Urban Forestry & Urban Greening 83 (2023) 127918

Contents lists available at ScienceDirect

Urban Forestry & Urban Greening

journal homepage: www.elsevier.com/locate/ufug

How do urban forests with different land use histories influence soil organic carbon?

Xinhui Xu [a,b,c], Cheng Wang [a,b,*], Zhenkai Sun [a,b,*], Zezhou Hao [d], Susan Day [e]

[a] Research Institute of Forestry, Chinese Academy of Forestry, Beijing 100091, China
[b] Key Laboratory of Tree Breeding and Cultivation and Urban Forest Research Centre, National Forestry and Grassland Administration, Beijing 100091, China
[c] Guangdong Eco-Engineering Polytechnic, Guangzhou 510520, China
[d] Research Institute of Tropical Forestry, Chinese Academy of Forestry, Guangzhou 510520, China
[e] University of British Columbia, Vancouver, BC, Canada V6T 1Z4

ARTICLE INFO

Handling Editor: Dr Cecil Konijnendijk van den Bosch

Keywords:
Historical land use
Labile soil organic carbon
Plant functional type
Soil organic carbon
Urban soils

ABSTRACT

Urban forests play a vital role in building soil organic carbon pools in urban areas. In many cases, urban forests are constructed on land previously used for agriculture, parks, or buildings. However, it is still being determined whether historical land use affects soil organic carbon (SOC) stocks in these forests. In this study, we asked: 1) How are SOC and its labile fractions (LOC) in urban forests affected by historical land use? and 2) How do SOC and LOC vary with time and vegetation type in urban forests built on land with different histories? We collected soil samples at three soil depths, 0–10, 10–20, and 20–30 cm, in 48 evergreen and 77 deciduous forest plots in 77 parks in Beijing, all built within the last 30 years. Plots represent two historical land use types, vegetated or non-vegetated, and three planting time classes, young (5–10 years), intermediate (11–20 years), and old (21–30 years). Our findings showed that there were significant differences between historical land use types in SOC and microbial organic carbon (MBC), this may be due to backfill soil before greening on non-vegetated land. Urban forests that were built on vegetated land accumulated SOC over time, while those on historically non-vegetated land did not. Evergreen forests had greater SOC and LOC than deciduous forests only on historically non-vegetated land. In addition, SOC and LOC were found to be negatively affected by increased soil bulk density. However, soil bulk density was not significantly different between both historical land use types and urban forest types. Overall, our study indicates that if SOC sequestration is a high priority in urban forests, cities could concentrate on more efficient management to increase SOC, such as soil rehabilitation and the use of evergreen tree species.

1. Introduction

Soil is an essential part of the urban ecosystem in maintaining stability and mitigating climate change. Importantly, soil organic carbon (SOC) is a key soil property affecting other soil functions and properties (Wiesmeier et al., 2019; Zhao et al., 2014). Multiple factors are thought to likely influence SOC in cities (Lal, 2012; Pouyat et al., 2006). Land use pattern is one of these important determinants for SOC stocks at the city or park scale (Bae and Ryu, 2015; Canedoli et al., 2020; Takahashi et al., 2008), because it decides whether the soil is sealed or unsealed. Open or vegetated soils in urban green spaces, parks, and roadsides are more likely to accumulate SOC (Bae and Ryu, 2020; Cambou et al., 2018; Edmondson et al., 2012). In contrast, the sealed soils have much lower carbon content than surrounding unsealed soils (Raciti et al., 2012). However, if the sealed soil is transformed before afforestation, it is hard to say whether the transformed soil has lower or higher carbon content than open soil. For example, Chen et al. (2013) found that the simple topsoil backfill would decrease the soil C storage compared with undisturbed pasture soil, but the profile rebuilt soil could have relatively higher total soil carbon at 15–30 cm than the undisturbed pasture soil. Furthermore, Layman et al. (2016) found that trees grew better in the profile rebuilt soil than in the undisturbed soil, which will lead to higher SOC accumulation. Nowadays, many urban areas of China with open or sealed soils have been changed into urban forests to improve the urban environment quality (Jin et al., 2021), but we know less about the continuous influence of historical land use on SOC stocks (Raciti et al.,

* Corresponding authors at: Research Institute of Forestry, Chinese Academy of Forestry, Beijing 100091, China.
E-mail addresses: wch8361@163.com (C. Wang), zksun_caf@caf.ac.cn (Z. Sun).

https://doi.org/10.1016/j.ufug.2023.127918
Received 17 June 2022; Received in revised form 23 March 2023; Accepted 26 March 2023
Available online 27 March 2023

2011). In this study, we want to figure out whether there are significant differences in SOC content and distribution between urban forests built on historically vegetated land and non-vegetated land.

The urban environment is a complex of land use types with different land use histories and vegetation conditions (Zhou et al., 2017), which can lead to differences in soil functions (Vasenev et al., 2013). Many studies have shown significant differences in SOC among different land use types, such as residential, recreational, or traffic land (Canedoli et al., 2020; Hao et al., 2013; Sun et al., 2010; Zhang et al., 2021). There were also studies showed that SOC was influenced by vegetation types and tree species of urban forests, which was likely due to the differences in litter decomposability or root production (Lu et al., 2021; Setälä et al., 2016; Takahashi et al., 2008). Xu et al. (2021) found that soils under the coniferous forest group had higher SOC than those under the broad-leaved forest group. However, there are few studies focus on the interaction effects between land use histories and urban forest types on the SOC. Moreover, studying the interaction of historical land use and forest types within cities is useful for developing a comprehensive understanding of the process driving SOC accumulation in urban area.

In addition to the effects on SOC, land use and urban forests can affect labile organic carbon (LOC) in soil. LOC is the component of SOC considered to have a fast turnover rate, so it responds very quickly to the effects of management and vegetation factors (Stockmann et al., 2013). LOC in soil includes, among other soil constituents, dissolved organic carbon (DOC) and microbial organic carbon (MBC), which are important components of plant secretions and microbial metabolites (Li et al., 2018). DOC may be an important source of soil organic matter accumulation and is highly sensitive to ecosystem disturbance (Kalbitz et al., 2000; Tang et al., 2019). As the most active and variable part of soil organic matter, soil MBC is an important indicator reflecting the activity intensity of soil microorganisms and the decomposition process of organic matter (Dilly et al., 2003). In addition, MBC is highly sensitive to initial disturbance and recovery at the ecosystem level and is often used as an early response indicator of SOC dynamics (Oduor et al., 2018; Smith and Paul, 1990). In a study on the influencing factors of urban soil labile organic carbon, DOC and MBC were found to decrease with time since tree planting (Huang et al., 2021), which is contrary to the general trend of SOC as we know. Therefore, it will be helpful to understand the quality of organic carbon in soil by measuring LOC after the construction of urban forests.

