

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

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

3

4 **Abstract**

5 Accurate estimation of soil organic carbon (SOC) storage and determination of its pattern
6 controlling factors is critical to understanding the ecosystem carbon cycle and ensuring
7 ecological security. The Sanjiang Plain, an important grain production base in China, is typical
8 of ecosystems, yet its SOC storage and pattern has not been fully investigated because of
9 deficient soil investigation. In this study, 419 soil samples obtained in 2012 for each of the three
10 soil depth ranges 0 - 30 cm, 30 - 60 cm, 60 - 100 cm, and a geostatistical method are used to
11 estimate the total SOC storage and density (SOCD) of this region. The results give rise to 2.32
12 Pg C for the SOC storage, and 21.20 kg m⁻² for SOCD which is higher than the mean value for
13 the whole country. The SOCD shows notable changes in lateral and vertical distribution. In
14 addition, vegetation, climate, and soil texture, as well as agricultural activities, are
15 demonstrated to have remarkable impacts on the variation of SOCD of this region. Soil texture
16 has stronger impacts on the distribution of SOCD than climate in the Sanjiang Plain.
17 Specifically, clay content can explain the largest proportion of the SOC variations (21.2% in
18 the top 30 cm) and is the most dominant environmental controlling factor. Additionally, the
19 effects of both climate and soil texture on SOCD show weakening with increasing soil layer
20 depth. This study indicates that reducing the loss of SOC requires effective wetland and
21 forestland conservation and restoration, rational distribution of crop types and fertilization. The
22 results from this study provide the most updated knowledge on the storage and pattern of SOC
23 in the Sanjiang Plain, and have important implications for the determination of ecosystem
24 carbon budgets and understanding ecosystem services.

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

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1 **1 Introduction**

2 Soil is the largest terrestrial organic carbon pool, contains twice as much carbon as those in
3 the atmosphere or vegetation (Batjes, 1996), and plays an important role in the global carbon
4 cycle. Accurate quantification of soil organic carbon (SOC) storage and further investigating
5 its association with environmental factors is essential to in-depth analyses of the terrestrial
6 carbon cycle and updating the carbon budget (Conant et al., 2011; Dorji et al., 2014; Piao et al.,
7 2009).

8 In the past decades, numerous studies were undertaken to investigate the storage and
9 distribution heterogeneity of SOC in different regions, which includes the North American
10 Arctic (Ping et al., 2008), the Amazon (Batjes and Dijkshoorn, 1999), the British moorland
11 (Garnett et al., 2001), Laos (Chaplot, et al., 2010), France (Martin et al., 2011), and China (Ni,
12 2013; Yu et al., 2007). Globally, 32% of SOC is stored in tropical soils, and mainly in forest
13 soils (Eswaran et al., 1993). In China, the total SOC storage has been estimated using field
14 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}
15 gC), representing ~5.0 % of the world storage (Xie et al., 2007). However, the large of the two
16 estimated SOC values implies a necessity of improving SOC estimation at regional and local
17 scales to achieve accurate updating of the world and national SOC budget.

18 The storage and distribution heterogeneity of SOC depend on climate conditions (Davidson
19 and Janssens, 2006), land-use patterns (Poeplau and Don, 2013; Yu et al., 2012), and human
20 activities and policies (Cao et al., 2011a, 2011b; Heikkinen et al., 2013; Wang et al., 2011). The
21 distribution of SOC has been correlated with various climate factors, soil texture, and land cover
22 types (Batjes and Dijkshoorn, 1999; Jobbágy and Jackson, 2000; Li and Zhao, 2001; Saiz et al.,
23 2012; Wang et al., 2004; Yang et al., 2007). Globally, total SOC content has been shown to
24 increase with precipitation but decrease with temperature, and the two climate factors control
25 SOC in shallow soil layers (Jobbágy and Jackson, 2000). Jobbágy and Jackson (2000) also
26 showed that total SOC increases with clay content, which drives SOC in deeper soil layers.
27 Plant functional types can significantly impact the vertical distribution of SOC (Jobbágy and

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

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

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

25 **2 Data and Methods**

26 **2.1 Study area**

27 The Sanjiang Plain is located in the northeast corner of China and separated from Russia by

1 the Heilongjiang and Wusuli rivers (Fig. 1). The region has 23 counties and extends from 129 °
2 11' E to 134° 47' E in longitude and from 43° 49' N to 48°25' N in latitude, with a total area of
3 108 596 km² (Wang et al., 2011). It is a low alluvial plain deposited by the Heilongjiang,
4 Songhua, and Wusuli rivers with elevation in the southwest being higher than in the northeast.
5 Annual precipitation is between 500 mm and 650 mm, and 80% of rainfall occurs in growing
6 seasons (May to September). The mean air temperature ranges from 1.4 to 4.3 °C, and the frost-
7 free period is 120 - 140 days. The climate of this area belongs to the temperate humid or sub-
8 humid continental monsoon climate (Wang et al., 2006), which is suitable for natural wetlands
9 and growing grains.

