Global Change Biology (2003) **10**, 79–92, doi: 10.1046/j.1529-8817.2003.00717.x

Storage and sequestration potential of topsoil organic carbon in China's paddy soils

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Abstract

Carbon (C) storage and sequestration in agricultural soils is considered to be an important issue in the study of terrestrial C cycling and global climatic change. The baseline C stock and the C sequestration potential are among the criteria for a region or a state to adopt strategies or policies in response to commitment to the Kyoto Protocol. Paddy soils represent a large portion of global cropland. However, little information on the potential of C sequestration and storage is available for such soils. In this paper, an estimation of the topsoil soil organic carbon (SOC) pool and the sequestration potential of paddy soils in China was made by using the data from the 2nd State Soil Survey carried out during 1979–1982 and from the nationwide arable soil monitoring system established since then. Results showed that the SOC density ranged from 12 to 226 t C ha^{-1} with an area-weighted mean density of 44 t C ha^{-1}, which is comparable to that of the US grasslands and is higher than that of the cultivated dryland soils in China and the US. The estimated total topsoil SOC pool is 1.3 Pg, with 0.85 Pg from the upper plow layer and 0.45 Pg from the plowpan layer. This pool size is $\sim$2% of China's total storage in the top 1 m of the soil profiles and $\sim$4% of the total topsoil pool, while the area percentage of paddy soil is 3.4% of the total land. The C pool in paddy soils was found predominantly in southeast China geographically and in the subgroups of Fe-accumulating and Fe-leaching paddy soils pedogenetically. In comparison with dryland cultivation, irrigation-based rice cultivation in China has induced significant enrichment of SOC storage (0.3 Pg) in paddy soils. The induced total C sequestration equals half of China's total annual CO_2 emission in the 1990s. Estimates using different SOC sequestration scenarios show that the paddy soils of China have an easily attainable SOC sequestration potential of 0.7 Pg under present conditions and may ultimately sequester 3.0 Pg. Soil monitoring data showed that the current C sequestration rate is 12 Tg yr^{-1}. The total C sequestration potential and the current sequestration rate of the paddy soils are over 30%, while the area of the paddy soils is 26% that of China's total croplands. Therefore, practicing sustainable agriculture is urgently needed for enhancing SOC storage to realize the ultimate SOC sequestration of rice-based agriculture of China, as the current C sequestration rate is significantly lower than the potential rate.

Keywords: C sequestration, C stock, global change, irrigation agriculture, paddy soils of China, soil organic carbon

Received 3 June 2003; revised version received and accepted 11 August 2003

Introduction

World soils hold as much as 1500 Pg of organic carbon (C) in the terrestrial ecosystem (Batjes, 1996; Lal, 1999; Amundson, 2001). Preservation or release of this giant C pool has been considered as a key factor in impacting the atmospheric CO_2 concentration (Kirschbaum, 2000; Amundson, 2001; Rustad *et al.*, 2001). Estimates of soil organic carbon (SOC) density and pool size in typical ecosystems (Tate *et al.*, 1997; Bernoux *et al.*, 2002; Chhabra *et al.*, 2003) at regional (Titlyanova *et al.*, 1995; Bhattacharyya *et al.*, 2000; Arrouys & Balesdent, 2002; Bhatti *et al.*, 2002a,b) or continental scales (Smith *et al.*, 2001; Batjes, 2002) have been widely reported.

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However, little information is available on the C pool in paddy soils.

C loss from agricultural soils has been extensively discussed in the research on global climatic change (Rounsevell *et al*., 1999; West & Marland, 2002; Wu *et al*., 2003). Soil C sequestration through well-managed agriculture is considered a potential measure for mitigating the rise of atmospheric CO_2 (Lal, 1999; 2000a, b; 2002a, b; Smith *et al*., 2000a, b; Uri, 2001; Vleeshouwers & Verhagen, 2002; West & Marland, 2002). Changes in SOC storage in agricultural soils have been reported by Eve *et al*. (2002a). In particular, SOC storage as affected by tillage was evaluated by West & Marland (2002), rangeland managements by Schuman *et al*. (2002), residue applications by Jacinthe *et al*. (2002), drainage by Jacinthe *et al*. (2001), and fertilizer application by Hao *et al*. (2002). The emission rate of methane by rice-based agriculture has also been evaluated as part of national greenhouse emission budgets (Gupta *et al*., 2002). In contrast, information on soil C storage and C sequestration in paddy soils with frequent irrigation is lacking except for some preliminary studies by Zdruli *et al*. (1995).

China is a country with a long history of agricultural development as well as diverse soil types. Various estimates of the total SOC pool of China's soils range from 50 to 200 Pg (Wang & Zhou, 1999; Ni, 2001; Pan *et al*., 2003b), while the topsoil (0–20 cm) SOC pool is estimated to be at the level of 20 Pg (Pan *et al*., 2003b). While industrial C emission is rising, C loss from soils due to intensive agricultural land use in the world has also raised serious concerns (Lindert *et al*., 1996; Li, 2000; Lal, 2002b; Wu *et al*., 2003). However, data available from field studies in various regions of China showed considerable C sequestration in the last decade (Pan *et al*., 2003a, b). In discussing approaches for offsetting China's increasing CO_2 emission, Lal (2002b) recently considered C pool enhancement in paddy soils as a potential C sequestrator. Thus, an accurate estimate of soil C density and total C pool size is critical for evaluating the C sequestration potential.

Paddy soils are a group of anthropogenic soils with a long history of rice cultivation under irrigation, and unique soil type in China's taxonomy (Gong, 1999). The total area of paddy soils in China reached 30 Mha in the mid-1980s (23% of the world's total irrigated lands). Paddy soils produce one-quarter of grains for China's market (Gong, 1999). The purposes of this paper are to present an estimation of the total topsoil SOC pool and the potential for C sequestration in China's paddy soils by using data available from the 2nd State Soil Surveys and from monitoring sites, and to discuss the role of paddy soil in C storage and its contribution to mitigating atmospheric CO_2.