Since 1980, Beijing has carried out several huge afforestation projects. For example, the Million-Mu (mu is a Chinese unit of area and is equal to 667 m^2) Plain Afforestation Project, had increased the forest cover in Beijing's plain area from 14.85 % in 2012 to 25 % in 2015. These extensive afforestation projects in urban areas provide an excellent opportunity to study the differences in SOC in urban forests built on different land uses (Jin et al., 2021; Li, 2020). To pursue how historical land use influences urban forest SOC, we studied the soil of urban forests built in Beijing in the past 30 years on sites with different historical land use patterns. Specifically, we studied the effects of two historical land use types, vegetated and non-vegetated, and their interactions with vegetation type or the planting time on SOC. To rule out the influence of current land use types on SOC, such as residential, traffic land, or parks (Canedoli et al., 2020; Zhang et al., 2021), we took soil samples only in urban parks. In this research, we ask: 1) whether historical land use affects the content and distribution of SOC and LOC in urban forests? 2) How do SOC and LOC change with different vegetation types and planting times after urban forest construction on different historical land uses?

2. Materials and methods

2.1. Study area

The study was conducted in the capital city of China, Beijing (115°24′–117°30′E, 39°28′–41°05′N). Beijing belongs to the warm, temperate, semi-humid continental monsoon climate, with an annual mean temperature of 14 °C and annual mean precipitation of 500 mm, and has a resident population of over 19 million (BMBS, 2010). The urban area of Beijing, located in the south-central part of the city, spreads out along a concentric ring road system. These circular roads are designated as the second to the sixth ring roads and represent historical expansions of the city. The third ring road of Beijing was built in the 1980s concurrently with an effort to develop the city's urban forest (Han et al., 2021). Therefore, we used the urban forests built within 30 years from the third ring to the sixth ring as our study sites. Moreover, we divided the sampling area into three zones, UZ3, UZ4, and UZ5, following the method described by Han et al. (2021). UZ3, UZ4, or UZ5 is the area between the third, fourth, fifth, and sixth ring roads in sequence (Fig. 1). The urbanization gradient decreases from UZ3 to UZ5. Soil samples were collected from each urban forest plot during September and October 2017, as described below.

Forest sample plots were selected in 77 urban parks from the third ring road to the sixth ring road (Fig. 1), including 48 evergreen forest plots and 77 deciduous forest plots, for a total of 125 plots selected. The sizes of plots ranged from 100 m^2 (10 m × 10 m) to 225 m^2 (15 m × 15 m). We identified the planting time, historical land use, and park size with the help of Google Earth online imagery and by conducting field investigations with local people. The planting time range of the sample was between 5 and 30 years. Plots were divided into three age groups based on planting time: young: 5–10 years, intermediate: 11–20 years, and old: 21–30 years, with 43, 57, and 25 replicates per planting time class. The prior land use was divided into two types: vegetated land use (VLU, e.g., agricultural land, grassland, and orchards) and non-vegetated land use (NVLU, e.g., construction land, derelict land, and brownfields). We also investigated the diameter at breast height (DBH) of trees in sample plots to represent the aboveground carbon investment ability (Xu et al., 2021).

2.2. Soil sampling design

In the soil sample collection, soil samples of three depths, 0–10, 10–20, and 20–30 cm, were collected in each sample plot. A steel push corer with a 3.8-cm inner diameter and 20-cm length (Hongguang Instrument Inc., Shaoxing, China) was used to obtain the samples. Every soil sample was taken by 10 cm one time. Within each plot, six samples were collected at each depth and mixed to get a composite sample. The composite samples were stored in sealed polyethylene bags and transported in a cooler to the laboratory for chemical analysis. Soil bulk density samples were collected next to the chemical sample location. We analyzed soil bulk density, soil moisture content, pH, SOC concentration, DOC concentration, and MBC concentration. In brief, all laboratory tests followed standard methods. The sampling and measurement of bulk density and the measurements of soil pH and SOC concentration were the same as in Xu et al. (2021). DOC was extracted with 0.5 mol/L K_2SO_4 (Rousk and Jones, 2010), and MBC was extracted by a fumigation–extraction method (Vance et al., 1987). Then DOC and MBC were measured using a TOC analyzer (Multi N/C 3100, Analytik, Jena, Germany).

2.3. Statistical analysis

In this study, all statistical analyses were performed using the statistical software R 3.6.3 (R Core Team, 2020) to estimate the effects of historical land use, urban forest vegetation type, and planting time on SOC and LOC. All datasets were checked for normality using the Shapiro–Wilk test ($p > 0.05$) prior to analysis and then normalized or scaled if necessary.

Pearson's correlation analysis between SOC, DOC, and MBC was carried out using the bivariate correlations procedure. We used linear mixed-effects models (LMMs) to test the effects of soil depth, historical land use (HL), urban zone (UZ), vegetation type (VT), and planting time

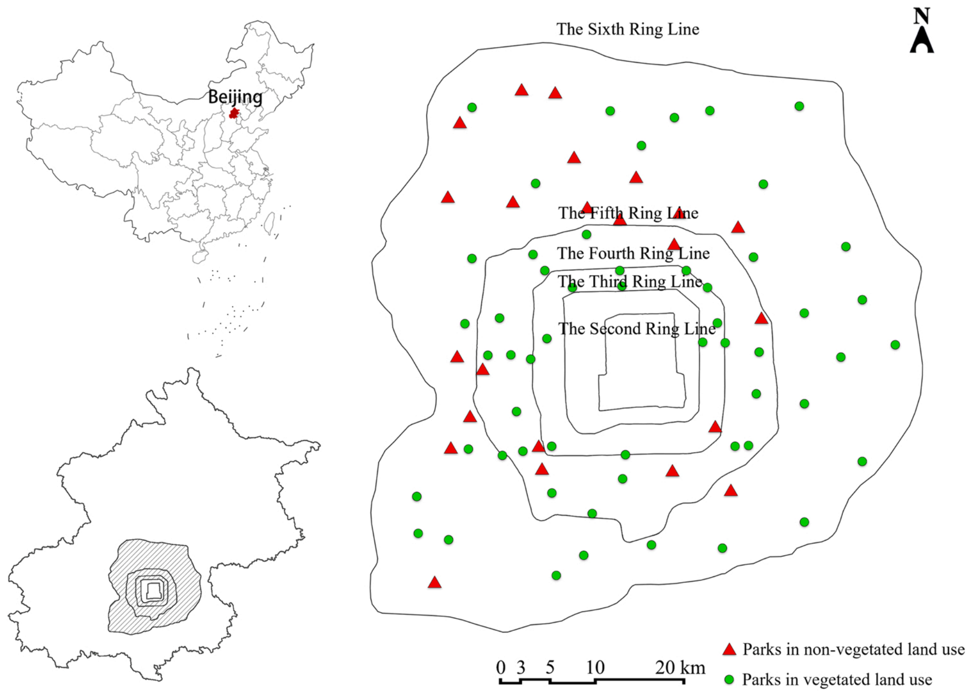

Fig. 1. Location of 77 sample parks within Beijing. Parks in vegetated land use were in agricultural or horticultural use prior to the construction of an urban forest, while parks in non-vegetated land use were previously constructed or derelict land.

