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Effects of land use change on the spatiotemporal variability of soil organic carbon in an urban-rural ecotone of Beijing

YE Hui-chun[1, 2], Huang Yuan-fang[3], CHEN Peng-fei[4], HUANG Wenjiang[1, 2], ZHANG Shi-wen[5], HUANG Shan-yu[6], HOU Sen[3]

[1] *Key Laboratory of Digital Earth Science, Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, Beijing 100094, P.R.China*
[2] *Hainan Key Laboratory of Earth Observation, Sanya 572029, P.R.China*
[3] *College of Resources and Environment, China Agricultural University, Beijing 100193, P.R.China*
[4] *State Key Laboratory of Resources and Environment Information System, Institute of Geographic Science and Natural Resources Research of Chinese Academy of Sciences, Beijing 100101, P.R.China*
[5] *College of Earth and Environment, Anhui University of Science and Technology, Huainan 232001, P.R.China*
[6] *Institute of Geography, University of Cologne, Köln 50923, Germany*

Abstract

Understanding the effects of land use changes on the spatiotemporal variation of soil organic carbon (SOC) can provide guidance for low carbon and sustainable agriculture. In this paper, based on the large-scale datasets of soil surveys in 1982 and 2009 for Pinggu District — an Urban-rural Ecotone of Beijing, China, the effects of land use and land use changes on both temporal variation and spatial variation of SOC were analyzed. Results showed that from 1982 to 2009 in Pinggu District, the following land use change mainly occurred: grain cropland converted to orchard or vegetable land, and grassland converted to forestland. The SOC content decreased in region where the land use type changed to grain cropland (e.g., vegetable land to grain cropland decreased by 0.7 g kg^{-1}; orchard to grain cropland decreased by 0.2 g kg^{-1}). In contrast, the SOC content increased in region where the land use type changed to either orchard (excluding forestland) or forestland (e.g., grain cropland to orchard and forestland increased by 2.7 and 2.4 g kg^{-1}, respectively; grassland to orchard and forestland increased by 4.8 and 4.9 g kg^{-1}, respectively). The organic carbon accumulation capacity per unit mass of the soil increased in the following order: grain cropland soil < vegetable land/grassland soil < orchard soil < forestland soil. Therefore, to both secure supply of agricultural products and develop low carbon agriculture in a modern city, orchards has proven to be a good choice for land using.

Keywords: Land use change, soil organic carbon, spatiotemporal variability, urban-rural ecotone

土地利用变化对北京城乡交错带土壤有机碳时空变异的影响

摘要：揭示土地利用变化对有机碳的时空变异规律的影响，对实施低碳农业和可持续农业提供指导。本文以北京城乡交错带—平谷区1982年和2009年两次大规模采样数据基础，分别从时间变异和空间变异角度分析了土地利用及其变化对土壤有机碳含量时空变异的影响。结果表明，从1982年至2009年，平谷地区形成了以粮田转变为果园和菜地、草地转变为林地为主的土地利用转变格局。土地利用方式转变为粮田SOC含量下降（如菜地转为粮田SOC下降0.7 g kg^{-1}，果园转为粮田SOC下降0.2 g kg^{-1}），而转变为果园（林地除外）和林地SOC含量（如粮田转为果园和林地SOC分别增加2.7和2.4 g kg^{-1}，草地转为果园和林地SOC分别增加4.8和4.9 g kg^{-1}，），单位质量土壤的固碳能力沿着粮田、菜地/草地、果园、林地的顺利依次增大。因此，在现代城市既要保障农产品供应又要发展低碳农业的双重任务下，果园被证明是一个较佳的土地利用方式。

关键词：土地利用变化；土壤有机碳；时空变异；城乡交错带

1. Introduction

Soil is the largest reservoir of carbon in the terrestrial biosphere. The total stores of soil carbon is 3.3-fold larger than the atmospheric carbon pool and 4.5-fold greater than the biological carbon pool, and the soil organic carbon (SOC) pool accounts for more than half of the soil carbon pool (Lal 2004). Therefore, a small variation in soil carbon pool could lead to marked change in the CO_2 concentration of atmosphere (Smith and Fang 2010; Luo *et al.* 2010). There is sufficient evidence that land use/land cover change (LUCC) is a major driving factor for the balance of SOC stocks and the global carbon cycle in terrestrial ecosystems (Watson *et al.* 2000; Wilson *et al.* 2008; Luo *et al.* 2010; Poeplau *et al.* 2011; Dunn *et al.* 2013; Gerber *et al.* 2013). In particular, changes among land use types such as cropland, forestland, and pastureland will result in clear changes in SOC reserves (Smith 2008; Poeplau *et al.* 2011). According to an Intergovernmental Panel on Climate Change (IPCC) report, 1.6 Pg carbon is emitted into the atmosphere in association with LUCC each year, which is the second largest atmospheric carbon source after the carbon emitted from the combustion of fossil fuels (7.2 Pg C/year) (Solomon *et al.* 2007). Numerous studies reported decreasing SOC stocks after a land use change from natural or semi-natural ecosystems (forestland and grassland) to cropland, and a cultivation induced SOC decline of about 20–60% when forestland and grassland were converted to cropland (Murty *et al.* 2002; Guo and Gifford 2002; Poeplau *et al.* 2011; Oberholzer *et al.* 2014; Wiesmeier *et al.* 2012, 2015). Also, the SOC stocks increased by 20–50% after land use changes from cropland to grassland or forestland reported by Guo and Gifford (2002), who also indicated that wherever one of the land use changes decreased soil C, the reverse processusually increased soil carbon and vice versa. However, the results of changes between grassland and afforestation land are uncertain. This land use change could result in either a slight decrease in net SOC sequestration rate or an increase in net SOC sequestration rate (Soussana *et al.* 2004; Davis *et al.* 2007; Ritter 2007). Moreover, the recovery rate of SOC is greater at the early stage after a land use change than during the later stages (Coleman *et al.* 1997).

