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# Soil organic carbon in the Sanjiang Plain of China: storage, distribution and controlling factors

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## Abstract

Accurate estimation of soil organic carbon (SOC) storage and determination of its pattern controlling factors is critical to understanding the ecosystem carbon cycle and ensuring ecological security. The Sanjiang Plain of China, an important grain production base, is typical of ecosystems, yet the SOC storage and pattern of this region has not been fully investigated because of the deficient soil investigations. In this study, 419 soil samples and a geostatistical method were used to estimate the total SOC storage and density (SOCD) of this region with the former being 2.324 Pg C, and the latter value being higher than the mean value for the whole country. The SOCD was found to have notable changes in spatial and vertical distribution. In addition, the vegetation, climate, and soil texture, as well as the agricultural activities, were demonstrated to have remarkable impacts on the variation of SOCD. Soil texture had stronger impacts on the distribution of SOCD than climate in the Sanjiang Plain. Specifically, the clay content explained the largest proportion of the SOC variation and was thus the most dominant environmental controlling factor. As far as climatic factors are concerned, precipitation exhibited more significant effects on SOCD than temperature. In addition, the effects of both climate and soil texture on SOCD were reduced with increasing soil layer depth. The results from this study provide the most updated knowledge on the storage and pattern of SOC in the Sanjiang Plain, and the analysis conducted here could contribute to the determination of ecosystem carbon budgets and understanding of ecosystem services.

## 1 Introduction

Soil is the largest terrestrial organic carbon pool, containing twice as much carbon as those in the atmosphere or vegetation (Batjes, 1996), and thus, it plays an important role in the global carbon cycle. Accurate quantification of soil organic carbon (SOC) storage and further investigating its association with environmental factors is essential





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to understanding the terrestrial carbon balance and quantifying the carbon budget (Conant et al., 2011; Dorji et al., 2014; Piao et al., 2009).

In previous decades, numerous studies were undertaken to investigate the storage and distribution heterogeneity of SOC in different regions, such as the North American Arctic region (Ping et al., 2008), the Amazon region (Batjes and Dijkshoorn, 1999), the British moorland (Garnett et al., 2001), Laos (Chaplot et al., 2010), and France (Martin et al., 2011), as well as in China (Ni, 2013; Yu et al., 2007). Globally, 32 % of SOC is stored in the soils of the tropics, mainly in forest soils (Eswaran et al., 1993). In China, the total SOC storage in soils has been estimated to be 70.31 Pg C (1 Pg = $10^{15}$ g), which represents 4.7 % of the world storage (Wu et al., 2003). These estimates of SOC based on field samplings suggest a large difference of SOC in storage and distribution. Therefore, an accurate estimation of SOC at a local scale is essential for improving the determination of the SOC budget.

The storage and distribution heterogeneity of SOC depend on climatic conditions (Davidson and Janssens, 2006), land-use patterns (Poeplau and Don, 2013; Yu et al., 2012), and human activities (Heikkinen et al., 2013), which could lead to significant variability of SOC storage. First, the distribution trend of SOC has been correlated with various climate factors, soil texture, and land cover types (Batjes and Dijkshoorn, 1999; Jobbágy and Jackson, 2000; Li and Zhao, 2001; Saiz et al., 2012; Wang et al., 2004; Yang et al., 2007). Globally, total SOC content increases with precipitation and clay content but decreases with temperature while the climate controls SOC in shallow soil layers, and clay content drives SOC in deeper layers. Furthermore, plant functional types also significantly affect the vertical distribution of SOC (Jobbágy and Jackson, 2000; Yang et al., 2010).

Although the influences of climate, vegetation and soil texture significantly on the spatial and vertical distribution of SOC storage has been noticed (Chaplot et al., 2010; Liu et al., 2011; Yang et al., 2008), the lack of appropriate data makes it difficult to assess this influence because of the large uncertainties existing in characterizing the distribution heterogeneity of SOC. It is thus desirable to exploit a large amount of





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data and the most recently updated field investigation to understand the environmental controls of SOC storage for different typical regions. An accurate estimation of SOC storage would significantly improve the knowledge about SOC sequestration and its role in carbon cycles.

The Sanjiang Plain, located in Northeast China, is one of the main food and agricultural bases and the largest concentrated area of the natural wetlands in China (Wang et al., 2011). Typical monsoon climates of medium latitudes, diverse ecosystems, dramatic land use changes and other human disturbances in recent decades make this plain an ideal region for investigating the pattern and environmental controls of SOC storage in Northeast Asia. Previous studies have mainly focused on the topsoil organic carbon and used limited numbers of soil profiles (Wang et al., 2002). Comprehensive investigation on the spatial and vertical distribution characteristics and differences of SOC in various ecosystems are extremely limited. In addition, the associations of the spatial and vertical heterogeneity with regional environment determinants also have not been discussed. Significant wetland reclamation, translation from dry farmland to paddy field, and intensive chemical fertilizer applications have been observed in this region (Wang et al., 2011). Consequently, a study on the current status of regional storage, distribution of SOC and its associations with various environmental factors is imperative for further revealing regional soil carbon sources or sinks in this region.

In this study, the SOC storage in the Sanjiang Plain was quantified based on 1 m depth soil profiles measured in 2012 and Geographic Information Systems (GIS) technology. The primary objective of the study was to achieve an improved estimation of SOC in this typical region in China using extensive soil sampling and a spatial interpolation technology. The secondary objectives were to (1) explore the SOC storage and its spatial and vertical distribution characteristics, (2) investigate the differences of SOC among different terrestrial ecosystems and (3) examine the impacts of environmental factors on the spatial and vertical variability of SOC storage.