(AG) on the soil organic carbon. Models were conducted with the package 'lmerTest' (Kuznetsova et al., 2017). Our first model was to test the effect of soil depth. Soil depth was included as a fixed effect, and sampling park was used as a random effect. To find out the interaction effect between HL and soil depth, we used the interaction between HL and soil depth as a fixed effect, sampling park as a random effect in our second model. Since there were significant differences among soil depths in SOC, soil depth was included as a random effect, and HL, UZ, VT, AG, the interaction between HL and VT, the interaction between HL and AG were included as fixed factors in our third model. Tukey honestly significant difference (HSD) tests were used to analyze SOC differences among soil depths, urban zones, and planting times, respectively. Redundancy analysis (RDA) was performed to determine the key environmental factors that affected SOC. R packages of 'Hmisc,' 'survival,' 'Formula,' 'htmlTable,' 'lmerTest,' 'lme4,' 'stats,' 'ggplot2,' 'multcomp,' 'mvtnorm,' 'tidyverse,' 'vegan,' 'permute' and 'lattice' were used to perform the analyzes.

3. Results

3.1. Variation of SOC stocks

The values of SOC, DOC, and MBC across all the parks were (means ± standard error) 7.60 ± 0.14 g/kg, 188.75 ± 3.18 mg/kg, and 218.31 ± 3.97 mg/kg, respectively. SOC, DOC, and MBC were positively correlated with each other by using Pearson's correlation analysis (all $p < 0.01$). History land uses (HL) had a weakly significant effect on the SOC and a significant effect on the MBC but had no significant effect on the DOC (Table 1). Specifically, the values of SOC and MBC were bigger in NVLU than in VLU (Table 2). There were significant interaction effects between HL and soil depth on the SOC, DOC, and MBC (all $p < 0.01$). SOC, DOC, and MBC in the 0–10 cm were significantly bigger than in the lower two layers when we considered all the parks together (Table 2). This pattern was also found in the soil of VLU (Fig. 2A–C). However, we only found this pattern for SOC in the soil of NVLU (Fig. 2A). There was

Table 1
The effects of historical land use (HL), urban zone (UZ), vegetation type (VT), urban forest planting time (AG), and the interaction effects between HL and VT, HL and AG on soil organic carbon (SOC), dissolved organic carbon (DOC) and microbial organic carbon (MBC), respectively. The effects were analyzed by mixed-model ANOVA using type III hypotheses with *p*-values calculated by *F* statistics. Values of $p < 0.05$ are in bold. Abbreviation: ANOVA, analysis of variance.

Sources	SOC (g/kg)				DOC (mg/kg)			
	NumDF	DenDF	*F*	*p*	NumDF	DenDF	*F*	*p*
HL	1	355	3.76	0.053	1	355	1.61	0.21
UZ	2	355	33.59	**< 0.001**	2	355	42.41	**< 0.001**
VT	1	355	2.02	**0.026**	1	355	3.42	0.065
AG	2	355	1.82	0.16	2	355	0.96	0.38
HL: VT	1	355	3.20	0.074	1	355	1.31	0.25
HL: AG	2	355	0.46	0.63	2	355	1.18	0.31

Sources	MBC (mg/kg)			
	NumDF	DenDF	*F*	*P*
HL	1	355	5.92	**0.015**
UZ	2	355	33.57	**< 0.001**
VT	1	355	9.35	**0.002**
AG	2	355	1.61	0.20
HL: VT	1	355	4.81	**0.029**
HL: AG	2	355	0.44	0.64

Table 2
The values of soil organic carbon (SOC), dissolved organic carbon (DOC), and microbial organic carbon (MBC) of different historical land uses, depths, urban zones, vegetation types, and planting times, respectively. Results are presented as means ± standard error. The different small letters mean that there are significant differences. Abbreviations: VLU, vegetated land use; NVLU, non-vegetated land use; UZ3, the area between third and fourth ring roads; UZ4, the area between fourth and fifth ring roads; UZ5, the area between fifth and sixth ring roads.

Sources		SOC (g/kg)	DOC (mg/kg)	MBC (mg/kg)
Historical land uses	VLU	7.45 ± 0.17	187.68 ± 3.74	213.06 ± 4.70
	NVLU	7.89 ± 0.28	191.02 ± 5.98	229.40 ± 7.27
Depths	0–10 cm	8.58 ± 0.23a	208.91 ± 4.74a	235.76 ± 6.34a
	10–20 cm	7.15 ± 0.27b	180.87 ± 5.99b	213.33 ± 7.47b
	20–30 cm	7.05 ± 0.24b	176.27 ± 5.29b	205.64 ± 6.51b
Urban zones	UZ3	9.28 ± 0.35a	227.60 ± 9.31a	264.14 ± 9.22a
	UZ4	8.52 ± 0.21b	212.99 ± 5.00a	245.26 ± 5.80b
	UZ5	6.62 ± 0.20c	164.27 ± 3.71b	190.46 ± 5.30c
Vegetation types	Evergreen	7.89 ± 0.23	194.80 ± 4.93	229.63 ± 6.57
	Deciduous	7.43 ± 0.19	185.27 ± 4.12	211.80 ± 4.94
Planting times	Young	7.20 ± 0.21	177.78 ± 4.16	204.27 ± 5.70
	Intermediate	7.89 ± 0.22	196.76 ± 4.92	229.23 ± 5.95
	Old	7.88 ± 0.48	197.39 ± 11.65	226.05 ± 12.61

only significant difference between the layers of 0–10 cm and 20–30 cm for DOC, and there were no significant differences among the three layers for MBC (Fig. 2B, C). There were no significant differences in SOC, DOC, and MBC between VLU and NVLU in the same soil layers (all $p > 0.05$, Fig. 2). There were significant differences in SOC, DOC, and MBC among different urban zones (Table 1). The values of SOC and MBC decreased significantly from UZ3 to UZ5 (Table 2). The values of DOC in UZ3 and UZ4 were not significantly different but were both bigger than in UZ5 (Table 2).