City suburb is an urban-rural transition zone. The rapid progression of the urbanization process in recent years has resulted in constant increases in the degree of agricultural intensification and land use intensity. In particular, the progression of urbanization has resulted in relatively large changes in land use types and management practices for agricultural lands, which will have important impacts on SOC content (Fu *et al.* 1999). The Pinggu District, located in a northeastern suburb of Beijing, China, has evolved from an agricultural area that mainly focused on grain production to an important fruit and vegetable production base for Beijing. Thus, the Pinggu District is highly representative of an urban-rural ecotone. Hence, an evaluation of the effect of land use change on the spatiotemporal variation in organic carbon in this area is of utmost significance for implementing urban low-carbon and sustainable agriculture.

To date, numerous researchers have used geostatistical methods to study the spatial variability of SOC. Field-scale studies have mainly revealed the effects of random factors, such as agricultural management practices, on the spatial variation of SOC (Cambardella *et al.* 1994; Yanai *et al.* 2005). Regional-scale studies have mainly revealed the effects of structural factors, such as climate, terrain, soil type, cropping system and land use type, on the spatial variation of SOC (Sun *et al.* 2003; Huang *et al.* 2007; Liu *et al.* 2014). However, there have been few

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YE Hui-chun, E-mail: yehc@radi.ac.cn; Correspondence HUANG Wen-jiang, Tel: +86-10-82178169, Fax: +86-10-82178177

studies on the spatiotemporal variation of SOC in an urban-rural ecotone, particularly the effects of land use change on the spatiotemporal variation of SOC. In addition, many studies have only conducted parallel comparisons for SOC contents among different land use types (Rodríguez-Murillo 2001; Davy and Koen 2013), but neglected the longitudinal historical processes associated with the land use change dynamics over different time periods (Schulp and Verburg 2009). Therefore, the results of these studies cannot satisfactorily assess the effects of time and changing process on SOC.

In this paper, we chose the Pinggu District in Beijing City, China, as a typical urban-rural ecotone for the following aims: (1) to investigate the temporal variation and spatial variation of SOC content in the Pinggu District from 1982 to 2009. (2) to evaluate the effects of different land use types and dynamic land use changes on the spatiotemporal variability of SOC content from 1982 to 2009. The results can provide guidance for the implementation of low-carbon and sustainable agriculture in an urban-rural ecotone.

2. Results

2.1. Characteristics of spatiotemporal changes of land use

Generally, the changes in land use between two time periods can be classified into two types: (1) the original type of land use is maintained, i.e., maintained land (denoted by the symbol "—"); or (2) there is a change in land use type, i.e., changed land (denoted by the symbol "→"). The transfer of land use matrix was generated by overlaying the maps of land use in Pinggu District for 1982 and 2009 (Table 1). In the urban-rural ecotone of Beijing, there were three major land use types, including: urban building land, ecological regulation land (mainly forestland and grassland), and agricultural production land (mainly grain cropland, vegetable land, and orchard). This study focuses primarily on the effects of land use dynamics on SOC content in the ecological regulation land and agricultural production land.

The main land use type in Pinggu District in 1982 was grain cropland (Table 1 and Fig. 1). Grain cropland covered 472.1 km^2, which accounted for approximately half of the land area of the Pinggu District and was mainly distributed in the plains region. The secondary land use type in 1982 included grassland and forestland, and the former covered an area of 257.4 km^2, while the latter covered 123.0 km^2. Both the lands were mainly distributed in the mountainous region in the north of Pinggu. Vegetable land and orchard were only found scattered throughout Pinggu District and together covered a total area of less than 20 km^2. In order to support the overall economic development and eco-environmental improvement of Beijing, the agricultural planting structure in Pinggu District has been substantially altered in recent decades. Large areas of grain cropland have been changed to other land use types. In 2009, the areas covered by grain cropland, vegetable land, orchard, forestland, and grassland were 114.6 km^2, 15.9 km^2, 220.8 km^2, 345.2 km^2, and 92.6 km^2, respectively. Compared to 1982, the areas of grain cropland and grassland decreased by 76% and 64%, respectively, whereas the areas of orchard, vegetable land, and forestland increased by 1171%, 137%, and 181%, respectively. From 1982 to 2009, 37%, 3%, 13%, and 4% of grain cropland changed to orchard (mainly in the piedmont transition zone), vegetable land (mainly in the plain), forestland, and grassland (mainly in the mountainous region and the protected forest of the plain region). For grassland, 68% of the grassland area switched to forestlands (mainly in the mountainous region). The total area that underwent a land use change was 639.5 km^2, which accounted for 67% of the total land area.

The following land use change mainly occurred during this time period: grain cropland→orchard and vegetable land or grassland→forestland.

