

Spatiotemporal changes in cropland soil organic carbon in a rapidly urbanizing area of southeastern China during 1980-2015

Enze Xie¹, Xiu Zhang¹, Fangyi Lu¹, Yuxuan Peng¹, and Yongcun Zhao²

¹Institute of Soil Science Chinese Academy of Sciences

²Institute of Soil Science, Chinese Academy of Sciences

April 15, 2021

Abstract

Understanding the spatiotemporal changes in soil organic carbon (SOC) and their driving factors is an important prerequisite for decision-making in maintaining sustainable agricultural development and addressing climate change. A total of 1219 cropland topsoil SOC data (0-20 cm) collected from southern Jiangsu Province of China in 1980, 2000, and 2015, and geostatistical sequential Gaussian simulation were used to identify the changes in the spatiotemporal patterns of SOC during the period of 1980-2015. Results showed that the changes in SOC within the different time periods were significantly different, with a net increment of 3.65 g kg⁻¹ during the period of 1980-2000 and a net decrement of 2.32 g kg⁻¹ during the period of 2000-2015. Significant SOC accumulation occurred throughout the study area during 1980-2000, while SOC decline became predominant in the southeast during 2000-2015. Overall, the SOC contents for 60% of the study area increased significantly over the entire 35-year period. The SOC increase during the first two decades (1980-2000) was largely attributed to the increasing soil C input that resulted from the enhanced crop productivity by chemical fertilizers, while the stagnant soil carbon inputs associated with the rapid urban expansion were the primary reason for constraining cropland SOC accumulation in the subsequent 15 years (2000-2015). These findings highlight the importance of balancing agricultural development and urbanization processes to maintain SOC levels, and may also provide some guidance for planning cropland soil C management strategies in many areas that are undergoing similar urbanization processes.

Introduction

Soil organic carbon (SOC), as a critical component of soil fertility, not only affects soil quality and crop production (Vågen & Winowiecki, 2013; Jiang et al., 2014; Zhao et al., 2018), but also plays an important role in the global carbon cycle (Wei et al., 2011; Borrelli et al., 2018). The SOC levels are influenced by natural factors and human activities (Bolinder et al., 1997; Wang et al., 2015a; Fujisaki et al., 2018; Fan et al., 2019), while management practices usually have more profound influences on the cropland SOC levels (Nandwa, 2001; Li et al., 2016; Sandeep et al., 2016). For example, unreasonable management practices (i.e., overuse of chemical fertilizers and straw burning) may cause soil nutrient imbalances, and further accelerate cropland SOC loss in a short time (de Blécourt et al., 2019; Keel et al., 2019; Yang et al., 2019). Consequently, information and knowledge on the spatiotemporal changes in cropland SOC and their driving factors are extremely important for developing effective management practice recommendations and addressing climate change.

Multiple factors affect the spatiotemporal changes in cropland SOC, including natural factors such as climate, soil types, and topography (Meersmans et al., 2011; Ou et al., 2017; Yang et al., 2019), and anthropogenic factors such as agricultural management practices (i.e., tillage, fertilization) (VandenBygaert et al., 2004;

Han et al., 2018; Zhou et al., 2019) and land use change (Guo & Gifford, 2002; Luo et al., 2019). The systematic review of existing SOC studies (Schillaci et al., 2018; Ramesh et al., 2019; Wiesmeier et al., 2019) shows that natural factors are generally recognized as important contributors to spatial variability of SOC in cropland. For example, Li et al., (2018b) found that topographic factors such as slope and aspect significantly influenced the spatial distributions of cropland SOC in central Iowa and explained more than 62% of the spatial variability of SOC in that area. The spatial prediction of topsoil SOC with the random forest model in an intensively cultivated area in eastern China demonstrated that soil properties, climate, and geographic locations were the most important predictors for mapping SOC distributions (Deng et al., 2018). However, numerous studies have indicated that anthropogenic factors, in particular management practices and land use changes, have even more profound influences on the spatiotemporal changes in cropland SOC (Bas et al., 2010; Leifeld et al., 2013; Zhao et al., 2018; Shi et al., 2019), because anthropogenic activities usually alter the balance between soil carbon inputs and decomposition over a relatively short time period (Jiang et al., 2014). For example, a significant difference in the annual SOC change rates across different agricultural regions of China (-2.0% to 0.6% yr⁻¹) was mainly caused by regional differences in management practices, such as cultivation, fertilization, and straw/residue return rate (Yan et al., 2011). The CENTURY model analysis of the SOC changes in the agricultural soils of northeastern Spain also revealed that the soil carbon inputs associated with management practices were the primary reasons for SOC increases (rate of 0.27 Mg C ha⁻¹ yr⁻¹) over the period of 1977-2007 (Álvaro-Fuentes et al., 2011). Qiu et al., (2013) identified spatiotemporal changes in SOC in eastern China over the period of 1979-2006, and found that the changes in SOC were closely related to the conversion from croplands to urban lands due to rapid urban expansion.

China has been experiencing rapid economic growth since the 1980s (Bao et al., 2019). Meanwhile, in the rapidly urbanizing area, the urban expansion and the industry-dominated economic growth have caused a significant shrinkage of cropland area and a decrease of economic investment in cropland management (Bren d’Amour et al., 2017; van Vliet et al., 2017; Zhong et al., 2020). However, the impacts of these changes on the spatiotemporal changes of SOC and their implications remain unclear, in particular over different time periods. Therefore, the specific objectives of this study were (1) to map the spatial distribution of cropland SOC in a representative area that has been experiencing rapid urbanization; (2) to quantify the changes in SOC spatial distributions over different time periods while considering the associated mapping uncertainties; and (3) to identify the primary driving factors of the SOC spatiotemporal changes.

2. Material and methods

<Fig. 1>

2.1 Study area

The study area is located in southern Jiangsu Province of southeastern China, including three prefecture-level cities (Suzhou, Wuxi, and Changzhou) and two county-level cities (Danyang and Dantu), with a total land area of 18,700 km² (Fig. 1a). The area has a subtropical monsoon climate with a mean annual rainfall of 900-1200 mm, and an average temperature of 15.6 °C (Song et al., 2019). Most parts of the study area are lowlands with elevations ranging from 0 to 10 m above sea level, while the mountains with elevations >100 m are mainly located in the southwest (Fig. 1b). Paddy soil (Stagnic Anthrosols) is the dominant soil type, and fluvo-aquic soil (Aquic Cambosols) and yellow brown soil (Ferri-Udic Argosols) are the other two major soil types (Fig. 1c). The parent materials for paddy soils in the area were mainly composed of alluvial materials, loess, and lacustrine deposits, while the fluvo-aquic soils in the northern parts of the study area were developed from the Yangtze River alluvium. Yellow brown soils derived from residual and slope deposits were mainly distributed in the low-mountain areas.

Southern Jiangsu Province has thousand years of agriculture planting history, while the rapid urbanization only began in the early 1980s. The rapid urbanization process and economic growth due to industrial

development have greatly influenced the soil quality in the area (Liu et al., 2010).

2.2 Soil sampling and analysis

Cropland topsoil data (0-20 cm) in 1980 were collected from the soil survey reports of each city within the study area (Fig. 1a). These legacy data have been further checked for quality control, such as the correction of likely wrong samples and outlier detection (Schillaci et al., 2019), resulting in a total of 399 data on soil organic matter (SOM) being collected. The SOM in 1980 was determined by using the potassium dichromate oxidation method with external heating (Institute of Soil Science Chinese Academy of Sciences, 1978), and was converted to SOC by the $SOM \times 0.58$ based on the Van Bemmelen factor (Yan et al., 2011) (denoted as SOC_{1980} hereafter). Soil data recorded in these soil survey reports, including the text descriptions of the soil type, topography, bulk density, rock fragments with the fraction >2 mm (coarse fraction), and sampling locations, were the findings of the second National Soil Survey of China. So far, these legacy data were still the most comprehensive and detailed historical data that were available for extracting information about the soil properties of the study area in 1980.

In 2000, a total of 413 topsoil samples were collected for better coverage of the study area. These sampling locations were chosen to (i) match the 1980's sampling locations as closely as possible, (ii) be on the identical soil types and topographic characteristics, and (iii) have the most typical cropping systems around the sites. In 2015, the sampling locations were determined by the same rules as the sampling campaign in 2000. However, because of the significant changes in land use (i.e., cropland converted to urban land over the period of 2000-2015), some sampling locations in 2015 were slightly different from those in 2000, resulting in a total of 407 soil samples being collected in 2015. Hand-held GPS (global positioning system, positioning error <10 meters) was used to record the sample locations in 2000 and 2015, and the related information such as soil types, land use, and topographic characteristics were also recorded in detail. The average sampling density over the three sampling campaigns is approximately one sample per 33 km^2 . And the SOC contents in 2000 and 2015, which were denoted as SOC_{2000} and SOC_{2015} hereafter, were all determined by the same method as SOC_{1980} .

2.3 SOC change mapping and uncertainty assessment

The geostatistical ordinary kriging (OK) may reflect the mechanism of spatial variations in soil properties and is relatively transparent and straightforward, compared to the complicated algorithm such as machine learning (Veronesi & Schillaci, 2019). Therefore, the OK method was employed to map the spatial distributions of SOC_{1980} , SOC_{2000} , and SOC_{2015} , and then, the spatial patterns of the SOC changes over the three time periods were determined by subtracting the OK-predicted SOC_{1980} from the OK-predicted SOC_{2000} , the OK-predicted SOC_{2000} from the OK-predicted SOC_{2015} , and the OK-predicted SOC_{1980} from the OK-predicted SOC_{2015} , respectively.