3.2. The interaction effects of historical land use with vegetation type and planting time

There were significant differences between vegetation types in SOC and MBC (Table 1). Evergreen communities had greater values in SOC and MBC than deciduous communities (Table 2). Moreover, the interaction effect between historical land use and vegetation type was weakly significant on SOC but was significant on MBC (Table 1). Specifically, evergreen communities had higher values of SOC, DOC, and MBC than deciduous communities only in NVLU (Fig. 3A–C). Moreover, evergreen communities growing in NVLU had higher values of SOC and MBC than in VLU (Fig. 3A, C). In contrast to our expectation, the planting time had no significant effects on the SOC, DOC, and MBC by using LMMs (Table 1). We also found no significant interaction effects between historical land use and planting time on the SOC, DOC, and MBC (Table 1).

3.3. Correlation between soil organic carbon and environmental factors

According to the RDA analysis, the included environmental factors explained 25.89 % of the variation in SOC and LOC across all sites. Our RDA model was significant through Permutation test. All the environmental factors had significant effects on the SOC and LOC (all $p < 0.01$). Specifically, the effects of soil bulk density (BD), urban zones (UZ), pH, and park size (size) were negative (Fig. 4); they contributed 15.01 %, 17.33 %, 5.51 %, and 3.66 % to all the variation, respectively. The effects of soil moisture content (SMC), planting time (age), and DBH were positive (Fig. 4); they contributed 2.98 %, 2.60 %, and 4.11 % to all the variation, respectively. The position of sampling points in Fig. 4, which were divided into NVLU and VLU groups, did not show obvious connections between historical land use and SOC. This may imply that the legacy effect from land use history on the urban forest SOC is not evident and strong. Meanwhile, there were no significant differences between NVLU and VLU in BD, SMC, and pH (Table A1). We only found a significant difference between evergreen and deciduous communities in pH when we tested the interaction effects of HL and VT on the soil factors (Table A2).

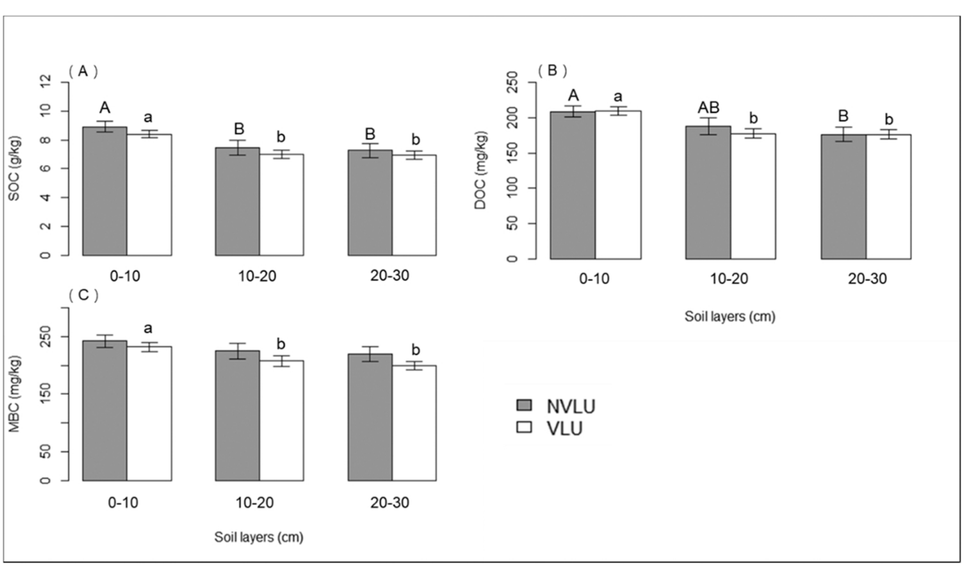

Fig. 2. The interaction effects of historical land use and soil depth on the SOC (A), DOC (B) and MBC (C). The different capital letters mean that there are significant differences between soil layers in NVLU. The different small letters mean that there are significant differences between soil layers in VLU. Abbreviations: SOC, soil organic carbon; DOC, dissolved organic carbon; MBC, microbial organic carbon; NVLU, non-vegetated land use; VLU, vegetated land use.

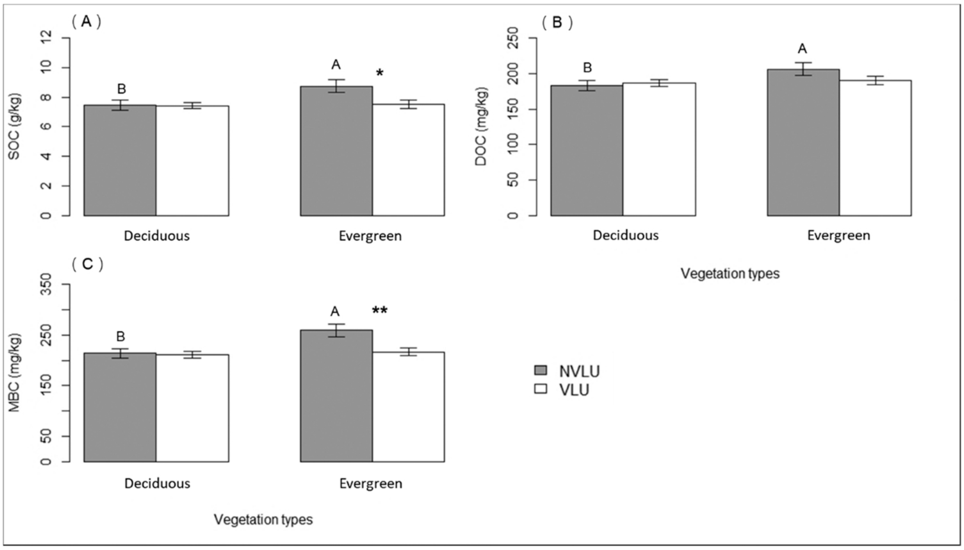

Fig. 3. The interaction effects of historical land use and vegetation type on the SOC (A), DOC (B), and MBC (C). The different capital letters mean that there are significant differences between vegetation types in NVLU. The "*" and "**" indicate significant differences between historical land uses of evergreen communities at the 0.05 and 0.01 levels, respectively. Abbreviations: SOC, soil organic carbon; DOC, dissolved organic carbon; MBC, microbial organic carbon; NVLU, non-vegetated land use; VLU, vegetated land use.