2.2. Overall characteristics of SOC content of samples

The Kolmogorov–Smirnov test result demonstrates that the SOC contents in 1982 and 2009 both followed a lognormal distribution (p>0.05) (Table 2). In 1982, the SOC contents ranged from 1.8 g kg^{-1} to 27.6 g kg^{-1} with the mean of 7.3 g kg^{-1}. While in 2009, the SOC contents ranged from 1.0 g kg^{-1} to 27.9 g kg^{-1} with the mean of 9.6 g kg^{-1}, which increased by 2.3 g kg^{-1} from 1982 to 2009. The coefficients of variation (CV) of the SOC contents in 1982 and 2009 were 0.41 and 0.40, respectively, showing an intermediate level of variation in both 1982 and 2009.

Moreover, the SOC contents of different land use types in 1982 and 2009 were both analyzed by analysis of variance (Table 3). In 1982, the SOC contents in the grain cropland, vegetable land, orchard, forestland, and grassland soils were 6.6, 6.4, 7.5, 12.9, and 11.4 g kg^{-1}, respectively. The SOC contents in semi-natural ecological regulation land (forestland and grassland) were significantly higher than those of the agricultural production land (grain cropland, vegetable land, and orchard), whereas there was no significant difference among the SOC contents of the grain cropland, vegetable land and orchard (least significant difference (LSD), p<0.05). In 2009, the SOC contents of the cropland, vegetable land, orchard, forestland, and grassland soils were 8.2, 7.9, 10.2, 12.9, and 14.2 g kg^{-1}, respectively, which differed significantly among all of the land use types, except between the grain cropland and vegetable land soils. From 1982 to 2009, the SOC contents increased by 1.5-2.8 g kg^{-1} for all of the land use types, except that the SOC content of the forestland soil basically remained the same. In contrast, the SOC content of the orchard soils increased the most.

2.3. Effects of land use changes on the temporal variation of SOC content

The effects of land use dynamics on SOC content were analyzed based on the overlaying of the land use change map and the distribution map of sampling sites. The results reveal that from 1982 to 2009, the SOC contents decreased in association with the following land use changes: vegetable land→grain cropland, orchard→grain cropland, grassland→grain cropland, and forestland→orchard, whereas the SOC contents increased by 1%-75% for other land use changes (Table 4). The SOC contents in the areas characterized by original land use types of grain cropland, vegetable land, orchard, forestland, and grassland increased by 38%, 38%, 23%, -10%, and 31%, respectively. Among the land use changes converted from the same original land use types, the SOC contents increased the most in association with the following land use changes: grain cropland→orchard (by 39%), vegetable land→orchard (by 75 %), orchard—orchard (by 40%), forestland—forestland (by 1%), and grassland→forestland (by 46%).

The variations in the SOC contents of changed and maintained land were comparatively analyzed. From 1982 to 2009, SOC of the maintained grain cropland increased by 2.2 g kg^{-1}, while SOC of the changed grain cropland increased by 2.6 g kg^{-1}, which has an increase by 18% (0.4 g kg^{-1}) than the former. Specifically, compared to grain cropland maintained, the variable quantity of SOC contents increased by 23% and 9%, respectively, for the grain cropland→orchard and grain cropland→forestland land use changes but decreased by 5% for grain cropland→vegetable land. SOC of the maintained vegetable land increased by 3.3 g kg^{-1}, while SOC of the changed grain cropland increased by 1.9 g kg^{-1}, which has decrease by 42% (1.4 g kg^{-1}) than the former. Specifically, compared to vegetable land maintained, the variable quantity of SOC content increased by 61% for the vegetable land→orchard land use change but decreased by 121% for the change from vegetable land→ grain cropland. SOC of the maintained orchard increased by 3.1 g kg^{-1}, while SOC of the changed grain cropland (orchard→grain cropland) decreased by 0.2 g kg^{-1}, which has decrease by 106% than the former. There was a small change of SOC for both maintained and changed forestland with the variable quantity increased by 0.1 g kg^{-1} for the former and decreased by 1.3 g kg^{-1} for the latter. However, there was a large variation of SOC change between maintained and changed grassland. The SOC of the former increased by 1.0 g kg^{-1} and the latter increased by 4.0 g kg^{-1} from 1982 to 2009. Specifically, compared to grassland maintained, the variable quantity of SOC content increased by 380% and 390%, respectively, for the grassland→orchard and grassland→forestland land use change but decreased by 110% a result of grassland→grain cropland.

Overall, the SOC content decreased in areas where the land use type changed to grain cropland (e.g., vegetable land to grain cropland decreased by 0.7 g kg^{-1}; orchard to grain cropland decreased by 0.2 g kg^{-1}). In contrast, the SOC content increased in area where the land use type changed to either orchard (excluding forestland) or forestland (e.g., grain cropland to orchard and forestland increased by 2.7 and 2.4 g kg^{-1}, respectively; grassland to orchard and forestland increased by 4.8 and 4.9 g kg^{-1}, respectively). The organic carbon accumulation capacity per unit mass of the soil increased in the order of grain cropland soil<vegetable land soil/grassland soil<orchard soil<forestland soil.

2.4. Effects of land use changes on the spatial variability of SOC content

Spatial structure analysis of SOC content The semivariogram analysis indicates that the SOC content data was fitted with a spherical model for 1982 and an exponential model for 2009 (Table 5). The nugget to sill ratio $C_0/(C_0+C_1)$ for the SOC contents in 1982 and 2009 were 0.45 and 0.50, respectively, demonstrating an intermediate degree of spatial heterogeneity arising from random components to that the total spatial heterogeneity in both 1982 and 2009. The spatial correlation range in 2009 (143.67 km) was greater than that in 1982 (26.09 km).