During the OK prediction, the experimental variogram that summarized the spatial relations in SOC data was first calculated. For a set of SOC data $z(x_i)$ at location $x_i (i=1,2,\dots,n)$, the semivariance $\gamma(h)$ for a spatial distance h can be estimated by using the following equation (Veronesi & Schillaci, 2019):

$$(1),$$

where $N(h)$ is the number of pair observations $z(x_i)$ and $z(x_i+h)$ that separated by the spatial distance h . The experimental variogram can be fitted by some theoretical variogram models such as spherical, exponential, and Gaussian models. The sill of the fitted model is the semivariance value at which the fitted variogram model first flattens out (represents the spatial variance of the data), and the range is the distance at which the variogram reaches the sill (represents the distance at which the data are no longer auto-correlated), while the nugget is the model-fitted semivariance value when the distance is zero (represents the influences of measurement error and/or small-scale variations).

In this study, the variogram models were fitted to the experimental variograms of SOC₁₉₈₀, SOC₂₀₀₀, and SOC₂₀₁₅, respectively, and then the optimal model for each of the three sampling dates was chosen according to the goodness of fit (the value of R^2) of spherical, exponential, and Gaussian models (Goovaerts, 1997). Sequential Gaussian Simulation (SGS) was used to generate equiprobable realizations of SOC for quantifying the uncertainties associated with the OK-predicted SOC. Based on the best-fitted variogram models from the OK method, the SGS was first conducted 1000 times for each of the SOC₁₉₈₀, SOC₂₀₀₀, and SOC₂₀₁₅ values, and then, random subtractions of the 1000 times SOC₁₉₈₀ maps from the 1000 times SOC₂₀₀₀ maps were used to obtain the 1000 equiprobable realizations of the SOC changes during 1980-2000. This process was repeated to generate the SOC change realizations for the periods of 2000-2015 and 1980-2015. Finally, the realizations of the SOC changes were used to quantify the uncertainty intervals of the SOC changes.

Ensure that the sample data are normal or approximately normal distribution, and the SGS algorithm used in this study was summarized as follows (Webster & Oliver, 2007):

1. Model the variogram model of the SOC data.
2. Define a random path visiting all grid nodes across the study area.
3. For each un-sampled node, determine a searching window to obtain the conditional dataset (sample data and simulated values within the searching window) for the node.
4. Estimate the mean and variance of SOC for the node location using kriging and the conditional dataset, and build the conditional cumulative distribution function (ccdf) of SOC based on the assumption of Gaussian behavior;
5. Draw a simulated value randomly from the ccdf and add the simulated value to the conditioning dataset;
6. The calculation proceeds to the next node until all grid nodes have been simulated.

Since the sampling locations in 1980 were recorded by text descriptions, some location errors may have occurred; thus, the assumption of a 500 m location description error was applied during the SGS of SOC₁₉₈₀ based on our field-work experiences in the area. Specifically, the SOC₁₉₈₀ sampling locations were first perturbed randomly within a buffer circle of 500 m in diameter, and then the SGS was conducted to generate 200 SOC₁₉₈₀realizations. A total of 1000 SGS-generated SOC₁₉₈₀realizations were obtained by repeating this procedure 5 times (the sampling locations in SOC₁₉₈₀ were randomly perturbed 5 times). Thus, the uncertainties resulting from the location description error of SOC₁₉₈₀ were considered in this study. While for SOC₂₀₀₀ and SOC₂₀₁₅, the SGS method was directly used.

3. Results

3.1 Descriptive statistics of the SOC contents

<Fig. 2>

Descriptive statistics of the SOC contents on the three sampling dates (Fig. 2) showed that the mean topsoil SOC contents increased from 13.34 g kg⁻¹ in 1980 to 16.99 g kg⁻¹ in 2000, and then decreased to 14.67 g kg⁻¹ in 2015. The net increment of SOC contents during the period of 1980-2000 was 3.65 g kg⁻¹, while the net decrement during the subsequent 15 years (2000-2015) was 2.32 g kg⁻¹. The ranges between the minimum and maximum values for SOC₁₉₈₀, SOC₂₀₀₀, and SOC₂₀₁₅ were 35.22 g kg⁻¹, 29.29 g kg⁻¹, and 30.62 g kg⁻¹, respectively. The coefficients of variation (CV) for SOC₁₉₈₀, SOC₂₀₀₀, and SOC₂₀₁₅ were all moderate (CVs ranging from 25% to 36%). However, all CVs exceeded 20%, indicating considerable variations in the SOC contents among the three sampling dates. The value distribution of SOC₁₉₈₀ was slightly positively skewed, with a skewness of 1.39. While for SOC₂₀₀₀ and SOC₂₀₁₅, their value distributions were symmetrical, with small skewness values of 0.36 and 0.06, respectively. The normal Q-Q graphs further indicated that SOC₂₀₀₀ and SOC₂₀₁₅ were both approximately normal distributions, while the value distribution of SOC₁₉₈₀ was approximately normal after 2 outliers were removed (Figure S1).

The experimental variograms of SOC in the three sampling dates were presented in Fig. 3. Fig. 3 showed that the nugget to sill ratios for the SOC contents in 1980, 2000, and 2015 were 38%, 55%, and 84%, respectively, indicating an overall trend of decreasing SOC spatial autocorrelation over the past 35 years. The range of the spatial autocorrelation continuously decreased from 38km in 1980 to 33km in 2015 (35km in 2000), and the R-squared values for the fitted variogram models of SOC₁₉₈₀, SOC₂₀₀₀, and SOC₂₀₁₅ were 0.95, 0.83, and 0.29, respectively. Therefore, compared to the spatial structures of SOC₁₉₈₀ and SOC₂₀₀₀, the relatively short range of spatial autocorrelation and the worse goodness of fit for SOC₂₀₁₅ indicated that external factors, such as anthropogenic activities, may have a significant impact on the spatial variability of SOC₂₀₁₅ in the area.

<Fig. 3>

3.2 Spatial distribution patterns of SOC

<Fig. 4>

The spatial distribution maps of the SOC contents derived by the OK method were presented in Fig. 4, with a kriging error range of 1.16-3.67 g kg⁻¹, 1.11-4.41 g kg⁻¹, and 1.57-2.29 g kg⁻¹ for SOC₁₉₈₀, SOC₂₀₀₀, and SOC₂₀₁₅, respectively (Figure S2). Overall, the SOC distribution patterns on the three sampling dates were similar, with high SOC contents in the southeast (mainly surrounding Taihu Lake) and low SOC contents in other parts of the study area. However, differences in the local details of the spatial patterns of SOC still existed among the three sampling dates. The high-value areas with SOC₁₉₈₀ exceeding 18 g kg⁻¹ were mainly distributed in the southeast of the study area, while the low-value areas with SOC₁₉₈₀ < 10 g kg⁻¹ were scattered along the southern side of the Yangtze River and the areas near the western boundary of the study area. The SOC₁₉₈₀ in most parts of the study area ranged from 10 to 18 g kg⁻¹. However, in 2000, the high-value areas with SOC > 18 g kg⁻¹ expanded significantly across the study area; these areas were located throughout the whole southeastern parts of the study area and in several small areas in Jiangyin, Yixing, and Jintan city. The areas with moderate values of SOC₂₀₀₀ between 10-18 g kg⁻¹ were observed in the northwest (Dantu, Danyan), in the southwest (Liyang, Jintan), and near the Yangtze River (Zhangjiagang, Taicang). In 2015, the SOC contents in most parts of the study area varied from 10 g kg⁻¹ to 18 g kg⁻¹, while the high-value areas with SOC₂₀₁₅ > 18 g kg⁻¹ were very limited and were only distributed in Yixing and southwestern Changshu.

3.3 Temporal changes in SOC

<Fig. 5>

The spatial patterns of the SOC changes during the three time periods were presented in Fig. 5. In the first two decades (1980-2000), the areas with relatively large SOC increments (> 5 g kg⁻¹) were mainly distributed in the north (along the Yangtze River) and southwest of the study area, while the areas with relatively large SOC decrements (> 5 g kg⁻¹) were scattered in the northeastern parts (brown areas in Fig. 5a). Changes in the SOC contents in the major croplands of the study area varied from -12.4 to 15.1 g kg⁻¹. In contrast, the SOC contents for most of the study area decreased during the period of 2000-2015; in particular, the areas with SOC decrements > 5 g kg⁻¹ expanded significantly (mainly located in the east, Fig. 5b). A slight decrease in the SOC contents (decrement < 3 g kg⁻¹) across the study area could be intuitively observed (yellow areas), while the increases in SOC mainly occurred in the northeastern, northwestern, and southeastern parts of study area (green areas in Fig. 5b), with a small increment of less than 5 g kg⁻¹. Over the entire 35 years (Fig. 5c), changes in the SOC contents in the topsoil of the major croplands varied from -21.3 to 10.2 g kg⁻¹, and the SOC for most parts of the study area increased, except for that in the southeastern parts (close to Changshu city), where SOC declined significantly (with SOC decrement > 5 g kg⁻¹).

3.4 Probability of SOC increase/decrease

<Fig. 6>

The probability maps for the increases/decreases in SOC over the three time periods were calculated based on the SGS-generated SOC realizations (Text S1 and Fig. 6). During 1980-2000, the areas with significant SOC increases were mainly distributed throughout the study area, except for several areas (green regions in Fig. 6a) scattered around Taihu Lake. However, from 2000-2015, the probabilities of SOC increase in most areas were less than 0.40, while the areas with higher probabilities (0.50-0.70) of SOC increase were mainly distributed in the western parts and the northeastern corner of the study area (Fig. 6b). Over the entire 35-year period (1980-2015), the areas with significantly increased SOC were identified in the western and northeastern parts near the Yangtze River (Fig. 6c). However, for the probability of SOC decreases (Fig. 6d-f), a high probability of SOC decreases over the period of 2000-2015 in the southeastern parts of the study area can be intuitively observed. Over the entire 35-year period (1980-2015), the areas with significantly decreased SOC appeared to be very limited and were mainly located in northwestern Kunshan city.

