Comparison on Soil Carbon Stocks Between Urban and Suburban Topsoil in Beijing, China

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Abstract: The urban population and urbanized land in China have both increased markedly since the 1980s. Urban and suburban developments have grown at unprecedented rates with unknown consequences for ecosystem functions. In particular, the effect of rapid urbanization on the storage of soil carbon has not been studied extensively. In this study, we compared the soil carbon stocks of different land use types in Beijing Municipality. We collected 490 top-soil samples (top 20 cm) from urban and suburban sites within the Sixth Ring Road of Beijing, which cover approximately 2400 km², and the densities of soil organic carbon (SOC), soil inorganic carbon (SIC), and total carbon (TC) were analyzed to determine the spatial distribution of urban and suburban soil carbon characteristics across seven land use types. The results revealed significant differences in soil carbon densities among land use types. Additionally, urban soil had significantly higher SOC and SIC densities than suburban soil did, and suburban shelterbelts and productive plantations had lower SIC densities than the other land use types. The comparison of coefficients of variance (CVs) showed that carbon content of urban topsoil had a lower variability than that of suburban topsoil. Further findings revealed that soil carbon storage increased with built-up age. Urban soil built up for more than 20 years had higher densities of SOC, SIC and TC than both urban soil with less than 10 years and suburban soil. Correlation analyses indicated the existence of a significantly negative correlation between the SOC, SIC, and TC densities of urban soil and the distance to the urban core, and the distance variable alone explained 23.3% of the variation of SIC density and 13.8% of the variation of TC density. These results indicate that SOC and SIC accumulate in the urban topsoil under green space as a result of the conversion of agricultural land to urban land due to the urbanization in Beijing.

Keywords: urban soil; soil organic carbon (SOC); soil inorganic carbon (SIC); carbon stock; land use change; built-up age; Beijing; China

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1 Introduction

Although urban settlements cover less than 1% of the earth's surface, more than 50% of the world's population lives in cities and towns (Schneider *et al.*, 2010), with the majority of future population growth predicted to be in these urban areas. The latest projection by the United Nations predicts that the proportion of urban population relative to total population will rise to nearly 70%

worldwide by 2050, and that 86% of this growth will be in developing regions in Asia and Africa (United Nations, 2012). Urban land coverage around the world is expanding, on average, twice as quickly as their populations are (Angel *et al.*, 2011; Seto *et al.*, 2011). By 2030, urban land areas will have increased by 1.2×10^6 km², which would nearly triple the extent of global urban land area since 2000 (Seto *et al.*, 2012). The impact of urban area increase on the global environment will

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become even more pronounced in the future (Grimm *et al.*, 2008; Seto and Shepherd, 2009; Pickett *et al.*, 2011; Seto *et al.*, 2012).

Soil carbon stock, including soil organic carbon (SOC) and soil inorganic carbon (SIC) stock, is the largest carbon pool in the terrestrial ecosystem. How land use and management changes affect soil carbon storage is an important focus in global climate change research (Houghton, 1995; Lal, 2004). However, the effects of urbanization on soil remain poorly characterized (Lehmann and Stahr, 2007; Pickett and Cadenaso, 2009). A central principle in urban ecological theory implies that in urbanized landscapes anthropogenic drivers will dominate natural drivers in the control of soil carbon storage (Kaye *et al.*, 2006). Urban land use changes entail a complex array of ecosystem alterations that are often missing from local, regional, and global estimates of soil carbon stocks (Svirejeva-Hopkins *et al.*, 2004; Pataki *et al.*, 2006; Pouyat *et al.*, 2006). Therefore, the expansion of urban areas worldwide makes our understanding of the effects of urbanization on soil carbon storage increasingly important (Seto *et al.*, 2012). There is increasing evidence that urban ecosystems may be able to store considerable amounts of organic carbon in their vegetation and soils, but little is known about soil inorganic carbon (Nowak and Crane, 2002; Golubiewski, 2006; Lorenz *et al.*, 2006; Pouyat *et al.*, 2006; Churkina *et al.*, 2010; Hutyra *et al.*, 2011). Urban land use areas have been shown to contain larger organic carbon pools than some native deserts, grasslands, and agricultural and forested areas (Kaye *et al.*, 2005; Pouyat *et al.*, 2009; Koerner and Klopatek, 2010; Raciti *et al.*, 2011). Previous research has observed the increase in inorganic carbon storage in urban soil (Koerner and Klopatek, 2010).