Spatial distribution patterns of SOC content Fig. 2 presents the spatial distributions of the SOC contents in 1982 and 2009. Overall, in both 1982 and 2009, the SOC contents in the northern region were greater than those in the southern region. In 1982, the patch of each SOC fraction was smooth and uniform, whereas the patch of each SOC fraction was relatively fragmented in 2009, indicating that the landscape pattern of the distribution of SOC gradually changed from a simple and continuous distribution to a complex, heterogeneous and discontinuous patch mosaic. Regionally, the areas with the highest SOC contents (≥ 12 g kg^{-1}) were distributed in the northeastern mountainous region in 1982, whereas the areas with lowest SOC contents (< 6 g kg^{-1}) were largely distributed in the southern and southwestern plain regions. By 2009, the total area with SOC contents < 6 g kg^{-1} had decreased significantly, and these areas were distributed only as scattered locations in the southwestern marginal region. The total area with SOC contents > 10 g kg^{-1} increased, and these areas were mainly distributed in the northern region.

It is evident from the maps of the variation in the SOC content in 1982 and 2009 that, in the majority of locations, the SOC content increased (Fig. 3). The SOC content increased by more than 4 g kg^{-1} in large areas in the northwestern region. However, the SOC contents exhibited a decreasing trend in the northeastern region.

Effects of land use change on the spatial variation of SOC content Table 6 lists the statistical results for the regions of the SOC fractions obtained by overlaying land use change map and SOC maps. Regions where the SOC contents increased included the following: the region where grain cropland was maintained (grain cropland—grain cropland, area: 103.5 km^2), the region where grain cropland→orchard (area: 176.0 km^2), the region where grain cropland→forestland (area: 61.4 km^2), the region where forestland was maintained (forestland—forestland, area: 94.9 km^2), the region where grassland was maintained (grassland—grassland, area: 55.8 km^2), and the region where grassland→forestland (area: 174.1 km^2). Regions with SOC contents greater than 4 g kg^{-1} included the following: the region where grain cropland→orchard (area: 11.5 km^2), the region where forestland was maintained (forestland—forestland, area: 9.2 km^2), the region where grassland was maintained (grassland—grassland, area: 6.2 km^2), and the region where grassland→forestland (area: 12.2 km^2). Regions with SOC contents of 2-4 g kg^{-1} included the following: the region where grain cropland was maintained (grain cropland—grain cropland, area: 36.9 km^2), the region where grain cropland→orchard (area: 102.4 km^2), the region where grain cropland→forestland (area: 21.2 km^2), the region where forestland was maintained (forestland—forestland, area: 22.7 km^2), the region where grassland was maintained (grassland—grassland, area: 23.5 km^2), and the region where grassland→forestland (area: 46.4 km^2). Regions with SOC content of 0-2 g kg^{-1} included the following: the region where grain cropland was maintained (grain cropland—grain cropland, area: 62.9 km^2), the region where grain cropland→orchard (area: 52.4 km^2), the region where grain cropland→forestland (area: 28.8 km^2), the region where forestland was maintained (forestland—forestland, area: 29.5 km^2), the region where grassland was maintained (grassland—grassland, area: 16.9 km^2), and the region where grassland→forestland (area: 53.9 km^2). Regions where the SOC content decreased included the following: the region where forestland was maintained (forestland—forestland, area: 33.5 km^2) and the region where grassland→forestland (area: 61.6 km^2).

3. Discussion

In this study, the SOC contents in the semi-natural ecological regulation land (forestland and grassland) were greater than those in the agricultural production land (grain cropland, vegetable land, and orchard). The SOC content decreased when an ecological regulation land changed to an agricultural production land, which is consistent with the results of numerous studies (Murty *et al.* 2002; Guo and Gifford 2002). This phenomenon is attributed to the fact that the forestland and grassland soils has a relatively higher quantity and quality of litter inputs which can improve stability of SOC, whereas the soils of grain cropland, vegetable land, and orchard has a lower net productivity with the residues removed and it is also frequently disturbed by human activities, which increases soil erosion and soil bareness to accelerate the decomposition of SOC. In this study, the SOC contents decreased in areas where the land use type changed to grain cropland. In contrast, the SOC contents increased in areas where the land use type changed to either orchard (excluding forestland) or forestland. The organic carbon accumulation capacity per unit mass of the soil increased in the order of grain cropland soil<vegetable land soil/grassland soil<orchard soil<forestland soil. The occurrence of these phenomena is attributed to the fact that, driven by economic interests, orchard and vegetable farmers have had active attitudes towards production and been relatively highly devoted. According to the survey statistics, relatively large quantities of organic fertilizers

are used in orchards and vegetable land. The organic fertilizer input level was 1,500–3,750 *yuan* RMB ha^{-1} for 59% of the orchard and over 1,500 *yuan* RMB ha^{-1} for 73% of the vegetable land, but organic fertilizers were not used or only rarely applied to 90% of grain cropland (Wang *et al.* 2008).

