Responses to the comments from editor

Dear editor,

We have received the comments on our manuscript entitled “Soil organic carbon in the Sanjiang Plain of China: storage, distribution and controlling factors” (bgd-11-14765-2014). We are very grateful for having the opportunity to revise our paper. We like to thank you for your constructive comments and advices, which have improved the quality of this manuscript. We have tried our best to address these comments. Our responses to the editor’s comments are attached. We hope you would be satisfied with the revised manuscript.

If you have any questions about this paper, please feel free to contact us.

Comment “Thank you for contribution to Biogeosciences. Now, your Manuscript received 4 reports from Dr. Ding and three anonymous referees, including a number of comments. I read these comments and your replies and conclude that the manuscript has been revised appropriately for most points. Additionally, as several referees concern about the English writing, you called for an English editing service. I found requirement of more your clarification for one point: i.e., comment 13 by referee #3. In Table 1, SOCD of paddy field does not look significantly higher than that of dry farmland. If ‘SOCD is proportional to SOC content (your reply to this comment)’, I could not understand why the relationship found in Fig 8 occurs. Please provide additional explanation. One minor point: in the revised manuscript, you cited IPCC (2001). This is the Third Assessment Report of IPCC, and the latest one, the Fifth Assessment Report of WG1, was published in 2013. Why not cite the latest one? These revisions may not take long time, and I’m looking forward to receiving your revised manuscript.”

Response: We thank the editor for the comments. In this study, the SOCD (soil organic carbon density) of paddy field does not look significantly higher than that of dry farmland (Table 1). In the previous draft of the manuscript, we reported that the areal proportion of paddy fields relative to cropland is significantly correlated to the topsoil SOC content, which may confused the editor and reviewers, because SOCD is proportional to SOC content.

In this round of revision, we carefully checked the data and found that, in the whole 23 counties of the study region, paddy field is only distributed in 14 counties, so Figure 8 was drawn only for the data from these 14 counties, which is incomplete for the analysis and produced contradictory results. To clarify the issue and avoid confusion, we deleted Figure 8 and related sentences. We seriously went through the revised manuscript and think that the deletion of these sentences will not affect the integrity and completeness of the paper. Accordingly, corresponding references were also deleted. Please see the revised manuscript.

Additionally, the cited IPCC report, in the subsection of "4.5 Impacts of agricultural activities on SOC" of the previous draft, is no longer necessary, so the comment about the citation of IPCC report was addressed. Thank you.

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

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

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, an important grain production base in China, is typical of ecosystems, yet its SOC storage and pattern has not been fully investigated because of deficient soil investigation. In this study, 419 soil samples obtained in 2012 for each of the three soil depth ranges 0 - 30 cm, 30 - 60 cm, 60 - 100 cm, and a geostatistical method are used to estimate the total SOC storage and density (SOCD) of this region. The results give rise to 2.32 Pg C for the SOC storage, and 21.20 kg m^{-2} for SOCD which is higher than the mean value for the whole country. The SOCD shows notable changes in lateral and vertical distribution. In addition, vegetation, climate, and soil texture, as well as agricultural activities, are demonstrated to have remarkable impacts on the variation of SOCD of this region. Soil texture has stronger impacts on the distribution of SOCD than climate in the Sanjiang Plain. Specifically, clay content can explain the largest proportion of the SOC variations (21.2% in the top 30 cm) and is the most dominant environmental controlling factor. Additionally, the effects of both climate and soil texture on SOCD show weakening with increasing soil layer depth. This study indicates that reducing the loss of SOC requires effective conservation and restoration efforts of wetlands and forestlands ~~conservation and restoration~~, rational ~~distribution of crop types and~~ fertilization. The results from this study provide the most updated knowledge on the storage and pattern of SOC in the Sanjiang Plain, and have important implications for the determination of ecosystem carbon budgets and understanding ecosystem services.

Key words: soil organic carbon, climate, soil texture, agricultural activities, the Sanjiang Plain of China

1 Introduction

Soil is the largest terrestrial organic carbon pool, contains twice as much carbon as those in the atmosphere or vegetation (Batjes, 1996), and 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 to in-depth analyses of the terrestrial carbon cycle and updating the carbon budget (Conant et al., 2011; Dorji et al., 2014; Piao et al., 2009).

In the past decades, numerous studies were undertaken to investigate the storage and distribution heterogeneity of SOC in different regions, which includes the North American Arctic (Ping et al., 2008), the Amazon (Batjes and Dijkshoorn, 1999), the British moorland (Garnett et al., 2001), Laos (Chaplot, et al., 2010), France (Martin et al., 2011), and China (Ni, 2013; Yu et al., 2007). Globally, 32% of SOC is stored in tropical soils, and mainly in forest soils (Eswaran et al., 1993). In China, the total SOC storage has been estimated using field samples, and the value was 89.61 Pg C in the 1980s and 86.75 Pg C in the 2000s (1 Pg C = 10^{15} gC), representing ~5.0 % of the world storage (Xie et al., 2007). However, the large of the two estimated SOC values implies a necessity of improving SOC estimation at regional and local scales to achieve accurate updating of the world and national SOC budget.

The storage and distribution heterogeneity of SOC depend on climate conditions (Davidson and Janssens, 2006), land-use patterns (Poeplau and Don, 2013; Yu et al., 2012), and human activities and policies (Cao et al., 2011a, 2011b; Heikkinen et al., 2013; Wang et al., 2011). The distribution 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 has been shown to increase with precipitation but decrease with temperature, and the two climate factors control SOC in shallow soil layers (Jobbágy and Jackson, 2000). Jobbágy and Jackson (2000) also showed that total SOC increases with clay content, which drives SOC in deeper soil layers. Plant functional types can significantly impact the vertical distribution of SOC (Jobbágy and

Jackson, 2000; Yang et al., 2010). Although the influence of climate, vegetation and soil texture on SOC storage has been noticed (Chaplot et al., 2010; Liu et al., 2011; Yang et al., 2008), it has been difficult to assess this influence because of large uncertainties in characterizing the distribution of SOC. One reason for causing this difficulty is due to lack of appropriate data. A large amount of data from recent field investigations are required to facilitate the assessment of SOC storage in typical regions.

