

Estimating topsoil SOC sequestration in croplands of eastern China from 1980 to 2000

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Abstract. Cropland may play a significant role in mitigating climate change by sequestering atmospheric CO₂. To evaluate the extent of carbon sequestration, an examination of the changes in soil organic carbon (SOC) is essential. We compiled data from 50 published papers that reported changes in the SOC in eastern China over an area of 17.9 Mha. These data covered 76% of the total cropland in this area, with >8500 soil sample measurements. Changes in SOC density (ΔD_{oc}) in cultivated layers (Ap horizon) were estimated on the basis of the administrative regions and soil usage (paddy and upland soils), respectively. Linear relationships between ΔD_{oc} in topsoil (Ap and P horizons, P horizon refers to the sub-cultivated layer) and in the Ap horizon were established to estimate the changes in topsoil organic carbon density. Changes in the SOC stock were determined from the acreage-weighted ΔD_{oc} . Results indicated that the topsoil organic carbon density of croplands in eastern China increased by 5.78 t C/ha between 1980 and 2000, ranging from 4.24 to 7.49 t C/ha. The SOC stock increased by 75.4–134.1 Tg with an average of 103.5 Tg. Paddy soils, comprising 51.7% of the cropland area, accounted for ~70% of the total increase. The SOC increase in the Ap horizon accounted for ~88% (upland soils) and 71% (paddy soils) of that in the topsoil, respectively. The increase in SOC may be attributed to an increased biomass (e.g. residue retainment) input into soils due to increased crop net primary production.

Additional keywords: SOC change, upland soil, paddy soil, administrative regions, soil usage.

Introduction

Global atmospheric concentrations of CO₂, CH₄, and N₂O have increased markedly as a result of human activities since 1750, and now far exceed pre-industrial values determined from ice cores that were created over thousands of years. Annual fossil carbon dioxide emissions, for example, increased from an average of 23.5 (22.0–25.0) Pg CO₂ per year in the 1990s to 26.4 (25.3–27.5) Pg CO₂ per year in 2000–2005 (IPCC 2007). The conversion of natural ecosystems for agriculture has depleted soil organic carbon (SOC) by as much as 60% in soils of temperate regions and 75% or more in the cultivated soils of the tropics (Lal 2004). Agricultural soils are believed to have the potential to sequester atmospheric CO₂ (Lal 2004). Sustainable agricultural management has been considered a profitable option that can reduce atmospheric CO₂ over the next 20–30 years (Smith 2004).

Estimates in the IPCC Second Assessment Report suggested that 400–800 Tg C/year (equivalent to ~1400–2900 Tg CO₂/year) could be sequestered in global agricultural soils with a finite capacity saturating after 50–100 years (Smith *et al.* 2007). Lal (2004) suggested that carbon sequestration by the agrosystem has the potential to offset 5–15% of global fossil-fuel carbon emissions. Several studies have indicated that the net CO₂ exchange from agricultural soils in Canada was very close to equilibrium (Monreal and Janzen 1993;

Nyborg *et al.* 1995), while it is believed that most agricultural soils have the potential to help mitigate climate change by sequestering additional carbon, and hence decreasing CO₂ in the atmosphere (Janzen *et al.* 1998). Dumanski *et al.* (1998) estimated that implementation of appropriate management practices could result in the sequestration of ~50–75% of the total agricultural emissions of CO₂ in Canada over the next 30 years. Summarised in 4 scenarios for sustainable agricultural management, Niles *et al.* (2002) suggested that annual carbon sequestration rates could be 0.3–3.1 t/ha.year for arable lands and 0.1 t/ha.year for irrigated rice. Smith (2004) revealed the biological potential for carbon storage in European (EU15) cropland as 90–120 Tg C/year, with available options including reduced and zero tillage, set-aside, more efficient use of organic amendments, etc. By employing the IPCC inventory methods combined with land-use and cropping information, climate data, and tillage practices, Sperow *et al.* (2003) suggested that US cropland soils had the potential to increase sequestered soil C by an additional 60–70 Tg C/year over the present rate of 17 Tg C/year with widespread adoption of soil C sequestering management practices.

China has a large acreage of intensively cultivated soils, and its SOC dynamics and sequestration potential have been gaining international interest since the 1990s (e.g. Lal 2002, 2004;

Li *et al.* 2003a). In 2004, Peng *et al.* (2006) measured 627 samples taken from cropland soil types typical of red earths and showed that the SOC content increased by 22.6% over that in 1979. Yu *et al.* (2003) reported that, from 1980 to 2000, the SOC in 69 of 80 soil-sampling sites in Jiangsu Province increased. Measurements of 207 paddy soil samples taken from 10 counties in Jiangxi Province indicated that the SOC contents increased by 3.5 g/kg from 1981 to 1997 (Luo *et al.* 2004). Model simulations also suggested that Chinese rice paddies covering 22.6 Mha sequestered $\sim 0.15 \pm 0.07$ Pg C from 1980 to 2000 (Zhang *et al.* 2007). Wu *et al.* (2003) reported that $\sim 57\%$ of the cultivated soil subgroups have experienced a significant carbon loss, while the SOC has increased in paddy and irrigated soils especially in north-west China.

Based on the data collected in the Second National Soil Survey of China that was completed in the early 1980s, Song *et al.* (2005) estimated that the topsoil (~ 0.30 m) SOC density was 35 ± 32 and 50 ± 47 tC/ha in cultivated and uncultivated soils, respectively, suggesting that cultivation may have induced an average decrease in the SOC density of 15 tC/ha. By running the biogeochemical model DNDC with databases of climate and agricultural managements, Li *et al.* (2003a) estimated that China's croplands lost 1.6% of their SOC (to a depth of 0.3 m) in 1990, although regions of rice paddy dominance located in southern China might bear lower losses or even slight gains. However, Pan *et al.* (2003) reported that the SOC pool of irrigation-based rice cultivation had increased by 0.28 Pg compared with dryland cultivation, by pooling the datasets from the State Extension Service of Agricultural Technology. Huang and Sun (2006) analysed data extracted from 132 articles and pointed out that, as a whole, the SOC concentration increased in the topsoil of Chinese croplands. The SOC increased considerably in Inceptisols and Ustochrepts and decreased conspicuously in black soil. A significant C sequestration of 311.3–401.4 Tg was estimated for the top 0.20 m of soil in Chinese croplands during 1980–2000.