The majority of previous research has been focused on a limited number of samples in the United States, where historical land use and climatic factors are likely to result in differences in soil carbon storage compared to other regions. The study on urban soil carbon stocks in developing regions, where urban expansion takes place on prime agricultural land and at higher speeds, is somewhat sparse.

China, with the largest urban population and the highest rate of urban land expansion in the world, has undergone intense land use changes since the 1980s (Liu *et al.*, 2005; Chen, 2007; Seto *et al.*, 2011). The urban-

ization rate in China increased from 17.9% in 1978 to 51.3% in 2011, double the world average (United Nations, 2012). Total urban area in the nation has increased by 2.31 times over the past two decades, with more than half of this area converted from arable land (Liu *et al.*, 2005; Wang *et al.*, 2012a).

In this paper, we assessed the impact of rapid urbanization on soil carbon stocks through comparing the soil organic and inorganic carbon densities of top soils from different land use types in urban and suburban sites in Beijing, the largest city in the northern China. In this study, we aim to 1) reveal the variability of soil organic and inorganic carbon stocks in Beijing; 2) assess the effects of different land uses on soil carbon stocks; and 3) assess the impact of land use changes on soil carbon.

2 Materials and Methods

2.1 Study area

Beijing is a historical city located on the northern tip of the roughly triangular North China Plain (39°28'–41°25'N, 115°25'–117°30'E) (Fig. 1). The city has undergone rapid and sprawling urbanization over the past three decades, with urban land cover and population increasing markedly during this time period. By 2011, Beijing had a population of 2.1×10^7 , of which 86.2% were urban residents. The urban land area has expanded from 232 km² in 1978 to over 1200 km² in 2005, with nearly 50% of the increase being converted from arable land (Mu *et al.*, 2007). The urban area of Beijing is situated in the south-central part of the city and spreads out through several concentric ring roads, of which the Sixth Ring Road passes through several satellite towns.

The city has a monsoon climate, characterized by hot, humid summer due to the East Asian monsoon, and generally cold, windy, dry winter due to the vast Siberian anticyclone. Its average annual temperature is approximately 11.5°C and annual precipitation exceeds 600 mm (more than 70% of precipitation falls from June to August). The dominant soils in the studied area are fluvo-aquic soils developed from deposited alluvium, which are classified as Fluvents of Entisols in the United States Department of Agriculture (USDA) soil taxonomic system.

2.2 Field sampling

The sampling of soils was conducted between July and

August of 2009. The sampling region was centered on the Beijing urban center (Tian'anmen Square) and extends to the Sixth Ring Road, encompassing a total of 2400 km². We used a dual gradient, spatially stratified sampling design with 128 sampling sites (Fig. 1). Sampling sites were established using a square grid of roughly 6 km × 6 km, situating sampling sites at the center of the grid. Additional sampling sites were situated at 3-km intervals along the east-west, south-east-northwest, south-north and southwest-northeast transects. Within 500 m radius from each site, one to five 20 m × 20 m plots of different land uses were randomly designated. Soil cores (3.3 cm in diameter) were collected from three locations within each 20 m × 20 m plot. The top 20-cm sections of the three replicate soil cores from each plot were mixed to give a single sample per plot. In total, we obtained 490 soil samples. Three additional soil samples were collected from each plot with a 100-cm³-cylindrical core for the analyses of bulk density and soil water content.

All sites were divided into groups based on urbanization level (urban or suburban) and the land use types. Urban sites included built-up areas inside Fifth Ring Road and its surroundings, while suburban sites consisted of areas with minimal development between the Fifth Ring Road and Sixth Ring Road. The seven land-use categories were institutional ($n = 56$, urban 32, suburban 24), residential ($n = 76$, urban 60, suburban 16), park ($n = 49$, urban 27, suburban 22), transportation

(roadside green space, $n = 123$, urban 64, suburban 59), roadside pit ($n = 104$, urban 55, suburban 49), shelter-belt (green buffer, $n = 55$, suburban 55), and productive plantation (nurseries/orchards, $n = 27$, suburban 27). The land use types are in according with Chinese standards for the classification of urban green space (CJJ/-T-85-2002).