The Sanjiang Plain is one of the main food and agricultural bases and has the largest natural wetland in China (Wang et al., 2011). Typical monsoon climate of medium latitudes, diverse land-cover types, dramatic land use changes and other human disturbances in recent decades (Song et al., 2014) make it an ideal region for investigating the pattern and environmental controls of the SOC storage in Northeast Asia. Previous studies have mainly focused on the topsoil organic carbon and used a limited number of soil profiles measured in this area, which would not allow for a comprehensive investigation on and a comparison of the lateral and vertical distribution of SOC in various ecosystems (Wang et al., 2002). In addition, significant wetland reclamation, conversion from dry farmland to paddy field, and intensive chemical fertilizer applications have been observed in this region (Wang et al., 2011), which could implicate in the SOC cycle. These considerations create the need for studying the current SOC storage and distribution as well as their associations with various environmental factors so that regional soil carbon sources or sinks can be determined for this region.

In this study, the SOC storage in the Sanjiang Plain was estimated based on extensive 1 m depth soil profiles. The primary objective of the study was to further characterization of SOC of this region. The secondary objectives were to 1) estimate the SOC storage and map its lateral and vertical distribution, 2) compare SOC across different terrestrial land-cover types and 3) examine the associations of environmental factors with the lateral and vertical variability of SOC storage.

2 Data and Methods

2.1 Study area

The Sanjiang Plain is located in the northeast corner of China and separated from Russia by the Heilongjiang and Wusuli rivers (Fig. 1). The region has 23 counties and extends from 129 ° 11′ E to 134° 47′ E in longitude and from 43° 49′ N to 48°25′ N in latitude, with a total area of 108 596 km^2 (Wang et al., 2011). It is a low alluvial plain deposited by the Heilongjiang, Songhua, and Wusuli rivers with elevation in the southwest being higher than in the northeast. Annual precipitation is between 500 mm and 650 mm, and 80% of rainfall occurs in growing seasons (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), which is suitable for natural wetlands and growing grains.

Fig. 1. Position and terrain of the Sanjiang Plain

2.2 Land-cover and soil type datasets

The Landsat thematic mapper (TM) and Chinese Huan Jing (HJ) satellite images (Zhang et al., 2014) acquired in 2010 for the study region were classified using the eCognition software to extract land-cover data (Mao et al., 2014a). All the images (32 of them being TM and 6 for HJ) were atmospherically corrected using the 6S radiative transfer model and geometrically rectified. Furthermore, based on the digital elevation model (DEM) and field investigations, image segmentation was performed for these satellite images. Validation of the land cover classification on the field data collected in 2010 (1326 points) resulted a kappa coefficient of 0.894 and overall accuracy of 89%. Area for each land cover type was calculated through the ArcMap software. Statistic results further revealed that the major land cover types in the Sanjiang Plain were cropland, forestland, and wetland (Fig. 2A), with an area of 59 531.49 km^2, 36 556.49 km^2, 6 527.89 km^2, respectively.

The soil type dataset covering the Sanjiang Plain was clipped from the soil map of China, resulting from Chinese second soil investigations at a scale of 1: 1 000 000 (Wang et al., 2006). Five main soil types in the area were dark-brown soil, meadow soil, lessive, swamp soil, and black soil, and occupied more than 95% of the whole area (Fig. 2B). In the Sanjiang Plain, dark-brown soil and meadow soil are the largest and second largest soil type with an area of 32103.54

km^2 and 31017.36 km^2, respectively. Considering the SOC content and density differ among soil types (Mao et al., 2014b; Yu et al., 2007), different soil types need to be accommodated in the deployment of field sampling sites.

Fig. 2. Spatial distribution of field samples, land cover (A) and soil types (B) in the Sanjiang Plain

2.3 Soil sampling and determination

Soil samples were collected in 2012 on the basis of visual navigation via a GPS unit linked with ArcGIS installed laptop. Each of these samples was collected using a standard container with a volume of 100 cm^3 and a cloth pocket. For each soil site (three soil profiles at each site), the SOC content for each depth range (i.e. 0 - 30 cm, 30 - 60 cm, and 60 - 100 cm) was represented by the average of SOC values of three spatially random profiles at the sampling site. Land-cover types, sampling time and depth, and geographic locations were recorded while sampling. Because of the inaccessibility of some land-cover types and the areal difference 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) for each soil depth range were obtained, and their locations were overlaid on the land-cover and soil types as shown in Fig. 2.

All of the soil samples were air-dried and then oven-dried at 105℃ to determine their bulk densities. Visible plant detritus and all rock fragments were removed from the soil samples in the cloth pockets before the soil samples were further processed by grounding and sieving with 2-mm meshes and analyzed for SOC concentration and soil texture. 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).

2.4 Climate data

The mean annual temperature (MAT) and mean annual precipitation (MAP) were calculated from the meteorological data recorded during 1981 - 2012. 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 bettering the accuracy of spatial interpolation of climate factors, 35 meteorological stations (12 of them being Russia and 23 in China) were used and spatially interpolated using the Kriging method. The MAT and MAP for each sampling site were extracted based on its geographical position from the interpolated raster with a spatial resolution of 8 km.

2.5 Amounts of Fertilizer

The amounts of fertilizer for each of 23 counties in the Sanjiang Plain was obtained from the statistical yearbook of Heilongjiang Province in 2012. The ratio (kg ha^{-1}) of the amount of fertilizer to the area of croplands of each county was calculated. A relation of the fertilization amount to the SOC content was derived for the individual soil layers considered in this study.

2.6 Estimation of SOC storage

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

$$SOCD_h = \sum_{i=1}^{n} \frac{(1-\delta_i\%) \times \rho_i \times C_i \times T_i}{100} \quad (1)$$

$$SOC_h = SOCD_h \times AREA \quad (2)$$

where n is the number of the soil layer; δ_i is the concentration of gravel larger than 2 mm in the i_{th} soil layer (volume percentage); ρ_i and C_i are the bulk density and the SOC content (g kg^{-1}) in the i_{th} soil layer, respectively; T_i is the thickness of the i_{th} soil layer.

The Kriging interpolation and the semivariable function were used to determine the spatial distribution of SOC. Kriging is a geostatistical method that is commonly used to interpolate a 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 an input parameter for a spatial interpolation (Liu et al., 2011). All of the calculations for mapping SOC within individual soil depth ranges were performed using the ArcGIS software (Version 9.3).