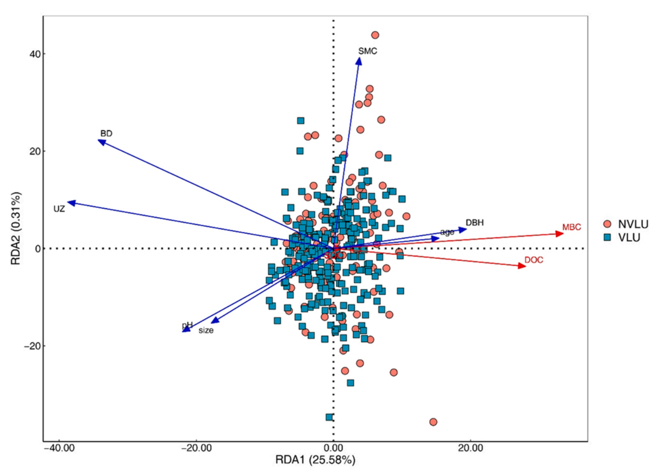

Fig. 4. Redundancy analysis (RDA) on SOC, DOC, and MBC constrained by environmental factors. Abbreviations: SOC, soil organic carbon; DOC, dissolved organic carbon; MBC, microbial organic carbon; NVLU, non-vegetated land use; VLU, vegetated land use; BD, soil bulk density; UZ, urban zones; DBH, diameter at breast height; SMC, soil moisture content; size, park size.

4. Discussion

4.1. Soil organic carbon status

Our results showed the averaged values of SOC, DOC, and MBC across all the sample parks and all three layers (Table 2), which are the same as the results of other studies showing the lack of nutrients in Beijing urban soils (Liu et al., 2018; Zhao et al., 2013). For example, Zhao et al. (2013) investigated the SOC of different land use types in Beijing in 2010. They found that the averaged value of SOC in the 0–10 cm was about 9.11 g/kg in parks, which was lower than that in secondary forest sites and roadside trees. Another study was carried out within the fifth ring road of Beijing in 2012 by using a grid network sampling method, and the results showed that the averaged value of MBC in the 0–10 cm was 150 mg/kg, which was also lower than the suburban forest soils of Beijing (370 mg/kg) (Liu et al., 2018). The limited carbon sequestration for the whole urban soil is probably due to the reasons of low microbial activity, lack of organic matter, or poor management practices (Liu et al., 2018). On the other hand, our results imply that there is great potential in increasing the level of soil organic carbon in Beijing's urban soils. Because the SOC in our study varied between 1.15 and 17.09 g/kg, which means that we can increase the soil organic carbon to the maximal level. Similarly, it has been reported that SOC values in the urban soils (0–10 cm) of Hangzhou (China), Kaifeng (China), Milan (Italy), and Baltimore (USA) varied from 9.20 to 86.40, 14.65 to 26.56, 8.12 to 58.93 and 2.88 to 75.06 g/kg, respectively (Zhang et al., 2021). These higher values of SOC in urban soils will offer useful implications for urban forest management.

Land use change can have a strong effect on soil carbon dynamics, yet whether in the urban context or non-urban context, there is still considerable disagreement about the associated change of soil carbon stocks with land use change (Deng et al., 2016; Hao et al., 2013). At present, within the city land, the effects of current land use or land cover have been most frequently studied on urban soil (Greinert, 2015; Vasenev et al., 2012), while studies on the effects of the former land use on urban SOC are still quite limited. Our results showed that historical land use significantly affected the SOC and MBC (Table 1), and non-vegetated land use had higher values, which means that land use history may affect the quantity of SOC in urban forests. According to the RDA analysis, soil bulk density, pH, and soil moisture content had significant effects on the soil organic carbon variation. However, historical land use type did not significantly influence these environmental factors (Table A1). The influence mechanism of land use change on urban forest soil may be complex. Studies have found that the soil carbon sequestration of urban forests built on different historical land use was related to the impact of soil sources and site preparation (Lal and Stewart, 2017; Oldfield et al., 2014). For example, urban soil rehabilitation treatments can increase tree growth and survival and increase carbon stores (Chen et al., 2013; Layman et al., 2016). However, we did not find that historical land use could significantly influence the DBH for both evergreen and deciduous communities in our study (data not shown). Therefore, the ecological effects of urban soil rehabilitation treatment on SOC need to be further studied.

Urbanization had increased soil organic carbon according to our results, and the position of urban zones contributed 17.33 % to all the SOC and LOC variation in our RDA analysis. Many studies have also shown the positive effects of urbanization on SOC (Jin et al., 2022; Wang et al., 2019; Zhai et al., 2017), although urban soils as a whole usually have lower SOC than forest soils (Liu et al., 2018; Xu et al., 2012). Urban soil organic carbon is mainly derived from plant residue, organic waste, and organic fertilizers (Vasenev and Kuzyakov, 2018; Xu et al., 2012). Vasenev and Kuzyakov (2018) concluded that higher urbanization area usually has longer-term and stronger human disturbances, which is more likely to accumulate soil organic carbon. In our study, the RDA ordination plot of Fig. 4 shows that UZ (urban zones) had positive relationships with soil BD (bulk density) and pH. Because the urbanization gradient is increased from UZ5 to UZ3 in our paper, we can infer that parks in higher urbanization areas of Beijing have better soil conditions, and the lower soil bulk density and pH will lead to higher soil organic carbon (Zhao et al., 2013). Our results also showed a positive relationship between urbanization and MBC, although many studies have shown that urbanization had negative effects on some carbon-related microbial activities (Wang et al., 2018; Wang et al., 2020). Therefore, the effects of urbanization on the whole and specific carbon-related microbial activities should also be widely studied.

Our findings also indicate that SOC and LOC will increase over time after urban forest construction by using ANOVA analysis but not LMMs, and this phenomenon was only demonstrated for previously vegetated land (VLU) (Fig. A1). Similarly, Paul et al. (2002) found that soil carbon storage decreased in the first five years and then increased after urban forest afforestation on agricultural land, which was possibly due to the disturbance caused by the transition. Other studies have also shown that SOC generally increased with forest planting time, whether in the urban environment or natural environment (Błońska et al., 2016; Setälä et al., 2016; Zhai et al., 2017). In our research, we found that only the SOC and LOC of urban forests built on VLU followed this pattern. In contrast, SOC and LOC of urban forests built on NVLU did not show an increasing trend with the planting time. When urban forests are constructed on non-vegetated land in Beijing, the soil is frequently brought in from outside, which may have the same amount of carbon as old parks. Unfortunately, the source of the imported soil is unknown to us. In addition, we do not have a long-term continuous sampling of the same sites, which may make the influence mechanism more complicated, while the time since planting is one of the most likely reasons in our study to demonstrate the dynamics of SOC and LOC. Therefore, studies that keep track of the soil sources of urban forest construction will greatly help better understand the dynamics of urban forest soil.