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# 2 Data and methods

## 2.1 Study area

The Sanjiang Plain is located in the northeastern corner of China and is separated from Russia by the Heilongjiang and Wusuli rivers (Fig. 1). It is a low alluvial plain deposited by the Heilongjiang, Songhua, and Wusuli rivers, extending from 129°11′ to 134°47′ E in longitude and from 43°49′ to 48°25′ N in latitude, with a total area of 108 596 $km^2$. The elevation in the southwest is higher than in the northeast. Annual precipitation is between 500 and 650 mm, and 80 % of rainfall occurs in the growing season (May to September). The mean air temperature ranges from 1.4 to 4.3°, and the frost-free period is 120–140 days. The climate of this area belongs to the temperate humid or sub-humid continental monsoon climate (Wang et al., 2006). Superior hydrological conditions are critical to the existence of natural wetlands and grain base development.

## 2.2 Land-cover and soil type datasets

Land-cover data covering the Sanjiang Plain are necessary to assist in field sampling and examining the SOC storage in different ecosystems. Landsat thematic mapper (TM) and Chinese Huan Jing (HJ) satellite images acquired in 2010 were classified using the eCognition software to extract land-cover data. All images were atmospherically corrected using the 6S radiative transfer model and geometrically rectified (Mao et al., 2014a). Furthermore, based on the digital elevation model (DEM) and field investigations, image segmentation was performed for the time series of satellite images. Validation of the land cover classification by the field investigation in 2010 (1326 points) displayed a kappa coefficient of 0.894 and overall accuracy of 89 %. The classification result revealed that the major land cover types (Fig. 2a) in the Sanjiang Plain are forestland, cropland, wetland and grassland.

The soil type dataset covering the Sanjiang Plain was clipped from the soil map of China, which was based on Chinese second soil investigations at a scale of

1 : 1 000 000. Five main soil types are found in the area namely dark-brown soil, meadow soil, lessive, swamp soil, and black soil, which occupy more than 95 % of the whole area (Fig. 2b). The SOC content or density differs among soil types (Mao et al., 2014b; Yu et al., 2007). Therefore, different soil types were considered in the spatial distribution of sample plots for an optimal field investigation.

### 2.3 Soil sampling and determination

Considering the spatial pattern and area of land-cover and soil types, 419 samples were obtained on the basis of visual navigation accomplished using the ArcGIS software with a linked GPS and laptop. The SOC data of the soil profiles with different layers (0–30, 30–60, and 60–100 cm) for a plot were averaged from the values for three replicates homogenized in each plot of 100 m × 100 m. These soil samples were collected using a standard container with a volume of 100 $cm^3$ and a cloth pocket. Land-cover types, sampling time and depth, and geographic locations were recorded while sampling. Because of the inaccessibility of some land-cover types and difference in area of land-cover types, a total of 419 soil samples (59 for forestland, 13 for grassland, 59 for paddy field, 206 for dry farmland, and 82 for wetland) in the Sanjiang Plain were obtained, and their locations were overlaid on the land-cover and soil types as shown in Fig. 2.

All of the soil samples with a volume of 100 $cm^3$ were air-dried and then oven-dried at 105° to determine bulk density. Visible plant detritus and all rock fragments were removed from the soil samples in cloth pockets before the soil samples were grounded to pass through a 2 mm sieve mesh and prepared for the SOC and soil texture measurements. The SOC concentration was measured by wet combustion with $K_2Cr_2O_7$ (Yang et al., 2007). A Mastersizer 2000 instrument was used to measure the soil texture of 80 sample profiles equally distributed in the study area, including clay content (< 0.002 mm), silt content (0.02–0.002 mm), and sand content (0.02–2 mm).





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## 2.4 Climatic data

The mean annual temperature (MAT) and mean annual precipitation (MAP) were calculated from the meteorological data recorded during 1981–2012 at 35 meteorological stations with 12 in Russia and 23 in China. All of these data were downloaded from the National Climatic Data Center of NOAA (NCDC, http://www.ncdc.noaa.gov/) and the China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn), respectively. For better accuracy of the spatial interpolation of the climate data, meteorological stations surrounding the Sanjiang Plain stations, including in Russia, were selected. Both MAT and MAP were spatially interpolated using the Kriging method. The MAT and MAP for each sample plot were extracted based on its geographical position from the interpolated raster with a spatial resolution of 8 km.

## 2.5 Fertilization amount

The fertilization amounts for 24 counties in the Sanjiang Plain were obtained from the statistical yearbook of Heilongjiang Province in 2012. The ratio ($\mathrm{kg\,h\,m^{-2}}$) between the fertilization amount and the area of croplands of each county was calculated. The relations of the fertilization amount to SOC content per unit weight ($\mathrm{g\,kg^{-1}}$) were regressed for the different soil layers.

## 2.6 Estimation of SOC storage

This study analyzed the spatial distribution of soil organic carbon density (SOCD) in different soil layers (0–30, 0–60, and 0–100 cm). The SOCD and SOC storage in a depth of $h$ (cm) were calculated as follows:

$$\mathrm{SOCD}_h = \sum_{i=1}^{n} \frac{(1-\delta_i\%)\cdot\rho_i\cdot C_i\cdot T_i}{100} \quad (1)$$

$$\mathrm{SOC}_h = \mathrm{SOCD}_h \cdot \mathrm{AREA} \quad (2)$$





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where $n$ is the number of the soil layer; $\delta_i$ is the concentration of gravel larger than 2 mm in the $i$th soil layer (volume percentage); and $\rho_i$ and $C_i$ are the bulk density and the SOC content ($g\,kg^{-1}$) in the $i$th soil layer, respectively. The SOC content at a given depth is calculated from the soil organic matter in individual layers and by use of the Bemmelen index (0.58). $T_i$ is the thickness of the $i$th soil layer.