Materials and methods

Soil data

Data for C density calculation and C pool estimation of paddy soils were obtained from the 2nd State Soil Survey completed in the early 1980s. The data were published in a series of monographs in the China Soil Series Vols. 1–6 (State Soil Survey Service of China (SSSSC), 1993; 1994a, b; 1995a, b; 1996a). The 2nd State Soil Survey identified 525 soil series for paddy soils. Since the upper portion of a typical paddy soil is composed of a plow layer and a plowpan (Li, 1992), we used the means of these two layers to calculate the C density in paddy soils. The 2nd State Soil Survey required soil sampling at a scale of 1 : 200 ha to determine the SOC content, thickness, and bulk density in the plow layers of most heavily cultivated soils. A total of 150 504 plow-layer samples were analyzed, and statistical means and standard deviations were reported for all of the 525 soil series. The plowpans were sampled at a larger scale (thus, a smaller number of samples) from those typical pedons of the paddy soil series with a total of 3000 samples analyzed for SOC, layer thickness, and bulk density.

To evaluate the SOC dynamics and the sequestration potential, data from the national soil monitoring stations (State Extension Service of Agricultural Technology of China (SESATC), 2003) and from several case studies published in the literature were used in this research.

Calculation of C density and pool estimation

Although many researchers have assumed the thickness of topsoil to be 30 cm (Arrouys & Balesdent, 2002; Bernoux *et al*., 2002; Bhatti *et al*., 2002a) or considered the upper 20–25 cm when estimating C pools (Tate *et al*., 1997; Li & Zhao, 2001), we used the measured thickness from sampling records to estimate the C pool in paddy soils because it is common that in paddy soils, stratification of SOC is usually basically restricted to pedologically recognizable horizons and is featured by a sharp decrease down the profile (Pan *et al*., 2000). The SOC pools for the plow layer and the plowpan of each soil series were individually calculated, and the total SOC pools of a soil were calculated from combining the SOC of the two layers of each soil series.

The SOM content from the original data was converted to SOC by multiplying a constant of 0.580, since the C determination was carried out by rational wet combustion (SSSSC, 1996b). The SOC density of a single layer of a paddy soil was calculated by using the equation similar to that used by Schwager &

Mikhailova (2002):

$$D_{oc} = \mathrm{SOC} \times \gamma \times H \times (1 - \delta_{2\,mm}/100) \times 10^{-1}, \quad (1)$$

where D_{oc} and SOC are the density ($\mathrm{t\,ha^{-1}}$) and content ($\mathrm{g\,kg^{-1}}$), respectively, of organic C, γ is the bulk density ($\mathrm{g\,cm^{-3}}$), H is the thickness (cm), and $\delta_{2\,mm}$ is the fraction (%) of <2 mm soil. Since the paddy soils in China were mostly derived from deposits in flat areas, the sand fraction (>2 mm) of the total mass of topsoil is usually negligible (Li, 1992). Thus, the total SOC pool (P_{oc}) of the paddy topsoil is:

$$P_{oc}\ (\mathrm{t\,C}) = \sum_{i=1}^{n} S_i \times \sum_{j=1}^{n} \mathrm{SOC}_j \times \gamma_j \times H_j \times 10^{-1}, \quad (2)$$

where j is the layer number of topsoil (1 = plow layer, 2 = plowpan) and S_i is the total area (ha) of a given paddy soil series i.

In cases where data were missing, bulk density in the equation was estimated from regression analysis between the available bulk density and SOC content for a given layer. The SOC content of the plowpan was estimated from regression between the available SOC data both of the plowpan and the overlying plow layer where the SOC data of plowpans were not available in soil monitoring data (Wu *et al*., 2003).

Results and discussions

Relationship between SOC content and bulk density

The empirical relationships between soil bulk density and SOC content from regression analysis depend on soil types and their origins. For examples, Wu *et al*. (2003) used a logarithmic function obtained from 784 samples of soils to estimate the bulk density for a wide variety of mineral soils in China; Callesen *et al*. (2002) identified a significant correlation between bulk density and the square of SOC content for Canadian forest soils. In the present study, among the 525 soil series, 222 plow layers and 137 plowpans have means or single measurements, respectively, for both SOC content and bulk density (γ). The correlation equations between γ and SOC (Fig. 1) from regression analysis are as follows:

For the plow layer,

$$\gamma\ (\mathrm{g\,cm^{-3}}) = -0.220 \times \ln \mathrm{SOC}\ (\mathrm{g\,kg^{-1}}) + 1.780\ (R^2 = 0.157,\ P < 0.01) \quad (3)$$

and for the plowpan layer,

$$\gamma\ (\mathrm{g\,cm^{-3}}) = -0.018 \times \mathrm{SOC}\ (\mathrm{g\,kg^{-1}}) + 1.608\ (R^2 = 0.315,\ P < 0.001). \quad (4)$$

These regressions indicate that the dependence of bulk density on the SOC content varies with the horizons in the paddy soils due to differences in physical or chemical properties. Therefore, Eqns (3) and (4) were used to estimate the missing bulk density values for the plow layer and for the plowpan, respectively.

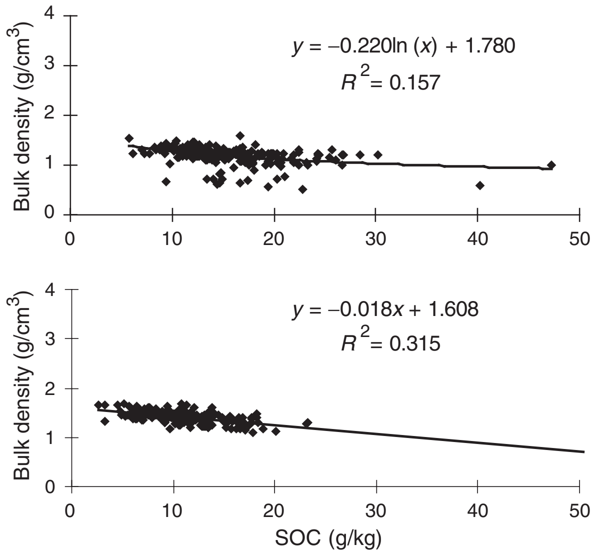

Fig. 1 Correlations between bulk density and soil organic carbon (SOC) content (a) for the plow layers ($n = 222$) and (b) plowpans ($n = 137$) of the paddy soil series surveyed during the 2nd State Soil Survey.

