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Spatial changes in soil organic carbon density and storage of cultivated soils in China from 1980 to 2000

Yanyan Yu,[1,2] Zhengtang Guo,[1] Haibin Wu,[1] Julia A. Kahmann,[1,3] and Frank Oldfield[4]

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[1] We address the spatial changes in organic carbon density and storage in cultivated soils in China from 1980 to 2000 on the basis of measured data from individual studies and those acquired during the second national soil survey in China. The results show a carbon gain in ~66% of the cultivated area of China as a whole with the increase in soil organic carbon (SOC) density mostly ranging from 10% to 30%. Soil organic carbon density increased in fluvi-aquic soils (fluvisols, Food and Agriculture Organization (FAO) of the United Nations) in north China, irrigated silting soils (calcaric fluvisols) in northwest China, latosolic red earths (haplic acrisols/alisols), and paddy soils (fluvisols/cambisols) in south China. In contrast, significant decreases are observed in black soils (phaeozems) in northeast China and latosols (haplic acrisols) in southwest China. No significant changes are detected in loessial soils (calcaric regosols) and dark loessial soils (calcisols) in the loess plateau region. The total SOC storage and average density in the upper 20 cm in the late 1990s are estimated to be ~5.37 Pg C and 2.77 kg/m^2, respectively, compared with the values of ~5.11 Pg C and 2.63 kg/m^2 in the early 1980s. This reveals an increase of SOC storage of 0.26 Pg C and suggests an overall carbon sink for cultivated soils in China, which has contributed 2–3% to the global terrestrial ecosystem carbon absorption from 1980 to 2000. Statistical analyses suggest an insignificant contribution to the observed SOC increase from climate change, and we infer that it is mostly attributable to improved agricultural practices. Despite the SOC density increases over 20 years, the SOC density of the cultivated soils in China in the late 1990s is still ~30% lower compared to their uncultivated counterparts in comparable soil types, suggesting a considerable potential for SOC restoration through improving management practices. Assuming a restoration of ~50% of the lost SOC in the next 30–50 years, these soils could potentially absorb ~1.03 Pg C from the atmosphere.

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1. Introduction

[2] In terrestrial ecosystems, the organic carbon pool in soils is about two times greater than in living vegetation [*Post et al.*, 1990; *Lal*, 1999]. Its increase, stabilization or decrease plays an important role in regional carbon balances and in atmospheric CO_2 concentrations [*Houghton et al.*, 1983]. Cultivated soils, affected by anthropogenic activity, have been overall a significant carbon source through the conversion of forests or rangeland in the last century [*Houghton*, 1999; *Wu et al.*, 2003]. Recent studies [*Bruce et al.*, 1999; *Lal*, 2004a, 2004b] revealed that improved soil management could turn such a source into a CO_2 sink. This method has been suggested as an option for offsetting CO_2 emission in the Kyoto Protocol and United Nations Framework Convention on Climate Change (United Nations Framework Convention on Climate Change, Kyoto Protocol, 1998, available at http://unfccc.int/resource/docs/convkp/kpeng.pdf).

[3] Currently, China has ~153.9 million hectares of cultivated land, representing ~10% of the world total [*World Resources Institute* (*WRI*), 2005]. Clarifying the temporal and spatial carbon changes and the sequestration potentials in such a large region is of importance for scheduling the emission of greenhouse gases and for carbon mitigation strategies. Using available data, the changes in SOC density and storage in cultivated soils in several regions in China during the period considered here have already been addressed in previous studies. These estimates include fluvi-aquic soils, Cinnamon soils (eutric cambisols) [*Xu et al.*, 2004; *Wang and Qiu*, 2004], black soils and Chernozems (Chernozems) [*Han et al.*, 2003, 2004; *Qiu et al.*, 2003, 2004; *Wang et al.*, 2007] in north China, paddy soils [*Shen et al.*, 2003; *Li et al.*, 2006; *Zhang et al.*, 2007]

[1]Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China.
[2]Graduate School of the Chinese Academy of Sciences, Beijing, China.
[3]Department of Geology, Baylor University, Waco, Texas, USA.
[4]Department of Geography, University of Liverpool, Liverpool, UK.

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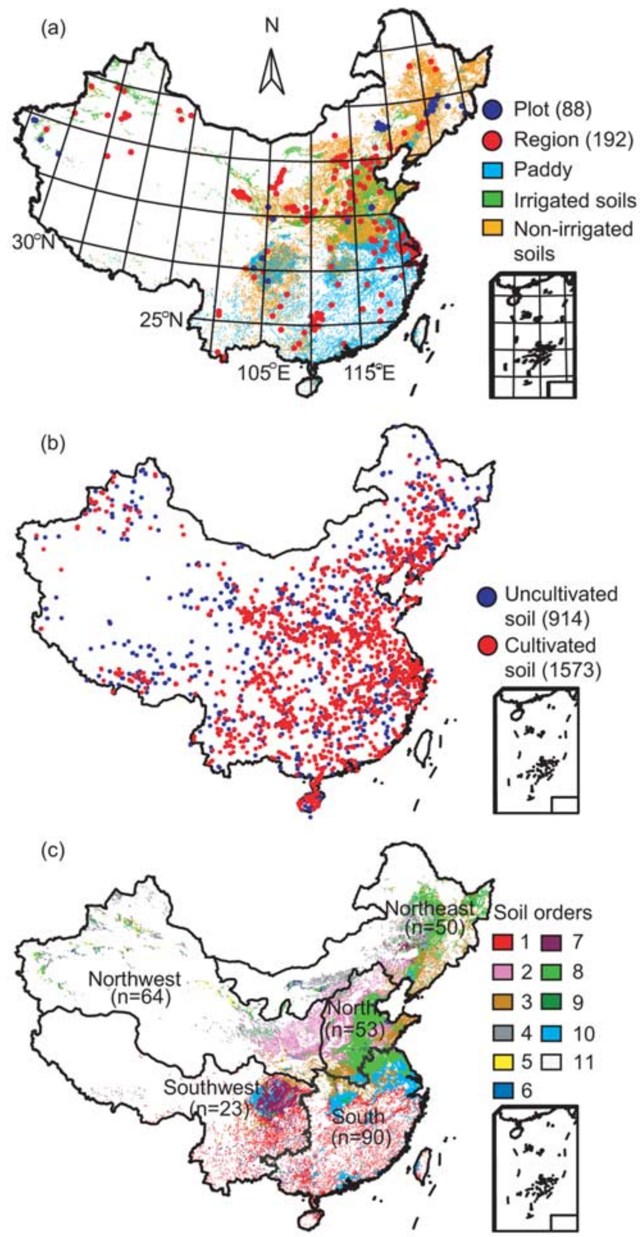