Based on the uncertainty intervals of the changes in SOC (Fig. 7), the average area percentages of the decreases in SOC over the periods of 1980-2000, 2000-2015, and 1980-2015 were estimated at 21%, 62%, and 40%, respectively. This global information on the area proportions of the SOC changes across the study area implied that the SOC changes went through two distinct stages: SOC increases were predominant over the first two decades (the SOC for 79% of the study area increased during 1980-2000, Fig. 7, left) while SOC decreases became predominant in the subsequent 15 years (the SOC for 62% of the study area decreased during 2000-2015, Fig. 7, middle). However, over the entire 35-year period (1980-2015), the SOC for 60% of the study area increased (Fig. 7, right), indicating an overall trend of SOC accumulation in the area.

<Fig. 7>

4. Discussion

4.1 Driving factors of spatiotemporal changes in SOC

The differing parent materials or bedrocks of the soil types have a profound influence on SOC levels (Araujo et al., 2017; Angst et al., 2018). Fig. 8a showed that the average SOC contents for the paddy soils (13.62 g kg⁻¹, 17.73 g kg⁻¹, and 14.79 g kg⁻¹ in 1980, 2000, and 2015, respectively) were the highest among the three predominant soil types in the area, followed by those of the yellow-brown soils (13.62 g kg⁻¹, 17.73 g kg⁻¹, and 14.79 g kg⁻¹ in 1980, 2000, and 2015, respectively) and the fluvo-aquic soils (10.31 g kg⁻¹, 12.71 g kg⁻¹, and 13.39 g kg⁻¹ in 1980, 2000, and 2015, respectively). The sorting order of the SOC contents for each soil type remained unchanged among the different sampling dates, indicating that the influences of soil types on the SOC levels in the area were still important. The paddy soils in southern Jiangsu Province were mainly developed from alluvial materials and lacustrine deposits. The high SOC contents were mainly caused by the waterlogged soils in paddy fields where the anaerobic conditions decreased the rate of SOC decomposition (Liu et al., 2006; Li et al., 2018a). Moreover, the physical and chemical properties of the paddy soils were significantly different from those of the other two soil types (fluvo-aquic soils and yellow-brown soils) due to the generally more intensive agricultural activities in the paddy soils (Liu et al., 2006; Liu et al., 2019). During the periodic submergence and drainage, a large amount of amorphous Fe and Al oxides resulting from the frequent rice cultivation significantly enhanced the soil aggregate stability, thereby promoting the accumulation of SOC in the paddy soils (Gong, 1999; Heng et al., 2010; Wei et al., 2017; Xue et al., 2019). However, the fluvo-aquic soils and yellow-brown soils were saturated with water for a relatively short time, and the amorphous Fe and Al oxides concentrations were significantly lower than those in paddy soils (Li et al., 2003; Heng et al., 2010). Therefore, the average SOC in the fluvo-aquic and yellow-brown soils was relatively low. In addition, compared to the fluvo-aquic and yellow-brown soils, the average SOC

in the paddy soils differed significantly among the three sampling dates, indicating a stronger influence of agricultural management practices on the SOC changes in the paddy soils in the area.

Agricultural management practices, in particular the application of chemical fertilizers, play an essential role in affecting SOC changes (Lu et al., 2009; Alavaisha et al., 2019). For example, the use of chemical fertilizers has been identified as one of the dominant anthropogenic contributors to SOC accumulation on the North China Plain (Han et al., 2018), in the Yellow River basin (Gong et al., 2011), in the Loess Plateau region (Guo et al., 2011), and on the Huang-Huai-Hai Plains of China (Kong et al., 2013). However, in southern Jiangsu Province, chemical fertilizer inputs to the soils went through two distinct stages over the past three decades. The application of chemical fertilizers, including synthetic N fertilizers, increased continuously before 2000, and declined thereafter (Fig. 8b). An increase in the inputs of chemical fertilizers (in particular synthetic N fertilizers) before 2000 made a significant contribution to the increased SOC because the enhanced crop biomass resulted in proportionally increased soil carbon inputs from the aboveground residues and roots over the first two decades (Li et al., 2013; Zhao et al., 2018). Since 1999, the chemical fertilizer inputs in the area have continuously declined, which was closely related to the decreased cropland areas due to the rapid urbanization process (Lu et al., 2017). Consequently, the importance of the changes in soil carbon input resulting from the land use change should not be overlooked when identifying the dominant driving factors of the SOC change in the area.

<Fig. 8>

Crop-derived carbon is the major source of carbon input in cropland soils (Wiesmeier et al., 2014; Wang et al., 2015b). Fig. 9a showed that the average soil carbon inputs in the major croplands in the area went through two distinct stages over the past three decades. The soil carbon inputs from the crops (straw/stover returned to the soils plus roots) increased continuously before 2000, and fluctuated greatly thereafter. The rapid increase of carbon inputs before 2000 was the significant contributor to SOC accumulation over the first two decades because the initial SOC content (13.34 g kg^{-1}) in 1980 was still relatively low. In 2000, the SOC levels in the area reached a relatively high level (16.99 g kg^{-1}). However, the cropland areas have decreased significantly since 2000 due to the rapid urban expansion, resulting in the strong fluctuations in the soil carbon inputs in the area. The mean soil carbon inputs of $1.44 \text{ t ha}^{-1} \text{ yr}^{-1}$ after 2000 may still be insufficient for maintaining the high SOC levels in 2000. The soil carbon inputs after 2000 differed significantly among the 14 county-level cities (Fig. 9b), with increased carbon inputs occurring in the west (Danyang, Liyang, Jintan, Yixing), while the areas with declining carbon inputs mainly surrounded Taihu Lake (Wujiang, Kunshan, Wuxian). This regional difference in soil carbon inputs was closely related to the rapid urbanization process in the study area (Fig. 10a).

Urban expansion may lead to fragmentation of the cropland landscape, which was a dominant factor limiting soil carbon inputs (Liu et al., 2011; Hao, 2012; Xia et al., 2017). Fig. 10b showed that the ratio between urban land area and cropland area was negatively correlated with the soil carbon inputs during the period of 2000-2015, indicating that the cropland soil C inputs in the areas with higher urbanization rates were low. Moreover, socioeconomic development actively pushes forward the marketization process of land use (Bao et al., 2019), particularly for industries and tertiary industries, resulting in the reduction of agricultural investment. For example, the number of people employed in agriculture in the area declined significantly during 2000-2015 (from 2.85 million to 1.42 million), while the employees in the tertiary industry increased by two times, and was almost 6 times higher than those in agriculture in southern Jiangsu Province (Jiangsu Bureau of Statistics, 2001-2016), implying that staple food agriculture in the area was becoming less important. This also caused poor management of the cropland soils. Therefore, although the increasing soil C input resulting from the enhanced crop productivity due to chemical fertilizers benefited the SOC accumulation over the first two decades, the stagnant soil carbon inputs associated with rapid urbanization and economic growth constrained the SOC accumulation in the subsequent 15 years (2000-2015).

<Fig. 9>

<Fig. 10>

4.2 Challenge for soil carbon sequestration

Our results, together with the existing studies in the area, provide more details on the regional differences of the changes in SOC during the period of 2000-2015 (Fig. 11), which may provide more insights into the future C sequestration in the area. Fig. 11a showed that a continuous decline in SOC during the period of 2000-2015 mainly occurred in the eastern part of the study area (i.e., Changshu, Wujiang), where the reduction in cropland area was more severe than that in the western parts, although the SOC levels in the west decreased first and then increased steadily (i.e., Jintan, Yixing) (Fig. 11b). The trend of the SOC changes in the western parts of the study area can be attributed to the large-scale implementation of the crop straw/stover return policy since 2000 (Zhao et al., 2018).

Moreover, the SOC stock in croplands of the study area increased from 30.95 t ha⁻¹ in 1980 to 42.12 t ha⁻¹ in 2000, and then decreased to 37.53 t ha⁻¹ in 2015, which was highly consistent with the changes in SOC contents (Table 1, Text S2, and Figure S3). The increase rate of SOC stock over the past 35 years was 0.19 t ha⁻¹yr⁻¹, which was slightly higher than the estimate of Jiangsu Province (0.16 t ha⁻¹ yr⁻¹) by (Liao et al., 2009) and the estimate of Chinese cropland soils (0.14 t ha⁻¹ yr⁻¹) by (Zhao et al., 2018), indicating a considerable SOC sequestration potential in the study area. However, although cropland SOC accumulation can be achieved through enhancing the C input (i.e., improving the straw/stover management), future SOC sequestration in the area is still facing big challenges, in particular the balance between agricultural development and the urbanization process for ensuring soil carbon input to maintain the SOC levels. A high SOC level not only benefits the biodiversity of agroecosystems (Wiesmeier et al., 2019), but also improves key soil functions, such as the capacity for acid buffering (Ritchie & Dolling, 1985), which are especially important for areas with accelerated soil acidification, e.g., this study area (Xie et al., 2019). Therefore, management practices and policies for enhancing the soil carbon input should still be given the top priority for maintaining the stability of SOC levels.

<Fig. 11>

4.3 Implications and limitations

Our study explored the spatiotemporal changes of cropland SOC in a rapidly urbanizing area and identified their primary drivers. We found that, although the enhanced soil C input benefited the cropland SOC accumulation during 1980-2000, the rapid urban expansion and industrial economic growth during the subsequent 15 years may lower SOC due to the decreased soil C input. The urbanizing and industrializing area may overlook the development of agriculture, and the low economic investment in cropland management often caused decreased C input in cropland soils, which implied that the coordinated development of industry, agriculture, and urbanization process is particularly important for cropland SOC sequestration.