4.2. The influence of HL on the SOC vertical distribution

Sealed soil in the urban area will be transformed before afforestation which will change the soil structure (Chen et al., 2013; Layman et al., 2016). For example, according to the technical guidelines of the Beijing Million-Mu Afforestation Project made by the Beijing Gardening and Greening Bureau (2019), soils should be replaced and restored with backfill soil after the demolition and removal of buildings. Moreover, the backfill soil should be improved by humus. Therefore, the differences in soil nutrients among different soil layers will be diminished. As a result, the vertical distribution patterns of DOC and MBC on NVLU differed from that on VLU in our study. Moreover, we only investigated the soil organic carbon in a shallower depth of less than 30 cm like many other studies (Wang et al., 2019; Zhang et al., 2021). However, since the tree roots, microbes, and human activities can affect the deeper soil layers (Vasenev and Kuzyakov, 2018; Wang et al., 2017; Xu et al., 2012), we should consider studying deeper soil layers to understand the importance of urban soils for C sequestration fully.

4.3. The influence of HL and VT on the SOC content

Our research found that urban forests built on different historical land uses had different effects on SOC and LOC. On VLU, there was no significant difference in SOC and LOC between deciduous and evergreen urban forest vegetation types. While on NVLU, evergreen forests held significantly higher SOC and LOC than deciduous forests did, indicating that the use of evergreen tree species in urban areas may effectively improve the content and activity of SOC, especially in converting urban building land into forest land. Moreover, evergreen communities grown on the NVLU had higher values of SOC and MBC than those grown on the VLU. The change of SOC on NVLU is consistent with the known research results that vegetation type or tree species has a significant effect on the content of SOC (Setälä et al., 2016; Vesterdal et al., 2008). The different effects of deciduous and evergreen urban forests on SOC and LOC may be due to the type of fallen leaves, the feedback of root system, and the change of soil respiration caused by the shift of microenvironment provided by the urban forest (Lu et al., 2021). We tried to use the soil trait differences to explain the soil organic carbon differences. However, only pH significantly differed between evergreen and deciduous communities on VLU (Table A2), which could not explain the higher values in evergreen communities on NVLU. Therefore, the mechanisms under the interaction effects of historical land use and forest type on the soil SOC also need further study.

5. Conclusion

Our study indicates that historical land use can affect LOC's vertical distribution patterns, probably due to the previous soil backfill treatment. Historical land use can also affect SOC and LOC with urban forest type and planting time. On NVLU, evergreen urban forests held significantly higher SOC and LOC than deciduous, which did not happen on VLU. On VLU, SOC and LOC increased with planting time, but this did not occur on NVLU. These results could shed light on urban forest planning and estimation of SOC in the urban forest, advancing our understanding on how SOC and LOC change in urban forests with different land use histories. In conclusion, we found evidence for that historical land use can have long-term effects on critical ecosystem processes, such as SOC and LOC accumulation. Therefore, urban planners and managers need to be aware of land use history and keep track of urban forest construction to help improve the ecological service of the urban forest. In addition, urban soil research can benefit from long-term monitoring of soil sources and historical land uses. Such information could better inform urban forest construction and be more conducive to developing a complete understanding of the mechanisms for SOC changes over time on urban sites.

CRediT authorship contribution statement

Xinhui Xu: Conceptualization, Investigation, Methodology, Writing – original draft. **Cheng Wang:** Funding acquisition, Conceptualization, Writing – review & editing. **Zhenkai Sun:** Writing – review & editing. **Zezhou Hao:** Investigation, Methodology. **Susan Day:** Conceptualization, Writing – review & editing.

Funding

This work was supported by National Non-Profit Research Institutions of the Chinese Academy of Forestry (grant numbers: CAFYBB2020ZB008) and by the China Scholarship Council (CSC) (grant numbers: 201903270038).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ufug.2023.127918.

References

Bae, J., Ryu, Y., 2015. Land use and land cover changes explain spatial and temporal variations of the soil organic carbon stocks in a constructed urban park. Landsc. Urban Plan. 136, 57–67. https://doi.org/10.1016/j.landurbplan.2014.11.015.

Bae, J., Ryu, Y., 2020. High soil organic carbon stocks under impervious surfaces contributed by urban deep cultural layers. Landsc. Urban Plan. 204, 103953 https://doi.org/10.1016/j.landurbplan.2020.103953.

Beijing Gardening and Greening Bureau, 2019. Technical guidelines of the New Beijing Million-Mu Afforestation Project. ⟨http://yllhj.beijing.gov.cn/zwgk/fgwj/qtwj/201911/P020191130665880373661.doc⟩.

Błońska, E., Lasota, J., Gruba, P., 2016. Effect of temperate forest tree species on soil dehydrogenase and urease activities in relation to other properties of soil derived from loess and glaciofluvial sand. Ecol. Res. 31, 655–664. https://doi.org/10.1007/s11284-016-1375-6.

BMBS, 2010. Beijing 2010 Population Census Data. Beijing Municipal Bureau of Statistics.

Cambou, A., Shaw, R.K., Huot, H., Vidal-Beaudet, L., Hunault, G., Cannavo, P., Nold, F., Schwartz, C., 2018. Estimation of soil organic carbon stocks of two cities, New York City and Paris. Sci. Total Environ. 644, 452–464. https://doi.org/10.1016/j.scitotenv.2018.06.322.

Canedoli, C., Ferrè, C., El Khair, D.A., Padoa-Schioppa, E., Comolli, R., 2020. Soil organic carbon stock in different urban land uses: high stock evidence in urban parks. Urban Ecosyst. 23, 159–171. https://doi.org/10.1007/s11252-019-00901-6.

Chen, Y., Day, S.D., Wick, A.F., Strahm, B.D., Wiseman, P.E., Daniels, W.L., 2013. Changes in soil carbon pools and microbial biomass from urban land development and subsequent post-development soil rehabilitation. Soil Biol. Biochem. 66, 38–44. https://doi.org/10.1016/j.soilbio.2013.06.022.

Deng, L., Zhu, G. yu, Tang, Z. sheng, Shangguan, Z. ping, 2016. Global patterns of the effects of land-use changes on soil carbon stocks. Glob. Ecol. Conserv. 5, 127–138. https://doi.org/10.1016/j.gecco.2015.12.004.

Dilly, O., Blume, H.P., Sehy, U., Jimenez, M., Munch, J.C., 2003. Variation of stabilised, microbial and biologically active carbon and nitrogen in soil under contrasting land use and agricultural management practices. Chemosphere 557–569. https://doi.org/10.1016/S0045-6535(03)00237-6.

Edmondson, J.L., Davies, Z.G., McHugh, N., Gaston, K.J., Leake, J.R., 2012. Organic carbon hidden in urban ecosystems. Sci. Rep. 2, 1–7. https://doi.org/10.1038/srep00963.