Figure 1. Distribution of the soil data used in this study. (a) Distribution of the 280 measured plots and regions from individual publications and of land use types of cultivated soils in China. (b) Distribution of the 2487 soil profiles in the second national soil survey. (c) The five geographic regions discussed in the text and the distribution of soil orders of cultivated soils in China: 1, ferro-allitic soils; 2, eluvial soils; 3, semieluvial soils; 4, caliche soils; 5, arid soils; 6, desert soils; 7, primitive soils; 8, semihydromorphic soils; 9, hydromorphic soils; 10, anthropogenic soils; and 11, noncultivated soils. The little boxes on the right-hand side of the maps show Chinese islands in the South China Sea.

in south and eastern China [*X. Z. Gao et al.*, 2000; *Li et al.*, 2002; *Yu et al.*, 2003; *Huang et al.*, 2007; *Yu et al.*, 2007]. At the national scale, changes in total SOC storage in China were estimated on the basis of measured data [*Huang and Sun*, 2006]. The latter revealed an increase in SOC storage of 0.31–0.40 Pg C in cultivated soils from 1980 to 2000. In contrast, model-based estimates [*Li*, 2000; *Li et al.*, 2003] suggested a significant carbon loss for most cultivated soils with a total carbon loss of $\sim 7.38 \times 10^{-2}$ Pg C/a in 1990. In light of these conflicting inferences, it is thus necessary to reevaluate more critically the changes in SOC storage.

[4] Over the past 30 years, a significant amount of soil organic matter data has been accumulated by individual studies (Table S1).[1] Also, the data acquired during the second national soil survey [*National Soil Survey Office* (*NSSO*), 1993, 1994a, 1994b, 1995a, 1995b, 1996, 1998] have a good spatial coverage and include most of the soil types and land use types in China (Figure 1). Used in conjunction, these data sets document SOC content for two time periods, i.e., the early 1980s and late 1990s.

[5] The above data provide an opportunity to estimate SOC changes in the cultivated soils in China and their spatial patterns from 1980 to 2000. On the basis of these data, this study aims to (1) investigate the changes in SOC density and storage in the cultivated soils of China from 1980 to 2000 at the national scale using improved methods; (2) analyze the spatial pattern of these changes and the likely causes; and (3) evaluate the potential of carbon sequestration in the cultivated soils in China through improved soil management. These issues are of importance for quantifying changes in the soil carbon pool in China and for model validation.

2. Data

[6] The data used in this study are from two main sources. The first is 2487 representative soil profiles (Figure 1b) that were analyzed during China's second national soil survey [*NSSO*, 1993, 1994a, 1994b, 1995a, 1995b, 1996, 1998] in the early 1980s. These data include detailed descriptions on soil classification, land use conditions, thickness, soil organic matter, soil bulk density and volume percentage of rock fragments >2 mm, all sampled in the middle of each horizon for each soil type. Among them, 914 profiles were considered noncultivated soils on the basis of their land use history and had not experienced significant disturbance by human activity. Their vegetation appeared to be ecologically consistent with the climatic conditions [*NSSO*, 1993, 1994a, 1994b, 1995a, 1995b, 1996, 1998]. We use these profiles to estimate the SOC density and storage under uncultivated conditions. The other 1573 profiles described in the second national soil survey were cultivated soils in the early 1980s or before, and are used in this study to estimate SOC density and storage in the cultivated soils for the early 1980s.

[7] The second part of the data is derived from published literature from individual studies (Table S1 and Figure 1a). They contain measurements of SOC content from 88 soil

[1]Auxiliary materials are available in the HTML. doi:10.1029/2008GB003428.

plots and 192 county-scale regions (thus a total of 280 location specific data items). The data used here, which apply to the upper 20 cm of normal tillage depth (Table S1) are computed from measurements derived from more than 60,000 soil profiles obtained mostly for the purpose of county-scale soil surveys. Measured plot data were calculated from the average SOC content of 3–5 surface soil samples (0–20 cm), which were collected within a 100 m radius of the plot [*Su et al.*, 2004]. On the basis of an area-weighted method, data from each regional survey were synthesized using hundreds of plot-specific measurements classified according to their soil types or land use types [*Chen et al.*, 2003]. Because each of the 280 data items compiled in this way document the SOC content in both the early 1980s and late 1990s, they are used here to estimate the SOC changes from 1980 to 2000. Among the 280 data items, 130 contain detailed descriptions on soil classification and land use conditions.