From 1982 to 2009, the landscape pattern of the spatial distribution of SOC gradually changed from a simple and continuous distribution to a complex, heterogeneous and discontinuous patch mosaic. This change was associated with the implementation of the household contract responsibility system in the 1980s in China. Lands were divided into smaller units and, subsequently, relatively large variations in land management modes were implemented among various farmer households. As evident in the map of variation in SOC, the regions in which the organic carbon contents increased the most are mainly distributed in Dahuashan Town in the northwest of the Pinggu District. Dahuashan Town has the largest planting area and the highest yield of peaches among all the villages and towns of Beijing and, consequently, Dahuashan Town has been honored as the “first peach town in Beijing suburbs”. The continuous input of large amounts of organic fertilizers into the orchards has resulted in the continuous accumulation of SOC. Areas in which the organic carbon contents decreased are mainly distributed in the northwestern mountainous region, as well as a small area of semi-natural ecological regulation land that was switched to agricultural production land. The majority of the area in the northwestern mountainous region underwent one of the following types of land use change: grassland→forestland or forestland—forestland. However, the SOC contents exhibited increasing trends in other portions of the study area where changes between forestland and grasslands occurred (e.g., grassland→forestland), indicating that changes between forestland and grassland can either reduce or increase SOC contents, which is consistent with previous findings (Post and Kwon 2000; Soussana *et al.* 2004; Davis *et al.* 2007; Ritter 2007). In addition, the spatial correlation range of semivariogram of SOC in 2009 was larger than that in 1982. This decreasing trend would be due to decreasing of SOC in the northeast region where the initial SOC value was highest in 1982 and increasing of SOC in the southwest where the initial SOC value was lowest (Fig. 2 and Fig. 3), which enhance the correlation of SOC between neighbor sampling sites.

Beijing has a population of more than 20 million, the land in this region has an increasingly important role of its ecological regulation services. In this study, the land use of orchard has proven to be a good choice to develop low carbon and sustainable agriculture in Beijing. Moreover, it is also suggested that the grain cropland should been enhanced the organic fertilization inputs, especially encouraging farmers to develop green manures and return straws to fields to increase the SOC contents in grain croplands.

4. Conclusion

Our results revealed the land use from 1982 to 2008 in Pinggu District has been mainly changed as follow: grain cropland changed to orchard and vegetable land, and grassland changed to forestland. The soil organic carbon (SOC) contents of the natural or semi-natural ecological regulation land (forestland and grassland) were significantly greater than those of the agricultural production land (grain cropland, vegetable land, and orchard). Our findings indicated that the SOC contents decreased in the region where the land use type changed to grain cropland, while the SOC contents increased in the region where the land use type changed to either forestland or orchard (excluding forestland). The organic carbon accumulation capacity per unit mass of the soil increased in the order of grain cropland soil<vegetable land soil/grassland soil<orchard soil<forestland soil. Therefore, to both

secure supply of agricultural products and develop low carbon agriculture in a modern city, orchards has proven to be a good choice for land using.

5. Materials and methods

5.1. Study location

A typical urban-rural ecotone, the Pinggu District of Beijing in China, was selected as the study area. The Pinggu District (116˚55”E–117˚24”E, 40˚02”N–40˚22”N) is located between two major central cities, Beijing and Tianjin, in China. It is 70 km southwest of the Beijing urban area and 90 km east of the Tianjin urban area. The altitude of the region gradually decreases from northeast to southwest and ranges from 13 to 1,230 m. The Pinggu District is surrounded by mountains to the north, east, and south, while the center and southwest of the region are composed of diluvial-alluvial fans and have flat terrain (Fig. 4). The soil types are classified as Leptic Luvisols, Chromic Luvisols and Eutric Cambisols, according to IUSS Working Group WRB (2006). The Leptic Luvisols and Eutric Cambisols account for 98.4% of the total area of the district. The Pinggu District has a warm temperate monsoon climate. The mean annual temperature is 11.5 ˚C and the mean annual precipitation is 644 mm. The seasonal distribution of the precipitation is uneven, with 70% of the precipitation concentrated from July to September. Since the 1980s, in order to support the overall economic development and eco-environmental protection of Beijing, the degree of land intensification in Pinggu District has been continuously increasing, and the agricultural planting structure has also been substantially readjusted. The agricultural production structure in this region has been gradually transforming from one dominated by grain crops to one that includes economic crops (e.g., fruits and vegetables) as the main crops cultivated and grain crops as minor crops.

5.2 Data sources and laboratory analysis

The SOC data for 1982 were obtained from the Second National Soil Survey conducted in the Pinggu District. Site positioning was performed based on the descriptions of the site positions and the soil types to which these site positions belonged, which were recorded in paper format, and a total of 651 effective sampling sites were collected. In 2009, sampling was conducted at the same field of 1982 sampling sites or within a distance of 30 m around the 1982 sampling sites. Besides, about 90 new sites in the typical land, where the land use type has been changed from 1982 to 2009, were also sampled in 2009. The GPS receiver was used to locate the latitude and longitude for each sampling location. A group of four samples were collected within radius of 5 m surrounding a GPS location and then homogenized by hand mixing, extracted about 1–1.5 kg by quarter method, air-dried and sieved through 2 mm openings for laboratory analysis. A total of 740 samples were collected in final (Fig. 4). The SOC contents in 1982 and 2009 were both determined using the potassium dichromate digestion method (Nelson and Sommers 1982).