Greinert, A., 2015. The heterogeneity of urban soils in the light of their properties. J. Soils Sediment. 15, 1725–1737. https://doi.org/10.1007/s11368-014-1054-6.

Han, D., Zhang, C., Wang, C., She, J., Sun, Z., Zhao, D., Bian, Q., Han, W., Yin, L., Sun, R., Wang, X., Cheng, H., 2021. Differences in response of butterfly diversity and species composition in urban parks to land cover and local habitat variables. Forests 12, 140. https://doi.org/10.3390/f12020140.

Hao, C., Smith, J., Zhang, J., Meng, W., Li, H., 2013. Simulation of soil carbon changes due to land use change in urban areas in China. Front. Environ. Sci. Eng. 7, 255–266. https://doi.org/10.1007/s11783-013-0485-4.

Huang, R., Lan, T., Song, X., Li, J., Ling, J., Deng, O., Wang, C., Gao, X., Li, Q., Tang, X., Tao, Q., Zeng, M., 2021. Soil labile organic carbon impacts C: N: P stoichiometry in urban park green spaces depending on vegetation types and time after planting. Appl. Soil Ecol. 163, 103926 https://doi.org/10.1016/j.apsoil.2021.103926.

Jin, J., Sheppard, S.R.J., Jia, B., Wang, C., 2021. Planning to practice: impacts of large-scale and rapid urban afforestation on greenspace patterns in the Beijing plain area. Forests 12, 1–22. https://doi.org/10.3390/f12030316.

Jin, T., Liu, W., Wang, Y., Zhao, M., Fu, Y., Dong, Y., Luo, T., Fu, H., Wang, Q., 2022. Effects of urbanization intensity on glomalin-related soil protein in Nanchang, China: influencing factors and implications for greenspace soil improvement. J. Environ. Manag. 318, 115611 https://doi.org/10.21203/rs.3.rs-1215776/v1.

Kalbitz, K., Solinger, S., Park, J.H., Michalzik, B., Matzner, E., 2000. Controls on the dynamics dissolved organic matter in soils: a review. Soil Sci. 165, 277–304. https://doi.org/10.1097/00010694-200004000-00001.

Kuznetsova, A., Brockhoff, P.B., Christensen, R.H.B., 2017. lmerTest package: tests in linear mixed effects models. J. Stat. Softw. 82, 1–26. https://doi.org/10.18637/jss.v082.i13.

Lal, R., 2012. Carbon sequestration in urban ecosystems. Carbon Sequestration in Urban Ecosystems. https://doi.org/10.1007/978-94-007-2366-5_8.

Lal, R., Stewart, B.A., 2017. Urban Soils. CRC Press; Taylor & Francis, Boca Raton; Cambridge.

Layman, R.M., Day, S.D., Mitchell, D.K., Chen, Y., Harris, J.R., Daniels, W.L., 2016. Below ground matters: urban soil rehabilitation increases tree canopy and speeds establishment. Urban For. Urban Green. 16, 25–35. https://doi.org/10.1016/j.ufug.2016.01.004.

Li, J., Wen, Y., Li, X., Li, Y., Yang, X., Lin, Z., Song, Z., Cooper, J.M., Zhao, B., 2018. Soil labile organic carbon fractions and soil organic carbon stocks as affected by long-term organic and mineral fertilization regimes in the North China Plain. Soil Tillage Res. 175, 281–290. https://doi.org/10.1016/j.still.2017.08.008.

Li, L., 2020. Impacts of plain afforestation on forest landscape patterns in Beijing. Chin. Urban 18, 5–10. https://doi.org/10.12169/zgcsly.2020.06.10.0001.

Liu, R., Wang, M., Chen, W., 2018. The influence of urbanization on organic carbon sequestration and cycling in soils of Beijing. Landsc. Urban Plan. 169, 241–249. https://doi.org/10.1016/j.landurbplan.2017.09.002.

Lu, C., Kotze, D.J., Setälä, H.M., 2021. Evergreen trees stimulate carbon accumulation in urban soils via high root production and slow litter decomposition. Sci. Total Environ. 774, 145129 https://doi.org/10.1016/j.scitotenv.2021.145129.

Oduor, C.O., Karanja, N.K., Onwonga, R.N., Mureithi, S.M., Pelster, D., Nyberg, G., 2018. Enhancing soil organic carbon, particulate organic carbon and microbial biomass in semi-arid rangeland using pasture enclosures. BMC Ecol. 18, 1–9. https://doi.org/10.1186/s12898-018-0202-z.

Oldfield, E.E., Felson, A.J., Wood, S.A., Hallett, R.A., Strickland, M.S., Bradford, M.A., 2014. Positive effects of afforestation efforts on the health of urban soils. For. Ecol. Manag. 313, 266–273. https://doi.org/10.1016/j.foreco.2013.11.027.

Paul, K.I., Polglase, P.J., Nyakuengama, J.G., Khanna, P.K., Paul, K.I., Polglase, P.J., Nyakuengama, P.K.K, J.G., 2002. Change in soil carbon following afforestation. For. Ecol. Manag. 168, 241–257. https://doi.org/10.1017/CBO9781107415324.004.

Pouyat, R.V., Yesilonis, I.D., Nowak, D.J., 2006. Carbon storage by urban soils in the United States. J. Environ. Qual. 35, 1566–1575. https://doi.org/10.2134/jeq2005.0215.

R Core Team (2020). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Raciti, S.M., Hutyra, L.R., Finzi, A.C., 2012. Depleted soil carbon and nitrogen pools beneath impervious surfaces. Environ. Pollut. https://doi.org/10.1016/j.envpol.2012.01.046.

Raciti, S.M., Groffman, P.M., Jenkins, J.C., Pouyat, R.V., Fahey, T.J., Pickett, S.T.A., Cadenasso, M.L., 2011. Accumulation of carbon and nitrogen in residential soils with different land-use histories. Ecosystems 14, 287–297. https://doi.org/10.1007/s10021-010-9409-3.

Rousk, J., Jones, D.L., 2010. Loss of low molecular weight dissolved organic carbon (DOC) and nitrogen (DON) in H_2O and 0.5 M K_2SO_4 soil extracts. Soil Biol. Biochem. 42, 2331–2335. https://doi.org/10.1016/j.soilbio.2010.08.017.

Setälä, H.M., Francini, G., Allen, J.A., Hui, N., Jumpponen, A., Kotze, D.J., 2016. Vegetation type and age drive changes in soil properties, nitrogen, and carbon sequestration in urban parks under cold climate. Front. Ecol. Evol. 4, 1–14. https://doi.org/10.3389/fevo.2016.00093.