The kriging interpolation and the semivariable function were used to obtain the spatial distribution of SOC. Kriging is a geostatistic method that is commonly used to interpolate an SOCD dataset from discrete points to a spatially continuous surface (Kumar et al., 2012; Khalil et al., 2013), and the semivariable function can be used to quantify the spatial autocorrelation and provides input parameters for a spatial interpolation (Liu et al., 2011). All of the calculations for mapping SOC in different soil layers were performed using the ArcGIS software (Version 9.3).

### 2.7 Statistical analysis

The General Linear Model (GLM) was applied to determine the relationship between SOCD and different environmental factors (MAT, MAP, clay content, silt content, and sand content) and to assess how these factors drive the variation of SOC (Yang et al., 2007). Variations of SOCD in different soil layers induced by each factor were analyzed using the GLM. All GLM analyses were performed with the software package R (R Development Core Team, 2005). The coefficient of determination ($R^2$) and the correlation coefficient ($p$) obtained from regressive and correlative analyses performed with SPSS software were employed to describe the effects of different controlling factors on SOC.





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## 3 Results

### 3.1 Storage and spatial distribution of SOC

SOCD varied remarkably across the 419 sampling profiles at different depths (Fig. 3). The mean value and the standard deviation of the SOCD of all sample profiles for the three depths (30, 60, and 100 cm) were 10.19 and 7.12 kg m$^{-2}$, 15.98 and 10.15 kg m$^{-2}$, 21.20 and 12.36 kg m$^{-2}$, respectively. Excluding the regions of water bodies, the total SOC storage within the top 1 m of the soil for the Sanjiang Plain was estimated to be 2.324 Pg C. The topsoil (0–30 cm) SOC was estimated to be 1.161 Pg C, and the SOC at 0–60 cm was estimated to be 1.801 Pg C.

Spatial variation of SOC storage in different soil layers was apparent (Fig. 4). A high SOC stock was mainly distributed in the northeast, northwest corner, and small areas of the north at a depth of 60 cm, whereas the north central area and southwest had low SOCD values. High SOC storage with a value above 24 kg C m$^{-2}$ mainly appeared in the northeast and northwestern corner of the Sanjiang Plain within the total 1 m layer.

### 3.2 Mean SOCD and SOC storage for different ecosystems

Table 1 provides a detailed description of SOC and SOC storage for different ecosystems. There was an increasing SOCD trend in the upper 30 cm with the order of dry farmland, paddy field, grassland, forestland, and wetland, whereas SOCD increased in the order of grassland, dry farmland, paddy field, forestland, and wetland at soil depths of 0–60 and 0–100 cm. Wetland had the largest SOCD at all three soil depths (0–30, 0–60, 0–100 cm). Forestland and dry farmland held 72.7 % of SOC storage in the top 1 m of soil in the Sanjiang Plain.

### 3.3 Vertical distribution characteristics of SOC storage for different ecosystems

An apparently vertical differentiation of SOC stock can be observed in the Sanjiang Plain (Fig. 5). Approximately 49 % of total SOC storage in the top 1 m of soil was





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concentrated in the top 30 cm. SOC storage in different soil layers (0–30, 30–60, and 60–100 cm) was significantly different among various ecosystems, and the percentage of SOC in the top 30 cm relative to the top 1 m was 52, 48, 53, 50, and 50 % for paddy fields, dry farmlands, grasslands, forestlands and wetlands, respectively. The relative distribution of SOC in the topsoil was deepest in the dry farmlands, intermediate in the forestlands and wetlands, and shallowest in the paddy fields and grasslands. The SOC storage decreased with the increasing soil depth for the paddy fields and wetlands. In contrast, the SOC storage was lower in the 30–60 cm than 60–100 cm soil layers for the grasslands and forestlands.

### 3.4 Effects of environmental factors on SOCD

The SOC storages at different soil depths were significantly affected by climate and soil texture (Fig. 6). The SOCD in the upper 30, 60, and 100 cm of soil decreased with increasing MAT up to $\sim 4.6^{\circ}$ and then increased with MAT (Fig. 6a1–a3). Similarly, the SOCD at different depths decreased and then increased with increases of soil clay content ($P < 0.01$). The change node in clay content tended to decrease with soil depth. In addition, SOCD had a significant increase with MAP (Fig. 6b1–b3) and soil silt content (Fig. 6d1–d3). The SOCD was observed to have a significant and negative correlation with sand content in the upper 60 and 100 cm of the soil, and an insignificant correlation in the upper 30 cm of soil.

The results from the GLM revealed that environmental factors explained 57.78, 52.03, and 37.67 % of the overall variation of SOCD at 0–30, 0–60, and 0–100 cm, respectively (Table 2). The associations of climate and soil texture with SOCD were weak with the increase in soil layer depth. Clay content, which explained the largest proportion of the SOCD variation (21.20 % in the upper 30 cm, 18.30 % in the upper 60 cm, and 15.40 % in the upper 100 cm), was the dominant control among the environmental variables examined. Silt content also played an important role in shaping the pattern of SOC storage, being the second largest proportion explaining the SOCD variation. Soil texture has more impacts on the distribution of SOCD than climate in the Sanjiang Plain. In addition, precipitation exhibited more significant effects than temperature on SOCD.