2.7 Statistical analysis

The General Linear Model (GLM) was used to determine the relationship between SOCD and each of different environmental factors (MAT, MAP, clay content, silt content, and sand content) and to assess how each factor influences the variation of SOC within a soil depth range (Yang et al., 2007). 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 the SPSS software were employed to describe the effects of individual controlling factors on SOC, such as climate factors and soil parameters. In addition, the estimated SOCD for the Sanjiang Plain was compared to the SOCD values estimated for different regions of the world to investigate the effects of climate factors and vegetation.

To address the effects of agricultural activities on the distribution of SOC, we examined the correlation of the amount of applied fertilizers ~~as well as the correlation of land-cover type~~ to the SOC content on the county scale. ~~For the second correlation analysis, the land-cover type was characterized by areal proportions of paddy fields relative to croplands. And also an ANOVA analysis was developed to compare the mean SOC content for dry farmland and paddy field.~~

3 Results

3.1 Storage and spatial distribution of SOC

SOCD of the 419 sampling profiles varied remarkably within each soil depth range (Fig. 3). The mean SOCD values of all sample profiles for the three depth ranges (0 - 30 cm, 0 - 60 cm, and 0 - 100 cm) were 10.19 kg m^{-2}, 15.98 kg m^{-2}, and 21.20 kg m^{-2}, and the standard deviation of the corresponding SOCD were 7.12 kg m^{-2}, 10.15 kg m^{-2}, and 12.36 kg m^{-2}, respectively. Excluding the regions of water bodies, the total SOC storage of the Sanjiang Plain was estimated to be 1.16 Pg C for the depth range 0 - 30 cm, 1.80 Pg C for 0 - 60 cm, and 2.32 Pg C for 0 - 100 cm.

Fig. 3. Frequency distributions of SOCD at different soil depth ranges (A: 0 - 30 cm; B: 0 - 60 cm; C: 0 - 100 cm)

The spatial variation of SOC storage within soil depth range is apparent (Fig. 4). For the soil depth range 0 - 60 cm, high SOCD values mainly present in the northeast, northwest corner, and small areas of the north, whereas low SOCD values present in the north central area and southwest. For the soil depth range 0 - 100 cm, the SOC storage values higher than 24 kg C m^{-2} mainly appear in the northeast and northwestern corner of the Sanjiang Plain.

Fig. 4. Spatial pattern of SOC storage at different soil depths (A: 0 - 30 cm; B: 0 - 60 cm; C: 0 - 100 cm)

3.2 Mean SOCD and SOC storage for different land-cover types

Table 1 provides a detailed description of SOCD and SOC storage for different land-cover types of the Sanjiang Plain. The SOCD for the soil depth range 0 - 30 cm increases in the order of dry farmland, paddy field, grassland, forestland, and wetland, whereas for the soil ranges 0 - 60 cm and 0 - 100 cm in the order of grassland, dry farmland, paddy field, forestland, and wetland. Wetlands have the largest SOCD at all three soil depths (0 - 30 cm, 0 - 60 cm, 0 - 100 cm). Forestlands covering the second largest area of the Sanjiang Plain have the second largest SOCD (23.40 kg m^{-2}) among the land cover types and stock the second largest SOC (827.52 Tg C, 1 Tg C = 10^{12} gC) in the soil depth range 0 - 100 cm, and forestlands and dry farmlands together account for 72.7% of SOC storage in the same depth range soil of the Sanjiang Plain.

Table 1 SOCD and SOC storage for different land-cover types in the Sanjiang Plain

3.3 Vertical distribution characteristics of SOC storage for different land-cover types

An apparent vertical differentiation of SOC storage can be observed in the Sanjiang Plain (Fig. 5). For the soil depth range 0 -100 cm, approximately 49% of total SOC storage is concentrated within the top 30 cm. The SOC storage within each soil depth range (0 - 30 cm, 30 - 60 cm, and 60 - 100 cm) varies significantly across different land-cover types. The percentage which SOC within the depth range 0 - 30 cm can account for SOC within the range 0 - 100 cm is 48%, 50%, 50%, 52%, 53% for dry farmlands, forestlands, wetlands, paddy fields, and grasslands, respectively, implying that the relative distribution of the SOC of the topsoil is the deepest in dry farmlands, intermediate in the forestlands and wetlands, and the shallowest in paddy fields and grasslands. These percentages also indicate that the SOC storage decrease with soil depth when the paddy fields and wetlands are considered. In contrast, the SOC storage increases from the depth range 30 - 60 cm to 60 - 100 cm for the grasslands and forestlands.

Fig. 5. Vertical distribution of SOC storage in different soil depth ranges for various land-cover types

3.4 Effects of environmental factors on SOCD

The SOC storages within different soil depth ranges are significantly affected by climate and soil texture. As shown in Fig. 6, SOCD in the Sanjiang Plain is not only significantly correlated with MAT (Fig. 6 A1 - A3) and MAP (Fig. 6 B1 - B3) for the different soil depth ranges, but strongly associated with soil texture as well (Fig. 6 C1 - E3 and Table 3). The SOCD in the depth ranges 0 - 30 cm, 0 - 60 cm, and 0 - 100 cm of soil decreases with increasing MAT up to ~4.6 ℃ and then increases with MAT (Fig. 6 A1 - A3). Similarly, the SOCD for the different depth ranges decreases and then increases with soil clay content ($P < 0.01$, Fig. 6 C1 - C3). In addition, SOCD increases with MAP (Fig. 6 B1 - B3) and soil silt content (Fig. 6 D1 - D3). The SOCD shows a significantly negative correlation with sand content within the depth range 0 - 60 cm and 0 - 100 cm, but an insignificant correlation for the depth range 0 - 30 cm (Fig. 6 E1 - E3).

Fig. 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)

Table 2 presents the results from the GLM, which reveal that environmental factors explain 57.78%, 52.03%, and 37.67% of the overall variation of SOCD for the depth range 0 - 30 cm, 0 - 60 cm, and 0 - 100 cm, respectively. Both the associations of climate and soil texture with SOCD are weak with increasing soil depth. Clay content explains the largest proportion of the SOCD variation (21.20% for the range 0 - 30 cm, 18.30% for 0 - 60 cm, and 15.40% for 0 - 100 cm), and thus is the most dominant environmental variable. Silt content also plays an important role in shaping the pattern of SOC storage, explaining the second largest proportion of SOCD variation. Therefore, soil texture has more impacts on the distribution of SOCD than climate factors in the Sanjiang Plain. When comparing temperature with precipitation, the former exhibits more significant effects on the SOCD within the depth range 0 - 100 cm than the latter as shown by a regressive coefficient (Fig. 6 A3, B3) for temperature and a more variance of SOCD explained by temperature (Table 2).