2.3 Laboratory analysis

Soil samples were air-dried and sieved to analyze the chemical properties (< 1 mm for pH determination and < 0.21 mm for total carbon (TC) and total nitrogen (TN) determination). Using a Delta 320 pH meter (Mettler-Toledo Instruments (Shanghai) Ltd., China), soil pH was determined in distilled water at a soil-to-solution ratio of 1 : 2.5 (by volume). The TC and TN concentrations were obtained by combustion using an elemental analyzer (Elementar, Hanau, Germany). The SOC was analyzed using the potassium-dichromate oxidation method, with a correction factor of 1.1 used to estimate 100% organic carbon recovery. Lastly, SIC content was calculated by subtracting SOC from TC.

Soil samples destined for soil water content and bulk density estimations were dried at 105°C to a constant mass and weighed to determine the soil bulk densities and soil water contents by dry weight. For all data, the density of carbon in a unit area (1 m²) was calculated as follows:

$$C_d = C_t B_d D (1 - \delta_{2mm}) / 100 \quad (1)$$

Fig. 1 Location of study area and sampling sites

where C_d is carbon density; C_f is content of SOC; B_d is bulk density; D is thickness (here, 20 cm); and δ_{2mm} is the fraction of material larger > 2 mm in the layer.

2.4 Statistical analysis

We used the Kruskal-Wallis test (a non-parametrical analogous test) followed by the Nemenyi test to examine the differences in soil carbon stocks between land use types. Correlation and regression analyses were used to test the relationships between soil carbon and distance to the urban center. Statistical significance was determined to be $p \leq 0.05$, unless otherwise noted. All statistical analyses were performed using PASW Statistics version 18.0.

3 Results

3.1 Soil properties

Large variations were observed within urban land, suburban land, and throughout the study area as a whole for SOC, SIC, TC, and TN (Table 1). The coefficients of variance (CVs) of soil carbon concentrations ranged from 41.3% for urban TC density to 64.6% for suburban SIC density. The CVs of soil carbon density ranged from 37.1% for urban TC density to 68.0% for suburban SIC density. The CVs of the ratio of TOC/TN and of SOC/TC ranged from 23.6% to 34.8%. In contrast, soil pH and bulk density had relatively low CVs of less than 10%.

The comparisons of soil properties between urban and suburban soils revealed significant differences, except for soil TN. The concentrations and densities of urban soil carbon were higher than those of suburban soils carbon. Urban soil carbon concentrations were 14%, 40%, and 25% higher for SOC, SIC, and TC respectively than suburban soil. Urban soil had 16%, 41% and 27% higher SOC, SIC and TC densities respectively than suburban soil. The percentages of SOC in urban soil were lower than those in suburban soil. Urban soil pH, bulk densities, and TN concentrations were slightly higher than those of suburban soil, and did not differ statistically.

3.2 Effect of land use

There were statistically significant differences in soil carbon density among different land use types (Fig. 2). For the urban sites, roadside pits had the highest SOC, SIC, and TC densities, while parks had the lowest. The differences in SOC between different urban land use types were not significant. For the suburban sites, roadside pits also had the highest SOC, SIC and TC densities. Similar to urban sites, the differences in SOC and TC between other land use types were not significant for suburban sites. However, shelterbelts and productive plantations had lower SIC densities than other land use types throughout the study area. Productive plantations, shelterbelts, and parks also had higher percentages of SOC.

Table 1 Descriptive statistics of soil properties sampled from urban and suburban sites in study area