The associations of climate and soil texture with vertical SOCD vary significantly (Table 3). For the differing soil intervals within the top 1 m of soil, SOCD was negatively correlated with MAT and sand content but positively and significantly correlated with MAP, clay content and silt content. Clay content has the largest correlation coefficient with SOCD ($P < 0.01$), which indicates that it plays a more important role in affecting SOCD vertical distribution than other environmental variables. Higher correlations with deeper soil layers were found between SOCD and sand content, whereas lower correlations were observed between SOCD and the other examined controlling factors.

### 3.5 Effects of fertilization amount and cropland types on SOC storage

Cropland, including dry farmlands and paddy fields, which covered 54.2 % of the whole area of the Sanjiang Plain, had the largest carbon pool among the land types (Table 1). Therefore, the changes of SOC content in cropland could result in significant variation in the spatial and vertical distribution of SOC.

We examined the cropland mean fertilization amount and SOC content in 24 counties and found that agricultural activities, especially fertilization, had reparable impacts on SOC content. Significantly negative correlations ($P < 0.01$) were found between mean fertilization amount and SOC content for the 0–30 and 30–60 cm layers (Fig. 7). Meanwhile, a decreased correlation between fertilization amount and SOC content was found with soil depth.

In this study, paddy fields had a larger SOC content than dry farmlands at a 1 m depth (Table 1), and the areal proportions of the two land cover types were thus related to SOC storage. The areal proportion of paddy fields relative to cropland in the Sanjiang Plain was significantly correlated to the topsoil SOC content with an $R^2$ of 0.423 ($P < 0.01$), as shown in Fig. 8.





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## 4 Discussion

### 4.1 SOC estimates in the Sanjiang Plain

Spatially explicit estimations of SOC at the regional scale are vital for monitoring carbon sequestration, which impacts global climate change and food security (Lal, 2004a). An updated and extensive soil investigation in the Sanjiang Plain was developed to quantify the SOC stock for understanding the terrestrial carbon cycle. In addition, the land cover types and soil types were adequately taken into consideration in the field collection of soil samples. Therefore, this study achieved more accurate estimation of SOC than previous studies (Wang et al., 2002; Yu et al., 2007) by use of the large volume dataset, which included the most recently measured data. A geostatistical approach was further used to map the regional pattern of SOC in the different soil layers. The method that was used for estimating the regional carbon pool in the present study is different from that used by Yang et al. (2008), who estimated SOC storage by correlating SOC content with a remote sensing vegetation index. Because of the rich ecosystem types and a coarse resolution of remote sensing imagery at the Sanjiang Plain scale, Kriging method was thus used in this study.

A larger mean SOCD for a depth of 1 m (21.2 kg $m^{-2}$) in the Sanjiang Plain than the mean value of SOCD in China (7.8 kg $m^{-2}$) reported by Yang et al. (2007) and in the whole world (10.8 kg $m^{-2}$) estimated by Post et al. (1982) was observed, most likely due to a lower temperature than in the south and more precipitation than in the western part of the country, as well as extensive wetlands and forests in the Sanjiang Plain (Yu et al., 2007). In addition, significant larger SOCD in the top 30 cm (10.19 kg $m^{-2}$) was observed than that on the Loess Plateau of China (7.70 kg $m^{-2}$, Liu et al., 2011) and that in France (5.91 kg $m^{-2}$, Martin et al., 2011). This is most likely attributed to the higher natural vegetation fraction ratio, i.e. forest and wetland. The forestland had a larger SOCD than grassland, which is different with the results reported by Wang et al. (2004) concerning SOC in China and the observation in France (Martin et al., 2011). We attribute this difference to different climatic zones.

The total estimate of SOC storage in the Sanjiang Plain is 2.324 Pg C for the first meter. It was compared to other estimates based on the previous report and the mapping of SOC concerning the Northeast China with 26.43 Pg C (Wang et al., 2003) and the whole Country with 69.1 Pg C within 1 m (Wu et al., 2003). We demonstrated that the present estimation might better represent the actual SOC storage distributions in the Sanjiang Plain, and consequently that the previous report at the Northeast China and the whole country level significantly underestimate the SOC storage. As mentioned by publications on SOC in the Laos (Chaplot et al., 2010) and France (Martin et al., 2011), SOC storage strongly depends on the land cover types. The notable patterns of SOC in different soil layers shown in Fig. 2 indicates that the SOC content is related to land cover types (Fig. 1a). It is thus necessary to investigate the impacts of land cover types on SOC storage.

### 4.2 Impacts of land cover type on SOC

Jobbágy and Jackson (2000) and Yang et al. (2007) observed that land cover types significantly affected the distribution of SOC, and this conclusion was supported by our study, as shown in Table 1 and Fig. 5. The results revealed that the wetlands had the highest SOCD, which is most likely related to the low decomposition rate of soil organic matter due to high soil moisture content (Taggart et al., 2012). Notable loss of topsoil SOC affected by cultivation was observed in China (Song et al., 2005). A significant loss of wetlands to croplands has occurred in the Sanjiang Plain in the past few decades (Wang et al., 2011), which may have led to marked increase carbon emission. This implies that implementation of effective wetland management and conservation in the Sanjiang Plain is required for the regional carbon sequestration and carbon budget. Intensive agricultural activities, such as tillage, have resulted in enhanced soil mineralization (Lal, 2002), which has led to low SOC in dry farmlands (red and orange colors in Fig. 4). Although a low SOCD was found for cropland, its large area made it the largest SOC pool among all land cover types considered in this study (Table 1).