Table 2 GLM results for correlating SOCD with environmental factors

The associations of climate and soil texture with vertical SOCD vary significantly (Table 3). For the different soil depths (0 - 30 cm, 30 - 60 cm, 60 - 100 cm), SOCD is negatively correlated to both MAT and sand content, but positively correlated with MAP, clay content and silt content. Clay content has the largest correlation coefficient with SOCD ($P < 0.01$), meaning that it plays a more important role in driving the SOCD vertical distribution as compared to other environmental variables. The correlations between SOCD and sand content are found high for deeper soil depth ranges, whereas the correlations between SOCD and other examined controlling factors are low.

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

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

We examined the amount of fertilizer and SOC content for croplands in the 23 counties and found that agricultural activities, especially fertilization, have remarkable impacts on SOC content. Significantly negative correlations ($P < 0.01$) between the amount of fertilizer and SOC content are found for the 0 - 30 cm and 30 - 60 cm depth ranges (Fig. 7). Meanwhile, the correlation between the amount of fertilizer and SOC content decreases with soil depth.

Fig. 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)

~~In this study, result of ANOVA analysis shows that mean value of SOC content for paddy field (27.81 g kg-1) is larger than that for dry farmland (22.19 g kg-1). Additionally, paddy fields show larger SOCD values than dry farmlands within the depth range 0 – 100 cm (Table 1), and the areal proportions of the two land cover types are thus related to SOC storage. The areal proportion of paddy fields relative to cropland in the Sanjiang Plain is significantly~~

~~correlated to the topsoil SOC content with an R^2 of 0.423 (P < 0.01), as shown in Fig. 8.~~

~~**Fig. 8. Correlations of topsoil SOC content with the areal ratio of paddy field to cropland in the Sanjiang Plain**~~

4 Discussion

4.1 SOC estimates in the Sanjiang Plain

Spatially explicit estimates of SOC at regional scales are vital for monitoring carbon sequestration, which impacts global climate change and food security (Lal, 2004a). In this study, extensive soil investigation that took land cover types and soil types into consideration has been undertaken to quantify the SOC storage in the Sanjiang Plain. A geostatistical approach was further used to map the regional pattern of SOC in different soil depth ranges. 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. Considering the rich ecosystem types of the Sanjiang Plain and coarse resolution remote sensing imagery, this study used the Kriging method to achieve more accurate estimation of SOC than those by previous studies (Wang et al., 2002; Yu et al., 2007). The SOC estimates were based on a large volume dataset including the most recently measured data.

Observed was the larger mean SOCD for the depth range 0 - 100 cm (21.20 kg m^{-2}) in the Sanjiang Plain as compared to the reported mean SOCD of China 7.8 kg m^{-2} (Yang et al., 2007) and the whole world 10.8 kg m^{-2} estimated by Post et al. (1982), which is mostly due to relatively low temperature as compared to the south, more precipitation than the western part of the country, as well as extensive wetlands and forests in the Sanjiang Plain (Yu et al., 2007). In addition, the estimated SOCD value 10.19 kg m^{-2} for the depth range 0 - 30 cm in the study area is higher than 7.70 kg m^{-2} observed in the Loess Plateau of China (Liu et al., 2011) and the value 5.91 kg m^{-2} for France (Martin et al., 2011). This is largely attributed to the humid climate and high natural vegetation (i.e. forest and wetland) cover. In this study, we have observed that forestlands have higher SOCD than grasslands, which is different from the SOC results of China reported by Wang et al. (2004) and of France by Martin et al. (2011). We attribute these differences to the climate zones in which these studies have focused on.

This study resulted in the total estimated SOC storage 2.32 Pg C within the soil depth range 0 - 100 cm in the Sanjiang Plain. Similar estimations yielded 26.43 Pg C for the Northeast China (Wang et al., 2003) and 69.10 Pg C for the whole China (Wu et al., 2003). Converting these two SOC storage values to SOCD based on related publications would give rise to SOCD values of the Sanjiang Plain, which are smaller than the SOCD result observed in this study. It is worth to discuss which SOCD estimate is more accurate.

Our results reveal that the farmland has a SOCD value smaller than those for the forestland and wetland. Fig. 6 shows negative correlation of SOCD with temperature and positive correlation with precipitation. Additionally, the Sanjiang Plain experienced significant losses of both forestland and wetland to farmland, obvious increases in temperature, and notable decreases in precipitation (Wang et al., 2011; Song et al., 2012, 2014). All these factors should contribute to the loss of SOC storage. Therefore, we are confident that the present SOCD estimation is more close to the actual SOC storage in the Sanjiang Plain, and that the previous reported SOCD for the Northeast China and the whole country level underestimated the SOC storage.

4.2 Impacts of land-cover type on SOC

It has been pointed out that the SOC storage strongly depends on land cover types (Chaplot et al., 2010; Martin et al., 2011). Fig. 2 supports the same observation. It is thus necessary to discuss the impacts of land cover types on SOC storage.

Jobbágy and Jackson (2000) and Yang et al. (2007) observed that land cover types significantly affected the distribution of SOC. This conclusion is supported by our result shown in Table 1 and Fig. 5. The results demonstrate that the wetlands have the highest SOCD, which is most likely related to a low decomposition rate of soil organic matter and high soil moisture content (Taggart et al., 2012). A notable loss of topsoil SOC as a result of cultivation was observed in China (Song et al., 2005). A significant loss of wetlands to croplands was reported in the Sanjiang Plain in the past few decades (Wang et al., 2009; 2011), which is believed to lead to enhanced carbon emission. These observations imply that implementation of an effective plan for wetland management, conservation, and restoration in the Sanjiang Plain is required for increasing regional carbon sequestration and reducing the carbon budget. Similarly, effectively reducing the loss of forestlands and rationally replacing cultivated land for forestland are essential for balancing the carbon budget (Cao et al., 2011b). Intensive agricultural activities (e.g. 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 croplands, their large areas make them the largest SOC pool among all land cover types considered in this study (Table 1).