	Urban ($n = 233$)				Suburban ($n = 257$)				Regional ($n = 490$)	
	Min	Max	Mean (SE)	CV	Min	Max	Mean (SE)	CV	Mean (SE)	CV
SOC (g/kg)	2.43	64.28	11.22 (0.38) ^a	52.2	1.68	51.73	9.80 (0.32) ^b	52.7	10.48 (0.25)	52.9
SIC (g/kg)	0.83	25.94	9.82 (0.31) ^a	47.5	0.19	22.73	7.00 (0.28) ^b	64.6	8.33 (0.22)	57.5
TC (g/kg)	8.54	85.82	21.04 (0.57) ^a	41.3	3.80	65.37	16.80 (0.48) ^b	45.8	18.81 (0.38)	44.9
SOCd (kg/m ²)	0.67	13.08	3.07 (0.09) ^a	45.7	0.48	15.48	2.63 (0.09) ^b	54.0	2.83 (0.06)	50.3
SICd (kg/m ²)	0.23	7.33	2.70 (0.08) ^a	46.7	0.05	6.91	1.91 (0.08) ^b	68.0	2.28 (0.06)	58.6
TCd (kg/m ²)	2.37	17.46	5.77 (0.14) ^a	37.1	1.12	19.56	4.54 (0.14) ^b	48.0	5.12 (0.10)	43.8
SOC/TC (%)	19.96	92.53	53.70 (0.97) ^b	27.5	15.77	97.99	59.91 (1.08) ^a	29.1	56.97 (0.74)	28.9
TN (g/kg)	0.30	2.46	0.91 (0.02) ^a	35.4	0.23	2.25	0.88 (0.02) ^a	33.9	0.89 (0.01)	34.6
TOC/TN	4.47	26.10	12.18 (0.19) ^a	23.6	4.09	42.59	10.97 (0.24) ^b	34.8	11.54 (0.16)	29.9
pH	7.43	8.77	8.06 (0.01) ^a	2.2	7.43	8.59	8.03 (0.01) ^b	2.5	8.04 (0.01)	2.4
Bulk density (g/cm ³)	1.02	1.66	1.39 (0.01) ^a	7.7	0.96	1.67	1.35 (0.01) ^b	10.3	1.37 (0.01)	9.2

Notes: SOC, soil organic carbon; SIC, soil inorganic carbon; TC, total carbon; TN, total soil nitrogen; TOC: total organic carbon; SOCd: soil organic carbon density; SICd: soil inorganic carbon density; TCd: total carbon density. Means with different letters were significantly different, and comparisons were done with analysis of variance

Fig. 2 Mean ($\pm$ SE) soil carbon densities (0–20 cm depths) of land use types in study area. Ins, institutional; Res, residential; Par, park; Tra, transportation; Roa, roadside pit; She, shelterbelt; Pro, productive plantation. SOC, soil organic carbon; SIC, soil inorganic carbon; TC, total soil carbon. Comparisons were done with a Kruskal–Wallis test. Means with different letters were significantly different

Comparing urban and suburban sites of the same land use type, urban institutional and transportation sites had significantly higher SOC densities than the same types located in suburban sites. On the other hand, SOC densities in parks and roadside pits were slightly higher in suburban samples. The SIC densities in transportation and TC densities in residential, transportation, and institutional sites were higher for urban land use types when compared to those of the same land use types located in suburban sites.

3.3 Effect of built-up age

There were notable differences in soil carbon densities between urban sites of varying built-up ages (Fig. 3). Urban soil with at least 20 years of buildup had higher SOC, SIC, and TC densities than urban soil with less than 10 years of buildup. The same trend was observed when comparing soil carbon densities between urban soil with at least 20 years of buildup and suburban soils. Urban soil with buildup dating back to the 1980s had 37%, 41%, and 39% more SOC, SIC, and TC, respectively, than urban soil with buildup dating back to the 2000s. Likewise, urban soil with buildup from the 1980s

had 34%, 68%, and 47% more SOC, SIC, and TC, respectively, than suburban soil. However, soil with buildup prior to 1980 had slightly lower carbon density than urban soil with buildup during the 1980s, but the

Fig. 3 Mean ($\pm$ SE) soil carbon densities (0–20 cm depths) of urban soil with different built-up ages and suburban soil in study area. SOCd, soil organic carbon density; SICd, soil inorganic carbon density; TCd, total carbon density. Comparisons were done with a Kruskal–Wallis test. Means with different letters were significantly different

differences were not significant.