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The results indicate different vertical patterns of SOC storage for the five ecosystems. Grassland had the shallowest root distribution and less fresh carbon supply in deep soil layers, and accounted for a large SOC proportion in the topsoils (Fontaine et al., 2007). The relatively lower decomposability and deep root distribution pattern in wetlands may contribute to the observed difference in the vertical features for the wetlands and grasslands (Jobbágy and Jackson, 2000). Loosened soil and plow tillage in dry farmlands which is favorable to the soil respiration, can explain the low SOC storage in the top 30 cm of soil in the Sanjiang Plain. In contrast, paddy fields have a large SOC content, which is most likely related to the stability of the soil environment (Pan et al., 2004), suggesting a relatively larger SOC proportion of the topsoil than that in dry farmland, as shown in Fig. 5. The associations of SOCD with the examined environmental factors decreased with the soil depth. This observation could be related to the changes in vegetation types. Vegetation affects the spatial and vertical pattern of SOC through the root distribution and production of above- or below-ground biomass.

### 4.3 Relationship between SOC and climatic factors

SOCD was significantly correlated with MAT and MAP for the different soil depths, as shown in Fig. 6a1–a3. MAT and MAP could explain a large amount of the variation of SOCD in different soil layers (Table 2), implying that climatic conditions are important environmental forces in controlling the spatial and vertical distribution of SOCD. Furthermore, more variances of SOCD affected by MAT were observed than MAP in this plain. This is different with the observation from France (Martin et al., 2011) which reported that the effect of temperature on SOC storage is less than rainfall. The potential difference can be related to different climatic types that France dominated with maritime climate while the present plain dominated with continental climate.

SOCD decreased and then increased with increasing MAT, which is most likely related to various balances between SOC inputs and outputs (Davidson and Janssens, 2006). A decrease in SOCD at low MAT could be caused by small carbon inputs of plant production and large carbon outputs of soil decomposition. MAT was mostly lower than





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4.6° in the Sanjiang Plain. This is why a significantly negative correlation ($r = -0.33$, $P < 0.01$) was observed between MAT and SOCD. On the contrary, an MAT higher than 4.6° may increase the vegetation productivity and thus contribute to an increase in carbon inputs that overrides the temperature-induced rise in the soil decomposition rate (Yang et al., 2008). Our results confirm the observation made by Yang et al. (2007) that the increase in SOCD from the tropical to cold-temperate zone in the eastern part of China is correlated with the variation of temperature. In the Sanjiang Plain, MAT can explain 4.23 % of the SOCD variation, suggesting that temperature plays an important role in shaping the pattern of SOC.

In this study, significant power relationships (Fig. 6b1–b3) were observed between SOCD and MAP for different soil depths. This finding indicates that SOCD increases with rainfall. The positive correlations between SOCD and MAP in the different soil layers can be explained by the fact that precipitation could enhance the vegetation productivity and thus lead to accumulation of SOC. A similar result was also found for the spatial pattern of SOC in Northern China, i.e., increased precipitation contributes to an increase in SOCD from the arid to semi-humid zone (Yang et al., 2007). Similarly, a higher SOCD in the Sanjiang Plain than the Loess Plateau (Liu et al., 2011) can be mostly related to the difference of the two areas in precipitation. MAP decreasingly explained the variation of SOCD with increasing soil depth (Table 2) and displayed a decreased correlation with SOCD (Table 3). This can be attributed to less carbon input in deep soil layers as a result of improved net primary productivity induced by increasing MAP.

### 4.4 Effects of soil texture on SOC

The SOCD in the Sanjiang Plain was strongly associated with soil texture (Fig. 6 and Table 3). The GLM results suggest that the observed soil texture explained 47, 43 and 36 % of the variation of SOCD at a depth of 30, 60, and 100 cm, respectively. For the country scale of China, climate was observed as the leading factor affecting the spatial pattern of SOCD (Wu et al., 2003; Yang et al., 2007). However, for the regional scale, such as the Sanjiang Plain, the variation of SOCD was mostly attributed to soil texture rather than climate. The similar result is also observed in Laos (Chaplot et al., 2010) that SOC storage was most affected by soil types and texture. Soil texture is related to the soil water holding capacity and the decomposition rate of organic matter, which thus suggests a key role in shaping the spatial pattern of SOCD at the regional scale. Corresponding to the climate controlling the pattern of SOC storage in a large scale, the soil texture maybe shows more effects on the distribution of SOC in a small or regional level.

Clay content contributed to the pattern of SOCD to a larger degree than silt and sand content in soil. A similar result was also observed by Jobbágy and Jackson (2000) where in clay content was the best predictor of SOCD in deeper layers. Moreover, in this study, SOCD was significantly correlated to silt content at different soil layers with positive correlation coefficients. This result may be due to the reason that high contents of clay and silt stabilize soil organic matter and thus slow down the soil carbon circle (Hassink et al., 1997). Negative relationships were observed between SOCD and sand content (Fig. 6e1–e3 and Table 3), which may be associated with low water holding capacity induced by high sand content, further restricting the vegetation growth and carbon sequestration. Decreased correlation coefficients could be explained by the low carbon inputs and relatively efficient decomposition of organic matter in deeper layers when a high sand content is present.

### 4.5 Impacts of agricultural activities on SOC

The soil texture and vegetation were influenced by climate, and soil texture had obvious effects on vegetation types. Therefore, the mechanism that influences the SOC distribution is complicated. The GLM results indicate that the examined environmental factors only explained 42.22 and 47.97 % of the SOCD variation at a depth of 30 and 60 cm, respectively. Therefore, we speculate that the anthropogenic factor is critical in affecting the pattern and storage of SOC.

Cropland management plays an important role in the carbon exchange of ecosystems (Lal, 2004b). In the Sanjiang Plain, soil tillage and the return of crop stubble into soils have a long history, which are the crucial forces for shaping the spatial and vertical pattern of SOC (Liu et al., 2006; Mao et al., 2014b). Additionally, increasing fertilization has increased SOC in most areas of China (Ren et al., 2012) and Australian wheat systems (Zhao et al., 2013). However, we observed that, spatially, the counties having a higher fertilization amount had lower SOC content (Fig. 7). This may be correlated to the difference in SOC decomposition resulting from variation of temperature and soil moisture and differences in soil types on this plain.