Although great efforts have been made towards investigating the SOC changes of the agricultural soils in China, notable uncertainties remain because attempts to estimate historical SOC loss have been complicated by high soil variability, a wide range of climate and field management practices, and a lack of adequate knowledge regarding all the factors involved (Neill and Davidson 2000). Further knowledge may therefore help to reduce the uncertainty of these estimates.

Eastern China, including the provinces of Jiangsu, Anhui, Zhejiang, Jiangxi, and Fujian, and Shanghai City, is located between latitudes $24^{\circ}29'N$ and $35^{\circ}02'N$ and longitudes $113^{\circ}34'E$ and $123^{\circ}10'E$. It covers 6.7% of the national total territorial area and contains 13.8% of the cropland of mainland China. The average annual precipitation is 902–1560 mm and the mean temperature is 16.4–20.5°C. Plentiful precipitation and higher temperatures occur in the southern portion of this region. The dominant soils are mainly Inceptisols, Ustochrepts, Aridisols, Alfisols, Udert, Udalf, and Ultisols in terms of the Soil Taxonomy of the USDA (Shi *et al.* 2006; Zhao *et al.* 2006). Double and triple cropping systems with rice and/or upland crops have been dominant. Crop yields in this region account for $\sim 20\%$ of the national total. According to the State Soil Survey

Service of China (SSSSC 1993), the acreage of paddy soils is 9.25 Mha, accounting for 51.7% for croplands in eastern China.

Over the last 2 decades, Chinese researchers have made several field surveys in eastern China, which offer a great opportunity to evaluate the changes in SOC as a function of time. In this paper, we compiled these SOC data extracted from field surveys. The main objective was to estimate the carbon sequestration of cropland soils in this area. A further objective will focus on identifying the role of cropland soils in mitigating greenhouse gases on regional and/or national scales.

Data sources

Data were collected from 50 published papers that reported SOC dynamics in the cultivated layers (Ap horizon) over time, by field surveys and long-term oriented observations in eastern China. These datasets accord with the criteria of: (1) the reference period is the Second National Soil Survey (SNSS) that was completed in the early 1980s; (2) the methods to measure SOC content and bulk density are the same as that used in the SNSS; and (3) with the same sampling sites or coverage as the SNSS. The datasets from the model plots for high-yield cultivation were not taken into account in this study.

The potassium dichromate volumetric method (ISSAS 1978; Lu 2000; Schulz 2002) was used to measure SOC content. Soil bulk density was determined as a ratio of oven-dried mass to field volume of soil sample (ISSAS 1978; Lu 2000). The soil sample was taken by driving a cylindrical metal sampler into the soil to a desired depth and carefully removing it to preserve the volume of the sample as it existed *in situ*, oven-drying at 110°C, and weighing to obtain soil bulk density.

For sites where the SOC concentrations were recorded as soil organic matter (SOM), a conversion factor of 0.58 (Post *et al.* 1998; Evrendilek *et al.* 2004) was used to convert into SOC. The constructed database also included the number of samples or the number of long-term oriented observation sites, the area of the field surveys or the long-term oriented observations covered, and soil orders (Appendix A).

Datasets in the 50 published papers (Appendix A) covered 76% of the total croplands in eastern China, with >8500 soil sample measurements, representing paddy soil (Inceptisols) and upland soils (Ustochrepts, Aridisols, Alfisols, Udert, Udalf, and Ultisols). Figure 1 shows the spatial distribution of national croplands and soil sampling sites in eastern China, where 1 dot represents 100 or 200 soil sample measurements.

Intervals between the initial and final field measurements were 9–22 years in these field surveys (Appendix A). The intervals of 9–10 years, 11–15 years, 16–20 years, and 21–22 years accounted for 3.6%, 37.4%, 55.4%, and 3.6%, respectively, of the total measurements reported.

Methods

Batjes (1996) reported that globally the 0–0.30 m topsoil contributed to $\sim 46\%$ of the total SOC pool. Although some changes in the SOC may occur below 0.30 m, the vast majority of the changes occur here (Smith *et al.* 2000). Calculations with the data in the China Soil Series (SSSSC 1993) indicated that the average thickness of the cultivated layer (Ap horizon) of the croplands was 14.8 ± 2.5 cm ($n=209$) and the sub-cultivated

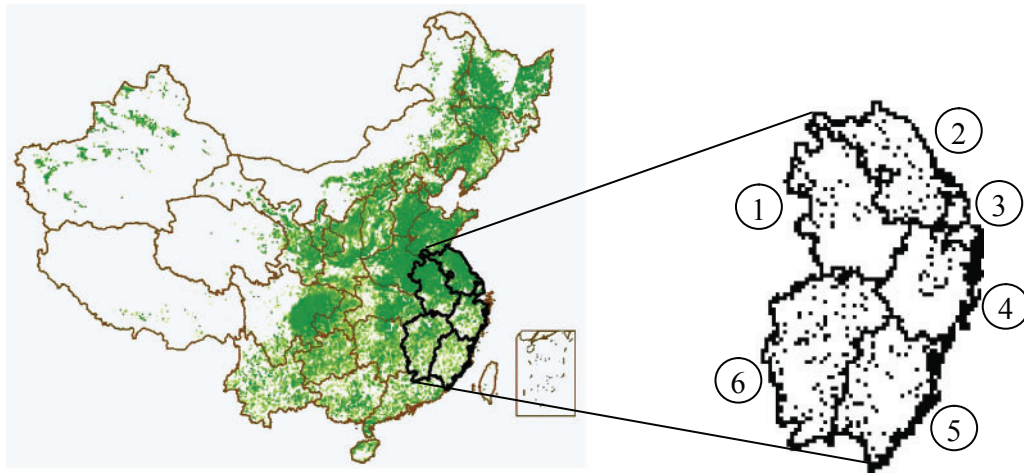


Fig. 1. Spatial distribution of national croplands and soil sampling in eastern China. The map at the left side shows the distribution of the national cropland (green-level filled), where the geographical location of eastern China is marked by the dark lines. Black dots in the map on the right side refer to soil sampling sites where 1 dot represents 100 or 200 soil sample measurements. The number in open circles refers to Anhui, Jiangsu, Shanghai, Zhejiang, Fujian, and Jiangxi Province/City, respectively, in the order 1–6.