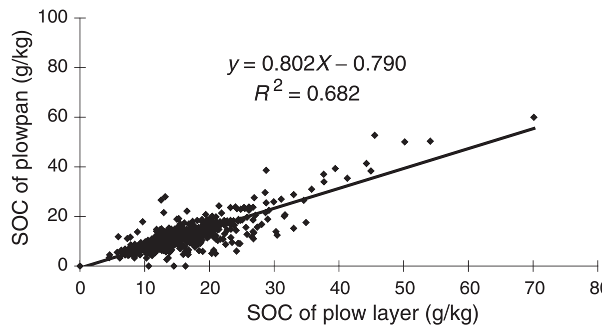

Fig. 2 Relationship between soil organic carbon (SOC) in the plowpans and SOC in the plow layers of paddy soils studied ($N = 525$, $P < 0.0001$).

A significant correlation between the SOC contents of the plowpan and the plow layer (Fig. 2) was found for the 523 soil series with SOM content <5%:

$$\mathrm{SOC_{pp}} = 0.802 \times \mathrm{SOC_{pl}} - 0.790\ (R^2 = 0.682,\ P < 0.001), \quad (5)$$

where $\mathrm{SOC_{pp}}$ and $\mathrm{SOC_{pl}}$ represent the SOC content of the plowpan and the plow layer in $\mathrm{g\,kg^{-1}}$, respectively. Equation (5) was used to estimate the SOC contents of plowpan layers where they were missing. In addition, a correlation between plow layer thickness and its SOC content was also observed:

$$\text{TH (cm)} = -1.907 \times \ln(\text{SOC, g kg}^{-1}) + 20.53 \quad (R^2 = 0.148,\ n = 525,\ P < 0.01). \tag{6}$$

This equation was used to estimate the thickness of the plow layer only for the few cases when the depth records of the plow layer were missing.

SOC content and distribution in the topsoil

The distribution of statistical means of SOC contents, values of bulk density, and thickness for the plow layers of the 525 paddy soil series are shown in Figs 3–5. Figure 6 represents the frequency distribution of SOC of the plowpans. All these parameters follow a normal distribution. About 60% of the soil series and of the area of paddy soils have SOC contents ranging from 12.5 to 22.5 g kg^{-1}, while 95% of the soil series and 99% of the

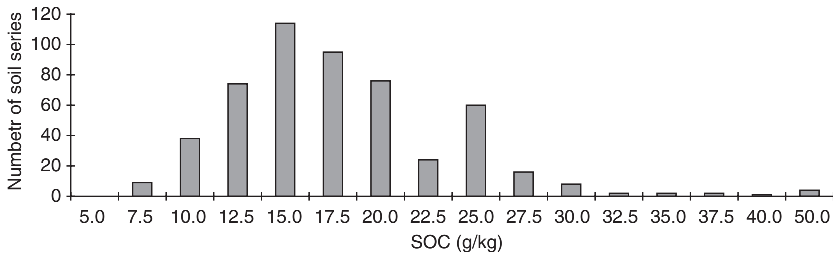

Fig. 3 Frequency distribution of soil organic carbon (SOC) of the plow layers in terms of (a) number and the (b) total area of the 525 paddy soil series.

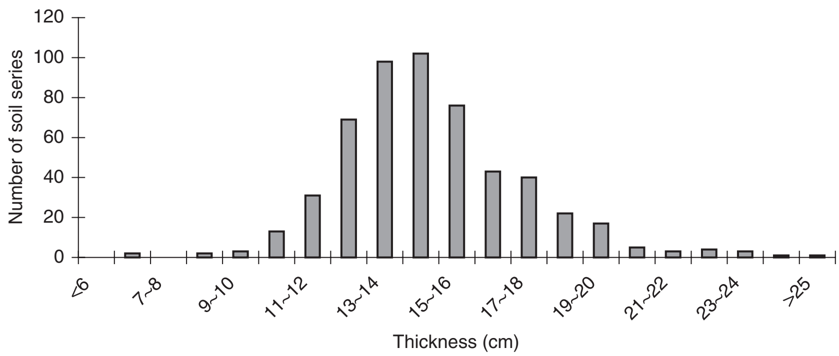

Fig. 4 Frequency distribution of plow layer thickness (cm) of the paddy soil series in China.

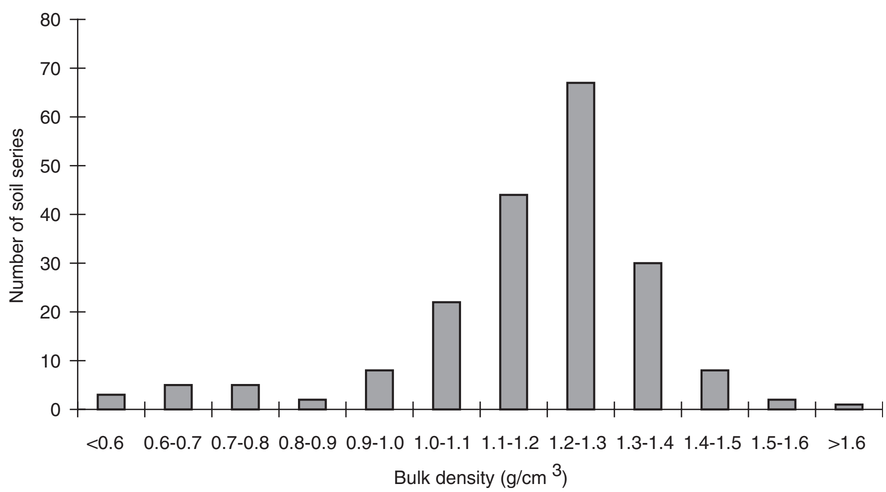

Fig. 5 Frequency distribution of plow layer bulk density of the paddy soil series in China.