10 **Fig. 1. Position and terrain of the Sanjiang Plain**

11 **2.2 Land-cover and soil type datasets**

12 The Landsat thematic mapper (TM) and Chinese Huan Jing (HJ) satellite images (Zhang et
13 al., 2014) acquired in 2010 for the study region were classified using the eCognition software
14 to extract land-cover data (Mao et al., 2014a). All the images (32 of them being TM and 6 for
15 HJ) were atmospherically corrected using the 6S radiative transfer model and geometrically
16 rectified. Furthermore, based on the digital elevation model (DEM) and field investigations,
17 image segmentation was performed for these satellite images. Validation of the land cover
18 classification on the field data collected in 2010 (1326 points) resulted a kappa coefficient of
19 0.894 and overall accuracy of 89%. Area for each land cover type was calculated through the
20 ArcMap software. Statistic results further revealed that the major land cover types in the
21 Sanjiang Plain were cropland, forestland, and wetland (Fig. 2A), with an area of 59 531.49 km²,
22 36 556.49 km², 6 527.89 km², respectively.

23 The soil type dataset covering the Sanjiang Plain was clipped from the soil map of China,
24 resulting from Chinese second soil investigations at a scale of 1: 1 000 000 (Wang et al., 2006).
25 Five main soil types in the area were dark-brown soil, meadow soil, lessive, swamp soil, and
26 black soil, and occupied more than 95% of the whole area (Fig. 2B). In the Sanjiang Plain, dark-
27 brown soil and meadow soil are the largest and second largest soil type with an area of 32103.54
28 km² and 31017.36 km², respectively. Considering the SOC content and density differ among

1 soil types (Mao et al., 2014b; Yu et al., 2007), different soil types need to be accommodated in
2 the deployment of field sampling sites.

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

5 **2.3 Soil sampling and determination**

6 Soil samples were collected in 2012 on the basis of visual navigation via a GPS unit linked
7 with ArcGIS installed laptop. Each of these samples was collected using a standard container
8 with a volume of 100 cm³ and a cloth pocket. For each soil site (three soil profiles at each site),
9 the SOC content for each depth range (i.e. 0 - 30 cm, 30 - 60 cm, and 60 - 100 cm) was
10 represented by the average of SOC values of three spatially random profiles at the sampling
11 site. Land-cover types, sampling time and depth, and geographic locations were recorded while
12 sampling. Because of the inaccessibility of some land-cover types and the areal difference of
13 land-cover types, a total of 419 soil samples (59 for forestland, 13 for grassland, 59 for paddy
14 field, 206 for dry farmland, and 82 for wetland) for each soil depth range were obtained, and
15 their locations were overlaid on the land-cover and soil types as shown in Fig. 2.

16 All of the soil samples were air-dried and then oven-dried at 105°C to determine their bulk
17 densities. Visible plant detritus and all rock fragments were removed from the soil samples in
18 the cloth pockets before the soil samples were further processed by grounding and sieving with
19 2-mm meshes and analyzed for SOC concentration and soil texture. The SOC concentration
20 was measured by wet combustion with K₂Cr₂O₇ (Yang et al., 2007). A Mastersizer 2000
21 instrument was used to measure the soil texture of 80 sample profiles equally distributed in the
22 study area, including clay content (< 0.002 mm), silt content (0.02 - 0.002 mm), and sand
23 content (0.02 - 2 mm).

24 **2.4 Climate data**

25 The mean annual temperature (MAT) and mean annual precipitation (MAP) were calculated
26 from the meteorological data recorded during 1981 - 2012. All of these data were downloaded
27 from the National Climatic Data Center of NOAA (NCDC, <http://www.ncdc.noaa.gov/>) and the

1 China Meteorological Data Sharing Service System (<http://cdc.cma.gov.cn>), respectively. For
2 bettering the accuracy of spatial interpolation of climate factors, 35 meteorological stations (12
3 of them being Russia and 23 in China) were used and spatially interpolated using the Kriging
4 method. The MAT and MAP for each sampling site were extracted based on its geographical
5 position from the interpolated raster with a spatial resolution of 8 km.

6 **2.5 Amounts of Fertilizer**

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

11 **2.6 Estimation of SOC storage**

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

15
$$SOCD_h = \sum_{i=1}^n \frac{(1 - \delta_i \%) \times \rho_i \times C_i \times T_i}{100} \quad (1)$$

16
$$SOC_h = SOCD_h \times AREA \quad (2)$$

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

20 The Kriging interpolation and the semivariogram function were used to determine the spatial
21 distribution of SOC. Kriging is a geostatistical method that is commonly used to interpolate a
22 SOCD dataset from discrete points to a spatially continuous surface (Kumar et al., 2012; Khalil
23 et al., 2013), and the semivariogram function can be used to quantify the spatial autocorrelation
24 and provides an input parameter for a spatial interpolation (Liu et al., 2011). All of the
25 calculations for mapping SOC within individual soil depth ranges were performed using the
26 ArcGIS software (Version 9.3).

27 **2.7 Statistical analysis**

1 The General Linear Model (GLM) was used to determine the relationship between SOCD
2 and each of different environmental factors (MAT, MAP, clay content, silt content, and sand
3 content) and to assess how each factor influences the variation of SOC within a soil depth range
4 (Yang et al., 2007). All GLM analyses were performed with the software package R (R
5 Development Core Team 2005).

6 The coefficient of determination (R^2) and the correlation coefficient (p) obtained from
7 regressive and correlative analyses performed with the SPSS software were employed to
8 describe the effects of individual controlling factors on SOC, such as climate factors and soil
9 parameters. In addition, the estimated SOCD for the Sanjiang Plain was compared to the SOCD
10 values estimated for different regions of the world to investigate the effects of climate factors
11 and vegetation.