layer (P horizon) extended a further 10.3 ± 4.9 cm ($n=209$) in eastern China. To capture the majority of the SOC changes, it was hypothesised that the changes in the SOC pool occurred mainly in the topsoil (Ap and P horizons). The Ap and P horizons for paddy soils refer to the plough layer and ploughpan (Pan *et al.* 2003), respectively.

Because the datasets from these published papers (Appendix A) were specified for the Ap horizon, the changes in SOC density in the topsoil were determined from a relationship between the changes that occurred in the topsoil and in the Ap horizon.

Calculations of changes in SOC density (ΔD_{oc})

The SOC density (D_{oc} , tC/ha) was calculated as (Pan *et al.* 2003):

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

where SOC and γ are the content of organic C (g/kg) and soil bulk density (g/cm^3), respectively. A negative exponential relationship of $\gamma = 1.377 \times e^{-0.0048 \times \text{SOC}}$ (Song *et al.* 2005) was used to estimate the values of γ when they were not reported in the literature (Appendix A). The $\delta_{2\text{mm}}$ is the fractional percentage (%) of >2 mm sands and has an average value of 6 in eastern China according to SSSSC (1993). H is the thickness (cm).

Changes in SOC density (ΔD_{oc}) over a 20-year period were determined by:

$$\Delta D_{oc} = 20 \times \left(\frac{D_{oc-F} - D_{oc-R}}{t} \right) \quad (2)$$

where D_{oc-F} and D_{oc-R} are the SOC density in the final and the reference year, respectively; t is the time interval between the final and the reference year.

Datasets from papers (Appendix B) that reported SOC values in the upland soil profiles were used to calculate changes of SOC density in the Ap and P horizons by using Eqns 1 and 2. These papers provided temporal data with long-term field experiments under various treatments including synthetic fertiliser application, manure and crop residue incorporation, and tillage (Appendix B).

Because very few papers could be found that recorded the changes in SOC in both the Ap and P horizons, particularly in paddy soils, we calculated the changes in SOC density with the ‘space-for-time substitution’ method in order to determine the relationship between the changes that occurred in the topsoil and in the Ap horizon. In the use of ‘space-for-time substitution’ (e.g. Pickett 1989; Sparling *et al.* 2003; Zaitsev *et al.* 2006), soils of different types and stages of development at separate locations (‘space’) are identified to obtain a chronosequence of ages (‘time’). Thus, changes in the SOC density (ΔD_{oc}) were calculated by:

$$\Delta D_{oc} = D_{oc} - \overline{D_{oc}} \quad (3)$$

where D_{oc} refers to the SOC density in either the Ap or the P horizon, and $\overline{D_{oc}}$ is the average value of D_{oc} for total recorded spatial patches in eastern China. The $\overline{D_{oc}}$ was calculated for paddy soils and upland soils, respectively. By using Eqn 1, D_{oc} was computed from the spatial data in the China Soil Series (SSSSC 1993), which recorded detailed information on the SOC content, bulk density, and thickness of the Ap and P horizons taken at different sites in eastern China.

Quantification of relationship between ΔD_{oc} in topsoil and in the Ap horizon

Assuming that the changes in topsoil SOC density (ΔD_{oc-T}) are proportional to that in the Ap horizon (ΔD_{oc-A}), linear regression

was used to estimate the relationship between ΔD_{oc_T} and ΔD_{oc_A} (Fig. 2).

The open circles ($n=42$) and the solid circles ($n=128$) in Fig. 2a were calculated from the spatial serial data (SSSSC 1993), respectively using Eqns 1 and 3 and from the temporal serial data (Appendix B) using Eqns 1 and 2. The slope of the regression in Fig. 2a suggests that the change in the SOC density in the topsoil was ~1.14 times that of the Ap horizon. Figure 2a also implies that the ΔD_{oc} computed by 'space-for-time substitution' method [Eqn 3] is acceptable.

Figure 2b presents the relationship between the changes in the SOC density in the topsoil and in the Ap horizon for paddy soils when the ΔD_{oc} was determined from the spatial data (SSSSC 1993) by Eqns 1 and 3. Note that the value of the slope in Fig. 2b is greater than in Fig. 2a, suggesting that the P horizon of the rice paddy contributed more than that of the upland soils to carbon sequestration in topsoil.

Estimation of the changes in SOC stock

By employing Eqns 1 and 2, the changes in the SOC density the Ap horizon (ΔD_{oc_A}) were calculated for each administrative region in Appendix A. Regional means of ΔD_{oc_A} on a provincial scale were estimated by weighting the area covered by the sampling in the given province (Appendix A). Calculations for the data in the China Soil Series (SSSSC 1993) suggested that the average thickness of the Ap horizon was 15.8 ± 2.6 (mean \pm s.d.) for upland soils ($n=44$) and 14.6 ± 2.3 cm ($n=165$) for paddy soils in eastern China. Because wide variations in the thickness existed, the lower and upper estimates of ΔD_{oc_A} were computed under the scenarios of $H - s.d.$ and $H + s.d.$ [Eqn 1], respectively.