The results show different vertical patterns of SOC storage for the five land-cover types. Grasslands have the shallowest root distribution and less fresh carbon supply in deep soil layers, and account for a large SOC proportion in the topsoils (Fontaine et al., 2007). The relatively low decomposability and deep root distribution pattern in wetlands can be used to explain the observed difference of the vertical SOC features between the wetlands and grasslands (Jobbágy and Jackson, 2000). Loosened soil and plow tillage in dry farmlands, which are favorable to the soil respiration, can explain the low SOC storage within the soil depth range 0 - 30 cm in the Sanjiang Plain. In contrast, paddy fields exhibit a large SOC content, which is most likely related to the stability of the soil environment (Pan et al., 2003), suggesting a SOC proportion of the topsoil larger than that in dry farmlands, as shown in Fig. 5. The correlations of SOCD with the examined environmental factors decrease with the soil depth. This observation could be related to the changes of vegetation types. Vegetation affects the lateral and vertical patterns of SOC through the distribution and production of above- or below-ground biomass. Severe population pressure, and misguided policies resulted significant changes of land cover types, especially in losses of forestlands and wetlands to croplands (Song et al., 2014; Wang et al., 2012). The SOC storage dynamics controlled by changes of land cover types needs to be investigated in future.

4.3 Relationships between SOC and climate factors

MAT and MAP explain a large amount of the variation of SOCD in different soil depth ranges (Table 2), implying that climate conditions are an important environmental force in controlling the lateral and vertical distribution of SOC. The results also show that the variances of SOCD is driven less by MAT than MAP for the soil depth range 0 - 30 cm of the study region. This is consistent with the observation made in France (Martin et al., 2011) because of humid climate in both France and the Sanjiang Plain.

With respect to the association of SOCD with MAT, SOCD goes down and then up 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 low carbon inputs of plant production and high carbon outputs of soil decomposition. MAT is often lower than 4.6 ℃ in the Sanjiang Plain. This is why a significantly negative correlation (r = -0.33, P < 0.01) is observed between MAT and SOCD (Table 3). On the contrary, MAT higher than 4.6 ℃ may increase the vegetation productivity and thus contribute to increasing 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 increasing trend of SOCD from the tropical to cold-temperate zone in the eastern part of China is correlated with temperature. In the Sanjiang Plain, MAT can explain 4.23% of the SOCD variability, suggesting that temperature plays an important role in shaping the pattern of SOC.

In relation to MAP, SOCD values within different soil depth ranges show strong positive correlations to MAP as shown by the power relationships in Fig. 6 B1 - B3). These positive correlations can be explained by the fact that precipitation enhances the vegetation productivity and thus leads to accumulation of SOC. This finding is in agreement with the observation made for the spatial pattern of SOC in Northern China, i.e., increasing precipitation contributes to an increase in SOCD from the arid to semi-humid zone (Yang et al., 2007). Similarly, the SOCD of the Sanjiang Plain estimated by this study is higher than that for the Loess Plateau (Liu e al., 2011) due to the difference of the two areas in precipitation. MAP explains the variation of SOCD at less degree when soil depth increases (Table 2) and shows diminishing correlation with SOCD (Table 3). This can be attributed to relative low soil moisture to deep soil depth layers which affects the root vertical distribution with increasing soil depth (Jobbágy and Jackson, 2000).

4.4 Effects of soil texture on SOC

The GLM results indicate that the observed soil texture explains 48%, 44% and 35% of the variability of SOCD for the depth ranges 0 - 30, 0 - 60, and 0 - 100 cm, respectively. For the country scale of China, climate was observed as the leading factor driving the spatial pattern of SOCD (Wu et al., 2003; Yang et al., 2007). However, at a smaller regional scale, such as the Sanjiang Plain, the variation of SOCD is mostly attributed to soil texture rather than climate. The similar result was shown in Laos (Chaplot et al., 2010) where SOC storage is mainly controlled by soil types and texture. Soil texture is closely related to the soil water holding capacity and the decomposition rate of organic matter, which thus signifies a key role in shaping the spatial pattern of SOCD at the regional scale (Chaplot et al., 2010). In spite of the fact that climate controls the pattern of SOC storage in a large continental scale, soil texture shows more effects on the distribution of SOC in a small regional level.

This study shows that clay content contributes to the pattern of SOCD more significantly than silt and sand do. This result supports the observation by Jobbágy and Jackson (2000) that clay content is the best predictor of SOCD in deeper depth layers. Moreover, this study shows that SOCD is highly and positively correlated to silt content within different soil depth ranges. This result is expected because high clay and silt contents can stabilize soil organic matter and largely slow down the soil carbon cycle (Hassink et al., 1997). However, negative relationships are observed for SOCD and sand content (Fig. 6 E1 - E3 and Table 3), which can be explained by the sandy soil properties: low water holding capacity, limited vegetation productivity and carbon sequestration. Small magnitude correlation coefficients for sandy soil could be explained by low carbon inputs and relatively efficient decomposition of organic matter within deep soil layers (Ontl et al., 2013).

4.5 Impacts of agricultural activities on SOC

Given the fact that both soil texture and vegetation types are highly influenced by climate, and that soil texture has obvious effects on vegetation types. These interactive systems drive the SOC distribution in very complicated ways. The GLM results indicate that the examined environmental factors only explain 57.78%, 52.03% and 47.67% of the SOCD variability within the depth range 0 - 30 cm, 0 - 60 cm and 0 - 100 cm, respectively. Therefore, we speculate that the anthropogenic factor is critical in explaining the pattern and storage of SOC.

Croplands, including dry farmlands and paddy fields, covering 54.2% of the whole area of the Sanjiang Plain, have the largest carbon pool among the land types (Table 1). Therefore, the change of SOCD in cropland could result in significant variation in the lateral and vertical distribution of SOC. It is well known that 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, and which are expected to be a crucial force for shaping the lateral and vertical pattern of SOC (Liu et al., 2006; Mao et al., 2014b). Generally, fertilization can raise the SOC storage by enhancing the carbon input from plant productivity and crop biomass (Ren et al., 2012, Zhao et al., 2013). However, over application of fertilizer can have negative net effects on carbon sequestration because organic carbon mineralization neutralizes the carbon input (Russell et al., 2005). Influences of fertilization on SOC are complicated, and can be related to the history of cropland, vegetation types, as well as soil types and texture. Comparing between the amount of fertilizer and SOC at the county scale, indicates that the counties using high amounts of fertilizer have low SOC content (Fig. 7). This may manifest different SOC decomposition scenarios due to temperature, soil moisture and soil types in this plain. Long-term field experiments for different crop types are needed to investigate the effects of fertilization on SOC at the local scale.