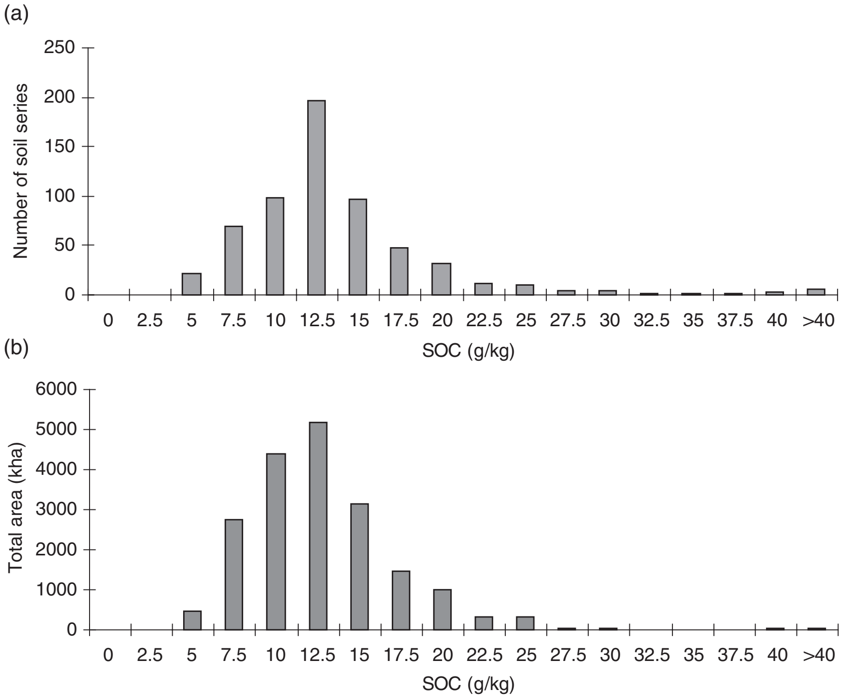

Fig. 6 Frequency distribution of plowpan soil organic carbon (SOC) of paddy soils in terms of number of (a) soil series and of (b) total area (kha).

Table 1 Means, standard deviations, and area-weighted means (in parentheses) of SOC content, bulk density, layer thickness, and the calculated C density for plow layers and plowpans of the 525 paddy soil samples

Soil layer	Number of samples	SOC ($g\,kg^{-3}$)	Bulk density ($g\,cm^{-3}$)	Thickness (cm)	SOC density ($t\,C\,ha^{-1}$)
Plow layer	150 589	16.58 ± 5.81 (15.40)	1.18 ± 0.14 (1.20)	15.28 ± 2.61 (15.40)	29.48 ± 11.35 (28.05)
Plowpan	525	2.66 ± 6.77 (11.48)	1.38 ± 0.13 (1.41)	10.24 ± 5.11 (10.00)	17.43 ± 13.38 (15.93)
Whole topsoil		15.01 ± 6.20 (13.83)	1.26 ± 0.14 (1.28)	25.52 ± 7.71 (25.40)	46.91 ± 25.73 (43.98)

SOC: soil organic carbon.

area have SOC contents ranging from 7.5 to 30 $g\,kg^{-1}$. About 66% of the soil series and of the total area have a plow-layer thickness of 12–16 cm, while 95% of them are in the range of 11–20 cm. The bulk density distribution is more skewed.

A summary of the means of SOC contents, values of bulk density, and the thickness of plow layers and plowpans is given in Table 1. The mean values of these three parameters for the plow layer are 16.58 ± 5.81 $g\,kg^{-1}$, 1.18 ± 0.14 $g\,cm^{-3}$, and 15.28 ± 2.61 cm, with the area-weighted means of 15.40 $g\,kg^{-1}$, 1.20 $g\,cm^{-3}$, and 15.40 cm, respectively (Table 1). The means and area-weighted means of SOC contents in plowpans are lower than those of plow layers by 4 $g\,kg^{-1}$. The SOC stratification ratio, as defined by Franzluebbers (2002), has an average of 1.40 ± 0.39 for all series, indicating a higher SOC content tendency in plow layers than those for dryland crops (Akala & Lal, 2001). The plowpan of a paddy soil is usually not available for rooting due to the compaction even when the topsoil is relatively shallow. Thus, extrapolation of topsoil SOC content to any depth below 20 cm will result in an overestimate of the topsoil SOC pool (Li & Zhao, 2001).

C density and the distribution in geographical regions and subgroups

The calculated SOC density varied widely ranging from 11.9 to 226.9 $t\,C\,ha^{-1}$ for the topsoil using measured depth. With an area-weighted SOC mean of 44 $t\,C\,ha^{-1}$, the C density of the plow layer is on average 12 $t\,C\,ha^{-1}$ higher than that of plowpan due to higher C content and greater thickness (Table 1). As shown in Fig. 7, 80% of the series and 90% of all the paddy cropland have a topsoil SOC density of 20–60 t C ha^{-1}, while 99% of the overall paddy cropland is in the range of 20–100 t C ha^{-1}, indicating a wide variability of SOC storage in paddy topsoils. The variations of SOC density in geographical regions and pedogenetical subtypes of paddy soils are listed in Tables 2 and 3, respectively. The paddy soils in northeast China have the highest SOC content and, therefore, the highest SOC density owing to the parent soils being relatively rich in SOC. Wang *et al*. (2002) reported a wide range of SOC density of 24–925 t C ha^{-1} with an area-weighted mean SOC density of over 200 t C ha^{-1} for 1 m depth in northeastern China soils under various vegetation types. The salinity and low organic C in parent material may account for the low SOC content and SOC density found in the area (Li, 1992).

A relatively higher mean SOC density ($\sim$60 t C ha^{-1}) and a greater standard deviation of $\sim$30 t C ha^{-1} in southwest China may be attributed to the winter fallow and surface water-logging in paddy soils in those small valleys of the hilly regions, which enhances methane production and emissions in the succeeding summer (Cai, 1999). A relatively low SOC density is found in south China, where SOC-poor red soils are extensive with SOC loss due to an aggressive cropping system (triple cropping annually) and severe erosion (Zhao, 2002). The extensive paddy soils in east China have a low mean SOC density plus a shallow plow layer compared to those in southeastern China. Li *et al*. (2001) showed that the soils in south China had a topsoil SOC density ranging from 12 to 97 t C ha^{-1}. Compared with the native soils, the cultivated soils have lost 20–63% of the SOC. Using approximate depth and SOC contents in lower profile, Li and Zhao (2001) reported an estimated SOC density ranging from 21 to 290 t C ha^{-1} for the soils under a variety of land uses in southern China, while the paddy soils in this region had a SOC density in the level of 40 t C ha^{-1} on average. They concluded that the SOC density of paddy soils in southern China was higher than that of soils under other land uses except for those under forest vegetation.