Analogous to the estimates of the changes in the SOC stocks that were observed on the basis of the administrative region, the means of ΔD_{oc_A} were estimated on the basis of soil order when they were specified (Appendix A). Due to a lack of sufficient data for Ustochrepts, Ultisols, Aridisols, and Udalf (Appendix A), we simply merged these soils into the upland soil in order to calculate the area-weighted mean ΔD_{oc_A} .

The changes in the SOC stock (ΔP_{oc}) were estimated by:

$$\Delta P_{oc} = \sum_i S_i \times \overline{\Delta D_{oc_i}} \quad (4)$$

where $\overline{\Delta D_{oc_i}}$ is the area-weighted mean ΔD_{oc_i} in a given sector i ; S_i is the area of the given sector; ΔD_{oc_i} in the topsoil was computed by using the relationship in Fig. 2.

To get the level of confidence in the values obtained for ΔP_{oc} , ΔD_{oc} was calculated in light of 2 bases, i.e. the administrative regions and soil usage (paddy and upland soils in terms of soil order). S_i was accordingly expressed as the area covered by the sampling in the given province and the area of the given soil order, respectively.

Results

Changes in the SOC contents in the Ap horizon

Of the 56 records (Appendix A), ~86% showed an increase, while only 14% described a decrease in the SOC contents in the Ap horizon. The average and standard deviation of the SOC increase was 2.48 ± 0.41 g/kg. Approximately 71% of this increase occurred in the range 1–5 g/kg and nearly half was 1–3 g/kg over the 2 decades (Fig. 3).

Changes in SOC stocks in the Ap horizon

Changes in SOC stocks on the basis of the administrative region

The computations indicated that the SOC density increased significantly in the provinces of Jiangsu, Jiangxi, and Anhui, with a weaker increase having occurred in the provinces of Fujian and Zhejiang. The area-weighted mean ΔD_{oc} ranged from 3.79 to 5.30 t/ha (Table 1).

The area covered by the sampling region, excluding the overlapped areas (Appendix A), was 13.66 Mha, accounting for ~76% of the total cropland in eastern China (Table 1). Assuming that the estimated ΔD_{oc} of the published data (Appendix A) were representative of the region, we calculated the changes in the SOC stock for each

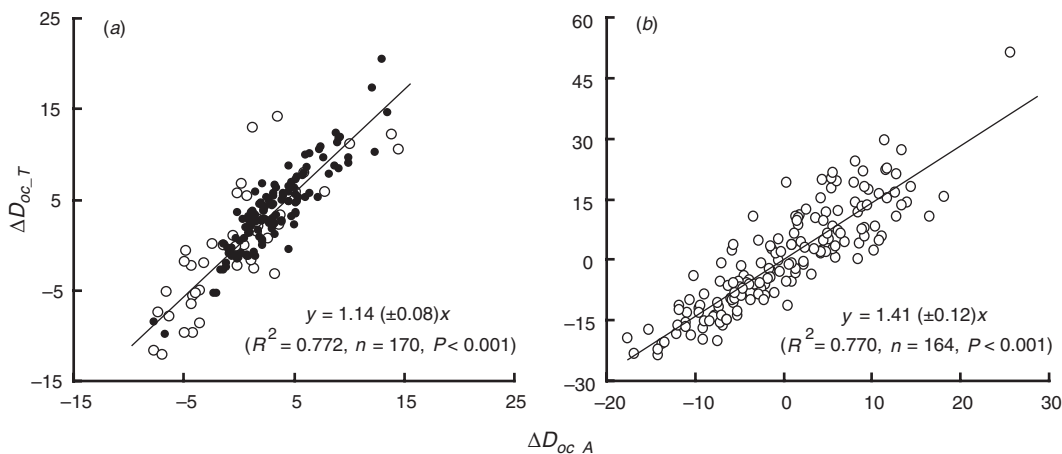


Fig. 2. Relationship between changes in carbon density in the topsoil (ΔD_{oc_T} , t/ha) and in the Ap horizon (ΔD_{oc_A} , t/ha) for (a) upland soils and (b) paddy soils. Solid circles are datasets derived from field experiments in Appendix B. Open circles are datasets derived from SSSSC (1993).

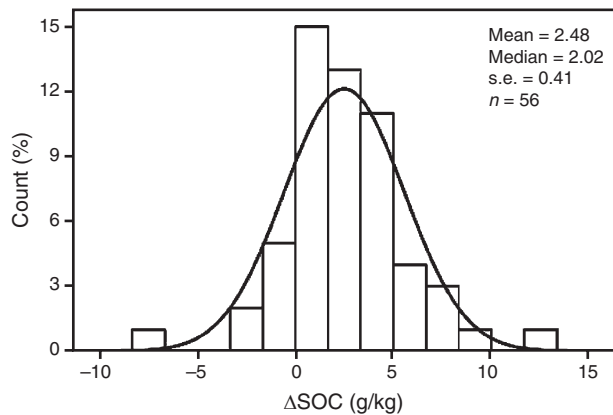


Fig. 3. Frequency distribution of the SOC change in eastern China. The ΔSOC was the difference between initial and final measurements of each record in Appendix A.

Table 1. Changes in the SOC in the Ap horizon on the basis of administrative regions

Province/city	Area (10^4 ha)		ΔD_{oc} (t/ha)	ΔP_{oc} (Tg)
	Total	Sampling area		
Shanghai	31.5	31.5	2.66–3.72	0.8–1.2
Anhui	597.2	262.8	2.73–3.81	16.3–22.8
Jiangsu	506.2	506.2	5.53–7.74	28.0–39.2
Zhejiang	212.5	122.6	1.33–1.87	2.8–4.0
Fujian	143.5	143.5	0.58–0.81	0.8–1.2
Jiangxi	299.3	299.3	6.39–8.93	19.1–26.7
Total/Mean	1790.2	1365.9	3.79–5.30	67.9–95.0

administrative region [Eqn 4] by extrapolating the area-weighted mean ΔD_{oc} (Table 1) to the corresponding region. The calculations suggested that the SOC stock increased by 67.9–95.0 Tg, with an average value of 81.4 Tg over the 2 decades (Table 1).