Our study investigated the spatiotemporal changes of SOC at a time scale of more than 10 years. However, using the geostatistical method to explore changes in SOC over a shorter time period (i.e., a time period of fewer than five years) may be not feasible, because the detectable changes in SOC still can not be directly measured due to the high stability of SOC pools and slow turnover time of SOC (Yang et al., 2015; Yang et al., 2020). Therefore, the development of new methodologies for incorporating SOC dynamical mechanism into the geostatistical mapping framework (i.e., through the “space for time” method) is necessary.

5. Conclusion

Our results revealed that the mean topsoil soil organic carbon (SOC) contents in 1980, 2000, and 2015 were 13.34 g kg⁻¹, 16.99 g kg⁻¹, and 14.67 g kg⁻¹, respectively. The SOC changes went through two distinct stages, with a net increment of 3.65 g kg⁻¹ in the period of 1980-2000 and a net decrement of 2.32 g kg⁻¹ over the period of 2000-2015. The areas with high SOC contents were identified in the southeast of the study area, while the SOC contents in other parts of the study area were relatively low. The spatial patterns of the

SOC changes were significantly different, with an overall SOC increase throughout the study area during the period of 1980-2000, the areas with declines in SOC were mainly distributed in the southeast during 2000-2015. The SOC increase over the first two decades (1980-2000) was largely attributed to the enhanced soil carbon inputs resulting from the increase in fertilizer application (in particular low-cost N fertilizers), while the stagnation of soil carbon inputs associated with the rapid urbanization and economic growth constrained the SOC accumulation in the subsequent 15 years (2000-2015).

With the rapid urbanization and socioeconomic development, significant regional differences in the SOC change between the east and west of the study area occurred in the last 15 years (2000-2015). Thus, we suggest that maintaining the stability of SOC by enhanced the soil carbon inputs is becoming a priority issue and needs to be addressed not only in the scientific realm, but also within the policy arena. Scientific management practices and powerful economic policy can be used as a guide for sustainable potential of SOC sequestration, especially in areas experiencing rapid urbanization processes.

Acknowledgments

This work was supported by the Natural Science Foundation of China (41971067) and the National Key Research and Development Program of China (2017YFA0603002).

References

- Alavaisha, E., Manzoni, S. and Lindborg, R. (2019). Different agricultural practices affect soil carbon, nitrogen and phosphorous in Kilombero -Tanzania. *Journal of Environment management*, 234, 159-166.<http://doi.org/10.1016/j.jenvman.2018.12.039>
- Álvaro-Fuentes, J., Easter, M., Cantero-Martinez, C. and Paustian, K. (2011). Modelling soil organic carbon stocks and their changes in the northeast of Spain. *European Journal of Soil Science*, 62, 685-695.<http://doi.org/10.1111/j.1365-2389.2011.01390.x>
- Angst, G., Messinger, J., Greiner, M., Häusler, W., Hertel, D., Kirfel, K., Kögel-Knabner, I., Leuschner, C., Rethemeyer, J. and Mueller, C. W. (2018). Soil organic carbon stocks in topsoil and subsoil controlled by parent material, carbon input in the rhizosphere, and microbial-derived compounds. *Soil Biology and Biochemistry*, 122, 19-30.<http://doi.org/10.1016/j.soilbio.2018.03.026>
- Araujo, M. A., Zinn, Y. L. and Lal, R. (2017). Soil parent material, texture and oxide contents have little effect on soil organic carbon retention in tropical highlands. *Geoderma*, 300, 1-10.<http://doi.org/10.1016/j.geoderma.2017.04.006>
- Bao, J., Gao, S. and Ge, J. (2019). Dynamic land use and its policy in response to environmental and social-economic changes in China: A case study of the Jiangsu coast (1750–2015). *Land Use Policy*, 82, 169-180.<http://doi.org/10.1016/j.landusepol.2018.12.008>
- Bas, V. W., Keith, P., Jeroen, M., Esther, G., Gabriela, B. and Mark, E. (2010). Agricultural management explains historic changes in regional soil carbon stocks. *Proceedings of the National Academy of Sciences of the United States of America*, 107, 14926-14930.<http://doi.org/10.1073/pnas.1002592107>
- Bolinder, M. A., Angers, D. A. and Dubuc, J. P. (1997). Estimating shoot to root ratios and annual carbon inputs in soils for cereal crops. *Agriculture, Ecosystems & Environment*, 63, 61-66.[http://doi.org/10.1016/S0167-8809\(96\)01121-8](http://doi.org/10.1016/S0167-8809(96)01121-8)
- Borrelli, P., Panagos, P., Lugato, E., Alewell, C., Ballabio, C., Montanarella, L. and Robinson, D. A. (2018). Lateral carbon transfer from erosion in noncroplands matters. *Global Change Biology*, 24, 3283-3284.<http://doi.org/10.1111/gcb.14125>

- Bren d'Amour, C., Reitsma, F., Baiocchi, G., Barthel, S., Guneralp, B., Erb, K. H., Haberl, H., Creutzig, F. and Seto, K. C. (2017). Future urban land expansion and implications for global croplands. *Proceedings of the National Academy of Sciences of the United States of America*, 114, 8939-8944. <http://doi.org/10.1073/pnas.1606036114>
- de Blécourt, M., Gröngroft, A., Baumann, S. and Eschenbach, A. (2019). Losses in soil organic carbon stocks and soil fertility due to deforestation for low-input agriculture in semi-arid southern Africa. *Journal of Arid Environments*, 165, 88-96. <http://doi.org/10.1016/j.jaridenv.2019.02.006>
- Deng, X., Chen, X., Ma, W., Ren, Z., Zhang, M., Grieneisen, M. L., Long, W., Ni, Z., Zhan, Y. and Lv, X. (2018). Baseline map of organic carbon stock in farmland topsoil in East China. *Agriculture, Ecosystems & Environment*, 254, 213-223. <http://doi.org/10.1016/j.agee.2017.11.022>
- Ding, W. (2009). GIS-based evaluation of farmland productivity of Liyang city, Jiangsu Province (In Chinese). Nanjing Agriculture University, Nanjing.
- Fan, J., McConkey, B. G., Liang, B. C., Angers, D. A., Janzen, H. H., Kröbel, R., Cerkowniak, D. D. and Smith, W. N. (2019). Increasing crop yields and root input make Canadian farmland a large carbon sink. *Geoderma*, 336, 49-58. <http://doi.org/10.1016/j.geoderma.2018.08.004>
- Fujisaki, K., Chevallier, T., Chapuis-Lardy, L., Albrecht, A., Razafimbelo, T., Masse, D., Ndour, Y. B. and Chotte, J.-L. (2018). Soil carbon stock changes in tropical croplands are mainly driven by carbon inputs: A synthesis. *Agriculture, Ecosystems & Environment*, 259, 147-158. <http://doi.org/10.1016/j.agee.2017.12.008>
- Gao, J., Han, G., Xu, M., Chen, X., Ding, R., Huang, H. and Ren, T. (2016). The problems on the quality of cultivated land in southern Jiangsu Province, China (In Chinese). *Shanghai Agricultural Science and Technology*, 4, 86-88. <http://doi.org/CNKI:ISSN:1001-0106.0.2016-04-054>
- Gao, J., Pan, J., Liu, S. and Jiang, X. (2011). Influence of land use change on topsoil organic carbon storage of paddy fields in Wujiang city. *Geo-information Science*, 13, 164-169. <http://doi.org/10.3724/sp.j.1047.2011.00164>
- Gao, Z., Peng, B., Yu, J., Pu, L. and Zhang, L. (2005). Effect of land use changes on soil conditions in the developed areas: a case of Kunshan in Jiangsu Province (In Chinese). *Journal of Natural resources*, 20, 44-51. [http://doi.org/CNKI:ISSN:1000-3037\(2005\)-01-0044-08](http://doi.org/CNKI:ISSN:1000-3037(2005)-01-0044-08)
- Gong, W., Yan, X. and Wang, J. (2011). The effect of chemical fertilizer on soil organic carbon renewal and CO₂ emission—a pot experiment with maize. *Plant and Soil*, 353, 85-94. <http://doi.org/10.1007/s11104-011-1011-8>
- Gong, Z. (1999). Chinese soil taxonomy: theory approaches and application (In Chinese). China Science Press, Beijing.
- Goovaerts, P. (1997). *Geostatistics for Natural Resources Evaluation*. Oxford University Press, New York.
- Guo, L. B. and Gifford, R. M. (2002). Soil carbon stocks and land use change: a meta analysis. *Global Change Biology*, 8, 345-360. <http://doi.org/10.1046/j.1354-1013.2002.00486.x>
- Guo, S., Wu, J., Coleman, K., Zhu, H., Li, Y. and Liu, W. (2011). Soil organic carbon dynamics in a dryland cereal cropping system of the Loess Plateau under long-term nitrogen fertilizer applications. *Plant and Soil*, 353, 321-332. <http://doi.org/10.1007/s11104-011-1034-1>
- Guo, Z., Zuo, Q., Li, M., Min, Y., Xu, J., Shen, W. and Gu, Y. (2007). Soil fertility investigation and quality assessment in Taicang, changes of soil pH, organic matter, total N, available P, rapidly available K and CEC (In Chinese). *Soils*, 39, 318-321. <http://doi.org/10.3321/j.issn:0253-9829.2007.02.029>
- Han, D., Wiesmeier, M., Conant, R. T., Kuhnel, A., Sun, Z., Kogel-Knabner, I., Hou, R., Cong, P., Liang, R. and Ouyang, Z. (2018). Large soil organic carbon increase due to improved agrono-