~~This study find that, paddy field has a larger SOC content than dry farmland, which can be explained by greater dry matter production of paddy field (Pan et al., 2003; Xu et al., 2007; Wang et al., 2008). For the study region, in the past two decades, large area of dry farmlands have been transformed into paddy fields, motivated by governmental policy for increasing grain production and stimulated by the fact that rice growing can yield more income than planting upland crops (Song et al., 2012). Paddy field not only store more carbon in soils, but also can sequestrate more carbon in the atmosphere than dry farmland. In the Sanjiang Plain, dry farmland was observed to have a net CO_2 emissions of ~47.1 gC m^{-2} yr^{-1} and a net CH_4 absorption of ~0.2 gC m^{-2} yr^{-1}, while paddy field has a net CO_2 uptake of ~255 gC m^{-2} yr^{-1} and~~

a net CH_4 emissions of ~7.5 gC m^{-2} yr^{-1} (Song et al., 2006; Wang et al., 2008; Song et al., 2009; Huang et al., 2010). Thus, conversion from dry farmland into paddy field means a transformation of carbon source to carbon sequestration, considering that the global warming potential of CH_4 is 23 times that of CO_2 (IPCC, 2001), which could foster the local carbon accumulation and mitigate climate change (Ouyang et al., 2014).

5 Conclusions

This study has used Kriging, a spatial interpolation technology, and 419 soil sampling sites (1257 profiles in total) collected in 2012 for each of the soil depth ranges 0 - 30 cm, 30 - 60 cm, and 60 - 100 cm to determine the SOC storage in the Sanjiang Plain, China. Relationships of SOCD with different environmental factors were examined. The results reveal that the total SOC storage within the depth range 0 - 100 cm in the Sanjiang Plain was estimated to be 2.32 Pg C, and mainly stocked in the topsoil. Over the Sanjiang Plain, soil texture plays more important roles than climate in determining the distribution of SOC with clay content contributing more than other observed factors. Vegetation, climate, and soil texture, as well as agricultural activities has remarkable impacts on the storage and distribution of SOC. Wetlands have the highest SOCD as compared with other land cover types, but display a significant loss in the recent decades. Thus, implementation of an effective wetland management and conservation plan in the Sanjiang Plain is required for fostering regional carbon sequestration. Moreover, policy and economic benefit-driven conversion from dry farmlands to paddy fields contribute to more carbon stocking in the soil. A comparison of the estimate to those by other previous studies demonstrates underestimation of the SOC storage in the Sanjiang Plain if values at the Northeast China and the whole country level are used. An accurate and the updated estimates of SOC storage by this study will significantly improve the knowledge of carbon cycles and the determination of the carbon budget for the Sanjiang Plain.

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Table1 SOCD and SOC storage for different land-cover types in the Sanjiang Plain

Land-cover types	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	41462.87	9.72	14.56	19.68	412.10	637.71	821.84
Paddy field	18068.62	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	36556.49	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

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, sum of squares, means the proportion of variances explained by a variable.

Table3 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] $P < 0.01$

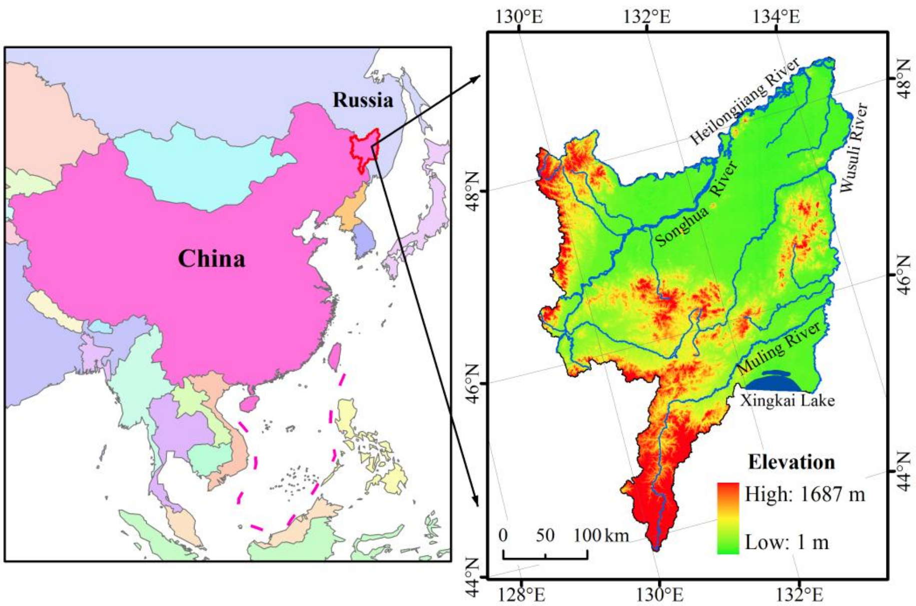


Fig. 1. Position and terrain of the Sanjiang Plain

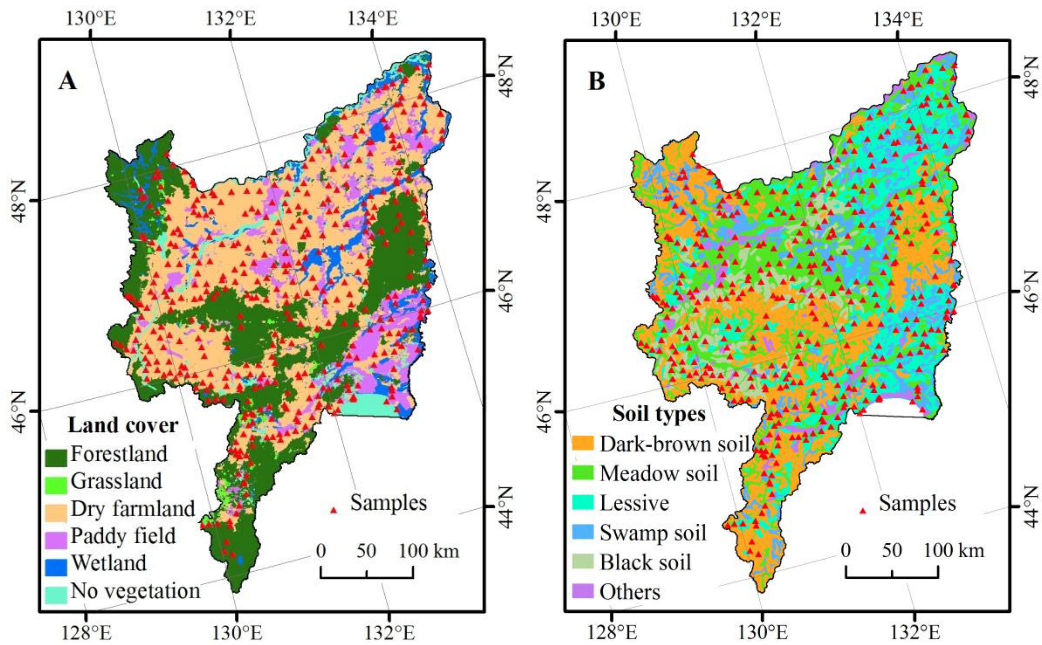


Fig. 2. Spatial distribution of field samples, land cover (A) and soil types (B) in the Sanjiang Plain