Changes in SOC stocks on the basis of soil usage

The areas of paddy soils and upland soils specified by the sampling region (Appendix A) were 447.5×10^4 ha and 221.0×10^4 ha, accounting for ~48% and 26% of the total paddy soils and upland soils in eastern China, respectively (Table 2). The area-weighted mean ΔD_{oc} was estimated to be 4.40–6.15 t/ha for paddy soils and 2.50–3.49 t/ha for upland soils (Table 2). Accordingly, the SOC stock increased by 40.7–56.9 Tg in the paddy soils and 21.6–30.2 Tg in the

Table 2. Changes in the SOC in the Ap horizon on the basis of soil usage

Soil type	Area (10^4 ha)		ΔD_{oc} (t/ha)	ΔP_{oc} (Tg)
	Total	Sampling area		
Paddy soils	924.9	447.5	4.40–6.15	40.7–56.9
Upland soils	865.3	221.0	2.50–3.49	21.6–30.2
Total/Mean	1790.2	668.5	3.48–4.87	62.3–87.1

upland soils when extrapolating ΔD_{oc} to the area of the corresponding soil usage in eastern China. A total increase in the SOC stock in the Ap horizon was estimated to range from 62.3 to 87.1 Tg with an average of 74.7 Tg on the basis of soil usage (Table 2).

Changes in topsoil organic carbon stocks

The slopes of the linear relationships shown in Fig. 2a and b were adopted as conversion factors to estimate the changes in SOC density in the topsoil via ΔD_{oc} in the Ap horizon (Tables 1 and 2). Statistical analysis indicated that the respective values of the slopes at the lower and upper 95% confidence bands were 1.06 and 1.22 for upland soils (Fig. 2a), 1.29 and 1.53 for paddy soils (Fig. 2b), and 1.26 and 1.41 for all soils ($n = 334$, data not shown).

The estimation of ΔD_{oc-T} was made under 4 scenarios: the lower estimates of ΔD_{oc-A} (Tables 1 and 2) with the lower slope value, the lower estimates of ΔD_{oc-A} with the upper slope value, the upper estimates of ΔD_{oc-A} with the lower slope value, and the upper estimates of ΔD_{oc-A} with the upper slope value. The mean and standard deviation in ΔD_{oc-T} in the topsoil were determined from these 4 scenarios.

The SOC density in the topsoil was estimated to increase by 6.07 tC/ha with a range of 4.77–7.49 tC/ha. The SOC stock increased accordingly by 108.7 Tg, with a range of 85.4–134.1 Tg, when it was calculated on the basis of the administrative region.

When calculated on the basis of soil usage, SOC density was estimated to increase by 3.41 tC/ha, with a range of 2.64–4.26 tC/ha for upland soils, and by 7.44 tC/ha with a range of 5.68–9.40 tC/ha for paddy soils. The area-weighted mean SOC density was estimated to increase by 5.49 tC/ha with a range of 4.21–6.92 tC/ha for both upland soils and paddy soils. Accordingly, the SOC stock was estimated to increase by 29.5 Tg with a range of 22.9–36.9 Tg for upland soils, and by 68.8 Tg with a range of 52.5–87.0 Tg for paddy soils. The whole of the increase in the topsoil organic carbon stock was 98.3 Tg with a range of 75.4–123.8 Tg. Paddy soils with 51.7% of the total croplands accounted for ~70% of the total increase.

In light of the results obtained on the basis of the administrative region and the soil usage, we suggest that the SOC density in the topsoil increased by 5.78 tC/ha, ranging from 4.24 to 7.49 tC/ha, and that the SOC storage increased by 75.4–134.1 Tg with an average of 103.5 Tg in eastern China between 1980 and 2000. The SOC increase in the Ap horizon accounted for ~88% (upland soils) and 71% (paddy soils) of that in the topsoil.

Discussion

Agricultural practice and SOC change

Management practices that lead to the depletion of the SOC stock in croplands are the cultivation of upland soils, residue removal, negative nutrient balance, and soil degradation by accelerated soil erosion. Agricultural practices that enhance the SOC stock include the conversion of the uplands to rice paddies, large quantities of residue retainment, integrated nutrient management based on the liberal use of biosolids and compost, and conservation-effective systems (Lal 2002).

The application of fertiliser to crops may improve SOC (Campbell *et al.* 2001; Hutchinson *et al.* 2007; Shen *et al.* 2007). Consumption of synthetic fertiliser in eastern China increased markedly from 3.30 Tg in 1980 to 9.28 Tg in 2000. Accordingly, the crop yield increased from 75.4 to 94.4 Tg (Statistics Bureau of China 2000). The increase in the SOC may be primarily attributed to the consumption of synthetic fertiliser in eastern China. Increasing fertiliser application results in an improvement of crop production, and hence residue (above-ground biomass with the exception of grain yields) retention. Recent investigations (Huang *et al.* 2007) indicated that the crop net primary production (NPP) in eastern China increased from 71 ± 21 Tg C/year in 1980 to 112 ± 35 Tg C/year in 1999, and the accumulative NPP was 1.56–2.41 Pg C over the 2 decades. Assuming that the ratio of the residue to the grain yield was 1.5, the ratio of the root to shoot was 0.1 (Huang *et al.* 2007), and that 40% of the above-ground crop residues were retained in the soil (Gao *et al.* 2002), a total input of residue carbon into the soils is estimated to be ~480–750 Tg C over the 2 decades. The present estimate of a 75.4–134.1 Tg increase in the SOC accounts for 16–18% of the crop residue-carbon retention, which is in accordance with the results of Huang *et al.* (2007).