- mic management in the North China Plain from 1980s to 2010s. *Global Change Biology*, 24, 987-1000.<http://doi.org/10.1111/gcb.13898>
- Han, S., Pu, L., Chen, F., Zhang, C., Zhang, J. and Peng, B. (2007). Response of soil properties to change in land use in a typical area of the Yangtze River Delta, a case study of Xishan city, Jiangsu Province, China (In Chinese). *Acta Ecologica Sinica*, 44, 612-619.<http://doi.org/10.11766/trxb200608210405>
- Hao, C. (2012). Research of land use and soil organic carbon dynamics in Binhai new area of China (In Chinese). Nankai University, Tianjin.
- He, L. and Cao, H. (2014). Soil organic matter content and its distribution in Jintan city (In Chinese). *Shanghai Agricultural Science and Technology*, 5, 109.<http://doi.org/CNKI:ISSN:1001-0106.0.2014-05-072>
- Heng, L., Wang, D., Jiang, X., Rao, W., Zhang, W., Guo, C. and Li, T. (2010). Relationship between Fe, Al oxides and stable organic carbon, nitrogen in the Yellow-Brown soils (In Chinese). *Environmental Science*, 31, 2748-2755.<http://doi.org/10.13227/j.hjzk.2010.11.040>
- Hu, J., Wang, D., Sun, R., Wang, C. and Liu, Q. (2008). Variation of soil fertility of farmlands in typical regions in the lower-reaches of the Yangtze River, a case study of Changshu county (In Chinese). *Acta Ecologica Sinica*, 45, 1087-1094.<http://doi.org/trxb10.11766/20007170611>
- Institute of Soil Science Chinese Academy of Sciences (1978). *Soil Physics and Chemistry Analysis*. Shanghai Science & Technology Press, Shanghai.
- Jiang, G., Xu, M., He, X., Zhang, W., Huang, S., Yang, X., Liu, H., Peng, C., Shirato, Y., Iizumi, T., Wang, J. and Murphy, D. V. (2014). Soil organic carbon sequestration in upland soils of northern China under variable fertilizer management and climate change scenarios. *Global Biogeochemical Cycles*, 28, 319-333.<http://doi.org/10.1002/2013gb004746>
- Jiangsu Bureau of Statistics (2001-2016). *Jiangsu Statistical Yearbook 2001-2016*. China Statistics Press, Beijing.
- Keel, S. G., Anken, T., Büchi, L., Chervet, A., Fließbach, A., Flisch, R., Huguenin-Elie, O., Mäder, P., Mayer, J., Sinaj, S., Sturny, W., Wüst-Galley, C., Zihlmann, U. and Leifeld, J. (2019). Loss of soil organic carbon in Swiss long-term agricultural experiments over a wide range of management practices. *Agriculture, Ecosystems & Environment*, 286, 106654.<http://doi.org/10.1016/j.agee.2019.106654>
- Kong, X., Li, B., Lal, R., Li, K. and Bai, Y. (2013). Soil Organic Carbon Pool under Diverse Chemical Fertilizer Management in Huang-Huai-Hai Plains, China. *Agricultural Research*, 2, 68-80.<http://doi.org/10.1007/s40003-013-0055-9>
- Leifeld, J., Angers, D. A., Chenu, C., Fuhrer, J., Katterer, T. and Powlson, D. S. (2013). Organic farming gives no climate change benefit through soil carbon sequestration. *Proceedings of the National Academy of Sciences of the United States of America*, 110, E984.<http://doi.org/10.1073/pnas.1220724110>
- Li, H. Y., Wang, H., Wang, H. T., Xin, P. Y., Xu, X. H., Ma, Y., Liu, W. P., Teng, C. Y., Jiang, C. L., Lou, L. P., Arnold, W., Cralle, L., Zhu, Y. G., Chu, J. F., Gilbert, J. A. and Zhang, Z. J. (2018a). The chemodiversity of paddy soil dissolved organic matter correlates with microbial community at continental scales. *Microbiome*, 6, 187.<http://doi.org/10.1186/s40168-018-0561-x>
- Li, S., Zhou, J., Wang, H., Chen, X. and Du, C. (2003). Characteristics of fixation and release of phosphorus in three soils (In Chinese). *Acta Pedologica Sinica*, 40, 908-914.<http://doi.org/10.11766/trxb200206240616>
- Li, X., McCarty, G. W., Karlen, D. L. and Cambardella, C. A. (2018b). Topographic metric predictions of soil redistribution and organic carbon in Iowa cropland fields. *Catena*, 160, 222-232.<http://doi.org/10.1016/j.catena.2017.09.026>
- Li, Z. T., Li, X. G., Li, M., Yang, J. Y., Turner, N. C., Wang, X. Y. and Li, F. M. (2013). County-scale changes in soil organic carbon of croplands in southeastern Gansu province of China from the 1980s to the

- Mid-2000s. Soil Science Society of America Journal, 77, 2111.<http://doi.org/10.2136/sssaj2013.05.0192>
- Li, Z. W., Liu, L., Nie, X. D., Chang, X. F., Liu, C. and Xiao, H. B. (2016). Modeling soil organic carbon loss in relation to flow velocity and slope on the Loess Plateau of China. Soil Science Society of America Journal, 80, 1341.<http://doi.org/10.2136/sssaj2016.03.0092>
- Liang, Y. (2004). The actualities, problems and countermeasures of soil and fertilizer in Yixing city, Tai Lake area (In Chinese). Nanjing Agriculture University, Nanjing.
- Liao, Q., Zhang, X., Li, Z., Pan, G., Smith, P., Yang, J. and Wu, X. (2009). Increase in soil organic carbon stock over the last two decades in China's Jiangsu Province. Global Change Biology, 15, 861–875.<http://doi.org/10.1111/j.1365-2486.2008.01792.x>
- Liu, K., Huang, J., Li, D., Yu, X., Ye, H., Hu, H., Hu, Z., Huang, Q. and Zhang, H. (2019). Comparison of carbon sequestration efficiency in soil aggregates between upland and paddy soils in a red soil region of China. Journal of Integrative Agriculture, 18, 1348-1359.[http://doi.org/10.1016/s2095-3119\(18\)62076-3](http://doi.org/10.1016/s2095-3119(18)62076-3)
- Liu, Q., Shi, X., Weindorf, D. C., Yu, D., Zhao, Y., Sun, W. and Wang, H. (2006). Soil organic carbon storage of paddy soils in China using the 1:1,000,000 soil database and their implications for C sequestration. Global Biogeochemical Cycles, 20, 1-5.<http://doi.org/10.1029/2006gb002731>
- Liu, W., Zhang, L., Ye, Y., Zou, J., Wang, Y. and Qi, Y. (2011). The content and density of soil organic carbon under different land use types in Shenzhen (In Chinese). Ecological Science, 30, 486-492.<http://doi.org/CNKI:ISSN:1008-8873.0.2011-05-004>
- Liu, Y. S., Wang, J. Y. and Long, H. L. (2010). Analysis of arable land loss and its impact on rural sustainability in Southern Jiangsu Province of China. Journal of Environment management, 91, 646-653.<http://doi.org/10.1016/j.jenvman.2009.09.028>
- Lu, F., Wang, X., Han, B., Ouyang, Z., Duan, X., Zheng, H. and Miao, H. (2009). Soil carbon sequestrations by nitrogen fertilizer application, straw return and no-tillage in China's cropland. Global Change Biology, 15, 281-305.<http://doi.org/10.1111/j.1365-2486.2008.01743.x>
- Lu, X., Shi, Y., Chen, C. and Yu, M. (2017). Monitoring cropland transition and its impact on ecosystem services value in developed regions of China: A case study of Jiangsu Province. Land Use Policy, 69, 25-40.<http://doi.org/10.1016/j.landusepol.2017.08.035>
- Luo, Y., Li, Q., Shen, J., Wang, C., Li, B., Yuan, S., Zhao, B., Li, H., Zhao, J., Guo, L., Li, S. and He, Y. (2019). Effects of agricultural land use change on organic carbon and its labile fractions in the soil profile in an urban agricultural area. Land Degradation & Development, 30, 1875-1885.<http://doi.org/10.1002/ldr.3388>
- Meersmans, J., Van Wesemael, B., Goidts, E., Van Molle, M., De Baets, S. and De Ridder, F. (2011). Spatial analysis of soil organic carbon evolution in Belgian croplands and grasslands, 1960-2006. Global Change Biology, 17, 466-479.<http://doi.org/10.1111/j.1365-2486.2010.02183.x>
- Nandwa, S. M. (2001). Soil organic carbon (SOC) management for sustainable productivity of cropping and agro-forestry systems in Eastern and Southern Africa. Nutrient Cycling in Agroecosystems, 61, 143-158.<http://doi.org/10.1023/A:1013386710419>
- Ou, Y., Rousseau, A. N., Wang, L. and Yan, B. (2017). Spatio-temporal patterns of soil organic carbon and pH in relation to environmental factors—A case study of the Black Soil Region of Northeastern China. Agriculture, Ecosystems & Environment, 245, 22-31.<http://doi.org/10.1016/j.agee.2017.05.003>
- Qiu, L., Zhu, J., Zhu, Y., Hong, Y., Wang, K. and Deng, J. (2013). Land use changes induced soil organic carbon variations in agricultural soils of Fuyang County, China. Journal of Soils and Sediments, 13, 981-988.<http://doi.org/10.1007/s11368-013-0684-4>
- Ramesh, T., Bolan, N. S., Kirkham, M. B., Wijesekara, H., Kanchikerimath, M., Srinivasa Rao, C., Sandeep, S., Rinklebe, J., Ok, Y. S., Choudhury, B. U., Wang, H., Tang, C., Wang, X., Song, Z. and Freeman Ii, O.