3.4 Effect of distance to urban center

Significant relationships ($p < 0.01$) were found when comparing SOC, SIC, and TC densities with respect to distance from the urban center. Spearman correlation coefficients were -0.233 , -0.538 , and -0.500 , respectively. Regressions of SOC, SIC and TC densities against distance to the urban center were also statistically significant. Distance from the urban center explained 23.3% and 13.8% variations of SIC and TC (Fig. 4), respectively, among plots, while the determination coefficient (R^2) of SOC was too low. These results suggested a general trend that SOC, SIC, and TC decreased as a function of distance from the urban center in the study area.

4 Discussion

4.1 Variability of soil carbon stock

Our results indicate that the soil carbon stock in the topsoil in the study area varied considerably. The coefficients of variation of SOC and SIC are both more than 50% (52.9% and 57.5%, respectively), which are much higher than those of soil pH and bulk density. These results support the previous findings of Pouyat *et al.* (2007) that urban soil chemical properties (with the exception of soil pH) generally varied more than physical properties did. In another study, they found that variations in SOC density were higher within a city than among cities for a given soil type (Pouyat *et al.*, 2002). The maximum compared to the minimum of SOC and SIC densities in the study area is over 10-fold, which is

consistent with previous studies in the United States and Germany (Pouyat *et al.*, 2002; Pouyat *et al.*, 2007; Lorenz and Lal, 2009). The results of these studies suggested that soil carbon stocks varied widely in urban landscapes, which can be described as 'urban soil mosaic' (Pouyat *et al.*, 2006; Pouyat *et al.*, 2007).

In comparison to the US cities, the mean SOC density (2.83 kg/m^2) of the study area is lower than that of many cities in the US, such as Baltimore and Denver (more than 4.0 kg/m^2), and Fort Collins (6.942 kg/m^2 , to 30 cm depth), but higher than that of Phoenix (less than 2 kg/m^2 , to 30 cm depth) (Kaye *et al.*, 2008). However, the mean SIC density of the study area (2.28 kg/m^2) is much higher than that of Phoenix (0.39 kg/m^2) and Fort Collins (0.325 kg/m^2 , to 30 cm depth) (Kaye *et al.*, 2005; Kaye *et al.*, 2008; Pouyat *et al.*, 2009). We suspect that the relatively low SOC densities in the study area are due to the lower SOC densities of native soils, while higher SIC densities are due to carbonate materials incorporated during green-space construction (Lehmann and Stahr, 2007; Yu *et al.*, 2007).

Another city within China that has experienced rapid and expansive development similar to Beijing is Shanghai, with a population of 2.3×10^7 persons. The comparison results of soil carbon density for the two cities reveal that the range and CVs of soil carbon density in Beijing were higher than those in Shanghai. The mean SOC densities of urban and suburban soil in Shanghai (3.93 kg/m^2 and 3.74 kg/m^2 , respectively) are higher than those in Beijing (3.07 kg/m^2 and 2.63 kg/m^2 , respectively), and the SIC densities of Shanghai (1.12 kg/m^2 and 0.73 kg/m^2 , respectively) are lower than those of Beijing (2.07 kg/m^2 and 1.91 kg/m^2 , respectively)

Fig. 4 Plot of total carbon (TC) and soil inorganic carbon (SIC) densities as a function of distance to urban center

(Xu *et al.*, 2012), in accordance with the trend observed between Beijing and US cities. However, the results of previous studies on Shanghai showed that the mean SOC concentration in urban areas (11.21 g/kg) is very close to that of Beijing (11.22 g/kg) (Hao *et al.*, 2011), and that Beijing and Shanghai have similar lower SOC density backgrounds (Yu *et al.*, 2007). These findings support the urban convergence hypothesis proposed by Pouyat *et al.* (2009) that urban land use change drives ecosystem structure and function (e.g., SOC density) toward a range of similar endpoints, and that anthropogenic drivers will dominate natural drivers in the control of SOC storage.

4.2 Effect of land use on soil carbon stock

Land use can serve as an indicator of disturbance, site history, and management; these factors have the potential to affect soil characteristics (Pouyat *et al.*, 2010). The results of this study demonstrated that land use has an important impact on soil carbon, as there were significant differences in SOC, SIC and TC densities among different land use types throughout the study area. In contrast, there were no significant differences in SOC, SIC, and TC densities among land use types within urban areas, with the exception of the roadside pits which had higher soil carbon density (Fig. 2). A similar pattern was found in the Chongwen District of Beijing where there were no differences between the soil organic matter (SOM) of urban parks, residential lands, and transport lands, although roadside pits had lower SOM (Liu *et al.*, 2010). This can be explained by the differences in sampling intensities, as fewer samples were collected within an area of 16.46 km² (Liu *et al.*, 2010) relative to the much more expansive sampling plan in this study.