It must be noted that manure amendment should also greatly contribute to the SOC in addition to crop residue retention. According to Li *et al.* (2003a), the amount of manure carbon incorporation into the croplands in China is ~45% higher than the residue carbon inputs. Manure comes partly from crop residues, and Gao *et al.* (2002) reported that 22.6% of harvested crop residue was used as animal fodder in China. While estimating the soil C retained, it is not possible from this study, nor is it the intention, to quantify the contribution of residue and manure input to carbon sequestration, because losses of carbon from decomposition offset some of the gain from residue and manure conversion to soil C. Moreover, the carbon loss from decomposition is complex (Chapin *et al.* 2002), and no simple approach could be applied to estimate the carbon losses from eastern Chinese croplands, which are distributed across a large area with various soils and cropping systems. Nevertheless, the quantification of residue and manure conversion to soil C would be helpful in understanding the contribution of crop NPP to SOC (Huang *et al.* 2007; Purakayastha *et al.* 2008).

Increase in cropping frequency and specific type of crops in rotation has potential benefit to increasing SOC gains (West and Post 2002; Hutchinson *et al.* 2007). Triple cropping systems with rice–rice–upland crop (e.g. wheat, rapeseed, barley, alfalfa) rotation in a 1-year circle are dominant in Zhejiang, Jiangxi, and Fujian Provinces, while double cropping systems with rice–upland crop rotation or 2 harvests of upland crops (e.g. wheat–maize, wheat–soybean) per year are prevalent in Jiangsu and Anhui Provinces (Li *et al.* 2008). According to the datasets from Huang *et al.* (2007), the crop NPP averaged 7.6 t C/year from 1980 to 1999 in Zhejiang, Jiangxi, and Fujian Province and 6.2 t C/year in Jiangsu and Anhui Province, suggesting the triple cropping system may input more residue carbon into the soils than the double cropping system. Table 1 shows that the increase in SOC density in Jiangxi Province is more significant than that in Zhejiang and Fujian Provinces, which could be due to the different rates of

residue retention. According to Gao *et al.* (2002), the rates of residue retention were 65% in Jiangxi Province, and 24% and 36% in Zhejiang and Fujian Province, respectively. As for the double cropping system, the crop NPP averaged 6.9 t C/year in Jiangsu Province and 5.6 t C/year in Anhui Province from 1980 to 1999 (Huang *et al.* 2007), which may partly explain why the increase in SOC density in Jiangsu Province is greater than that in Anhui Province, although the rates of residue retention were similar in the 2 provinces (Gao *et al.* 2002).

Based on the analysis of field survey datasets (Fig. 1), our results suggested an overall increase in SOC (Tables 1 and 2), while Li *et al.* (2003a) estimated a loss of SOC in Chinese croplands by running their DNDC model. Our results (Tables 1 and 2) could be supported by more recent work conducted by Lu *et al.* (2009), who reported a carbon sequestration rate of 16.5 Tg C/year in Chinese croplands. The DNDC model gave the crop productivity of 561–657 Tg C/year (Li *et al.* 2003a), in accordance with the result of Fang *et al.* (2007), while the residue/grain ratio (0.96) and the root/shoot ratio (0.06) derived from the modelled components of crop productivity (Li *et al.* 2003a) are much lower than those from other reports. Based on the harvest data of crops from 300 agro-meteorology stations in China, Zhang and Zhu (1990) gave the residue/grain ratio as 1.32 for rice ($n = 718$), 1.72 for wheat ($n = 605$), 1.56 for barley ($n = 26$), 1.27 for maize ($n = 387$), 1.30 for soybean ($n = 92$), and 2.99 for rapeseed ($n = 174$). According to Huang *et al.* (2007), the root/shoot ratio is 0.10 for rice, 0.11 for wheat, 0.09 for maize, 0.08 for bean, and 0.06 for rapeseed. The inappropriate residue/grain ratio and root/shoot ratio in the DNDC model may underestimate the residue carbon input into the soils, and thus resulted in an estimate of SOC loss in Chinese croplands.

Agricultural soils with low to intermediate organic matter levels often exhibit a linear relationship between carbon input and soil carbon levels (e.g. Larson *et al.* 1972; Rasmussen *et al.* 1980; Paustian *et al.* 1992; Havlin and Kissel 1997), such that soil carbon levels increase in direct proportion to increases in the residue incorporation (Paustian *et al.* 1998, 2000). Even if the SOC was at a relatively higher level, carbon sequestration was assured when agricultural practices were improved (VandenBygaart *et al.* 2004). In China, 31.5% of rice paddies and 69.4% of upland soils have lower organic carbon. Topsoil organic carbon in these soils was lower than 8.5 g/kg in the early 1980s (Lin 1998), which suggested that the increase in the SOC in eastern China most probably occurred over the past 2 decades and a great capacity to sequester carbon exists under sound agricultural management.

Uncertainties

Precise estimation of the changes in the SOC stock relies on the thickness ascertained for the given soil horizons when the SOC concentration is determined. Due to the lack of detailed information on the spatial distributions of the thicknesses of the Ap horizon, we simply took the scenarios of H (average thickness) – s.d. and $H + s.d.$ to obtain the lower and upper estimates of ΔD_{oc} [Eqns 1 and 2] in the Ap horizon. Such a simplification might induce uncertainties in the estimates.

The great majority of changes in SOC were thought to appear in the top 0.30 m, while some changes did occur below 0.30 m.