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

18

19 **3 Results**

20 **3.1 Storage and spatial distribution of SOC**

21 SOCD of the 419 sampling profiles varied remarkably within each soil depth range (Fig. 3).
22 The mean SOCD values of all sample profiles for the three depth ranges (0 - 30 cm, 0 - 60 cm,
23 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
24 of the corresponding SOCD were 7.12 kg m^{-2} , 10.15 kg m^{-2} , and 12.36 kg m^{-2} , respectively.
25 Excluding the regions of water bodies, the total SOC storage of the Sanjiang Plain was
26 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
27 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.

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

3.2 Mean SOCD and SOC storage for different ecosystems

Table 1 provides a detailed description of SOCD and SOC storage for different ecosystems 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, $1 \text{ Tg C} = 10^{12} \text{ gC}$) 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 ecosystems in the Sanjiang Plain

3.3 Vertical distribution characteristics of SOC storage for different ecosystems

22 An apparent vertical differentiation of SOC storage can be observed in the Sanjiang Plain
23 (Fig. 5). For the soil depth range 0 -100 cm, approximately 49% of total SOC storage is
24 concentrated within the top 30 cm. The SOC storage within each soil depth range (0 - 30 cm,
25 30 - 60 cm, and 60 - 100 cm) varies significantly across different ecosystems. The percentage
26 which SOC within the depth range 0 - 30 cm can account for SOC within the range 0 - 100 cm
27 is 48%, 50%, 50%, 52%, 53% for dry farmlands, forestlands, wetlands, paddy fields, and
28 grasslands, respectively, implying that the relative distribution of the SOC of the topsoil is the

1 deepest in dry farmlands, intermediate in the forestlands and wetlands, and the shallowest in
2 paddy fields and grasslands. These percentages also indicate that the SOC storage decrease with
3 soil depth when the paddy fields and wetlands are considered. In contrast, the SOC storage
4 increases from the depth range 30 - 60 cm to 60 - 100 cm for the grasslands and forestlands.

5 **Fig. 5. Vertical distribution of SOC storage in different soil depth ranges for various**
6 **ecosystems**

7 **3.4 Effects of environmental factors on SOCD**

8 The SOC storages within different soil depth ranges are significantly affected by climate and
9 soil texture. As shown in Fig. 6, SOCD in the Sanjiang Plain is not only significantly correlated
10 with MAT (Fig. 6 A1 - A3) and MAP (Fig. 6 B1 - B3) for the different soil depth ranges, but
11 strongly associated with soil texture as well (Fig. 6 C1 - E3 and Table 3). The SOCD in the
12 depth ranges 0 - 30 cm, 0 - 60 cm, and 0 - 100 cm of soil decreases with increasing MAT up to
13 ~4.6 °C and then increases with MAT (Fig. 6 A1 - A3). Similarly, the SOCD for the different
14 depth ranges decreases and then increases with soil clay content ($P < 0.01$, Fig. 6 C1 - C3). In
15 addition, SOCD increases with MAP (Fig. 6 B1 - B3) and soil silt content (Fig. 6 D1 - D3). The
16 SOCD shows a significantly negative correlation with sand content within the depth range 0 -
17 60 cm and 0 - 100 cm, but an insignificant correlation for the depth range 0 - 30 cm (Fig. 6 E1
18 - E3).

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

21 Table 2 presents the results from the GLM, which reveal that environmental factors explain
22 57.78%, 52.03%, and 37.67% of the overall variation of SOCD for the depth range 0 - 30 cm,
23 0 - 60 cm, and 0 - 100 cm, respectively. Both the associations of climate and soil texture with
24 SOCD are weak with increasing soil depth. Clay content explains the largest proportion of the
25 SOCD variation (21.20% for the range 0 - 30 cm, 18.30% for 0 - 60 cm, and 15.40% for 0 -
26 100 cm), and thus is the most dominant environmental variable. Silt content also plays an
27 important role in shaping the pattern of SOC storage, explaining the second largest proportion
28 of SOCD variation. Therefore, soil texture has more impacts on the distribution of SOCD than

1 climate factors in the Sanjiang Plain. When comparing temperature with precipitation, the
2 former exhibits more significant effects on the SOCD within the depth range 0 - 100 cm than
3 the latter as shown by a regressive coefficient (Fig. 6 A3, B3) for temperature and a more
4 variance of SOCD explained by temperature (Table 2).

5 **Table 2 GLM results for correlating SOCD with environmental factors**

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

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

16 **3.5 Effects of fertilization amount and cropland types on SOC storage**

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

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

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

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

2

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

5

6 **4 Discussion**

7 **4.1 SOC estimates in the Sanjiang Plain**

8 Spatially explicit estimates of SOC at regional scales are vital for monitoring carbon
9 sequestration, which impacts global climate change and food security (Lal, 2004a). In this study,
10 extensive soil investigation that took land cover types and soil types into consideration has been
11 undertaken to quantify the SOC storage in the Sanjiang Plain. A geostatistical approach was
12 further used to map the regional pattern of SOC in different soil depth ranges. The method that
13 was used for estimating the regional carbon pool in the present study is different from that used
14 by Yang et al. (2008), who estimated SOC storage by correlating SOC content with a remote
15 sensing vegetation index. Considering the rich ecosystem types of the Sanjiang Plain and coarse
16 resolution remote sensing imagery, this study used the Kriging method to achieve more accurate
17 estimation of SOC than those by previous studies (Wang et al., 2002; Yu et al., 2007). The SOC
18 estimates were based on a large volume dataset including the most recently measured data.