The results of our study showed that urban soil had a greater range of SOC and SIC concentration and density than suburban soil, but that the CVs of SOC, SIC, and TC of urban soil were lower than those of suburban soil. The suburban shelterbelt and productive plantation soils converted from agricultural soils had much lower SIC densities than those of the other land use types. These can be partially explained by anthropogenic organic or inorganic particles incorporated in soils during green-space construction, such as technogenic substrates like rubble, bricks, slags, ashes, waste, and sludge (Lehmann and Stahr, 2007; Xia *et al.*, 2011; Nehls *et al.*, 2012;

Wang *et al.*, 2012b). This also supports the hypothesis that the impact of human-caused disturbance (e.g., movements of soil and building construction) is more pronounced during, rather than after, the land-development process (Kaye *et al.*, 2006).

4.3 Effect of urbanization on soil carbon stock

Urban areas have the potential to either sequester or lose SOC. In a comparison of carbon stocks in urban and native soils around six US cities, Pouyat *et al.* (2006) found that in the northeastern cities, urban SOC densities were lower than those of natural or agricultural soils, but were higher than those of pre-urban development soils in warmer or more arid regions. Conversely, our observations revealed that urban soils contain higher SOC and SIC densities than suburban soils in the study area (Table 1) and that urban soils accumulate carbon with increasing time (Fig. 3) and decreasing distance to the urban center (Fig. 4).

We found that the SOC, SIC, and TC densities of urban soils were 1.17 times, 1.41 times, and 1.27 times higher, respectively, than those of suburban soils. Compared to the results of other agricultural soil investigations, our findings are consistent with others with respect to higher SOC concentrations and densities in metropolitan areas than those of rural and agricultural soils in Beijing. For example, the mean SOC concentrations of urban soil and suburban soil (11.22 g/kg and 9.8 g/kg, respectively) were higher than those of arable soil in the Daxing District (7.44 g/kg) (Hu *et al.*, 2007) and arable soil in the Pinggu District of Beijing (8.38 g/kg) (Wang *et al.*, 2008). Additionally, the mean SOC density (2.83 kg/m²) was higher than the SOC density of agricultural land in the Yanqing County, Beijing (from 2.47 kg/m² to 2.74 kg/m² at 0–25 cm depth) (Zhang *et al.*, 2006). In Shenyang City, urban green-space soil had 1.23–1.44 times more SOC content than rural agricultural land (Duan *et al.*, 2008); likewise, the mean urban topsoil SOC density in Kaifeng City was 2.53 times higher than that of the suburbs (Sun *et al.*, 2010). Urban surface SOC densities in Shanghai were 1.05 times and 1.26 times higher than those of suburban and rural areas (Xu *et al.*, 2012).

Previous studies outside China have confirmed higher SOC concentrations and densities in urban areas. Similar results were also found in the Colorado Front Range (Golubiewski, 2006) and Phoenix, both in the U.S.

(Kaye *et al.*, 2008), and Leicester, UK (Edmondson *et al.*, 2012). Therefore, the influence of urbanization on soil carbon may be particularly great in former agricultural areas, which are often depleted in carbon at the time of development, but may accumulate carbon over time (Compton and Boone, 2000; Knops and Tilman, 2000; Post and Kwon, 2000; Pouyat *et al.*, 2009). These results may be explained by both direct and indirect effects of urbanization on urban soils. Direct effects include physical disturbances, burial, coverage of soil by fill material and impervious surfaces, and soil management inputs (e.g., fertilization and irrigation). Indirect effects involve the changes in the abiotic and biotic environments as areas that can influence soil development in intact soils are urbanized (Zhang *et al.*, 2003; Kaye *et al.*, 2006; Pouyat *et al.*, 2006).