The SOC data from the soil testing conducted during the 2nd State Soil Survey allow a reliable estimation of SOC storage by different subgroups of paddy soils in terms of their water regimes. As shown in Table 3, significant variations of SOC content and SOC density were also found among the subgroups. The subgroups of Gleying and Degleying paddy soils have a higher SOC density due to their occurrence in lowlands

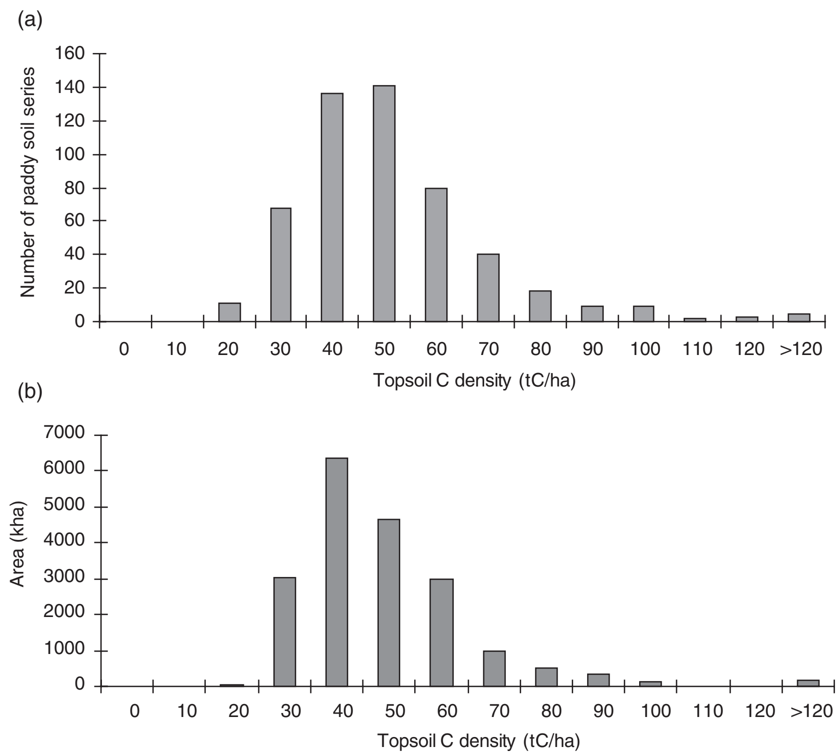

Fig. 7 Frequency distribution of mean topsoil C density in terms of (a) numbers and (b) area of the paddy soil series surveyed during the 2nd State Soil Survey of China in early 1980s.

Table 2 SOC storage of paddy soils in major geographical regions of Mainland China

Region	Area surveyed (kha)	Number of soil series	Number of samples	Layer of topsoil	SOC ($g\,kg^{-1}$)	Thickness (cm)	Bulk density ($g\,cm^{-3}$)	C density ($t\,ha^{-1}$)	C pool (Tg)	C pool (%)
East China	14 773.1	212	80 198	Plow layer	15.86 ± 4.42 (14.26)*	14.13 ± 1.73 (14.0)	1.18 ± 0.17 (1.21)	26.06 ± 7.78 (23.77)	351.2	42.3
				Plowpan	12.39 ± 5.74 (10.56)	9.46 ± 2.97 (9.20)	1.38 ± 0.19 (1.43)	15.90 ± 8.81 (13.72)	202.6	
North China	747.8	17	5418	Plow layer	10.03 ± 2.46 (9.65)	16.53 ± 3.69 (16.3)	1.29 ± 0.06 (1.29)	21.09 ± 6.36 (20.14)	15.00	1.9
				Plowpan	7.71 ± 3.60 (6.15)	15.10 ± 11.41 (15.10)	1.47 ± 0.10 (1.51)	15.12 ± 9.83 (12.78)	9.59	
Northwest China†	215.1	17	948	Plow layer	14.55 ± 4.84 (14.70)	17.24 ± 1.95 (17.6)	1.20 ± 0.07 (1.21)	29.91 ± 9.74 (30.61)	6.65	0.8
				Plowpan	11.39 ± 5.22 (12.04)	13.29 ± 8.11 (11.3)	1.49 ± 0.03 (1.38)	20.60 ± 8.82 (19.33)	4.18	
Southwest China	6478.0	96	4873	Plow layer	19.18 ± 7.54 (16.86)	17.38 ± 2.87 (18.2)	1.15 ± 0.08 (1.16)	37.09 ± 12.92 (35.00)	226.4	26.4
				Plowpan	15.75 ± 10.17 (13.28)	10.93 ± 4.99 (10.7)	1.48 ± 0.06 (1.37)	21.16 ± 8.85 (18.38)	119.1	
Northeast China	896.9	20	1213	Plow layer	19.24 ± 10.10 (17.90)	17.60 ± 1.47 (17.9)	1.31 ± 0.14 (1.34)	42.19 ± 17.83 (40.99)	36.81	4.8
				Plowpan	13.27 ± 8.05 (11.82)	12.20 ± 14.19 (14.6)	1.47 ± 0.03 (1.43)	23.02 ± 8.84 (29.22)	26.29	
South China	6669.4	163	15 118	Plow layer	16.56 ± 4.99 (16.86)	14.93 ± 2.36 (15.3)	1.16 ± 0.11 (1.17)	28.73 ± 10.56 (29.84)	199.1	23.8
				Plowpan	11.82 ± 4.92 (12.38)	9.78 ± 3.77 (9.8)	1.49 ± 0.03 (1.38)	16.46 ± 10.69 (16.88)	112.4	
Total/mean	29 780.3	525	107 589	/	13.83	25.4	1.28	43.98	1309.4	100.0

SOC: soil organic carbon.
*Numbers in parentheses are the geometrical means (area-weighted mean values).
†Mainly from the southern Shanxi valleys close to Sichuan Province.

favoring SOC accumulation. In contrast, those of Redoxing and Percolating, which are typically hydro-agric paddy soils with well-established diagnostic horizons and are rich in ferric hydroxides (Li, 1992), conserve a medium level of SOC ($\sim$30 t C ha^{-1}). Good correlations of SOC with the oxalate extractable Fe were often observed in these paddy soils (Pan *et al.*, 2003), suggesting a stabilization effect by iron cutans on C preservation (Soil Survey Service of Jiangsu (SSSJ), 1995). The lower SOC density of the other subgroups can be attributed to soil constraints such as salinity, continuous reduction conditions, and the lack of SOC protective materials like clay or hydroxides. Higher C density values over 100 t C ha^{-1} were found in those newly formed paddy soils in wetland areas. They are similar to the C density reported for Canadian boreal peat land (Bhatti *et al.*, 2002b).