19 Observed was the larger mean SOCD for the depth range 0 - 100 cm (21.20 kg m^{-2}) in the
20 Sanjiang Plain as compared to the reported mean SOCD of China 7.8 kg m^{-2} (Yang et al., 2007)
21 and the whole world 10.8 kg m^{-2} estimated by Post et al. (1982), which is mostly due to
22 relatively low temperature as compared to the south, more precipitation than the western part
23 of the country, as well as extensive wetlands and forests in the Sanjiang Plain (Yu et al., 2007).
24 In addition, the estimated SOCD value 10.19 kg m^{-2} for the depth range 0 - 30 cm in the study
25 area is higher than 7.70 kg m^{-2} observed in the Loess Plateau of China (Liu et al., 2011) and the
26 value 5.91 kg m^{-2} for France (Martin et al., 2011). This is largely attributed to the humid climate
27 and high natural vegetation (i.e. forest and wetland) cover. In this study, we have observed that

1 forestlands have higher SOCD than grasslands, which is different from the SOC results of China
2 reported by Wang et al. (2004) and of France by Martin et al. (2011). We attribute these
3 differences to the climate zones in which these studies have focused on.

4 This study resulted in the total estimated SOC storage 2.32 Pg C within the soil depth range
5 0 - 100 cm in the Sanjiang Plain. Similar estimations yielded 26.43 Pg C for the Northeast
6 China (Wang et al., 2003) and 69.10 Pg C for the whole China (Wu et al., 2003). Converting
7 these two SOC storage values to SOCD based on related publications would give rise to SOCD
8 values of the Sanjiang Plain, which are smaller than the SOCD result observed in this study. It
9 is worth to discuss which SOCD estimate is more accurate.

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

19 **4.2 Impacts of land cover type on SOC**

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

23 Jobbágy and Jackson (2000) and Yang et al. (2007) observed that land cover types
24 significantly affected the distribution of SOC. This conclusion is supported by our result shown
25 in Table 1 and Fig. 5. The results demonstrate that the wetlands have the highest SOCD, which
26 is most likely related to a low decomposition rate of soil organic matter and high soil moisture
27 content (Taggart et al., 2012). A notable loss of topsoil SOC as a result of cultivation was
28 observed in China (Song et al., 2005). A significant loss of wetlands to croplands was reported

1 in the Sanjiang Plain in the past few decades (Wang et al., 2009; 2011), which is believed to
2 lead to enhanced carbon emission. These observations imply that implementation of an
3 effective plan for wetland management, conservation, and restoration in the Sanjiang Plain is
4 required for increasing regional carbon sequestration and reducing the carbon budget. Similarly,
5 effectively reducing the loss of forestlands and rationally replacing cultivated land for
6 forestland are essential for balancing the carbon budget (Cao et al., 2011b). Intensive
7 agricultural activities (e.g. tillage) have resulted in enhanced soil mineralization (Lal, 2002),
8 which has led to low SOC in dry farmlands (red and orange colors in Fig. 4). Although a low
9 SOCD was found for croplands, their large areas make them the largest SOC pool among all
10 land cover types considered in this study (Table 1).

11 The results show different vertical patterns of SOC storage for the five ecosystems.
12 Grasslands have the shallowest root distribution and less fresh carbon supply in deep soil layers,
13 and account for a large SOC proportion in the topsoils (Fontaine et al., 2007). The relatively
14 low decomposability and deep root distribution pattern in wetlands can be used to explain the
15 observed difference of the vertical SOC features between the wetlands and grasslands (Jobb ágy
16 and Jackson, 2000). Loosened soil and plow tillage in dry farmlands, which are favorable to the
17 soil respiration, can explain the low SOC storage within the soil depth range 0 - 30 cm in the
18 Sanjiang Plain. In contrast, paddy fields exhibit a large SOC content, which is most likely
19 related to the stability of the soil environment (Pan et al., 2004), suggesting a SOC proportion
20 of the topsoil larger than that in dry farmlands, as shown in Fig. 5. The correlations of SOCD
21 with the examined environmental factors decrease with the soil depth. This observation could
22 be related to the changes of vegetation types. Vegetation affects the lateral and vertical patterns
23 of SOC through the distribution and production of above- or below-ground biomass. Severe
24 population pressure, and misguided policies resulted significant changes of land cover types,
25 especially in losses of forestlands and wetlands to croplands (Song et al., 2014; Wang et al.,
26 2012). The SOC storage dynamics controlled by changes of land cover types needs to be
27 investigated in future.

28 **4.3 Relationships between SOC and climate factors**

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

7 With respect to the association of SOCD with MAT, SOCD goes down and then up with
8 increasing MAT, which is most likely related to various balances between SOC inputs and
9 outputs (Davidson and Janssens, 2006). A decrease in SOCD at low MAT could be caused by
10 low carbon inputs of plant production and high carbon outputs of soil decomposition. MAT is
11 often lower than 4.6 °C in the Sanjiang Plain. This is why a significantly negative correlation
12 ($r = -0.33, P < 0.01$) is observed between MAT and SOCD (Table 3). On the contrary, MAT
13 higher than 4.6 °C may increase the vegetation productivity and thus contribute to increasing
14 carbon inputs that overrides the temperature-induced rise in the soil decomposition rate (Yang
15 et al., 2008). Our results confirm the observation made by Yang et al. (2007) that the increasing
16 trend of SOCD from the tropical to cold-temperate zone in the eastern part of China is correlated
17 with temperature. In the Sanjiang Plain, MAT can explain 4.23% of the SOCD variability,
18 suggesting that temperature plays an important role in shaping the pattern of SOC.