The results indicate that paddy fields had larger carbon sequestration capacity among the agricultural soils of the Sanjiang Plain (Table 1). As suggested in Fig. 8, the areal proportion of paddy fields to croplands was significantly correlated to the mean value of the topsoil SOC content in different counties ($P < 0.01$). Irrigation-based rice cultivation in China has induced significant enrichment of SOC storage in paddy soils, compared with dry farmland cultivation (Pan et al., 2004). In addition, the loss of SOC storage to the atmosphere plays a positive feedback role on climate change (Davidson and Janssens, 2006). Therefore, in previous decades, the project of transforming dry farmland into paddy fields driven by governmental policy and economic benefit in the Sanjiang Plain has contributed to the local carbon accumulation and mitigation of climate change by reducing $CO_2$ emission.

## 5 Conclusions

A kriging spatial interpolation technology and 419 soil plots (1257 profiles) within a depth of 1 m in 2012 were used to quantify the SOC storage in the Sanjiang Plain. The associations of SOCD were also examined with different environmental controlling factors. The results reveal that the total SOC storage within a 1 m depth for the Sanjiang Plain was estimated to be 2.32 Pg C, and mainly stocked in the topsoil. At the scale of the Sanjiang Plain, soil texture plays more important roles than climate in shaping





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the distribution of SOCD, and clay content contributes more than the other observed factors. Vegetation, climate, and soil texture, as well as the agricultural activities had remarkable impacts on the storage and distribution of SOCD. Wetlands had the highest SOCD as compared with other land cover types displaying a significant loss in recent decades. Thus, implementation of effective wetland management and conservation in the Sanjiang Plain is required for regional carbon sequestration. Moreover, policy and economic benefit-driven transformations from dry farmlands to paddy fields contribute to more carbon stocking in the soil. Based on the comparison between our estimate and the previous studies, we demonstrated that the previous report at the Northeast China and the whole country level significantly underestimate the SOC storage in the Sanjiang Plain. Therefore, accurate and the updated estimates of SOC storage will significantly improve the knowledge of carbon cycles and the determination of the carbon budget of the Sanjiang Plain.

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**Table 1.** SOCD and SOC storage for different ecosystems in the Sanjiang Plain.

| Ecosystems | Area ($km^2$) | SOCD ($kg\,m^{-2}$) | | | SOC storage (Tg C) | | |
|---|---|---|---|---|---|---|---|
| | | 0–30 cm | 0–60 cm | 0–100 cm | 0–30 cm | 0–60 cm | 0–100 cm |
| Dry farmland | 41 462.87 | 9.72 | 14.56 | 19.68 | 412.10 | 637.71 | 821.84 |
| Paddy field | 18 068.62 | 9.88 | 15.53 | 19.79 | 191.00 | 302.24 | 388.14 |
| Grassland | 124.30 | 10.65 | 11.33 | 17.38 | 1.47 | 2.31 | 71.58 |
| Forestland | 36 556.49 | 11.41 | 16.84 | 23.40 | 420.20 | 639.10 | 827.52 |
| Wetland | 6527.89 | 14.78 | 23.50 | 29.59 | 76.71 | 123.85 | 160.85 |





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**Table 2.** GLM results for correlating SOCD and environmental factors.

| Depth | Factors | MAT | MAP | Clay content | Silt content | Sand content | Others |
|---|---|---|---|---|---|---|---|
| | DF | 1 | 1 | 1 | 1 | 1 | 80 |
| 0–30 cm | MS | 0.87* | 1.49* | 4.70* | 4.65* | 2.40* | 0.02 |
| | SS(%) | 4.23 | 5.21 | 21.20 | 17.80 | 9.34 | 42.22 |
| 0–60 cm | MS | 2.24* | 1.45* | 8.23* | 6.54* | 5.23* | 0.05 |
| | SS(%) | 5.21 | 3.22 | 18.30 | 15.20 | 10.10 | 47.97 |
| 0–100 cm | MS | 1.11* | 0.23 | 6.21* | 5.07* | 4.21* | 0.07 |
| | SS(%) | 1.65 | 0.68 | 15.40 | 12.40 | 7.54 | 62.33 |

* $P < 0.01$; DF, degree of freedom; MS, mean squares; SS, proportion of variances explained by the variable.





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**Table 3.** Correlation coefficients between SOCD and environmental factors in different soil layers.

| Soil depth (cm) | MAT | MAP | Clay content | Silt content | Sand content |
|---|---|---|---|---|---|
| 0–30 | −0.33[b] | 0.29[b] | 0.49[b] | 0.35[b] | −0.18 |
| 30–60 | −0.30[b] | 0.22[a] | 0.46[b] | 0.34[b] | −0.37[b] |
| 60–100 | −0.11 | 0.20 | 0.42[b] | 0.22[a] | −0.38[b] |

[a] $P < 0.05$; [b] $P < 0.01$.





