 141–163.

van den Pol-van Dasselaar A, Oenema O, 1999. Methane production and carbon mineralization of size and density fractions of peat soils. *Soil Biology and Biochemistry*, 31: 877–886.

Wairiu M, Lal R, 2003. Soil organic carbon in relation to cultivation and topsoil removal on sloping lands of Kolombangara, Solomon Islands. *Soil and Tillage Research*, 70: 19–27.

Wang G X, Qian J, Cheng G D, Li Y M, 2002. Soil organic carbon pool of Grassland soils on the Qinghai-Tibetan Plateau and its global implication. *The Science of the Total Environment*, 291: 207–217.

Wang S Q, Zhou C H, 1999. Estimate of organic carbon pool of terrestrial soils of China. *Geographical Science*, 18: 349–355.

Wu H B, Guo Z T, Peng C H, 2003. Land use induced changes of organic carbon storage in soils of China. *Global Change Biology*, 9: 305–315.

Xu Q, Lu Y C, Liu Y C, Zhu H G, 1980. The Paddy Soil of Tai Lake Region in China. Shanghai: Shanghai Scientific and Technical Press. 37–70.

Yamashita T, Flessa H, John B, Helfrich M, Ludwig B, 2006. Organic matter in density fractions of water-stable aggregates in silty soils: Effect of land use. *Soil Biology and Biochemistry*, 38: 3222–3234.

Zhang X H, Li L Q, Pan G X, 2001. Effect of different crop rotation systems on the microaggregates and their SOC accumulation in Paludalfs in North Huai Region, China. *Chinese Journal of Ecology*, 20: 16–19.