19 In relation to MAP, SOCD values within different soil depth ranges show strong positive
20 correlations to MAP as shown by the power relationships in Fig. 6 B1 - B3). These positive
21 correlations can be explained by the fact that precipitation enhances the vegetation productivity
22 and thus leads to accumulation of SOC. This finding is in agreement with the observation made
23 for the spatial pattern of SOC in Northern China, i.e., increasing precipitation contributes to an
24 increase in SOCD from the arid to semi-humid zone (Yang et al., 2007). Similarly, the SOCD
25 of the Sanjiang Plain estimated by this study is higher than that for the Loess Plateau (Liu et al.,
26 2011) due to the difference of the two areas in precipitation. MAP explains the variation of
27 SOCD at less degree when soil depth increases (Table 2) and shows diminishing correlation
28 with SOCD (Table 3). This can be attributed to relative low soil moisture to deep soil depth

1 layers which affects the root vertical distribution with increasing soil depth (Jobbágy and
2 Jackson, 2000).

3 **4.4 Effects of soil texture on SOC**

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

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

26 **4.5 Impacts of agricultural activities on SOC**

27 Given the fact that both soil texture and vegetation types are highly influenced by climate,
28 and that soil texture has obvious effects on vegetation types. These interactive systems drive

1 the SOC distribution in very complicated ways. The GLM results indicate that the examined
2 environmental factors only explain 57.78%, 52.03% and 47.67% of the SOCD variability
3 within the depth range 0 - 30 cm, 0 - 60 cm and 0 - 100 cm, respectively. Therefore, we speculate
4 that the anthropogenic factor is critical in explaining the pattern and storage of SOC.

5 Croplands, including dry farmlands and paddy fields, covering 54.2% of the whole area of
6 the Sanjiang Plain, have the largest carbon pool among the land types (Table 1). Therefore, the
7 change of SOCD in cropland could result in significant variation in the lateral and vertical
8 distribution of SOC. It is well known that cropland management plays an important role in the
9 carbon exchange of ecosystems (Lal, 2004b). In the Sanjiang Plain, soil tillage and the return
10 of crop stubble into soils have a long history, and which are expected to be a crucial force for
11 shaping the lateral and vertical pattern of SOC (Liu et al., 2006; Mao et al., 2014b). Generally,
12 fertilization can raise the SOC storage by enhancing the carbon input from plant productivity
13 and crop biomass (Ren et al., 2012, Zhao et al., 2013). However, over application of fertilizer
14 can have negative net effects on carbon sequestration because organic carbon mineralization
15 neutralizes the carbon input (Russell et al., 2005). Influences of fertilization on SOC are
16 complicated, and can be related to the history of cropland, vegetation types, as well as soil types
17 and texture. Comparing between the amount of fertilizer and SOC at the county scale, indicates
18 that the counties using high amounts of fertilizer have low SOC content (Fig. 7). This may
19 manifest different SOC decomposition scenarios due to temperature, soil moisture and soil
20 types in this plain. Long-term field experiments for different crop types are needed to
21 investigate the effects of fertilization on SOC at the local scale.

22 The results of this study indicate that paddy fields show a relatively larger carbon
23 sequestration capacity as compared to other agricultural soils in the Sanjiang Plain (Table 1).
24 As displayed in Fig. 8, the areal proportion of paddy fields to croplands is strongly correlated
25 to the mean value of the topsoil SOC content in different counties ($P < 0.01$). Irrigation-based
26 rice cultivation in China has significantly enriched SOC storage in paddy soils, when compared
27 with dry farmland cultivation (Pan et al., 2004). In addition, the loss of SOC storage from
28 ground soil to the atmosphere has a positive feedback to climate change (Davidson and Janssens,

1 2006). It can be concluded that in the previous decades, the conversion of dry farmlands into
2 paddy fields in the Sanjiang Plain, which is enforced by governmental policy and stimulated by
3 economic benefit, has fostered the local carbon accumulation and mitigated climate change by
4 reducing CO₂ emission (Ouyang et al., 2014).

5

6 **5 Conclusions**

7 This study has used Kriging, a spatial interpolation technology, and 419 soil sampling sites
8 (1257 profiles in total) collected in 2012 for each of the soil depth ranges 0 - 30 cm, 30 - 60 cm,
9 and 60 - 100 cm to determine the SOC storage in the Sanjiang Plain, China. Relationships of
10 SOCD with different environmental factors were examined. The results reveal that the total
11 SOC storage within the depth range 0 - 100 cm in the Sanjiang Plain was estimated to be 2.32
12 Pg C, and mainly stocked in the topsoil. Over the Sanjiang Plain, soil texture plays more
13 important roles than climate in determining the distribution of SOC with clay content
14 contributing more than other observed factors. Vegetation, climate, and soil texture, as well as
15 agricultural activities has remarkable impacts on the storage and distribution of SOC. Wetlands
16 have the highest SOCD as compared with other land cover types, but display a significant loss
17 in the recent decades. Thus, implementation of an effective wetland management and
18 conservation plan in the Sanjiang Plain is required for fostering regional carbon sequestration.
19 Moreover, policy and economic benefit-driven conversion from dry farmlands to paddy fields
20 contribute to more carbon stocking in the soil. A comparison of the estimate to those by other
21 previous studies demonstrates underestimation of the SOC storage in the Sanjiang Plain if
22 values at the Northeast China and the whole country level are used. An accurate and the updated
23 estimates of SOC storage by this study will significantly improve the knowledge of carbon
24 cycles and the determination of the carbon budget for the Sanjiang Plain.