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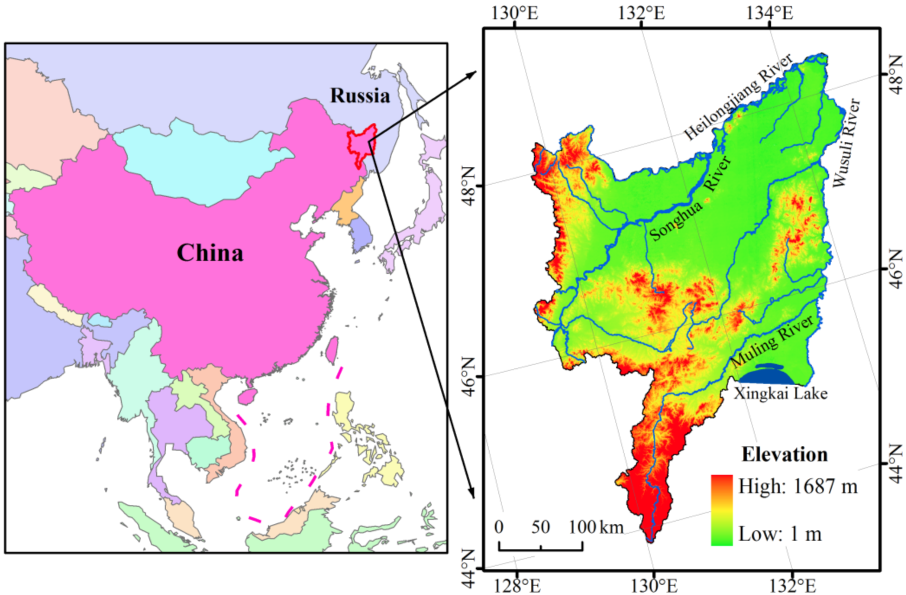


**Figure 1.** Position and terrain of the Sanjiang Plain.





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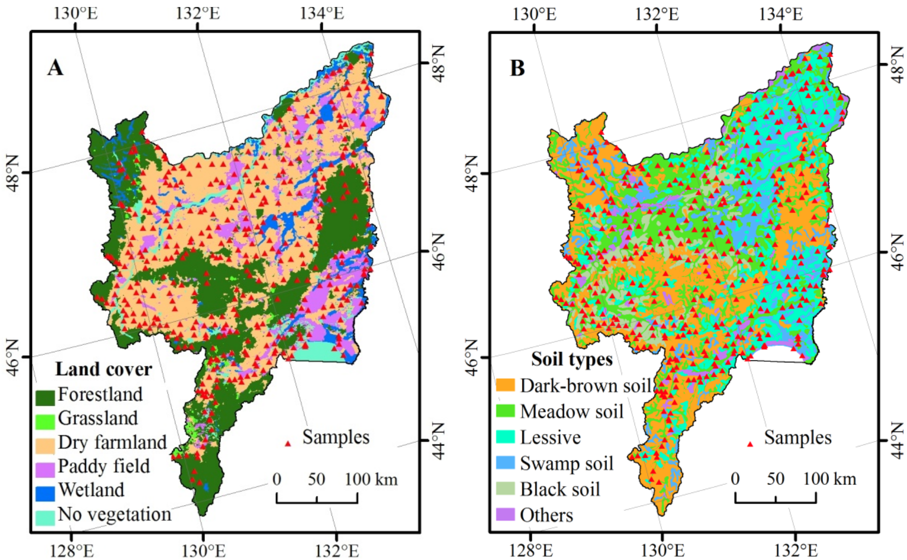


**Figure 2.** Spatial distribution of field samples, land cover **(a)** and soil types **(b)** in the Sanjiang Plain.





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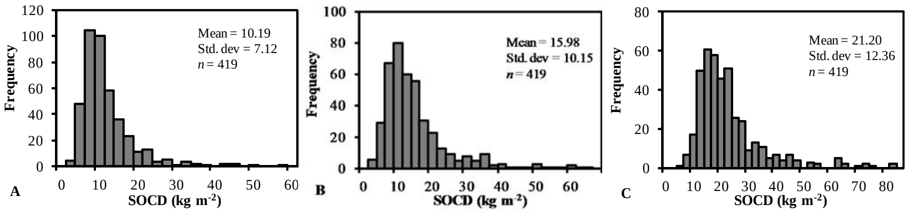


**Figure 3.** Frequency distributions of SOCD at different depths: **(a)** 0–30 cm, **(b)** 0–60 cm, **(c)** 0–100 cm.





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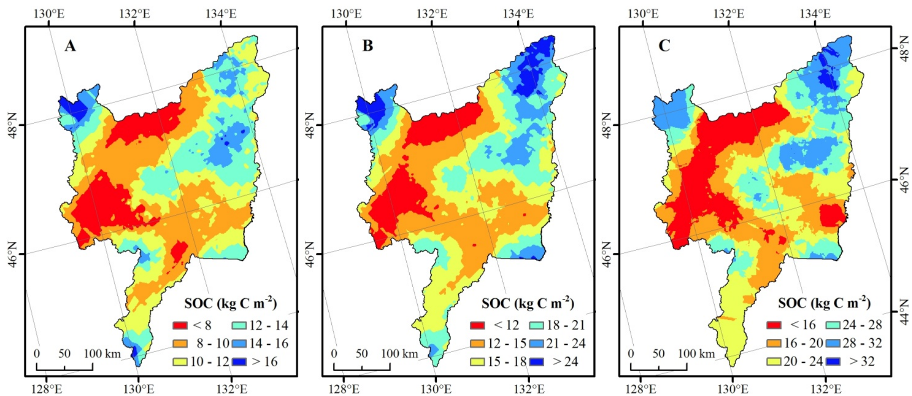


**Figure 4.** Spatial pattern of SOC storage at different soil depths: **(a)** 0–30 cm, **(b)** 0–60 cm, **(c)** 0–100 cm.