5.3 Data processing and analysis

Geostatistical methods described in Isaaks and Srivastava (1989) were used to calculate the semivariogram as follow:

$$\gamma(h)=\frac{1}{2N(h)}\sum_{i=1}^{N(h)}\left[Z(x_i)-Z(x_i+h)\right]^2 \qquad (1)$$

where $Z(x_i)$ and $Z(x_i+h)$ represents the observed value for a soil property at the location x_i and x_i+h, respectively, $\gamma(h)$ represents the semivariogram of a lag distance h between $Z(x_i)$ and $Z(x_i+h)$, and $N(h)$ is the number of data pairs separated by h. The $\gamma(h)$ of SOC in 1982 and 2009 were calculated and different theoretical semivariance models were used to fit the calculated values. The best model was selected and finally the cross-validation method was used to validate the parameters of the model (Isaaks and Srivastava, 1989)

The ArcGIS 9.3 software (ESRI, The Redlands, CA, USA) was used for geostatistical analysis consisting of, variogram calculation, crossvalidation, ordinary kriging and mapping. The SPSS 16.0 (SPSS Inc, Chicago, USA) software was used for conventional statistical analysis, Kolmogorov – Smirnov test and analysis of variance (ANOVA).

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Figures

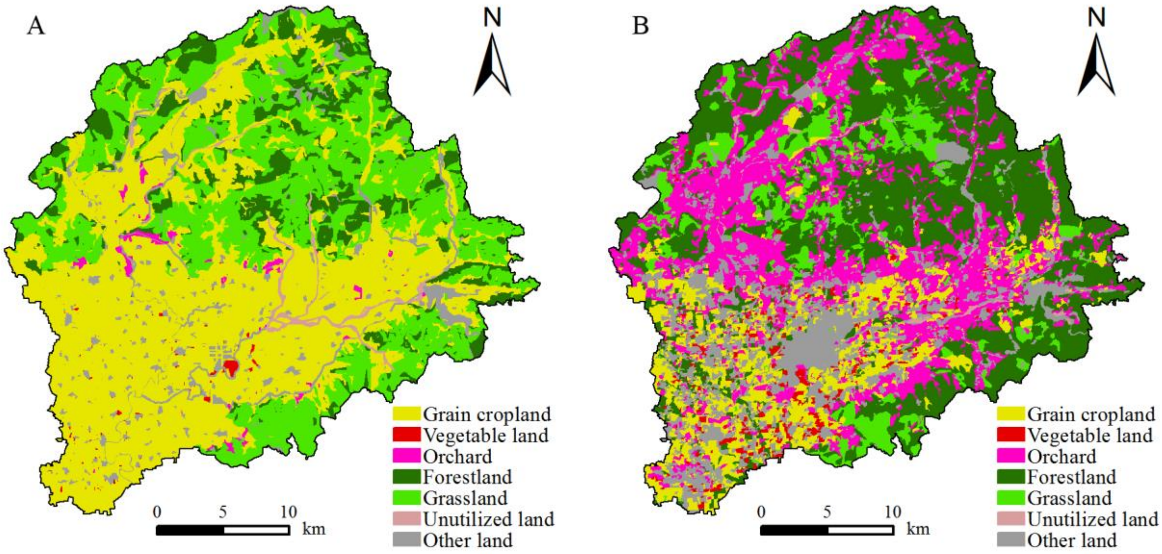

Fig. 1 Maps of land use types in 1982 (A) and 2009 (B) in Pinggu District.

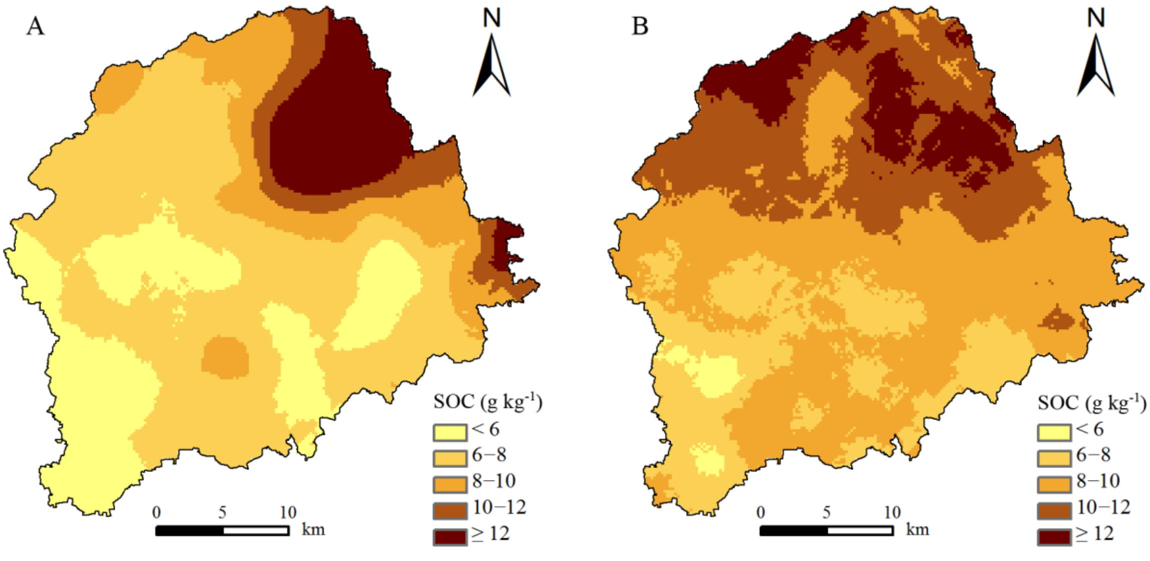

Fig. 2 Spatial distribution of soil organic carbon (SOC) contents in 1982 and 2009 in Pinggu District.