Smith, J., Paul, E., 1990. The significance of soil microbial biomass estimations. Soil Biochem. 357–397.

Stockmann, U., Adams, M.A., Crawford, J.W., Field, D.J., Henakaarchchi, N., Jenkins, M., Minasny, B., McBratney, A.B., Courcelles, V., de, R., de, Singh, K., Wheeler, I., Abbott, L., Angers, D.A., Baldock, J., Bird, M., Brookes, P.C., Chenu, C., Jastrow, J.D., Lal, R., Lehmann, J., O'Donnell, A.G., Parton, W.J., Whitehead, D., Zimmermann, M., 2013. The knowns, known unknowns and unknowns of sequestration of soil organic carbon. Agric. Ecosyst. Environ. 164, 80–99. https://doi.org/10.1016/j.agee.2012.10.001.

Sun, Y., Ma, J., Li, C., 2010. Content and densities of soil organic carbon in urban soil in different function districts of Kaifeng. J. Geogr. Sci. 20, 148–156. https://doi.org/10.1007/s11442-010-0148-3.

Takahashi, T., Amano, Y., Kuchimura, K., Kobayashi, T., 2008. Carbon content of soil in urban parks in Tokyo, Japan. Landsc. Ecol. Eng. 4, 139–142. https://doi.org/10.1007/s11355-008-0043-6.

Tang, J., Wang, W., Yang, L., Cao, C., Li, X., 2019. Variation in quantity and chemical composition of soil dissolved organic matter in a peri-urban critical zone observatory watershed in Eastern China. Sci. Total Environ. 688, 622–631. https://doi.org/10.1016/j.scitotenv.2019.06.270.

Vance, E.D., Brookes, P.C., Jenkinson, D.S., 1987. An extraction method for measuring soil microbial biomass C. Soil Biol. Biochem. 19, 703–707.

Vasenev, V., Kuzyakov, Y., 2018. Urban soils as hot spots of anthropogenic carbon accumulation: review of stocks, mechanisms and driving factors. Land Degrad. Dev. 29, 1607–1622. https://doi.org/10.1002/ldr.2944.

Vasenev, V.I., Ananyeva, N.D., Makarov, O.A., 2012. Specific features of the ecological functioning of urban soils in Moscow and Moscow oblast. Eurasia Soil Sci. 45, 194–205. https://doi.org/10.1134/S1064229312020147.

Vasenev, V.I., Stoorvogel, J.J., Vasenev, I.I., 2013. Urban soil organic carbon and its spatial heterogeneity in comparison with natural and agricultural areas in the Moscow region. Catena 107, 96–102. https://doi.org/10.1016/j.catena.2013.02.009.

Vesterdal, L., Schmidt, I.K., Callesen, I., Nilsson, L.O., Gundersen, P., 2008. Carbon and nitrogen in forest floor and mineral soil under six common European tree species. For. Ecol. Manag. 255, 35–48. https://doi.org/10.1016/j.foreco.2007.08.015.

Wang, Q., Zhang, D., Zhou, W., He, X., Wang, W., 2020. Urbanization led to a decline in glomalin-soil-carbon sequestration and responsible factors examination in Changchun, Northeastern China. Urban For. Urban Green. 48, 126506 https://doi.org/10.1016/j.ufug.2019.126506.

Wang, Q., Wang, W., He, X., Zhou, W., Zhai, C., Wang, P., Tang, Z., Wei, C., Zhang, B., Xiao, L., 2019. Urbanization-induced glomalin changes and their associations with land-use configuration, forest characteristics, and soil properties in Changchun, Northeast China. J. Soils Sediment. 19, 2433–2444. https://doi.org/10.1007/s11368-019-02266-x.

Wang, W., Zhong, Z., Wang, Q., Wang, H., Fu, Y., He, X., 2017. Glomalin contributed more to carbon, nutrients in deeper soils, and differently associated with climates and soil properties in vertical profiles. Sci. Rep. 7, 13003. https://doi.org/10.1038/s41598-017-12731-7.

Wang, W., Wang, Q., Zhou, W., Xiao, L., Wang, H., He, X., 2018. Glomalin changes in urban-rural gradients and their possible associations with forest characteristics and soil properties in Harbin City, Northeastern China. J. Environ. Manag. 224, 225–234. https://doi.org/10.1016/j.jenvman.2018.07.047.

Wiesmeier, M., Urbanski, L., Hobley, E., Lang, B., von Lützow, M., Marin-Spiotta, E., van Wesemael, B., Rabot, E., Ließ, M., Garcia-Franco, N., Wollschläger, U., Vogel, H.J., Kögel-Knabner, I., 2019. Soil organic carbon storage as a key function of soils – a review of drivers and indicators at various scales. Geoderma 333, 149–162. https://doi.org/10.1016/j.geoderma.2018.07.026.

Xu, N., Liu, H., Wei, F., Zhu, Y., 2012. Urban expanding pattern and soil organic, inorganic carbon distribution in Shanghai, China. Environ. Earth Sci. 66, 1233–1238. https://doi.org/10.1007/s12665-011-1334-z.

Xu, X., Sun, Z., Hao, Z., Bian, Q., Wei, K., Wang, C., 2021. Effects of urban forest types and traits on soil organic carbon stock in Beijing. Forests 12. https://doi.org/10.3390/f12040394.

Zhai, C., Wang, W., He, X., Zhou, W., Xiao, L., Zhang, B., 2017. Urbanization drives SOC accumulation, its temperature stability and turnover in forests, Northeastern China. Forests 8, 1–18. https://doi.org/10.3390/f8040130.

Zhang, P., Wang, Y., Sun, H., Qi, L., Liu, H., Wang, Z., 2021. Spatial variation and distribution of soil organic carbon in an urban ecosystem from high-density sampling. Catena 204, 105364. https://doi.org/10.1016/j.catena.2021.105364Zhao.

Zhao, D., Li, F., Yang, Q., Wang, R., Song, Y., Tao, Y., 2013. The influence of different types of urban land use on soil microbial biomass and functional diversity in Beijing, China. Soil Use Manag. 29, 230–239. https://doi.org/10.1111/sum.12034.

Zhao, L., Xu, Y., Hou, H., Shangguan, Y., Li, F., 2014. Source identification and health risk assessment of metals in urban soils around the Tanggu chemical industrial district, Tianjin, China. Sci. Total Environ. 468–469, 654–662. https://doi.org/10.1016/j.scitotenv.2013.08.094.

Zhou, W., Pickett, S.T.A., Cadenasso, M.L., 2017. Shifting concepts of urban spatial heterogeneity and their implications for sustainability. Landsc. Ecol. 32, 15–30. https://doi.org/10.1007/s10980-016-0432-4.