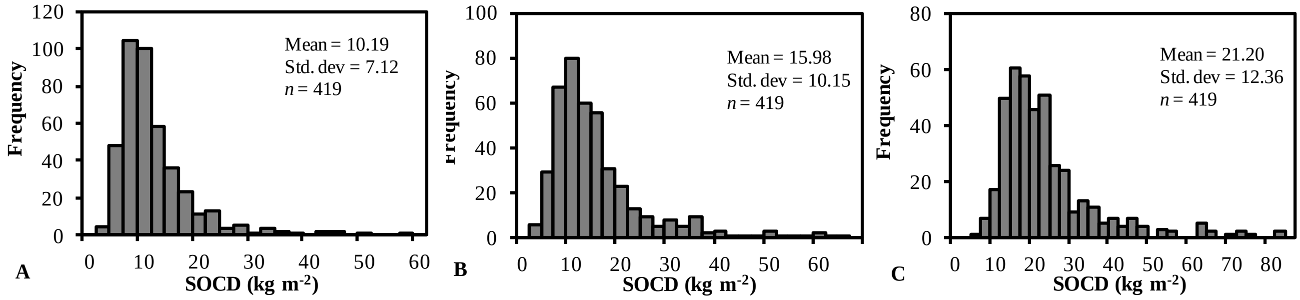


Fig. 3. Frequency distributions of SOCD at different soil depth ranges (A: 0 - 30 cm; B: 0 - 60 cm; C: 0 - 100 cm)

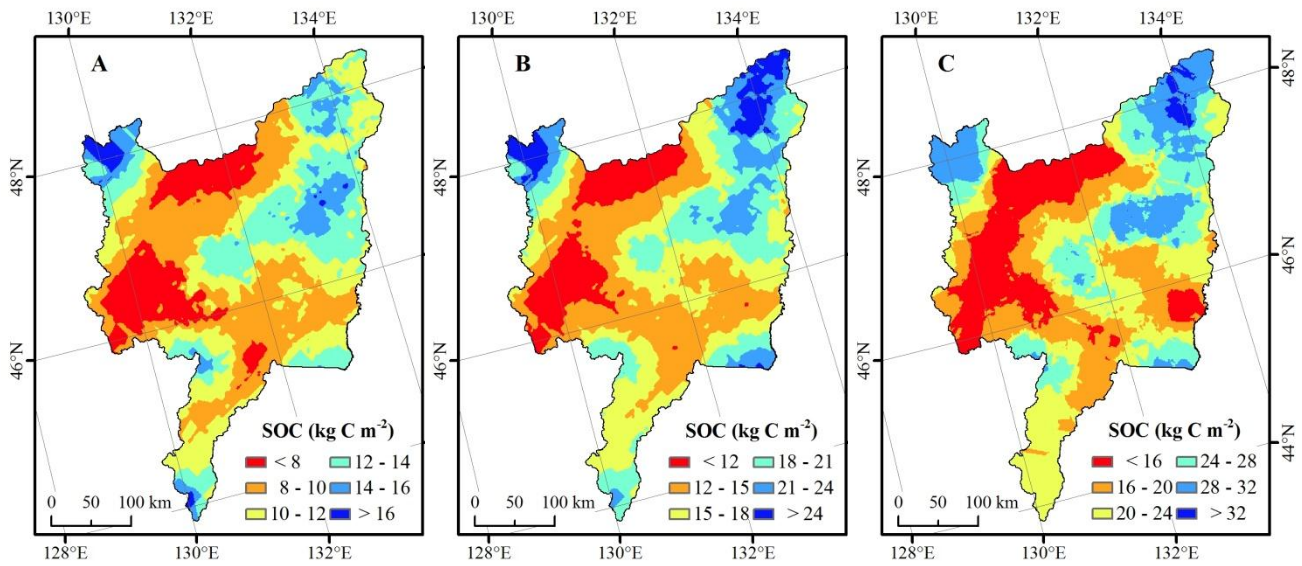


Fig. 4. Spatial pattern of SOC storage at different soil depths (A: 0 - 30 cm; B: 0 - 60 cm; C: 0 - 100 cm)

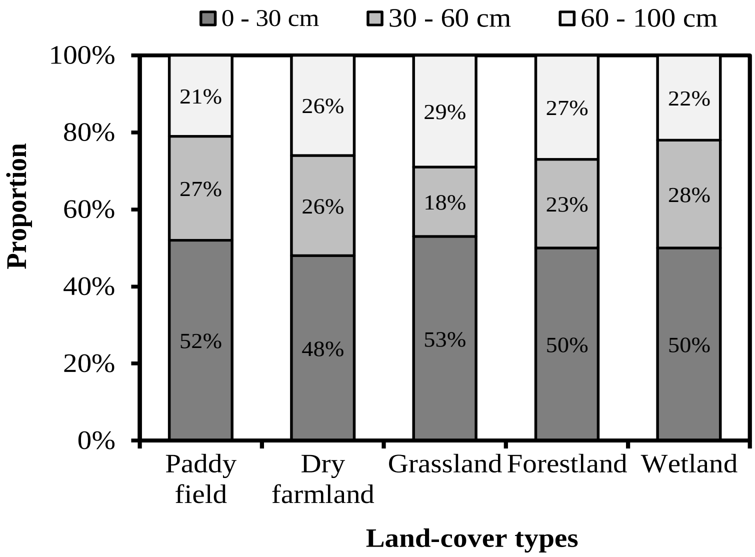


Fig. 5. Vertical distribution of SOC storage in different soil depth ranges for various land-cover types