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5

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Table1 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	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

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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

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

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1 **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

2 ^a $P < 0.05$; ^b $P < 0.01$

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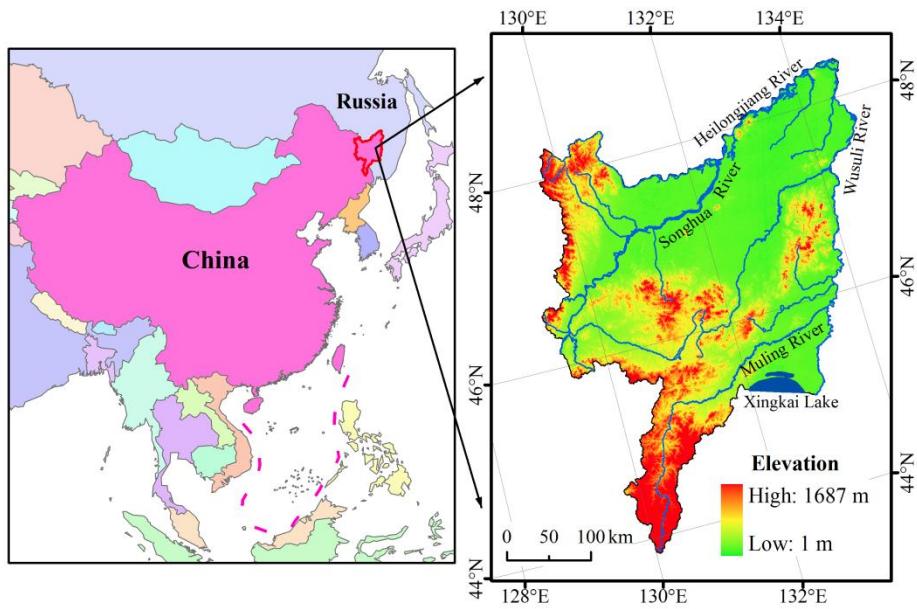
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1 **Fig. 1.** Position and terrain of the Sanjiang Plain

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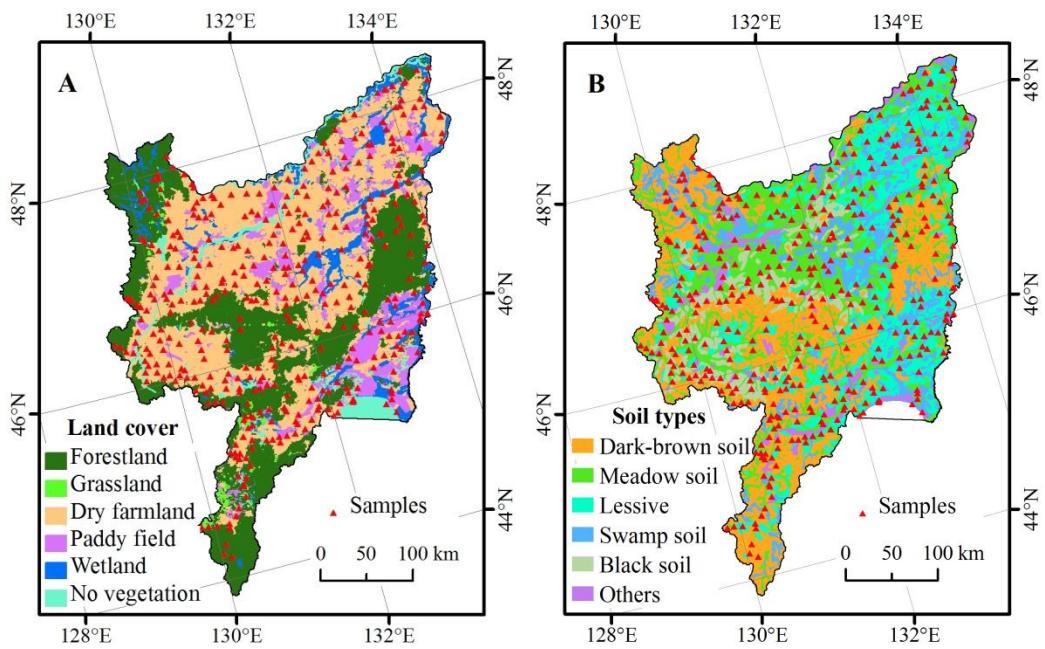


Fig. 2. Spatial distribution of field samples, land cover (A) and soil types (B) in the Sanjiang

3 Plain

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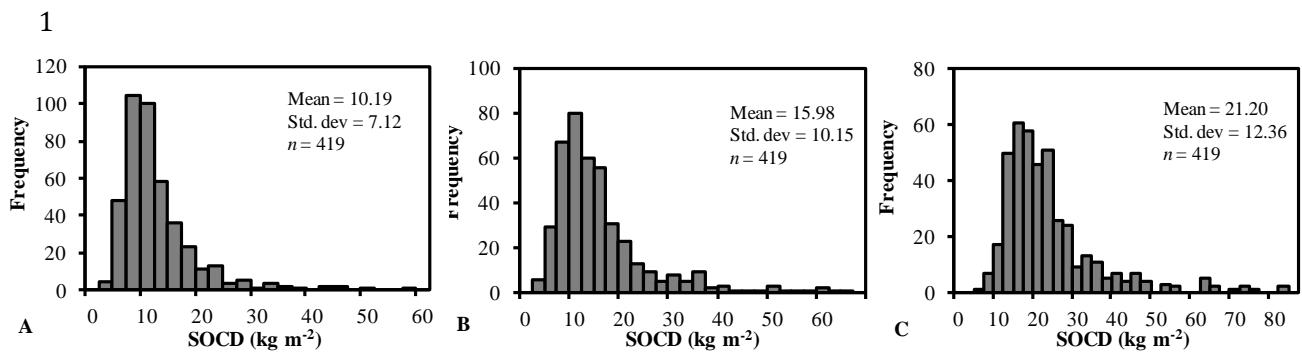
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2 **Fig. 3.** Frequency distributions of SOCD at different soil depth ranges (A: 0 - 30 cm; B: 0 - 60
 3 cm; C: 0 - 100 cm)