Paddy soil C stock and its role in China's SOC storage

The sum of the C storage of the individual soil series yielded a total C stock of 1.31 Pg, which is very close to the value of 1.32 Pg estimated from the soil subgroups. Thus, the SOC stock of 1.3 Pg in topsoils seems a reliable estimate for overall China's paddy soils. This corresponds to 2% of China's current total SOC pool as estimated by Wu *et al.* (2003), 6% of the country's surface soil pool (Pan *et al*, 2003b), and 0.2% of the world's (Batjes, 1996) topsoil SOC pool, respectively. In contrast, the paddy soils comprise 3.4% of China's territory and 0.2% of the world's territory. It is estimated that 92.5% of the paddy soil C stock is preserved in southeast China, where irrigation is frequently available due to high annual precipitation. Among these, the C stock in eastern China (consisting of provinces of Jiangsu, Shanggai, Zhejiang, Fujian, and Jiangxi) accounts for 42.3%, amounting to $\sim$0.55 Pg. We have shown that 44% of Jiangsu province's SOC stock was found in the Tai Lake region, where paddy soils dominate in a region with a long agricultural history of high rice production under delicate farming practices (Li & Pan, 1999; Pan *et al.*, 2003). Therefore, well-managed paddy systems can play an important role in the regional SOC stock.

Two-thirds of the total C stock was found in the two major subgroups of Redoxing and Percolating paddy soils. These two subgroups have been considered as the typical paddy soils that have formed under long-time hydro-agric soil development, and they were classified as Typic Stagnic Anthrosols (Gong, 1999).

Table 3 Distribution of topsoil C storage among the subgroups of paddy soils in China (calculated using data from the State Survey Soil Service of China (SSSSC), 1997)*

Subgroup of paddy soils†	Area (kha)	Sample number	SOC of plow ($g\,kg^{-1}$)	SOC of plowpan ($g\,kg^{-1}$)	C density ($t\,C\,ha^{-1}$)	C Pool (P, Tg)	C pool (PP, Tg)	Total C pool (topsoil, Tg)
Redoxing[1]	14 211.9	85 285	16.42 ± 8.00	12.38 ± 5.63	44.6	413.7	220.9	634.6
Waterlogged[2]	3803.4	15 388	13.40 ± 6.55	9.96 ± 4.47	33.3	96.2	49.4	145.6
Percolating[3]	5543.4	17 091	16.53 ± 8.41	12.47 ± 5.96	44.9	162.1	86.7	248.8
Gleying[4]	2645.6	14 662	18.62 ± 8.58	14.14 ± 6.09	49.1	83.9	45.9	129.8
Degleying[5]	1052.6	10 922	22.27 ± 9.57	17.07 ± 6.89	56.0	37.7	21.3	58.9
Bleached[6]	710.1	5890	11.72 ± 5.57	8.61 ± 3.68	34.5	16.4	8.2	24.5
Saline[7]	353.3	1256	9.92 ± 4.81	7.16 ± 3.17	30.4	7.2	3.5	10.7
Saltic and acid[8]	82.5	49	16.36 ± 4.87	12.33 ± 3.12	44.5	2.4	1.3	3.7
Total	28 402.7	150 543	15.65 ± 3.93 (16.26)‡	11.76 ± 3.16 (12.25)	(44.2 ± 8.2) (44.2)	819.6	437.1	1256.7 (1317.6)§

*SOC of the plowpan layer was estimated by Eqn (5), and bulk density for both layers by Eqn (2). The thickness of the plow layer was estimated by Eqn (6), while plowpan thickness used the area-weighted mean of 10.24 cm of the 525 soil series.
†As defined in the Soil Classification Manual by SSSSC (1996). 1, mostly Fe-leaching-Stagnic-Hydro-agric Anthrosols; 2, mostly Hap-Stagnic Anthrosols; 3, Fe-accumulating Stagnic Anthrosols; 4, Gleyic Stagnic Anthrosols; 5, Paleo-Gleyic Stagnic Anthrosols; 6, Albic Stagnic Anthrosols; 7, mostly sodic fluvents; 8, mostly sulfaquents.
‡Numbers in parentheses are the area-weighted mean values.
§Calculated for the total area of China's paddy soils of 29 780.3 kha.

Table 4 Change in SOC content and C storage increase due to irrigated rice production in China's agricultural soils

	SOC content ($g\,kg^{-1}$)			Increased C density		Increased C storage (Tg)		
Region	Unirrigated topsoil	Paddy plow layer	Paddy plowpan	Paddy plow layer	Paddy plowpan	Paddy plow layer	Paddy plowpan	Total
East China	8.79	14.26	10.56	9.27	2.33	136.89	34.40	171.3
South China	10.69	16.86	12.80	12.06	4.83	80.40	32.20	112.6
North China	6.81	9.65	6.15	5.97	−1.50	4.47	−1.13	3.3
Northwest China	14.00	14.70	12.04	1.49	−3.06	0.32	−0.66	−0.3
Northeast	16.21	17.90	11.82	4.05	−9.17	3.64	−8.22	−4.6
Total/mean	9.60	16.26	12.25	9.69	2.43	225.72	56.59	282.3

The data of topsoil organic carbon (SOC) content of non-irrigated soils are the area-weighted means calculated from the regional statistical data of SOC contents from the Soil Survey Database (SSSSC, 1997). For estimating the C density changes induced by irrigation-based agriculture, the area-weighted means of SOC, bulk density, and thickness of both plow layer and plowpan from Table 2 were used.

C sequestration by rice-based agriculture in China

There is a huge amount of estimated data on topsoil SOC storage of world soils at different stages of human disturbance. Batjes (1996) reported an average world SOC density of 106 $t\,C\,ha^{-1}$ for the upper 100 cm soil, which corresponds to a mean topsoil (0–30 cm) SOC density of about 50 $t\,C\,ha^{-1}$. Mineral soils in central Canada have topsoil (0–30 cm) SOC density ranging from 14 to 77 $t\,C\,ha^{-1}$ (Bhatti *et al.*, 2002a), while those from eastern European countries have a mean density of about 70 $t\,C\,ha^{-1}$ in the upper 0–30 cm (Batjes, 2002). The SOC stocks of most of the Brazilian topsoils (0–30 cm) under native vegetations were found in the range of 30–60 $t\,C\,ha^{-1}$(Bernoux *et al*, 2002). Arrouys & Balesdent. (2002) estimated a soil C density of 32 $t\,C\,ha^{-1}$ for vineyards and $<45\,t\,C\,ha^{-1}$ for other croplands in France. A typical SOC density of 25–30 $t\,C\,ha^{-1}$ was reported for upland crop soils under conventional tillage in Ohio, USA (Hao *et al.*, 2002). The SOC storage in China's paddy soil plow layers seems comparable to the SOC storage under forest vegetations in tropical regions and is higher than the SOC storage of the dry croplands of other regions of the world, although it is somewhat lower than the SOC storage in cold temperate regions.