[8] In the monitoring studies summarized above, measurements of organic matter, soil bulk density and the fraction >2 mm were reported using standard techniques. Soil organic matter concentration was measured by the potassium dichromate-volumetric method. Soil bulk density was determined from oven-dry soil mass and core volume. The fraction >2 mm was sieved out with a 2 mm screen [*Institute of Soil Science Chinese Academy of Sciences* (*ISSCAS*), 1978; *Su et al.*, 2004].

[9] We use the terminology of the Chinese soil taxonomy [*NSSO*, 1998] to ensure consistency with the nomenclature used in the second national soil survey. An approximate comparison with the *FAO-UNESCO* [1988] soil taxonomy is given in Table S2.

[10] The database of the electronic soil and land use map of China used here is from *Tian et al.* [1996a, 1996b]. Because the soil taxonomy in the legend of the base map [*Tian et al.*, 1996a] is not entirely consistent with the taxonomy used in the second national soil survey, some soil groups were merged at subgroup levels on the basis of soil properties and distribution [*Li et al.*, 2001].

[11] Elevation data are from the China Meteorological Administration (The web of movie and television information for weather in China, 2003, available at http://www.weathercn.com/) and Global 30 Arc Second Elevation Data Set (GTOPO30) of the U.S. Geological Survey (Global 30 Arc Second Elevation Data Set (GTOPO30), 1996, available at http://www.vterrain.org/Elevation/). Climate data from 590 stations in the early 1980s (1980–1985) and late 1990s (1996–2000) are also from the China Meteorological Administration.

3. Method

3.1. SOC Density Calculation

[12] Soil organic carbon density (SOCD) of the soil profiles is calculated as follows:

$$SOCD = 0.58 \times t \times \rho \times SOM \times (1 - C)/10 \qquad (1)$$

where 0.58 is the Bemmelen index that converts organic matter (OM) to organic carbon content (OC) because organic matter was calculated by wet combustion with $Cr_2O_7^{2-}$; t, ρ, SOM and C represent thickness (cm), bulk density (g/cm^3), content of organic matter and volumetric percentage of the fraction >2 mm (rocky fragments) in the surface layer, respectively. Division by 10 at the end of the equation is to convert from g/cm^2 to kg/m^2. In this study, only the SOC storage in the upper 20 cm depth is estimated, as it is the portion of the soil profile most susceptible to anthropogenic alteration.

[13] Because of the lack of bulk density measurements for the majority of the soil profiles, we had to estimate them using other variables. Current bulk density prediction functions are mainly derived from data manipulation using soil texture, depth, organic carbon, etc [*Calhoun et al.*, 2001; *Kaur et al.*, 2002; *De Vos et al.*, 2005; *Tranter et al.*, 2007]. Using 80% of 420 soil profiles (n = 340) in the second national soil survey and individual studies [*Chen et al.*, 1998; *Hu et al.*, 2001; *Wu et al.*, 2001; *Liu et al.*, 2003; *Pu et al.*, 2004; *Zhang and Song*, 2004], which spanned a range of different land use histories and provided measurements of the above variables along with bulk density, we have established two regression equations:

$$\rho = 1.39 \times e^{(-0.063\times \mathrm{SOC})}, R^2 = 0.84, \mathrm{RMSE} = 0.11 \qquad (2)$$

$$\begin{aligned}\rho = 1.38 - 0.079 \times SOC + 0.002 \times SOC^2 + 1.74\mathrm{E}-05 \times Clay \\ \times Sand + 2.43\mathrm{E}-05 \times Clay^2 - 0.001 SOC \times Clay, \\ R^2 = 0.74, \mathrm{RMSE} = 0.12 \qquad (3)\end{aligned}$$

(see Figure 2), using these variables and on the basis of previous studies [*Kaur et al.*, 2002; *Song et al.*, 2005]. These two equations were further verified by the remaining 80 (20% of 420) measured profiles (Figure 2). The R values of the equation established using organic carbon alone (equation (2), $R^2_{\mathrm{regression}}$ = 0.84, $R^2_{\mathrm{verification}}$ = 0.85) are closely comparable to the one (equation (3), $R^2_{\mathrm{regression}}$ = 0.85, $R^2_{\mathrm{verification}}$ = 0.85) including SOC, silt and clay as predictor variables (Figure 2), thus providing equivalent predictive power. Moreover, the measured and estimated values of equation (2) also closely follow the 1:1 line (Figure 2a) confirming that, in the case of the soils considered in the present study, bulk density can be estimated accurately from organic carbon measurements. This confirmation is vital since the 280 measured data items used in this study for estimating the SOC changes from 1980 to 2000 mostly have not recorded other soil parameters (i.e., soil texture) in addition to SOC content values. Therefore, we use equation (2) to estimate bulk density here, which is also widely used by previous studies [*Manrique and Jones*, 1991; *Callesen et al.*, 2003; *Wu et al.*, 2003; *Song et al.*, 2005; *Yang et al.*, 2007; Scottish Executive Environment and Rural Affairs Department, ECOSSE: Estimating carbon in organic soils sequestration and emissions, 2007, available at http://www.scotland.gov.uk/Publications/2007/03/16170508/0].