A long-term experiment conducted in India by Rudrappa *et al.* (2006) indicated that the SOC concentrations under an integrated use of farm-yard manure with synthetic fertilisers increased by 52%, 34%, and 11% in the soil depths 0–0.15, 0.15–0.30, and 0.30–0.45 m, respectively, in contrast to those that used solely synthetic fertilizers. Zinn *et al.* (2005) reported that an intensive land use system with annual tillage in Brazil caused a significant SOC loss of 10.3% in the upper 0–0.20 m of soil depth, but a statistically insignificant change over the top 0.40 m. Several studies (Zhou *et al.* 1993; Shi *et al.* 2002; Gu *et al.* 2004; Xie *et al.* 2004; Olson *et al.* 2005) have suggested that the SOC changes due to intensive cultivation might reach to more than 1.00 m deep, especially in the upland soils. The thickness of the topsoil (Ap and P horizons) in eastern China was determined to be 30.1 ± 7.7 cm ($n = 44$) for upland soils and 23.7 ± 4.1 cm ($n = 168$) for paddy soils, but until now we know little about the changes in the SOC below these depths.

Eastern China has developed much faster than China's other regions. Changes in soil usage have occurred over the last 2 decades. For example, the rice planted area in Jiangsu Province was 38.6%, 39.1%, and 41.5% of the grain crops in 1985, 1990, and 2000, respectively (Statistics Bureau of Jiangsu 2000). The soil usage might induce uncertainties in the estimates of SOC. Unfortunately, detailed information on soil usage change in eastern China is not available, which presents difficulty in quantifying the uncertainties.

Conclusions

Topsoil organic carbon of croplands in eastern China increased from 1980 to 2000. The SOC density in the topsoil increased by 5.78 t C/ha, ranging from 4.24 to 7.49 t C/ha. The SOC storage increase was then estimated to be 103.5 Tg with a range of 75.4–134.1 Tg during this period. The increase in SOC may be attributed to an increased biomass (e.g. residue retention) input into soils due to increased crop net primary production. Approximately 88% (upland soils) and 71% (paddy soils) of the increase occurred in the Ap horizon. Paddy soils with 51.7% of the total croplands in this region accounted for ~70% of the total increase in SOC, implying the great importance of paddy soils in mitigating atmospheric CO₂.

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Appendix A. Summary of the changes in cropland soil organic carbon (SOC) concentrations in eastern China

Values in parenthesis represent the numbers of monitoring sites, counties, or soil species

Province/ city	Locality	No. of samples or sites	Area (10 ⁴ ha)	Soil order in Soil Taxonomy	Initial			Final			References
					Year	SOC (g/kg)	Bulk density (g/cm ³)	Year	SOC (g/kg)	Bulk density (g/cm ³)	
Shanghai	City	152 (6)	31.50	Inceptisols	1982	14.2	1.29	2000	16.0	1.28	Mao (2001)
	Baoshan District	73 (12)	1.52		1980	11.7	1.30	1995	12.8	1.30	Jin and Bo (1998)
Jiangsu	Province	80	506.17	Inceptisols	1980	13.0	1.29	2000	16.8	1.27	Yu <i>et al.</i> (2003)
	Province				1985	9.5	1.32	1996	11.8	1.30	Liu and Wang (1998)
	Wuxi City	(4)	17.54	Inceptisols	1982	12.7	1.30	1996	15.1	1.28	Li <i>et al.</i> (2003b)
	Danyang City	79 (4)	5.58	Inceptisols	1983	10.9	1.31	1999	13.1	1.29	Xie <i>et al.</i> (2002)
	Yixing City	83	6.58	Inceptisols	1982	–	–	1999	0.34 ^A		Gao <i>et al.</i> (2001)
	Jintan City	40	4.63	Inceptisols	1984	–	–	2000	0.24 ^A		Zhang <i>et al.</i> (2004b)
	Nantong City	204	48.32	Inceptisols; Ustochrepts; Aridisols	1982	7.9	1.33	1997	9.2	1.32	Huang and Gu (1999)
	Nantong City				1982	7.95	1.33	2002	9.63	1.31	Wang <i>et al.</i> (2005)
	Jiangyin City		5.18		1981	13.3	1.29	1996	15.9	1.28	Liu <i>et al.</i> (1999)
	Rudong City	1239	11.03		1982	8.2	1.32	1997	9.4	1.32	Yao <i>et al.</i> (2001)
	Xincao Farm	181		Aridisols	1980	7.0	1.33	2000	7.3	1.33	Zhou <i>et al.</i> (2002)
	Huaihai Farm		0.50	Aridisols	1980	6.5	1.33	1997	9.2	1.32	Zhang (1998)
	Ganlu Township		0.13	Inceptisols	1981	15.5	1.28	2000	17.3	1.27	Chen <i>et al.</i> (2002)
	Zhejiang	Kunshan City	133	4.70		1981	17.2	1.27	1997	18.2	1.26
Qidong City			7.05	Ustochrepts; Aridisols	1980	9.2	1.32	1996	8.4	1.32	Zhu <i>et al.</i> (1998)
Haian County		590	5.45	Ustochrepts	1982	6.8	1.33	2001	10.0	1.31	Chen <i>et al.</i> (2005)
		361		Inceptisols	1982	10.7	1.31	2001	14.7	1.28	
Jiaxing Plain		729			1982	17.3	1.27	1995	18.8	1.26	Wang and Huang (1999)
Xiaoshan City		234	5.57	Inceptisols	1982	19.7	1.25	1995	21.2	1.24	He <i>et al.</i> (1997)
Cangnan, Chengzhou, Jinhua City		90	23.75	Inceptisols	1982	18.5	1.26	2002	18.8	1.26	Xie (2003)
Jinhua City		270	18.00	Inceptisols	1981	13.9	1.29	1999	14.6	1.28	Xu and Wu (2002)
Jinhua City					1980	14.6	1.28	1999	14.3	1.29	Jin and Hong (2001)
Haiyan County			2.38		1981	15.9	1.28	2000	20.5	1.25	Jiang <i>et al.</i> (2003)
Leqing City			11.79	Inceptisols	1982	26.3	1.21	1997	30.5	1.19	Zhao <i>et al.</i> (2000)
Cixi City		(6)	2.72	Ustochrepts; Inceptisols	1981	6.7	1.33	2002	7.9	1.33	Zhang <i>et al.</i> (2004a)
Shaoxing City		50	16.75	Inceptisols	1983	20.9	1.25	2002	20.5	1.25	Zhou <i>et al.</i> (2004)
Ningbo City		159	21.64	Inceptisols	1983	24.0	1.23	2000	24.9	1.22	Zhang (2002)
Anhui	Deqing County	141	2.00	Inceptisols	1984	18.2	1.26	2003	19.8	1.25	Li (2005)
	Hanshan County	(3)	4.80	Inceptisols Alfisols	1984	14.3	1.29	1998	18.9	1.26	Wang <i>et al.</i> (2001)
					1984	9.6	1.31	1998	8.2	1.32	
	Lingbi County	(3)	12.07	Inceptisols	1984	6.6	1.33	2002	8.2	1.32	Zhang and Zhang (2004)
				Ustochrepts	1984	8.9	1.32	2002	8.5	1.32	
				Udert	1984	5.4	1.34	2002	7.3	1.33	
	Shouxian County	192 (4)	11.70	Inceptisols	1984	7.4	1.33	2002	11.1	1.31	Hu <i>et al.</i> (2004)
	Liuan City	66 (12)	46.60	Inceptisols	1984	10.6	1.31	1998	11.6	1.30	Duan (2004)
				Udalf	1984	6.0	1.34	1998	8.0	1.33	
	Qimen County	(3)	1.33	Inceptisols	1984	17.0	1.27	1999	15.4	1.28	Chen and Gao (2001)
	Guichi District	(5)	2.96	Inceptisols	1984	11.6	1.30	1999	20.6	1.25	He <i>et al.</i> (2002)
				Ustochrepts	1984	14.2	1.29	1999	8.1	1.32	
	Changfeng County		9.00	Ustochrepts	1981	8.2	1.32	2003	9.3	1.32	Dai <i>et al.</i> (2004)
	Fuyang City	291	133.30	Ustochrepts	1984	7.1	1.33	1994	7.8	1.33	Zheng <i>et al.</i> (1996)
Chuzhou City		40.70		1982	8.5	1.32	1997	10.3	1.31	Liu <i>et al.</i> (2002)	
Qianmiao Township		0.35	Ustochrepts; Inceptisols; Udalf	1982	7.0	1.33	1998	8.4	1.32	Zhang <i>et al.</i> (2000)	
Juchao District	200		Ustochrepts	1985	9.4	1.32	2000	8.5	1.32	Yin <i>et al.</i> (2002)	