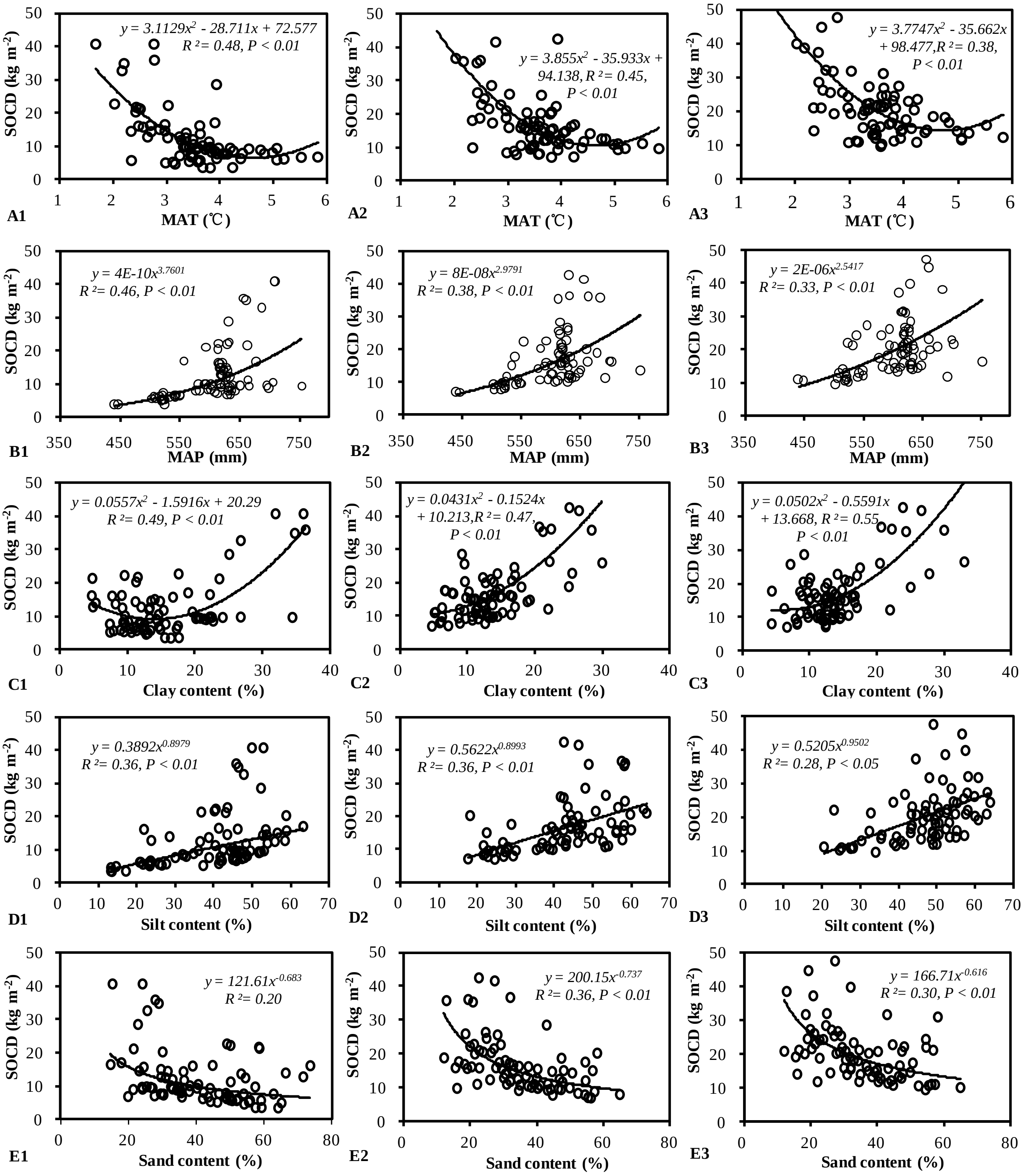


Fig. 6. Correlations of SOCD with various environmental factors for different soil depths in the Sanjiang Plain (A1 - E1: 0 - 30 cm; A2 - E2: 0 - 60 cm; A3 - E3: 0-100 cm)

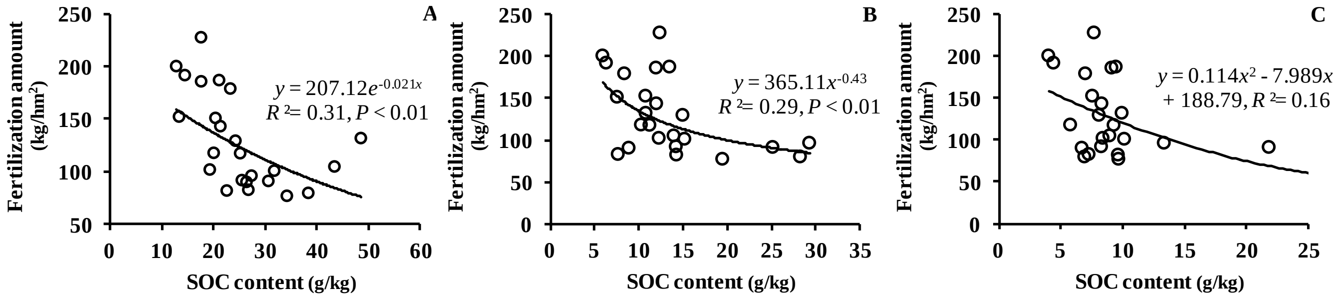
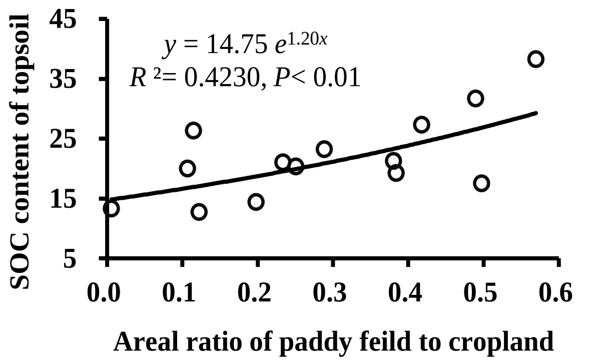


Fig. 7. Correlations of the cropland fertilization amount with SOC content in the Sanjiang Plain for different soil layers (A: 0 - 30 cm; B: 30 - 60 cm; C: 60 - 100 cm)



~~**Fig. 8.** Correlations of topsoil SOC content with the areal ratio of paddy field to cropland in the Sanjiang Plain~~