[14] For each subgroup of soils, the mean volumetric percentage of the fraction >2 mm, as provided in the second national soil survey, is used here. County-scale SOC values

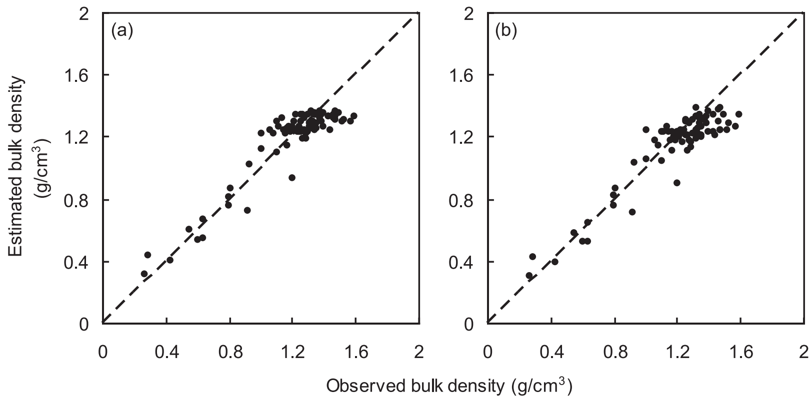

Figure 2. Comparison of the performance of two regression equations (see section 3.1) verified by 80 measured soil profiles: observed versus estimated bulk densities (g/cm^3) with reference to the 1:1 line. (a) Equation (2). (b) Equation (3).

are assigned to each soil type of the region, and area-weighted mean values are then used in calculating the regional SOC density.

3.2. Interpolation of SOC Density Changes

[15] Because SOC changes in cultivated soils result from the interactions of various environmental factors and anthropogenic management practices [*Schlesinger*, 1999], they are difficult to calculate through statistical methods. Artificial neural network (ANN) models can be used to model complex relationships between inputs and outputs in no-linear systems. They provide a way of accommodating a wide range of functions and their interactions [*Hornik*, 1991]. In order to examine the spatial changes of SOC in China, we use an ANN model [*Rumelhart et al.*, 1986] included in the 3Pbase software [*Guiot and Goeury*, 1996] for surface interpolation.

[16] The architecture of the 3 layers ANN used here is shown in Figure 3. Six input variables (latitude, longitude, elevation, soil and land use type, original SOM in early 1980s) and one output variable (relative change of SOM) have been chosen.

[17] The ANN has been calibrated on the training set, and its performance has been evaluated on the verification set. Data included in these two sets correspond to samples randomly extracted from the 280 measured values. Because of the high spatial variability of SOC changes in China, the 224 measurements used in the training set for the model (80% of 280 measured values) are divided into three groups (Table 1) according to their locations (northeast China, northwest China, and north, south, and southwest China) (Figure 1c). During the training run, the lowest verification error here is obtained with 5 neurons in the hidden layer after 5000 iterations, which thus corresponds to the optimal configuration. After training, the ANN's weights are used to estimate the relative changes of SOM from 1980 to 2000 with a 0.2° × 0.2° grid resolution for all cultivated soils in China.

[18] Thus, the SOM of each 0.2° × 0.2° grid in the late 1990s is calculated by the following equation:

$$SOM_{(B)} = SOM_{(A)} \times (1 + RE) \quad (4)$$

where RE is the relative change of SOM based on the ANN method, $SOM_{(A)}$ and $SOM_{(B)}$ are the values for the early 1980s and late 1990s, respectively, and the values of SOM are converted to that of SOCD by equation (1).

3.3. SOC Storage Estimates for the Cultivated Soils

[19] Soil organic carbon storage (SOCS) is then computed by:

$$SOCS = \sum_{i=1}^{n} area_{(i)} \times SOCD_{(i)} \quad (5)$$

where $area_{(i)}$ is the surface area, and $SOCD_{(i)}$ is the organic carbon density of each 0.2° × 0.2° grid.

4. Results and Discussions

4.1. ANN Method Validation

[20] In order to check the accuracy of our ANN calibration, we have examined the correlations between the observed and reconstructed SOC content change values on the basis of the ANN model (Table 1). The obtained calibration correlation coefficients (R value) are all above 0.7, and the verification R values (0.50 and 0.61) remain largely statistically significant, indicating the reliability of the approach.

4.2. Changes in SOC Density and Storage

[21] Soil organic carbon density changes can visually represent the temporal and spatial changes in soil organic carbon. Figure 4 shows the differences of SOC density between the late 1990s and early 1980s based on the 280 measured values. Among them, 55% (n = 154) show significant increases (>+5%) of SOC density, 20% (n = 57) show clear decreases (<−5%), and the other 25% (n = 69) remain unchanged (−5% to +5%).

[22] A significant negative correlation ($y = -5.68x + 25.2$, $R^2 = 0.98$) is obtained between the measured cultivated SOC changes and their original densities in the early 1980s in China. A threshold value of 4–5 kg/m^2 is observed for SOC density or 3–4% for SOC content. These values are close to the threshold value of 3.2% for carbon increases

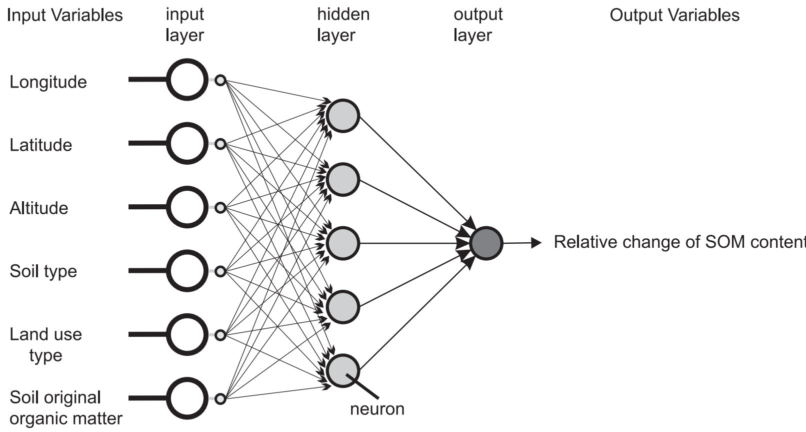

Figure 3. Diagram showing the Artificial Neural Network (ANN) for the interpolation of relative changes in SOC content. The input layer corresponds to the six environmental parameters; the output layer corresponds to the relative changes in SOM. Each neuron in the hidden and output layers receives weighted signals from the neurons in the previous layer.

and decreases in cultivated soils in England and Wales [*Bellamy et al.*, 2005], and to the value of 4.5 kg/m^2 for cultivated soils in northeast China [*Han et al.*, 2003, 2004].