- W. (2019). Soil organic carbon dynamics: Impact of land use changes and management practices: A review. *Advances in Agronomy*, 156, 1-107. <http://doi.org/10.1016/bs.agron.2019.02.001>
- Ritchie, G. S. P. and Dolling, P. J. (1985). The role of organic matter in soil acidification. *Australian Journal of Soil Research*, 23, 569-576. <http://doi.org/10.1071/SR9850569>
- Sandeep, S., Manjaiah, K. M., Pal, S. and Singh, A. K. (2016). Soil carbon fractions under maize-wheat system: effect of tillage and nutrient management. *Environmental Monitoring and Assessment*, 188, 14. <http://doi.org/10.1007/s10661-015-4995-3>
- Schillaci, C., Acutis, M., Vesely, F. and Saia, S. (2019). A simple pipeline for the assessment of legacy soil datasets: An example and test with soil organic carbon from a highly variable area. *Catena*, 175, 110-122. <http://doi.org/10.1016/j.catena.2018.12.015>
- Schillaci, C., Saia, S. and Acutis, M. (2018). Modelling of soil organic carbon in the Mediterranean area: a systematic map. *Rendiconti Online Societa Geologica Italiana*, 46, 161-166. <http://doi.org/10.3301/ROL.2018.68>
- Shi, P., Zhang, Y., Li, P., Li, Z., Yu, K., Ren, Z., Xu, G., Cheng, S., Wang, F. and Ma, Y. (2019). Distribution of soil organic carbon impacted by land-use changes in a hilly watershed of the Loess Plateau, China. *Science of the Total Environment*, 652, 505-512. <http://doi.org/10.1016/j.scitotenv.2018.10.172>
- Song, X., Yang, J., Zhao, M., Zhang, G., Liu, F. and Wu, H. (2019). Heuristic cellular automaton model for simulating soil organic carbon under land use and climate change: A case study in eastern China. *Agriculture, Ecosystems & Environment*, 269, 156-166. <http://doi.org/10.1016/j.agee.2018.09.034>
- Vågen, T. G. and Winowiecki, L. A. (2013). Mapping of soil organic carbon stocks for spatially explicit assessments of climate change mitigation potential. *Environmental Research Letters*, 8, 015011. <http://doi.org/10.1088/1748-9326/8/1/015011>
- van Vliet, J., Eitelberg, D. A. and Verburg, P. H. (2017). A global analysis of land take in cropland areas and production displacement from urbanization. *Global Environmental Change*, 43, 107-115. <http://doi.org/10.1016/j.gloenvcha.2017.02.001>
- VandenBygaart, A. J., Gregorich, E. G., Angers, D. A. and Stoklas, U. F. (2004). Uncertainty analysis of soil organic carbon stock change in Canadian cropland from 1991 to 2001. *Global Change Biology*, 10, 983-994. <http://doi.org/10.1111/j.1365-2486.2004.00780.x>
- Veronesi, F. and Schillaci, C. (2019). Comparison between geostatistical and machine learning models as predictors of topsoil organic carbon with a focus on local uncertainty estimation. *Ecological Indicators*, 101, 1032-1044. <http://doi.org/10.1016/j.ecolind.2019.02.026>
- Wan, Y., Zhou, S. and Zhao, Q. (2006). Study on spatial and temporal variability of soil basic properties in typical area of southern Jiangsu Province: a case study in Kunshan city (In Chinese). *Geographical Research*, 25, 303-310. <http://doi.org/10.11821/yj2006020014>
- Wang, G., Huang, Y., Zhang, W., Yu, Y. and Sun, W. (2015a). Quantifying carbon input for targeted soil organic carbon sequestration in China's croplands. *Plant and Soil*, 394, 57-71. <http://doi.org/10.1007/s11104-015-2508-3>
- Wang, J., Wang, X., Xu, M., Feng, G., Zhang, W. and Lu, C. a. (2015b). Crop yield and soil organic matter after long-term straw return to soil in China. *Nutrient Cycling in Agroecosystems*, 102, 371-381. <http://doi.org/10.1007/s10705-015-9710-9>
- Webster, R. and Oliver, M. A. (2007). *Geostatistics for Environmental Scientists*. John Wiley & Sons, New York.
- Wei, J., Xiao, D., Zhang, X. and Li, X. (2011). Topography and land use effects on the spatial variation of soil organic carbon: A case study in a typical small watershed of the black soil region in northeast China.

Eurasian Soil Science, 41, 39-47.<http://doi.org/10.1134/s1064229308010055>

Wei, Z., Ji, J., Li, Z. and Yan, X. (2017). Changes in organic carbon content and its physical and chemical distribution in paddy soils cultivated under different fertilisation practices. *Journal of Soils and Sediments*, 17, 2011-2018.<http://doi.org/10.1007/s11368-017-1676-6>

Wiesmeier, M., Hübner, R., Dechow, R., Maier, H., Spörlein, P., Geuß, U., Hangen, E., Reischl, A., Schilling, B., von Lützwow, M. and Kögel-Knabner, I. (2014). Estimation of past and recent carbon input by crops into agricultural soils of southeast Germany. *European Journal of Agronomy*, 61, 10-23.<http://doi.org/10.1016/j.eja.2014.08.001>

Wiesmeier, M., Urbanski, L., Hobbey, E., Lang, B., von Lützwow, M., Marin Spiotta, E., van Wesemael, B., Rabot, E., Ließ, M., Garcia Franco, N., Wollschläger, U., Vogel, H. J. and Kögel Knabner, I. (2019). Soil organic carbon storage as a key function of soils - A review of drivers and indicators at various scales. *Geoderma*, 333, 149-162.<http://doi.org/10.1016/j.geoderma.2018.07.026>

Wu, C. (2014). Analysis of cultivated land quality and agricultural production safety in Dantu city (In Chinese). *Agricultural Equipment & Techonlogy*, 40, 55-57.<http://doi.org/CNKI:ISSN:1671-6337.0.2014-06-020>

Xia, X., Yang, Z., Xue, Y., Shao, X., Yu, T. and Hou, Q. (2017). Spatial analysis of land use change effect on soil organic carbon stocks in the eastern regions of China between 1980 and 2000. *Geoscience Frontiers*, 8, 597-603.<http://doi.org/10.1016/j.gsf.2016.06.003>

Xie, E., Zhao, Y., Li, H., Shi, X., Lu, F., Zhang, X. and Peng, Y. (2019). Spatio-temporal changes of cropland soil pH in a rapidly industrializing region in the Yangtze River Delta of China, 1980–2015. *Agriculture, Ecosystems & Environment*, 272, 95-104.<http://doi.org/10.1016/j.agee.2018.11.015>

Xie, J., Zheng, W. and Tan, H. (2009). Technical report on evaluation of cultivated land and formulated fertilization by soil testing in Danyang City (In Chinese). *Agricultural Equipment & Techonlogy*, 35, 41-44.<http://doi.org/CNKI:ISSN:1671-6337.0.2009-02-029>

Xu, J. and Gong, K. (2014). Soil fertility condition and fertilization measures in farmland in Wuxi, city (In Chinese). *Modern Agricultural Science and Technology*, 24, 202-203.<http://doi.org/CNKI:ISSN:1007-5739.0.2014-24-120>

Xu, M., Wang, X., Jiang, J. and Shen, Q. (2006). Changes in cultivated land utilization pattern and countermeasures in south Jiangsu (In Chinese). *Soils*, 38, 825-829.<http://doi.org/10.3321/j.issn:0253-9829.2006.06.028>

Xu, X., Liu, J., Zhang, S., Li, R., Yan, C. and Wu, S. (2018). Remote sensing monitoring dataset of multi-period land cover in China<http://www.resdc.cn/DOI/doi.aspx?DOIid=54>.

Xue, B., Huang, L., Huang, Y., Zhou, F., Li, F., Kubar, K. A., Li, X., Lu, J. and Zhu, J. (2019). Roles of soil organic carbon and iron oxides on aggregate formation and stability in two paddy soils. *Soil and Tillage Research*, 187, 161-171.<http://doi.org/10.1016/j.still.2018.12.010>

Yan, X., Cai, Z., Wang, S. and Smith, P. (2011). Direct measurement of soil organic carbon content change in the croplands of China. *Global Change Biology*, 17, 1487-1496.<http://doi.org/10.1111/j.1365-2486.2010.02286.x>

Yang, J., Li, A., Yang, Y., Li, G. and Zhang, F. (2020). Soil organic carbon stability under natural and anthropogenic-induced perturbations. *Earth-Sci Rev*, 205, 103199.<http://doi.org/10.1016/j.earscirev.2020.103199>

Yang, L., Song, M., Zhu, A. X., Qin, C., Zhou, C., Qi, F., Li, X., Chen, Z. and Gao, B. (2019). Predicting soil organic carbon content in croplands using crop rotation and Fourier transform decomposed variables. *Geoderma*, 340, 289-302.<http://doi.org/10.1016/j.geoderma.2019.01.015>

Yang, Y., Ji, C., Chen, L., Ding, J., Cheng, X., Robinson, D. and Whitehead, D. (2015). Edaphic rather than climatic controls over ^{13}C enrichment between soil and vegetation in alpine grasslands on the Tibetan Plateau. *Functional Ecology*, 29, 839-848. <http://doi.org/10.1111/1365-2435.12393>

Zhang, X. and Wang, X. (2013). The relationship between the soil organic matter and total nitrogen in cropland in Taicang city (In Chinese). *Anhui Agricultural Science Bulletin*, 19, 57-58. <http://doi.org/10.16377/j.cnki>

Zhao, Y., Wang, M., Hu, S., Zhang, X., Ouyang, Z., Zhang, G., Huang, B., Zhao, S., Wu, J., Xie, D., Zhu, B., Yu, D., Pan, X., Xu, S. and Shi, X. (2018). Economics- and policy-driven organic carbon input enhancement dominates soil organic carbon accumulation in Chinese croplands. *Proceedings of the National Academy of Sciences of the United States of America*, 115, 4045-4050. <http://doi.org/10.1073/pnas.1700292114>

Zhong, C., Hu, R., Wang, M., Xue, W. and He, L. (2020). The impact of urbanization on urban agriculture: Evidence from China. *Journal of Cleaner Production*, 276, 122686. <http://doi.org/10.1016/j.jclepro.2020.122686>

Zhou, Y., Hartemink, A. E., Shi, Z., Liang, Z. and Lu, Y. (2019). Land use and climate change effects on soil organic carbon in North and Northeast China. *Science of the Total Environment*, 647, 1230-1238. <http://doi.org/10.1016/j.scitotenv.2018.08.016>

Table

Table 1 Changes in SOC stock in the study area over the three time periods

Time period	SOC stock change (t ha^{-1})	Annual changes ($\text{t ha}^{-1} \text{ yr}^{-1}$)
1980-2000	11.17	0.56
2000-2015	-4.59	-0.31
1980-2015	6.58	0.19

Figure Captions

Fig. 1 The sampling location (a), elevation (b), and soil type map (c) in the study area.