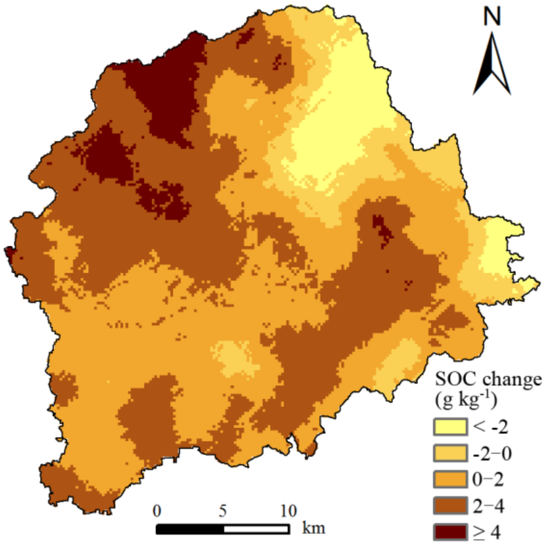

Fig. 3 Spatial distribution of soil organic carbon (SOC) changes from 1982 to 2009 in Pinggu District.

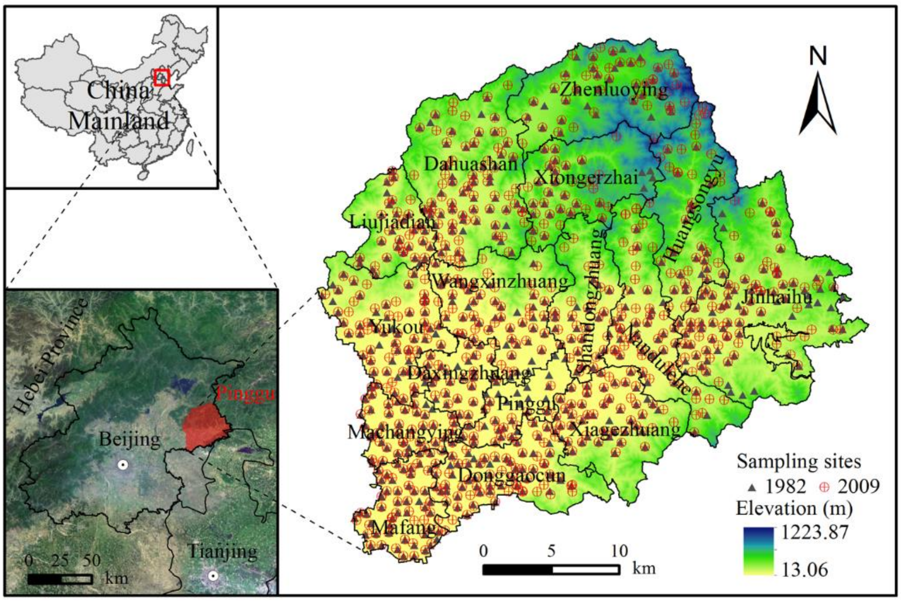

Fig. 4 The location of Pinggu District and distribution of elevation and sampilng sites.

Tables

Table 1 The transfer matrix of land use in Pinggu District from 1982 to 2009 (km^2)

1982	2009							Total (1982)
	Grain cropland	Vegetable land	Orchard	Forestland	Grassland	Unutilized land	Other land	
Grain cropland	103.4 (22%)	14.6 (3%)	176.0 (37%)	61.5 (13%)	19.7 (4%)	0 (0)	96.9 (21%)	472.1
Vegetable land	1.7 (25%)	0.9 (13%)	0.5 (7%)	0.4 (6%)	0 (0)	0 (0)	3.2 (48%)	6.7
Orchard	0.2 (2%)	0.1 (1%)	8.6 (73%)	1.1 (9%)	0.7 (6%)	0 (0)	1.1 (9%)	11.8
Forestland	1.8 (2%)	0 (0)	10.8 (9%)	94.8 (77%)	12.7 (10%)	0 (0)	2.9 (2%)	123.0
Grassland	4.9 (2%)	0 (0)	16.8 (6%)	174.1 (68%)	55.7 (22%)	0 (0)	5.9 (2%)	257.4
Unutilized land	0.6 (6%)	0 (0)	3.3 (33%)	1.0 (10%)	0.3 (3%)	1.0 (10%)	3.8 (38%)	10.0
Other land	2.0 (3%)	0.3 (0%)	4.8 (7%)	12.3 18%)	3.5 (5%)	0 (0)	46.2 (67%)	69.1
Total (2009)	114.6	15.9	220.8	345.2	92.6	1.0	160.0	950.1
Area change	-357.5	9.2	209.0	222.2	-164.8	-9.0	90.9	—
Change amplitude	-76%	137%	1771%	181%	-64 %	-90%	132%	—

Figures in brackets represent the percentages to total area in 1982.

Table 2 Descriptive statistics of SOC contents of sampling sites in Pinggu District

Year	*n*	Skewness	Kurtosis	Distribution type (K-S test[1)])	Minimum (g kg^{-1})	Maximum ((g kg^{-1})	Mean±SD (g kg^{-1})[2)]	CV[3)]
1982	651	0.52	4.27	Log-normal (0.053)	1.8	27.6	7.3±2.9	0.41
2009	740	-0.58	4.33	Log-normal (0.064)	1.0	27.9	9.6±3.8	0.40

1) K-S test, Kolmogorov–Smirnov test.

2) Mean±SD, mean±standard deviation.

3) CV, coefficient of variation.