[23] On the basis of the ANN interpolation, the changes of SOCD in China as a whole (Figure 5b) show a carbon gain for 58% of the cultivated surface, a carbon loss for 25% of the cultivated surface, and insignificant changes for 17% of the cultivated surface. The spatial distribution patterns are also essentially consistent between measured data (Figure 5a) and interpolated estimates (Figure 5b), and the R value of interpolated and measured SOC change is about 0.53 (>99% confidence level). For the ANN-interpolated areas of SOC density increase, about 62% of them lie in north and south China, and the changes mostly fall into the range of +10–30%. More than 57% of the areas which have clearly experienced decreases in SOC density lie in southwest and northeast China. No significant changes are shown in the loess plateau of northwest China.

[24] The ANN-interpolated results for different soil orders and land use types are shown in Figures 6a and 6b. Significant increases in carbon density are observed for arid soils (+50%), semihydromorphic soils (+18%), and anthropogenic soils (+10%), which mainly include brown caliche soils (haplic/haplic calcisols) (+51%), Sierozems (calcaric cambisols) (+48%), fluvi-aquic soils (+19%), irrigated silting soils (+19%) and paddy soils (+10%) widely distributed in north, northwest, and south China, respectively. In contrast, SOC density decreased by 20% in hydromorphic soils. There are no significant changes for eluvial soils (−1%) and semieluvial soils (+4%). In terms of land use conditions, the changes in SOC density show the following sequence in declining order: irrigated soils (+20%), paddy (+17%) and nonirrigated soils (−2%).

[25] These estimated changes in SOC storage form a basis for evaluating the role they have played quantitatively in global and regional carbon balance. The total SOC storage in cultivated soils in China was ∼5.11 Pg C in the early 1980s and ∼5.37 Pg C in the late 1990s, indicating a net increase of ∼5%, or 0.13×10^{-1} Pg C/a. This suggests that the cultivated soils in China have offset ∼2% of the industrial CO_2 emissions (12.2 Pg C) [*Zhang*, 2000] from 1980 to 2000, and also contributed 2–3% to the global terrestrial ecosystem carbon sink (9–16 Pg C) during the period [*Watson et al.*, 2000; *Prentice et al.*, 2001; *Plattner et al.*, 2002]. Nevertheless, the overall budget would depend on the size of any additional, indirect energy inputs associated with irrigation and fertilization.

[26] The increased rates of SOC storage driven by improved management in the USA and Canada since 1980 have been estimated to be 0.15×10^{-1} Pg C/a [*Eve et al.*, 2002] and 0.57×10^{-5} Pg C/a [*Vandenbygaart et al.*, 2004], respectively, while cultivated soils in Belgium, England, and Ireland were still acting as carbon sources [*Sleutel et al.*, 2003; *Bellamy et al.*, 2005; *King et al.*, 2005; *Lettens et al.*, 2005], because of the fertilizer application policies and climate change during the same period. Overall, we estimate that cultivated soils in China have played a positive role in the global carbon balance.

Table 1. Correlation Coefficients Between Observed and Reconstructed Values of Relative SOC Content Change Based on ANN Models[a]

Data Set	Region	R Value of Calibration	RMSE of Calibration (%)	R Value of Verification	RMSE of Verification (%)
N = 50	northeast China	0.75	17	0.61	23
N = 64	northwest China	0.90	8	0.50	18
N = 166	north, south, and southwest China	0.70	14	0.50	16

[a]ANN, artificial neural network.

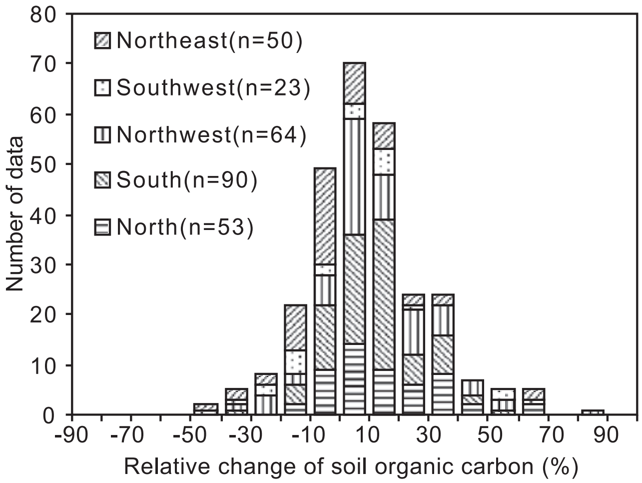

Figure 4. Frequency distribution of the relative changes in soil organic carbon density in the 280 measured plots and regions. Calculations are made at 10% intervals, $P < 0.001$.