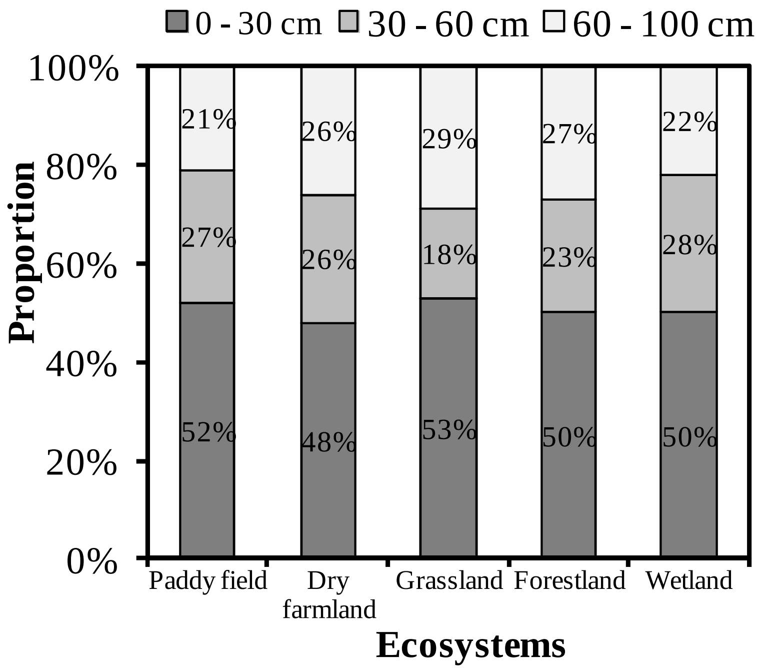


**Figure 5.** Vertical distribution of SOC storage in different soil layers for various ecosystems.

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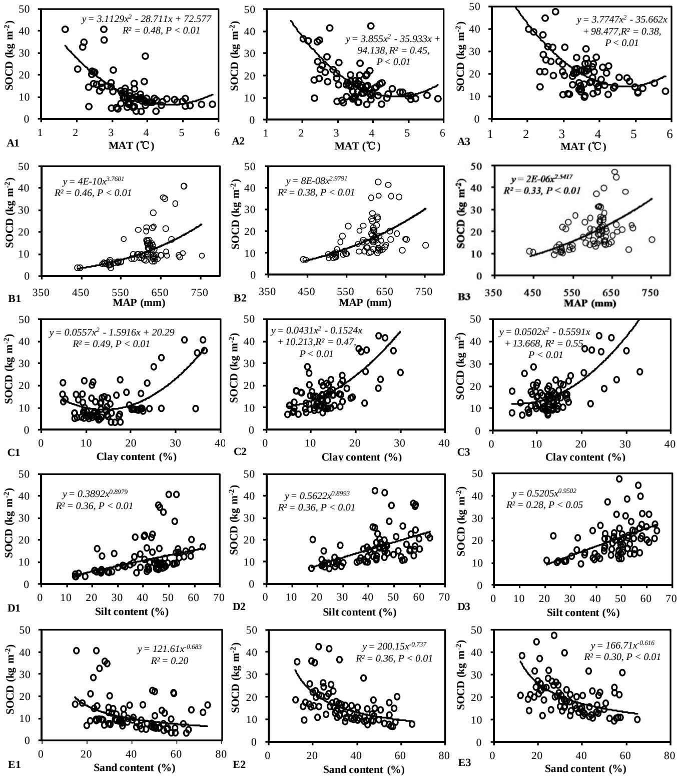


**Figure 6.** Correlations of SOCD with various environmental factors for different soil depths in the Sanjiang Plain (**a1**–**e1**, 0–30 cm; **a2**–**e2**, 0–60 cm; **a3**–**e3**, 0–100 cm).

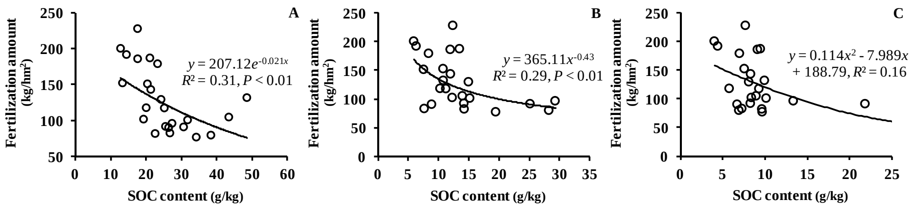


**Figure 7.** Correlations of the cropland fertilization amount with SOC content in the Sanjiang Plain for different soil layers (**a**, 0–30 cm; **b**, 30–60 cm; **c**, 60–100 cm).





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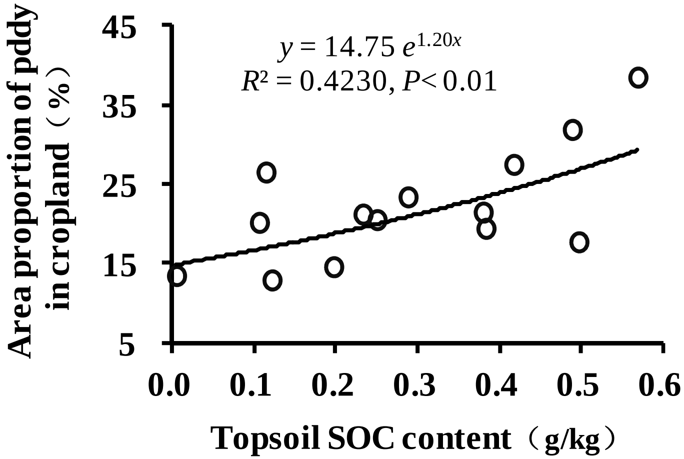


**Figure 8.** Correlations of topsoil SOC content with the area proportion of paddy fields relative to cropland in the Sanjiang Plain.





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