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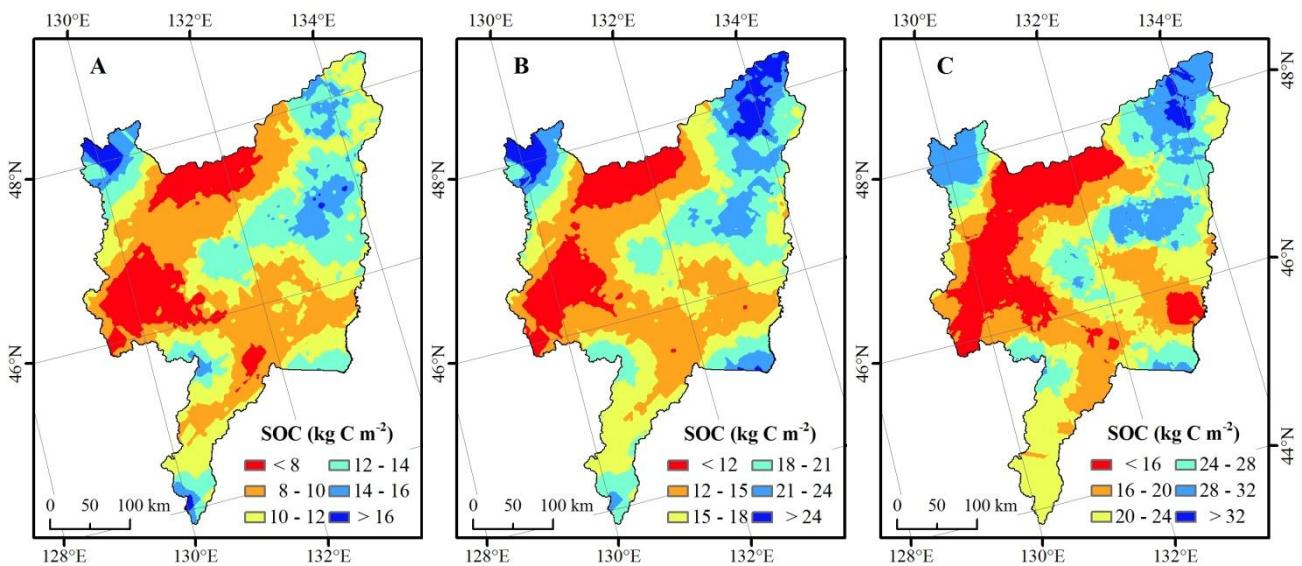
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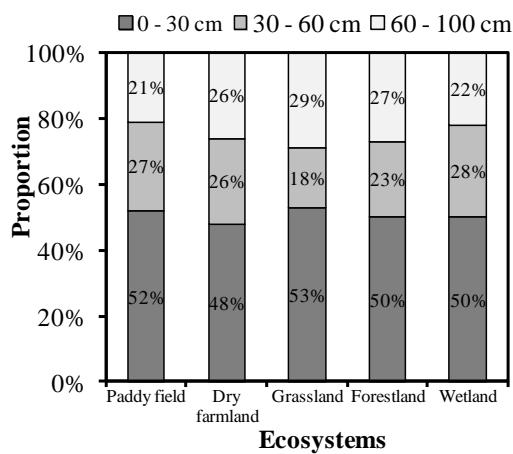
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1 **Fig. 4.** Spatial pattern of SOC storage at different soil depths (A: 0 - 30 cm; B: 0
2 - 60 cm; C: 0
3 - 100 cm)

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2 **Fig. 5.** Vertical distribution of SOC storage in different soil depth ranges for various
 3 ecosystems