[27] The estimated results by region are mostly consistent with earlier regional approaches [*X. Z. Gao et al.*, 2000; *Li et al.*, 2002; *Shen et al.*, 2003; *Yu et al.*, 2003; *Han et al.*, 2003, 2004; *Qiu et al.*, 2003, 2004; *Xu et al.*, 2004; *Wang and Qiu*, 2004; *Pan and Zhao*, 2005; *Li et al.*, 2006; *Huang et al.*, 2007; *Wang et al.*, 2007; *Yu et al.*, 2007; *Zhang et al.*, 2007]. Our estimate using more data and new methods for calculating the changes in total SOC storage in China is lower than that of *Huang and Sun* [2006] (0.31–0.40 Pg C). The difference may be mainly due to the different calculation procedures used in the two studies. First, *Huang and Sun* [2006] used arithmetical averages to estimate the missing bulk density values for given soil types, on the basis of measured values in the second national soil survey, while a regression equation by SOC was adopted here. Second, the change in SOC storage was estimated by the area-weighted mean SOC density change given by *Huang and Sun* [2006], while the ANN method, including 6 environment variables, is used here to interpolate the spatial changes of SOC density. Thus, we consider that our estimate is a more refined predicator for the spatial changes in SOC density and storage.

[28] In contrast, our estimates greatly differ from model-based estimates [*Li*, 2000; *Li et al.*, 2003]. This is partly attributable to the limitation of models in regional analyses, but two other important factors would have significantly affected the model outputs. First, most of the input parameters of the model of *Li* [2000] and *Li et al.* [2003] were derived from statistical data that represent the average conditions of the country, whereas the environmental conditions and agricultural practices in China have high spatial variability. Second, the input items of the model were mainly from the year 1990, which may not be representative over a longer period.

4.3. Possible Factors Affecting the SOC Changes

[29] At decadal scales, several factors may affect the SOC changes in cultivated soils. These include climate changes [*Smith et al.*, 2000; *Bellamy et al.*, 2005], soil erosion [*Lal*, 2005] and agricultural practices [*Lal*, 2002, 2004a, 2004b].

[30] Climate changes may affect soil carbon turnover, with increased temperature accelerating rates of organic decomposition. The effect of temperature also interacts in complex ways with changes in soil moisture, atmospheric CO_2, and nitrogen deposition [*Post et al.*, 1990; *Su and Zhao*, 2002; *Bellamy et al.*, 2005]. An increase of ~0.5°C in the mean annual temperature may have occurred in China from 1980 to 2000 and changes in rainfall patterns have also been reported [*Zuo et al.*, 2004; *Ren et al.*, 2005]. However, correlations between changes in SOC density and climate parameters (temperature: $y = -10.66x + 12.7$, $R = 0.28 < R_{0.001} = 0.55$; precipitation: $y = -0.05x + 2.9$, $R = 0.22 < R_{0.001} = 0.55$) indicate an insignificant role for climate changes in the observed SOC changes in the cultivated soils of China, both in the temporal and spatial analyses.

[31] Improved agricultural practices such as increased fertilizer input, returning crop residues to soils and irrigation could increase SOC through enhancing belowground biomass input [*Lal.*, 2004a, 2004b]. The positive effects of these management practices on soil organic restoration have

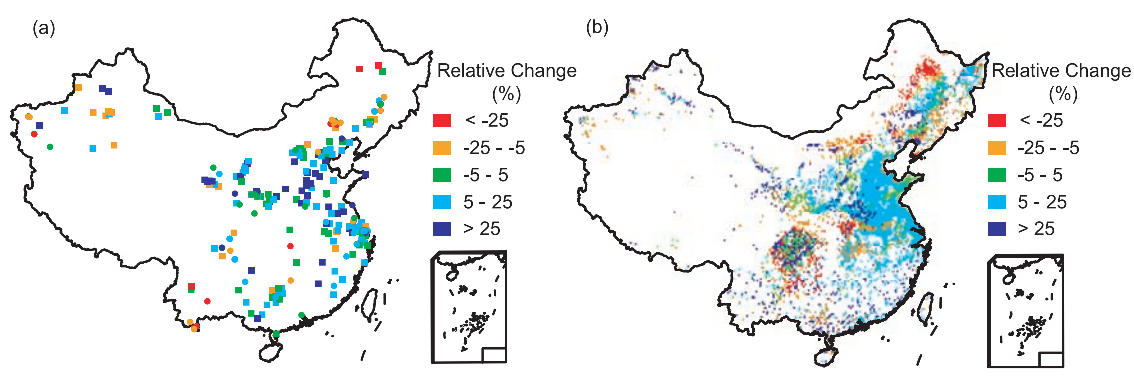

Figure 5. Comparison between the measured SOC changes and model outputs. (a) Distribution of the SOC density changes (%) from the early 1980s to the late 1990s in the 280 measured plots and regions. (b) Distribution of the ANN model–yielded SOC density changes (%) from the early 1980s to the late 1990s.