Comparisons of soil carbon storages between the different age subdivisions suggest that urban land use change can increase SOC and SIC densities with time in Beijing (Fig. 3). The results indicate that older urban soil disturbed by development accumulates more carbon than younger soil. This result is consistent with chronosequence studies in Beijing and other locations. Hu *et al.* (2007) and Kong *et al.* (2009) found that the SOM levels in the urban-rural transition zone in Beijing slightly increased from low to high levels during 1980–2000. In the Denver-Boulder metropolitan area in the U.S., urban SOC concentration decreased below native grassland concentration in the first decade after construction, but then rose and surpassed the SOC concentration of grasslands within two decades of development (Golubiewski, 2006). Results from chronosequence sites in Baltimore, U.S., suggest that former agricultural areas have the potential to accumulate carbon rapidly over the 40 years following residential development (Raciti *et al.*, 2011). A study on golf courses near metropolitan Denver and Fort Collins, U.S., showed sharp increase in soil carbon over the first 25–30 years after development and that maximum SOC accumulation in turf grass systems occurred between 30 and 50 years following development (Qian and Follett, 2002). The results of a study on Hangzhou, China also showed that urban turf SOC accumulation continued for over 40 years following development (Liu and Zhang, 2010). The results in Beijing indicating that the SOC density of >30-year-old urban soil is slightly lower than that of >20-year-old urban soil suggest that accumula-

tion of carbon in >30-year-soil is still uncertain in this region. The reason is that due to the Beijing 2008 Summer Olympics, a lot of new green-space construction took place and existing green space underwent a large-scale renovation and reconstruction in the old town area of Beijing, which had been urbanized for over 30 years. The topsoil carbon stocks were drastically disturbed during reconstruction.

The results of our study also revealed that soil carbon stock decreased with distance from the urban center. The same was true for SOC, SIC, and TC. This trend is consistent with a urban-rural gradient transect study in New York, U.S. (Pouyat *et al.*, 2002), which showed that urban environments can affect soil properties in remnant forest patches along urban-rural environmental gradients. In New York, distance from the urban core accounted for approximately 23% of the variations in SOM among plots, but organic carbon density and concentration were not statistically significant when regressed against distance. In this study, the distance from the urban center explained 23.3% and 13.8% of the respective variations in SIC and TC densities among plots, but the SOC densities were not statistically significant. This discrepancy can be explained by the effects of anthropogenic drivers (management and disturbance) coupled with environmental factors that result in more complex soil carbon dynamics.

The urban built-up area in Beijing was increased by over 1000 km² from 1973 to 2005, of which approximately 54% was converted from constructed land and approximately 43% was converted from arable land in the suburban area (Mu *et al.*, 2007). Now, over 42% of the built-up areas in Beijing are covered by green space. The results of this study found that the carbon densities of urban topsoil under green space were higher than those of suburban green space and rural arable land. This indicates that agricultural land converted to urban green space in Beijing has the strong potential to accumulate soil organic carbon and soil inorganic carbon.

Due to the difficulty of sampling, this study only involved surface soil (top 20 cm) in open, urban space, and did not involve soil carbon stock in subsurface soil or soil beneath impervious surfaces, which cover a substantial proportion of urban land. We suggest that more data are needed on highly disturbed soils, and that an understanding of the carbon characteristics of soil at higher depths and soil beneath impervious surfaces is

needed to fully address the changes occurring in soil carbon stocks due to urban land-use conversion. The drivers of soil carbon accumulation in metropolitan areas need further study.

5 Conclusions

The comparison of soil carbon storage in the vegetated spaces of urban areas with that of suburban areas reveals a certain increase in carbon storage. This study reveals that the topsoil carbon densities in the metropolitan area of Beijing have a high spatial variability, and that SOC and SIC have a large range and coefficient of variation. The significant differences in soil carbon densities among different land use types indicate the decisive role of the human effect on the nature of urban soils. The results suggest that urban soil carbon stock accumulates with the passage of the time, and urban soil with at least 20 years of buildup has higher SOC compared to soil with less 10 years and suburban soil. The analysis of the relationship between urban carbon densities and distance from the urban center indicates that TC and SIC densities decrease significantly with the distance to the urban center. These results suggest that SOC and SIC accumulate in the urban topsoil under green space as a result of the conversion of agricultural land to urban land due to the urbanization in Beijing.

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