Fig. 2 Histograms and descriptive statistics of the topsoil SOC contents (g kg^{-1}) in 1980 (a), 2000 (b), and 2015 (c).

SD represents standard deviation, and CV represents coefficient of variation.

Fig. 3 The experimental (dots) and fitted semi-variograms (solid lines) of SOC in 1980, 2000, and 2015.

Fig. 4 Spatial distribution maps of the cropland SOC in 1980 (a), 2000 (b), and 2015 (c).

Fig. 5 Spatial patterns of the SOC changes in cropland over the period of 1980-2000 (a), 2000-2015 (b), and 1980-2015 (c).

Fig. 6 Probability maps of the increases/decreases in cropland SOC over the three time periods

Fig. 6(a)-(c) represent the probability maps of the SOC increases over the period of 1980-2000, 2000-2015, and 1980-2015, respectively; Fig. 6(d)-(f) represent the probability maps of the SOC decreases over the period of 1980-2000, 2000-2015, and 1980-2015, respectively.

Fig. 7 The cumulative frequency curves and uncertainty intervals of the SGS-generated SOC changes over the period of 1980-2000 (a), 2000-2015 (b), and 1980-2015 (c).

Fig. 8 Average SOC contents for the different soil types (a) and the amounts of chemical fertilizers use over the past three decades in southern Jiangsu Province (b).

In Fig. 8a, the bold values represent the average SOC contents, and the error bars represent the standard deviation of the SOC contents. In Fig. 8b, data was sourced from the Jiangsu Bureau of Statistics, <http://tj.jiangsu.gov.cn>.

Fig. 9 Crop-derived carbon inputs over the period of 1980-2015 in southern Jiangsu Province (a), in county-level cities (b),

and the relationship between annual SOC change and carbon inputs among these county-level cities (c).

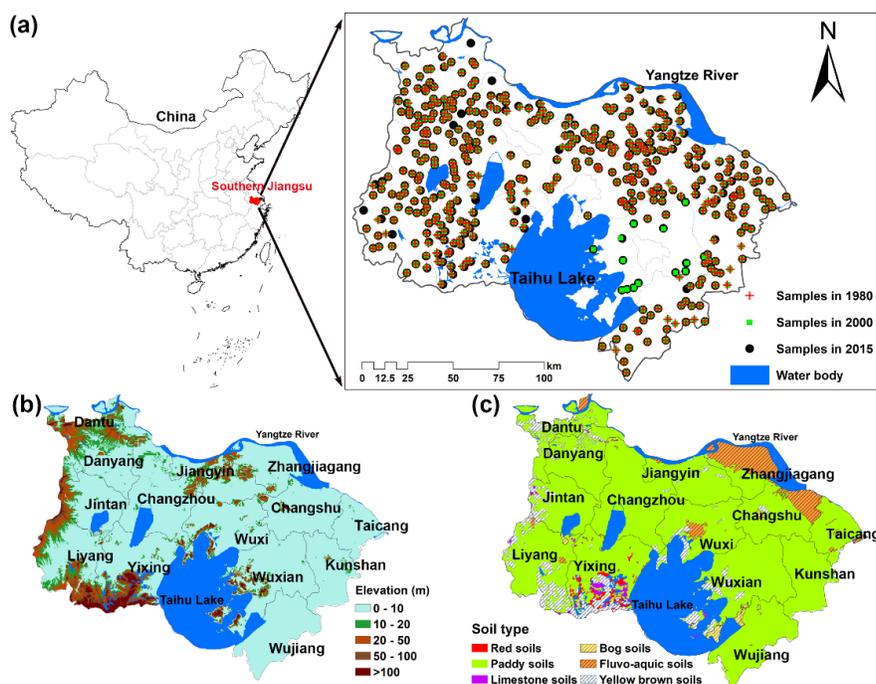
In Fig. 9c, annual SOC change represents the average SOC changes over the past 35 years; carbon inputs represent the average carbon inputs during 1980-2015; Carbon inputs were estimated using the crop yield data recorded by county-level agricultural census (Zhao et al., 2018).

Fig. 10 Changes in the industrial and residential lands over the period of 2000-2010 (a), the relationship between urban expansion and the annual carbon inputs during 2000-2015 (b).

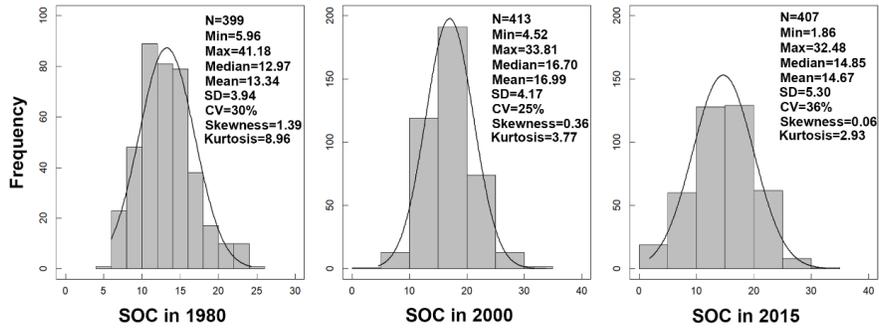
UL represents the area of urban land, CL represents the cropland area; land use data were obtained from Xu et al., (2018).

Fig. 11 SOC contents from previous studies during 2000-2015 in the east of study area (a), and in the west (b).

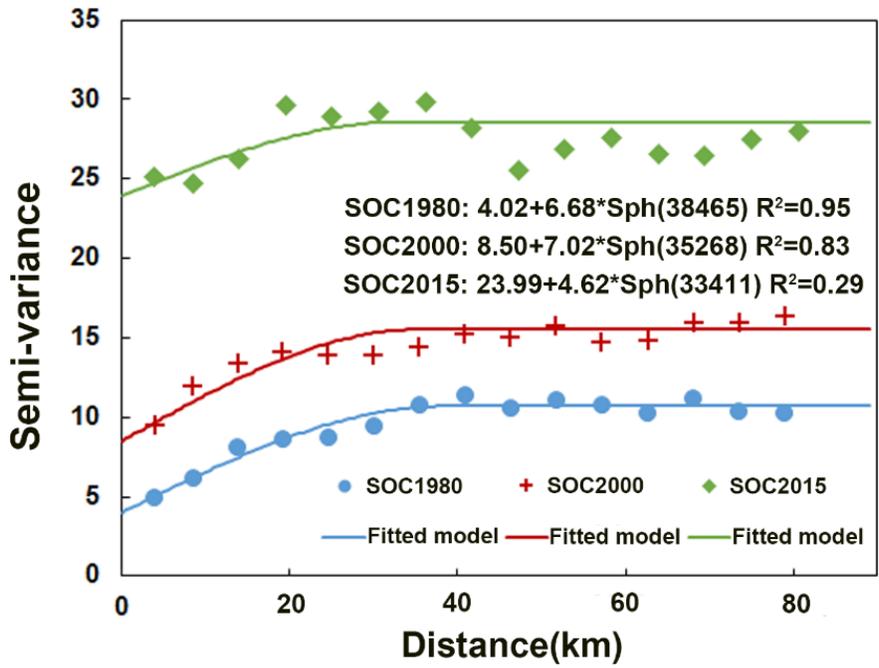
SOC data from previous studies were obtained from Ding, (2009), Gao et al., (2016), Gao et al., (2011), Gao et al., (2005), Guo et al., (2007), Han et al., (2007), He and Cao, (2014), Hu et al., (2008), Liang, (2004), Wan et al., (2006), Wu, (2014), Xie et al., (2009), Xu and Gong, (2014), Xu et al., (2006), and Zhang and Wang, (2013).