continued

Appendix A. (continued)

Province/ city	Locality	No. of samples or sites	Area (10 ⁴ ha)	Soil order in Soil Taxonomy	Initial		Year	Final		References	
					Year	SOC (g/kg)		Bulk density (g/cm ³)	Year		SOC (g/kg)
Fujian	Province	517	143.47				1984			Zhou and Chen (2000)	
	Longyan City	420 (4)	13.03	Inceptisols	1984	17.4	1.27	1998	21.1	1.24	Huang and Guo (2002)
	Fuan City	1221	2.35	Inceptisols	1984			1993	0.45 ^A		Zhang (1994)
	Guangze County		1.23	Inceptisols	1984	17.7	1.26	2000	18.9	1.26	Qiu (2004)
	Jiayang City		2.85		1984			1998	0.05 ^A		Yan (2000)
	Ansha Township	50		Inceptisols	1982	17.4	1.27	2001	20.8	1.25	Zhou <i>et al.</i> (2003)
Jiangsxi	Province	207	299.34	Inceptisols	1981	14.4	1.28	1997	18.0	1.26	Luo <i>et al.</i> (2004)
	Nanchang County etc.	142 (9)	13.90	Inceptisols	1981	13.7	1.29	1997	18.4	1.26	Ye <i>et al.</i> (2000)
	Nanchang County	60	7.21	Inceptisols; Ultisols	1981	13.1	1.29	1997	18.9	1.26	Ye <i>et al.</i> (1999)
	Xingguo County		3.12	Inceptisols; Ultisols	1981	11.5	1.30	1997	17.7	1.27	Ye and Liu (2000)

^ASOC change per year.

Appendix B. Summary of field experiments focusing on changes in nutrients in the soil profile under various agricultural practices

Country	Location	Soil type	Crop rotation	Years of experiment	Treatment	<i>n</i>	References
China	116.14°E, 40.13°N	Ustochrepts, Alfisols	Wheat–corn	10	Synthetic fertiliser, manure, crop residue incorporation	56	Song <i>et al.</i> (2002)
China	108.67°E, 34.30°N	Alfisols	Wheat–corn	12	Synthetic fertiliser, manure, crop residue incorporation	6	Gu <i>et al.</i> (2004)
China	111.17°E, 39.38°N	Alfisols	Cereal–potato	13	Synthetic fertiliser, manure	40	Wang <i>et al.</i> (2003)
China	108.09°E, 35.04°N	Alfisols	Wheat–maize	23	Synthetic fertiliser, manure, crop residue incorporation	6	Xie <i>et al.</i> (2004)
China	115.12°E, 37.54°N	Ustochrepts	Wheat–corn	16	Synthetic fertiliser, manure	3	Shi <i>et al.</i> (2002)
China	116.26°E, 28.37°N	Ultisols	Double corn–fallow	10	Synthetic fertiliser, manure	3	Shi <i>et al.</i> (2002)
Brazil	24.6°S, 50.4°W, 25.3°S, 50.3°W	Dark red latosol	Soybean, oat, corn, wheat, lupin, <i>Lolium</i> , bean	22	Tillage management	5	Sá <i>et al.</i> (2001)
USA	NA ^A	Albic luvisol	Maize–soybean	12	No-till, chisel plough and mouldboard plough	3	Olson <i>et al.</i> (2005)
India	77.17°E, 28.63°N	Haplustept	Millet–wheat–cowpea, corn–wheat–cowpea	12, 19	Synthetic fertiliser, manure	6	Rudrappa <i>et al.</i> (2006)

^ANot available.