Wu *et al*. (2003) reported a mean SOC density of 80 and 88 t C ha^{-1} in the upper 1 m soil, respectively, for China's current cultivated and uncultivated soils. Considering that the 0–30 cm topsoil contributes to 46% of the world (Batjes, 1996) and 44% to that of Central and Eastern Europe's total SOC pool, the SOC densities of 35 and 40 t C ha^{-1} seem to be reasonable estimates for China's current cultivated and uncultivated soils. Accordingly, the topsoil SOC density of paddy soils is 4 and 9 t C ha^{-1} higher than that of the uncultivated and cultivated soils, respectively. The increase of SOC storage in irrigated agriculture is, thus, the merit of paddy land use over upland cultivation. Li & Zhao (2001) found that the C density of paddy soils is similar to that of the land under bush and coppice forest in the tropical and subtropical regions of China while significant SOC loss was observed in upland crop soils in these regions. Wairiu & Lal (2003) reported a loss of half the SOC pool after the conversion of natural forest to traditional agricultural land use in the Solomon Islands.

The statistical data of SOC contents of different regions of China from the 2nd State Soil Survey (SSSSC, 1997) also allow for estimating the SOC storage enhancement induced by irrigation-based agriculture. The result of calculation is summarized in Table 5. It is estimated that the total enhanced topsoil SOC storage by China's paddy soils under irrigation amounts to 0.28 Pg, which is very close to the value of 0.27 Pg calculated by Wu *et al*. (2003) using the estimated baseline SOC density of 35 t C ha^{-1} under present cultivation. It is of great significance that the irrigation-based agriculture of China preserves this ~0.3 Pg SOC, while the SOC loss in other soils has been very extensive in the last decades (Lindert *et al*., 1996; Li, 2000; Wu *et al*., 2003). This enhanced SOC storage in paddy soils is equal to three times as much the total topsoil SOC pool of Jiangsu province (Pan *et al*., 2003a). However, the sequestered C is equal to only ~4% of the C loss due to cultivation of natural soils (Wu *et al*., 2003) or to the semiannual C emission in China in the 1990s (Marland & Boden, 1999).

C sequestration potential of paddy soils in China

The estimate of C sequestration potential of a region is usually conducted either by using long-term experiment data of SOC dynamics or by using SOC turnover models linked to the GIS database (Falloon *et al*., 2002). The turnover approach, recommended by the International Panel on Climate Change, has been used frequently in cases where long-term monitoring sites and SOC determinations were lacking (Eve *et al*., 2002a, b; Sperow *et al*., 2003). Smith *et al*. (1997) used five scenarios of long-term field experiment results to estimate C sequestration by European agricultural soils. However, Lal (2002b), using a compendium of literature documenting SOC dynamics under various land uses and soil management practices, gave an estimate of a total C sequestration potential of 11 Pg. Here we used the data available from the national soil monitoring sites of paddy soils along with some long-term pilot experiments to estimate both the C sequestration potential and the current sequestration rate of China paddy soils.

As it is observed that a decrease in soil thickness is often accompanied by a decrease in SOC (Lindert *et al*., 1996), the SOC sequestration of paddy soils can be realized either by the enhancement of the topsoil SOC sequestration or by deepening the plow layer. The rapid

Table 5 Change of SOC status in paddy soils from different geographical regions of China (data were taken from the State Extension Service of Agricultural Technology, 2003)

	Change of SOC level		
Region	Current mean	High level*	Very high level
East China	14.26	27.60 ± 3.00 (Jiangsu)	36.77–38.40 (2, Jiangsu)
		18.74 ± 5.63 (Fujian)	37.9 ± 4.4 (1, Fujian)
South China	16.86	19.26 ± 1.00 (Guangdong)	34.4–54.3 (1, Guangdong)
		21.44 ± 2.74 (Hunan)	
Southwest China	16.86	19.81 ± 5.61 (Guizhou)	36.6 (1, Guizhou)
		22.79 ± 3.17 (Sichuan)	48.78 (1, Yunnan)
North China	9.65	16.40 ± 1.19 (Xuzhou)	

SOC: topsoil organic carbon.
*Statistics of the monitoring sites sponsored, respectively, by the provincial and state governments (in each province, the number of sites >5).

decrease of SOC in north China and the SOC increase in south China in the last two to three decades (Lal, 2002b) indicate short turnover times for SOC change and the high potential of C sequestration. We noticed two general SOC levels in paddy soils: a considerably high SOC level usually observed in high-yielding paddy soils in various regions and a very high level observed in some pilot farms with delicate management practices (Table 5). The estimated topsoil SOC sequestration potential was 0.7 and 3.0 Pg (Table 6), respectively, for these two scenarios. Assuming a plow-layer depth of 20 cm and a mean SOC density of 2.5 t C ha^{-1} cm^{-1} (mean topsoil SOC density being 50 t C ha^{-1}) for all the paddy soils after sequestration managements, we arrive at a total topsoil SOC sequestration potential of 3.1 Pg. In the long run, a sequestration potential of 0.7 Pg can be easily realized but an ultimate potential of 3.1 Pg can be expected if well-designed management and conservation practices are implemented. The ultimate potential accounts for about 30% of China's total C sequestration of 11 Pg suggested by Lal (2002b). This means that 45% of the C loss from China's cultivated soils (Wu *et al*., 2003) can be offset. The easily reachable potential is mainly found in eastern China along with the Yangtze valleys where irrigation-based rice production is very extensive. A high ultimate sequestration potential can also be expected in south China and southwest China (Zhao *et al*, 1997).