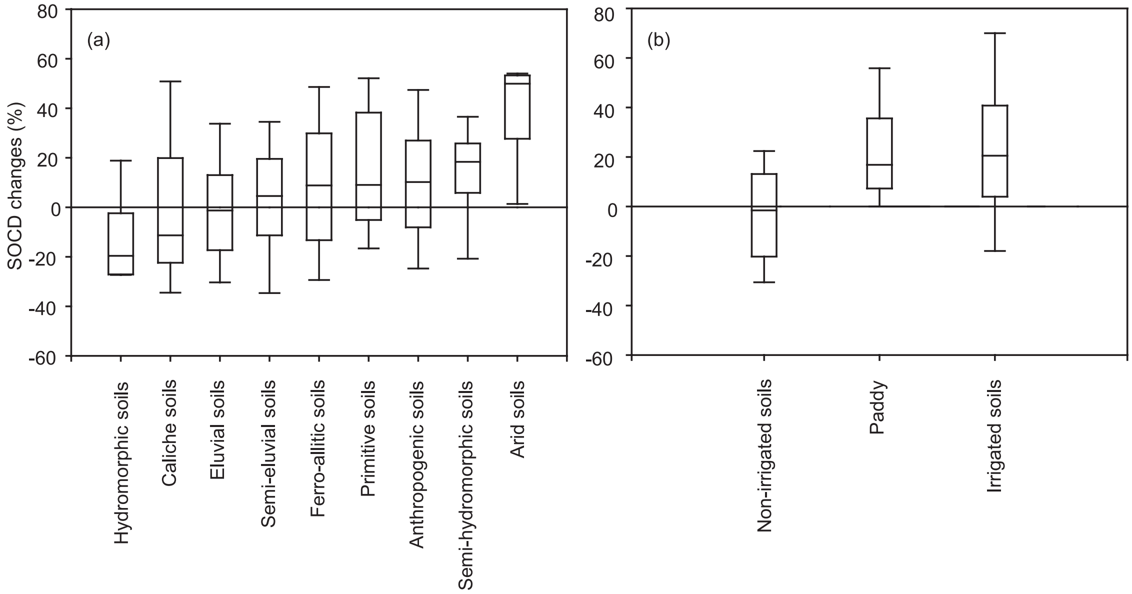

Figure 6. Box plots of the changes in soil organic carbon density, grouped by soil order and land use type. (a) Soil-order grouping. (b) Land use type grouping. The boxes indicate the interquartile intervals (25th and 75th percentiles), and the bars represent 90% intervals (5th and 95th percentiles).

been demonstrated by experimental approaches in China [*Yang and Janssen*, 1997; *Zhang et al.*, 1999; *Wu et al.*, 2004].

[32] From 1980 to 2000, with intercropping and rotation of the fields expanding, multiple cropping indices in China increased by 18%, chemical fertilizer input increased by 149% and the surface of irrigated fields increased by 17% [*National Bureau of Statistics of China* (*NBSC*), 2001; *Wu*, 2002]. A most important practice is the increased rate of returning crop residues to soils: 25% in 1990 [*Li et al.*, 2003] compared to 36.6% in 2000 [*Gao et al.*, 2002]. The overall increases in organic density and storage revealed in this study are mostly attributable to these agriculture management methods. The significant SOC increases in north and south China are consistent with the higher input of chemical fertilizers, 233 kg/ha in 1985 compared to 609 kg/ha in 2000 [*Wu*, 2002]. The decreased SOC density and storage in relatively fertile soils in northeast China are partly attributable to the lower increase in fertilizer input, from 98 kg/ha in 1985 to 270 kg/ha in 2000 [*Wu*, 2002]. The increased surface erosion of the black soils in this region, from 4.47×10^4 km^2 in 1986 to 7.43×10^4 km^2 in 1999 [*Yue et al.*, 1999; *Wang et al.*, 2002], would also have significantly contributed to the SOC decrease in these soils. In north and northwest China, the surface areas under irrigation increased by 3.0×10^4 ha from 1980 to 2000, representing ~40% of the increases in China [*NBSC*, 2001]. The significant increases of SOC in these regions are largely attributable to irrigation that leads to enhanced soil humidity and bioproductivity [*Lal*, 2004b].

[33] As for the negative relationship between cultivated SOC changes and their original densities, this also could be explained by different agricultural management practices between regions. People in regions with high soil carbon content may rely more on natural soil fertility and put in less fertilizer (i.e., northeast China), while in regions where the soils have low carbon content (i.e., north China), people may pay more attention to soil management [*Yu et al.*, 2003]. In addition, climate change may also lead to carbon decrease in soils with a high initial carbon content. These soils contain more slowly decaying organic matter and tend to be wetter, both of which are sensitive to warming which would induce more carbon loss by decomposition [*Bellamy et al.*, 2005].

[34] Several studies [*Dolan et al.*, 2006; *Gál et al.*, 2007] in the USA have stressed that no-tillage clearly induces more SOC content accumulation in the upper 30 cm relative to plow tillage, but it results in less SOC in the 30–50 cm depth range, thus indicating that changes in tillage may affect the depth distribution of SOC without influencing the total amount in the profile. However, from 1980 to 2000, increased fertilizer input is the dominant aspect of improved agriculture practices in China, and the no-tillage area comprised only 0.1% of the total cultivated land [*Wang et al.*, 2006], thus having a negligible affect on the SOC changes. This conclusion is reinforced by the results of an analysis of 108 0–100 cm deep soil profiles from sites treated by improved agriculture practices (i.e., increased fertilizer input and organic residue returned to the field) from 12 monitoring studies [*Lai et al.*, 1991; *Zhao and Li*, 1993; *Zhou et al.*, 1993; *Dang et al.*, 1995; *Sun and Larney*, 1997; *Wang et al.*, 1997; *Y. J. Gao et al.*, 2000; *Fan et al.*, 2001; *Sun et al.*, 2001; *Qian et al.*, 2003; *Xie et al.*, 2004; *Huang et al.*, 2006]. The profiles studied have a good spatial coverage and are representative of most cultivated soil types in China. The result indicated that SOC increased in all layers of the profile (0–100 cm) with an increase of 19%, 6%, 9%, and 10% for the depth intervals of 20–40 cm, 40–60 cm, 60–80 cm and 80–100 cm, respectively, but the major part of the increase (56%) is in the upper 20 cm.

Table 2. Soil Organic Carbon Storage in Different Regions of China

Regions	Time Periods		
	Uncultivated Condition (Pg C)	Early 1980s (Pg C)	Late 1990s (Pg C)
North China	1.49	0.88	0.95
Northwest China	0.64	0.42	0.45
South China	2.17	1.60	1.74
Southwest China	1.26	0.87	0.90
Northeast China	2.13	1.34	1.33

Thus, our study is a conservative estimate for the SOC changes of cultivated soils in China from 1980 to 2000. As more measured data become available, it may prove possible to calculate SOC changes below 20 cm in subsequent studies.