Table 3 SOC contents of sampling sites for static land use types in Pinggu District

Land use type	1982		2009		SOC change
	n	Mean (g kg^{-1})	*n*	Mean (g kg^{-1})	
Grain cropland	510	6.6 b	229	8.2 d	1.6
Vegetable land	27	6.4 b	59	7.9 d	1.5
Orchard	26	7.5 b	408	10.2 c	2.7

Forestland	24	12.9 a	27	12.9 b	0
Grassland	51	11.4 a	7	14.2 a	2.8

Means within a column with the same letters are not significantly different at p<0.05 according to LSD test

Table 4 Mean content of SOC for 1982 and 2009 in different land use changes in Pinggu District

Land use change[1] （from 1982 to 2009）	1982		2009		SOC change (g kg^{-1})	Change amplitude (%)	Relative change amplitude (%)[2]
	n	Mean (g kg^{-1})	n	Mean (g kg^{-1})			
Grain cropland							
— Grain cropland	172	6.2	198	8.4	2.2	35	
→ Vegetable land	34	5.9	47	8.0	2.1	36	-5
→ Orchard	285	7.0	323	9.7	2.7	39	23
→ Forestland	10	6.8	8	9.2	2.4	35	9
Total of changed land	329	6.9	378	9.5	2.6	38	18
Total of all	501	6.6	576	9.1	2.5	38	
Vegetable land							
— Vegetable land	8	6.4	9	9.7	3.3	52	
→ Orchard	8	7.1	8	12.4	5.3	75	61
→ Grain cropland	9	5.9	10	5.2	-0.7	-12	-121
Total of changed land	17	6.5	18	8.4	1.9	29	-42
Total of all	25	6.4	27	8.8	2.4	38	
Orchard							
— Orchard	16	7.7	12	10.8	3.1	40	
→ Grain cropland	8	7.2	9	7.0	-0.2	-3	-106
Total of changed land	8	7.2	9	7.0	-0.2	-3	-106
Total of all	24	7.5	21	9.2	1.7	23	
Forestland							
— Forestland	8	14.7	8	14.8	0.1	1	
→ Orchard	16	12.0	25	10.7	-1.3	-11	-1400
Total of changed land	16	12.0	25	10.7	-1.3	-11	-1400
Total of all	24	12.9	33	11.6	-1.3	-10	
Grass land							
— Grassland	9	13.2	7	14.2	1.0	8	
→ Orchard	25	11.1	35	15.9	4.8	43	380
→ Grain cropland	8	11.5	9	11.4	-0.1	-1	-110
→ Forest land	9	10.7	10	15.6	4.9	46	390
Total of changed land	42	11.1	54	15.1	4.0	36	300
Total of all	51	11.4	61	14.9	3.5	31	

1) The symbol "—" represents maintained land, "→" represents changed land;

2) Relative change amplitude represents the increasing amplitude of SOC changes for changed land compared with SOC changes for maintained land.

Table 5 Semivariogram parameters of SOC and its residuals in 1982 and 2009 in Pinggu District

Year	Model	C_0	C_1	$C_0/(C_0+C_1)$	Rang (km)	R^2	RMSSE[1]
1982	Spherical	0.053	0.065	0.45	26.09	0.97	1.01
2009	Exponential	0.129	0.129	0.50	143.67	0.96	0.95

1) RMSSE, root mean square standardized effect.

Table 6 Areas of SOC fractions in different land use changes from 1982 to 2009 in Pinggu District (km^2)

Land use change[1]（from 1982 to 2009）		SOC fractions					Total
		< -2 (g kg^{-1})	-2～0 (g kg^{-1})	0～2 (g kg^{-1})	2～4 (g kg^{-1})	≥ 4 (g kg^{-1})	
Grain cropland	— Grain cropland	0.2	2.3	62.9	36.9	1.2	103.5
	→ Vegetable land	0	0.2	9.0	5.4	0	14.6
	→ Orchard	2.3	7.4	52.4	102.4	11.5	176.0
	→ Forestland	3.0	6.0	28.8	21.2	2.4	61.4
	→ Grassland	2.7	1.6	5.1	8.5	1.9	19.8
Vegetable land	— Vegetable land	0	0.3	0.5	0.1	0	0.9
	→ Grain cropland	0	0.3	1.2	0.3	0	1.8
	→ Orchard	0	0	0.3	0.2	0	0.5
	→ Forestland	0	0	0.3	0.1	0	0.4
Orchard	— Orchard	0	0	2.0	6.2	0.3	8.5
	→ Grain cropland	0	0	0.1	0.2	0	0.3
	→ Vegetable land	0	0	0	0.1	0	0.1
	→ Forestland	0	0	0.2	0.9	0	1.1
	→	0	0	0.2	0.5	0.1	0.8

	Grassland						
Forestland	— Forestland	13.1	20.4	29.5	22.7	9.2	94.9
	→ Grain cropland	0.3	0	1.1	0.4	0	1.8
	→ Orchard	1.1	2.4	3.1	3.2	1.0	10.8
	→ Grassland	1.4	1.5	3.3	3.5	3.0	12.7
Grassland	— Grassland	4.9	4.3	16.9	23.5	6.2	55.8
	→ Grain cropland	0.6	0.1	2.8	1.4	0.1	5.0
	→ Orchard	2.6	2.6	4.3	6.3	1.1	16.9
	→ Forest land	26.8	34.8	53.9	46.4	12.2	174.1

1) The symbol "—" represents maintained land, "→" represents changed land.