By using the data compiled in Table 7, we can estimate the contemporary SOC sequestration rate in paddy soils in the recent years. The observed SOC sequestration rate of the plow layer ranged from 0.13 to 2.20, with a weighted mean of 0.40 t C ha^{-1} yr^{-1}. The observed C sequestration rate was high compared with the rate reported for the US rangeland soils (0.1–0.3 t C ha^{-1} yr^{-1} by Schuman *et al*., 2002) and with the rate for the observed cropland soils in the US (0.2–0.5 t C ha^{-1} yr^{-1}, Eve *et al*., 2002b).

Based on the fact that C in the plowpans increases as it does in plow layers, we estimated the total SOC density increase by taking into account the SOC pool increase due to the deepening of the plow layer and the SOC increase in plowpan layer. Thus, an estimated SOC sequestration rate of 12 Tg yr^{-1} for all paddy soils in China was obtained. This is one-third of the potential SOC sequestration rate by the total cropland of China (Lal, 2002b), while the area percentage of paddy soils is 24%. This rate is approximately 10% of the annual C loss of 140 Tg (using the estimated total loss of 7.1 Pg during the last 50 years by Wu *et al*., 2003) by China's cultivated lands.

Conclusion

Paddy soils, developed under rice-based agriculture with irrigation, play an important role in soil C storage. The estimated total SOC pool in China's paddy topsoils is 1.3 Pg, which is $\sim$2% of China's total storage in the topsoil (upper 1 m) and $\sim$4% of the total topsoil (the plow layer and the plowpan), while the area of the paddy soil is 3.4% of China's land. From this pool, 0.85 Pg is found in the plow layer, which is prone to agricultural practices, and 0.45 Pg is in the plowpan. The SOC density of the paddy topsoil is higher than the SOC density of the corresponding soils in dry cropland, although somewhat lower than the world mean. Irrigation has induced an enrichment of SOC stock in paddy soils at a level of 0.3 Pg, being equal to China's total CO_2 emission in half a year. The paddy soils in China have an easily reachable SOC sequestration

Table 6 Estimation of topsoil SOC sequestration potential by paddy soils in China using the two SOC scenarios from Table 5

Region	SOC of plow layer (g kg^{-1})		Increased SOC density (t C ha^{-1}) by			Total C sequestration (Tg)
	Present	Target	Plow layer	Plowpan	Plow depth to 20 cm	
Scenario 1: Commonly observed SOC level in high-yielding paddys						
East China	14.26	23.17	15.1	9.3	6.44	455.9
South China	16.86	20.36	6.2	4.9	1.93	87.3
Southwest China	16.86	21.78	10.1	9.2	1.04	131.9
Total/mean	15.48	22.18	11.8	5.8	4.1	675.1
Scenario 2: Highest SOC levels observed in a few very high-yielding paddys						
East China	14.26	37.33	39.1	21.9	16.7	1224.0
South China	16.86	44.35	48.8	40.4	15.1	864.7
Southwest China	16.86	42.69	53.2	41.3	5.4	879.0
Total/mean	15.48	40.25	44.7	30.8	13.7	2967.8

SOC: soil organic carbon.

Table 7 Estimated current C sequestration rate in plow layer as calculated using the observed SOC change from soil survey or regional soil monitoring system for paddy soils in China during the last decade

Region	Estimated rate ($t\,C\,ha^{-1}\,yr^{-1}$)	Location	Duration	Number of observations	Conditions
East China (Yangtze valleys)	0.37	Fujian Province	1982–1998	Provincial soil survey (538, 1998)	Conventional rice production
	0.45	Jinhua, Zhejiang	1985–2000	Two long-term pilot plots	With and without fertilization
	1.39	Zhejiang	1988–2002	Three monitoring sites	Conventional fertilization
	0.13	Northern Fujian	1979–2001	200 (2001)	Conventional
	0.19	Yixing County, Jiangsu	1982–1996	Means of county survey	Conventional
	0.28–0.41	Tai Hu region, Jiangsu	1987 ~ 2001	Four monitoring plots	Various fertilization treatments
	0.26	Taojiang County, Hunan	1988–1996	20 monitoring sites	Conventional
	1.12	Jiangyan County, Jiangsu	1984–1999	Means of county survey	Originally low in SOC, conventional
South China	0.22	Guangdong	1984–2001	54 of high-yielding farms	Conventional
	0.85	Xinyi County, Guangdong	1990–1999	Two monitoring sites	Low-yielding farms, conventional
	0.25	Hanshou County, Hunan	1990–2001	15 monitoring sites	Conventional
	1.84	Xinxing County, Guangdong	1988–2001	Two monitoring sites	Conventional
Southwest China	0.17	Guangxi	1982–2001	43 monitoring sites (2001)	Conventional
	0.21	Guizhou	1996–2001	Seven monitoring sites	Conventional
Northeast China	0.13	Heilongjiang	1998–2001	Four monitoring sites	Conventional
Northwest China	0.26	Ningxia	1982–1998	Means of soil survey	Yellow river water irrigated, conventional
North China	2.20	Sihong, Northern Jiangsu	1982–1990	12 (1982), 135 (1990)	State soil resilience project area, originally low in SOC
	1.10	Quwo County, Shanxi	1990–2001	Seven monitoring sites	Conventional, low in SOC

SOC: soil organic carbon.

potential of 0.7 Pg and may be expected to sequester as much as 3.1 Pg C from the atmosphere in the long run. The current C sequestration rate is in the range of 0.13–2.2 t C ha^{-1} yr^{-1}, contributing to an annual total SOC sequestration of 12 Tg. Both the total C pool and the C sequestration in paddy soils mainly occur in eastern, southern, and southwestern China. The paddy soils of Fe-leaching Stagnic Anthrosols or of Fe-accumulic Stagnic Anthrosols are the two predominant subgroups in storing and sequestering C in paddy soils. With an area of 26% of the total cropland, the current sequestration rate in paddy soils is about one-third of the estimated yearly sequestration rate of the total croplands. The total C sequestration potential in paddy soils, however, can reach 40% of the total cropland SOC sequestration potential of China. The current lower C sequestration rate, compared with its total potential, requires practices of sustainable agriculture for enhancing SOC storage to realize the ultimate SOC sequestration potential in China's paddy soils and to fulfill the requirements set by the Kyoto Protocol.

Acknowledgements

This study was partially supported by the China Natural Science Foundation (NSFC) under grant number 40231016. The first author is grateful to the University of California, Riverside, for offering him a visiting scholar program and the corresponding author wishes to thank the NSFC for a grant supporting the collaborative work in China.

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