4.4. Potential Capacity for Additional Carbon Sequestration

[35] To determine the potential for further carbon sequestration in cultivated soils, two factors are of particular importance. These are the current SOC content compared to the averages of their uncultivated counterparts under similar climate conditions and the recent changes in SOC storage that have occurred [*Sleutel et al.*, 2003].

[36] On the basis of the 914 uncultivated and 1573 cultivated soil profiles described in the second national soil survey [*NSSO*, 1993, 1994a, 1994b, 1995a, 1995b, 1996, 1998], and the 280 measured data points from published literatures (Table S1), the estimated regional SOC storage in China during three periods is shown in Table 2. Assuming a similar potential SOC reservoir for cultivated soils to that of their uncultivated counterparts, the SOC storage in the cultivated soils of the early 1980s was reduced by 41% in north China, 35% in northwest China, 26% in south China, 31% in southwest and 37% in northeast China, respectively. Although most of these regions experienced carbon gains from the early 1980s to late 1990s except for northeast China, total SOC storage in the cultivated soils in China in the late 1990s is only ~70% of their uncultivated counterparts. These findings suggest a large potential for organic carbon sequestration in the cultivated soils.

[37] Assuming that half of the SOC losses in the cultivated soils is restored during the next 30–50 years through improved management, a proportion suggested in earlier studies [*Cole*, 1996; *Lal*, 1999], the potential carbon sequestration for the cultivated soils would be 0.23 Pg C in north China, 0.08 Pg C in northwest China, 0.14 Pg C in south China, 0.17 Pg C in southwest China and 0.41 Pg C in northeast China. These total about 1.03 Pg C or $0.2-0.3 \times 10^{-1}$ Pg C/a for the whole country, which is consistent with the estimate ($0.25-0.37 \times 10^{-1}$ Pg C/a) obtained by applying the sequestration rate of recommended management practices to cultivated soils in China [*Lal*, 2004c]. The rate of future increase in carbon sequestration required to achieve this would be comparable to the rate of increase in SOC (0.13×10^{-1} Pg C/a) by agricultural practices during the last 2 decades indicated by this study.

[38] The amount of carbon restoration potential may be even greater than our estimate. First, some research [*Johnson*, 1995, *Janzen et al.*, 1997] suggests that well designed management, such as land use type conversions and repeated fertilizer addition, may increase the carbon content above the capacity of native counterparts. Second, the long agriculture history in China would have also decreased the organic carbon storage in the currently uncultivated soils, and consequently led to an underestimate of their natural potential of carbon storage. This can be well illustrated by comparing the soils in China with those in the New World. For example, SOCD values in the upper 20 cm of aeolian soils (arenosols) (0.72 kg/m^2), Peat soils (histosols) (13.64 kg/m^2) and Shrubby meadow soils (calcaric cambisols) (2.23 kg/m^2) in China are significantly lower than in their USA counterparts [*Shi et al.*, 2004], which were estimated to be ~2.32 kg/m^2, ~18.49 kg/m^2 and ~2.62 kg/m^2, respectively [*Burke et al.*, 1989; *Tan et al.*, 2004].

5. Conclusion

[39] On the basis of the data of China's second national soil survey and those from the recent literature, the spatial changes of organic carbon density and storage in the cultivated soils in China from 1980 to 2000 are estimated using an ANN model for spatial interpolation. The results are essentially consistent with measured data, and are also in broad agreement with earlier estimates [*Huang and Sun*, 2006], but greatly differ from the model-based estimates [*Li*, 2000; *Li et al.*, 2003].

[40] Our results indicate a significant increase in SOC density in fluvi-aquic soils (fluvisols) in north China, irrigated silting soils (calcaric fluvisols) in northwest China, latosolic red earth (haplic acrisols/alisols) and paddy soils (fluvisols/cambisols) in south China. By contrast, black soils (phaeozems) in northeast China and latosols (haplic acrisols) in southwest China show a net carbon loss. No significant changes occurred for loessial soils (calcaric regosols) and dark loessial soils (calcisols) in the loess plateau region. These changes suggest an increase in average SOC density of 0.14 kg/m^2 and an increase in total SOC storage of 0.26 Pg C from 1980 to 2000 in the cultivated soils of China. This amount corresponds to ~2% of industrial CO_2 emissions in China, and 2–3% of the global terrestrial ecosystem carbon absorption during the same period. Most of the SOC increases are attributable to improved agriculture practices, including fertilizer input, returning crop residues to soils and extended irrigation during the period considered.

[41] Despite the increase from 1980 to 2000, the total SOC storage in cultivated soils in China in the late 1990s is only ~70% of their uncultivated counterparts, suggesting a great potential for additional carbon sequestration in the cultivated soils in China. Assuming a restoration of ~50% of the lost SOC in the next 30–50 years for cultivated soils relative to their uncultivated counterparts, these soils would absorb ~1.03 Pg C from the atmosphere, an amount that would be a significant contribution to CO_2 sequestration under ongoing global warming scenarios.

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Z. Guo, J. A. Kahmann, H. Wu, and Y. Yu, Institute of Geology and Geophysics, Chinese Academy of Sciences, P.O. Box 9825, Beijing 100029, China. (ztguo@mail.iggcas.ac.cn)

F. Oldfield, Department of Geography, University of Liverpool, Liverpool L69 7ZT, UK.