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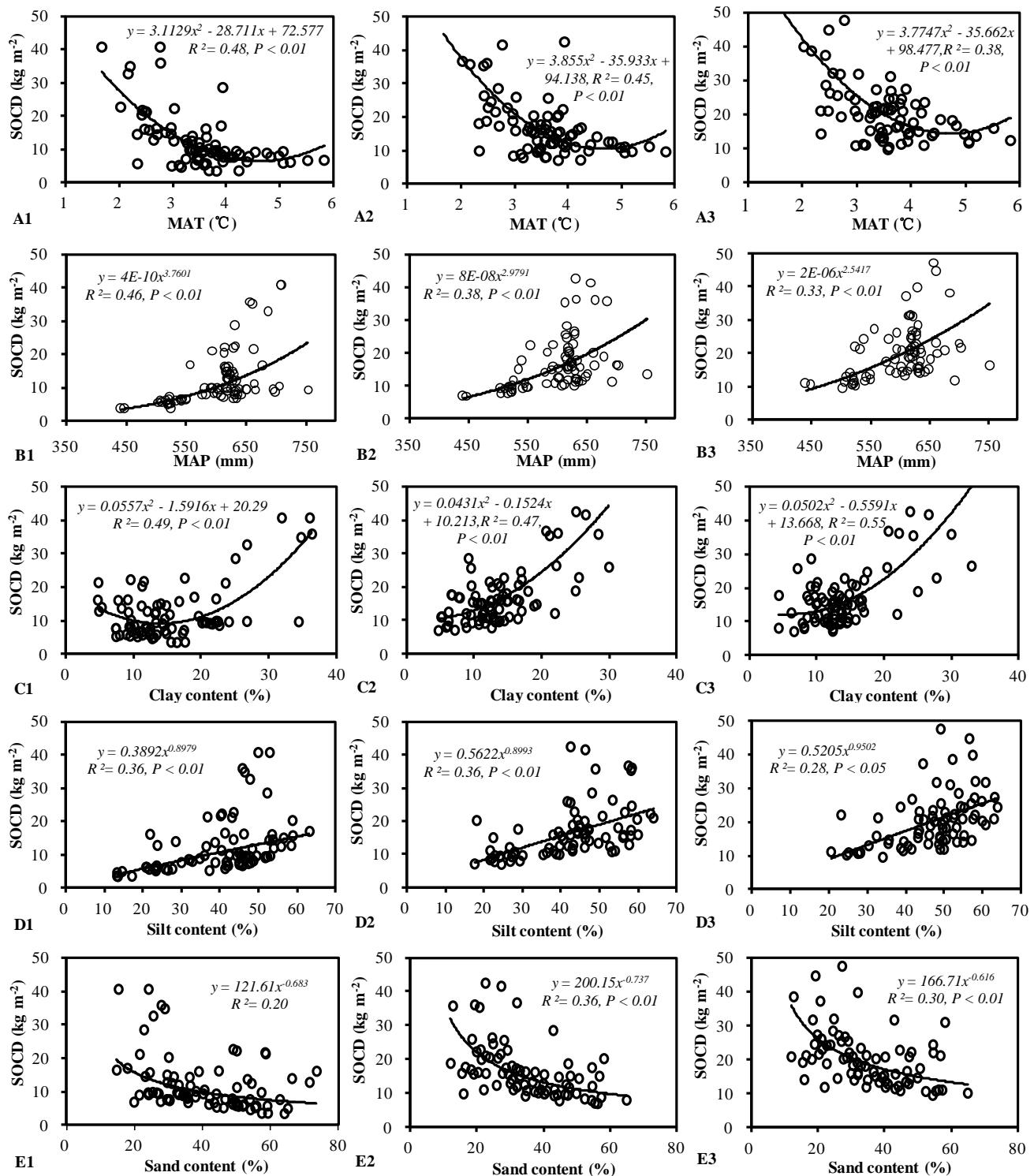
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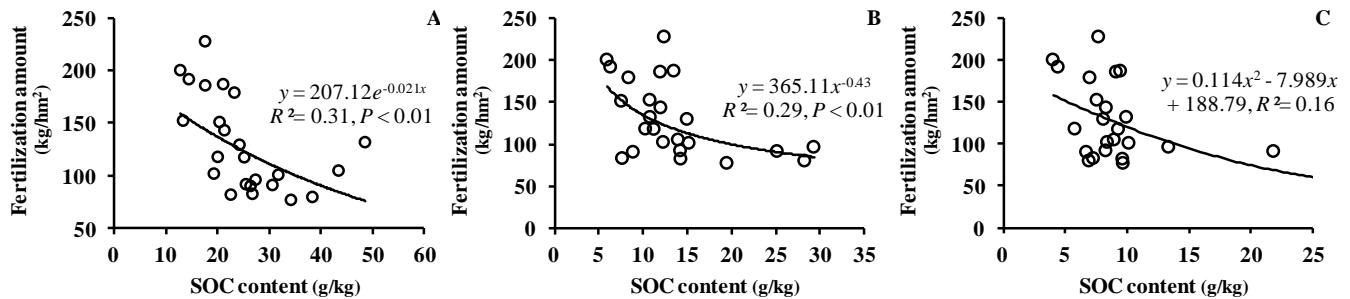
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1 **Fig. 6.** Correlations of SOCD with various environmental factors for different soil depths in
2 the Sanjiang Plain (A1 - E1: 0 - 30 cm; A2 - E2: 0 - 60 cm; A3 - E3: 0-100 cm)
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1 **Fig. 7.** Correlations of the cropland fertilization amount with SOC content in the Sanjiang

2 Plain for different soil layers (A: 0 - 30 cm; B: 30 - 60 cm; C: 60 - 100 cm)

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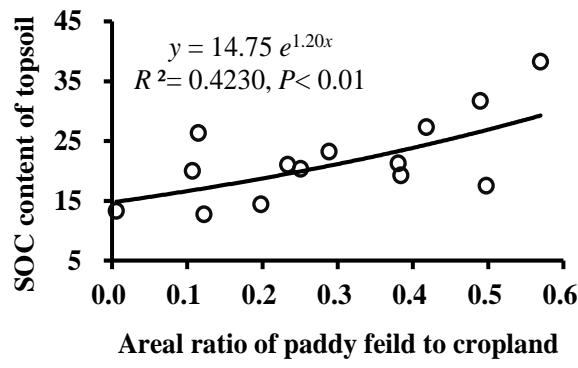
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2 **Fig. 8.** Correlations of topsoil SOC content with the areal ratio of paddy field to cropland in
3 the Sanjiang Plain

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