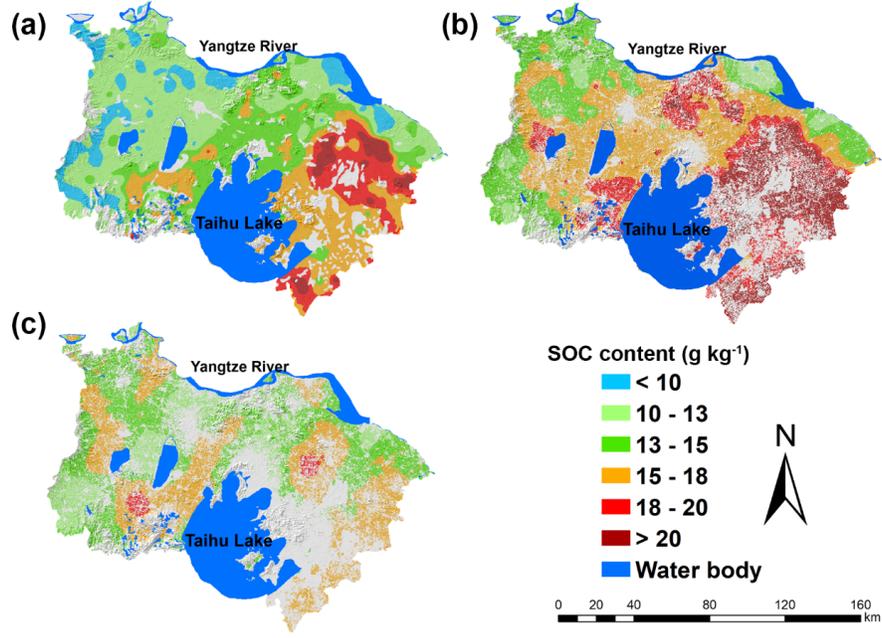
<Fig. 1>



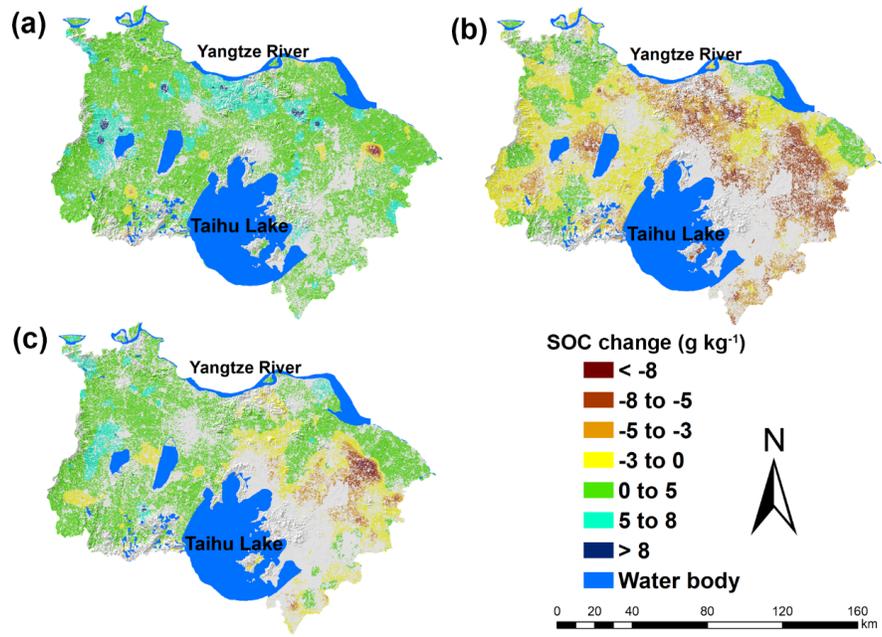
<Fig. 2>



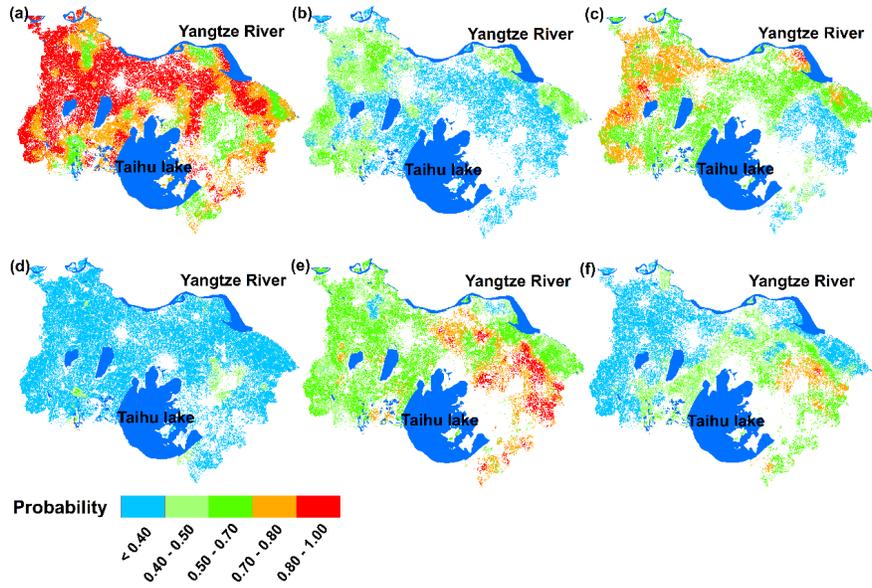
<Fig. 3>



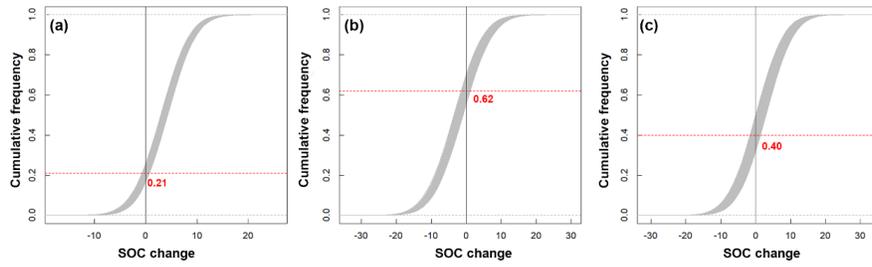
<Fig. 4>



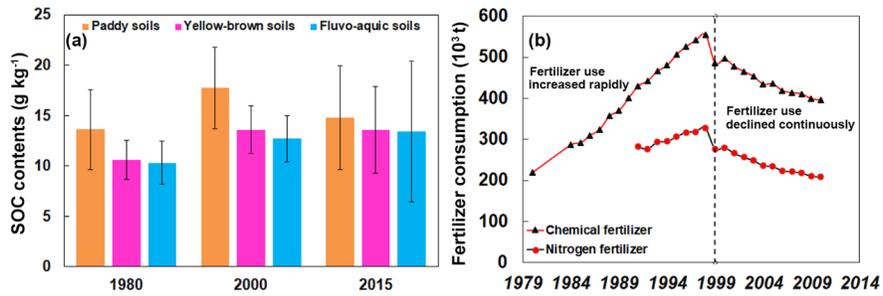
<Fig. 5>



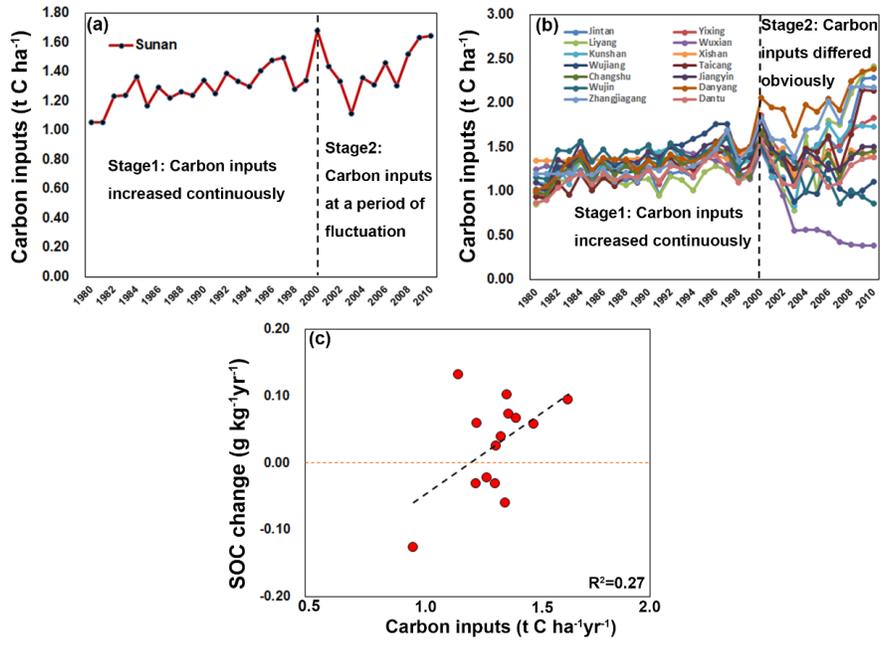
<Fig. 6>



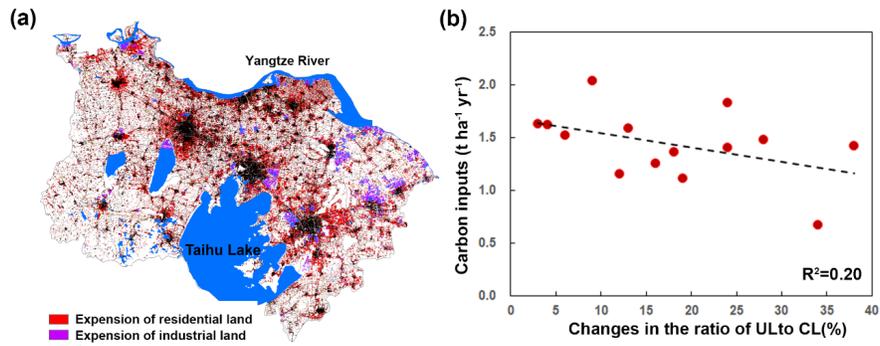
<Fig. 7>



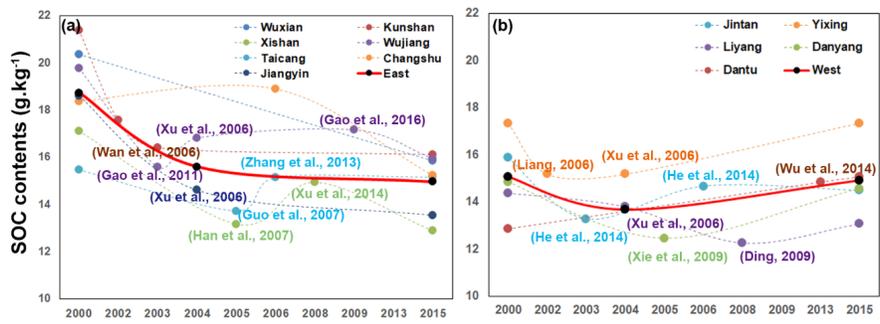
<Fig. 8>



<Fig. 9>



<Fig. 10>



<Fig. 11>