Master’s Thesis of Landscape Architecture

Land use and land cover changes explain spatial and temporal variations of the soil organic carbon stocks in a constructed urban park

토지 이용 및 피복 변화에 따른 도시 공원 내 토양 탄소 저장량의 시공간 변이 분석: 서울 숲 공원을 대상으로

February, 2019

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Abstract

Urban parks offer valuable ecosystem services to citizens and they have long been recognized for their recreational service; however, less attention has been paid to their carbon sequestration value. Here, we report on soil organic carbon (SOC) stocks in an urban park, Seoul Forest Park, which was built in 2004. We had two objectives: (1) to estimate SOC stocks (to a depth of 1 m) in different land-cover types (wetland, forest, lawn, and bare soil) and (2) quantify the change in the SOC concentration in topsoil in different land-use types over a 10 year period (2003–2013). We found a tenfold difference in SOC stocks across the different land-cover types within the park. Wetland soils had the highest stocks of SOC (13.99 ± 1.05 kg m^{-2}), followed by forest, lawn, and bare soils. We found that a “cultural layer” that preserved previous land use history located deep in the soil profile substantially increased SOC stocks in the wetland. SOC concentrations in the topsoil were approximately three times higher in 2013 than in 2003 (256 ± 130%). The normalized difference vegetation index (NDVI) derived from MODIS and Landsat satellite images revealed that land-use history, expansion of plant areas and growth of plants could explain the increase in SOC concentrations in topsoil over the 10 year period. These findings imply that urban park soils could act as a carbon sink, and understanding the land-use history and the choice of land-cover types in park planning can substantially influence the carbon budget of urban parks.

Keywords : *Land cover change, Land use change, NDVI, Soil carbon, Urban park*

Student Number : 2012-21136

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1. Introduction

The atmospheric carbon dioxide (CO_2) concentration surpasses its previous record every year, exceeding 400 ppm in 2013. Stocks of soil organic carbon (SOC) are a key component in carbon capture and storage to mitigate increasing atmospheric CO_2 concentration (Ingram & Fernandes, 2001; Lal, 2004). However, most soil surveys do not include urban areas, instead delineating them as partially empty space in regional soil monitoring systems (Rawlins et al., 2008; Rossiter, 2007). Most soil carbon studies have focused on agricultural and natural ecosystems (Don, Schumacher, & Freibauer, 2011; Guo & Gifford, 2002; Li, Niu, & Luo, 2012), whereas SOC stocks in urban areas have rarely been quantified (Jo & McPherson, 1995; Raciti et al., 2011). Consequently, the lack of SOC data for urban areas has made it difficult to estimate or predict the regional carbon budget in urban ecosystems.

Emerging evidence indicates that urban ecosystems could sequester large amounts of atmospheric CO_2. Churkina, Brown, and Keoleian (2010) confirmed high organic carbon densities (23–42 kg m^{-2} in urban areas and 7–16 kg m^{-2} in exurban areas) in developed areas of the United States. Pouyat, Yesilonis, and Nowak (2006) compared the variability in the SOC stocks in six different cities and found that urban soils have the potential to sequester a large amount of atmospheric CO_2. In particular, urban green spaces contained larger SOC stocks than native grasslands, agricultural, or forested areas in Colorado, U.S.A. (Golubiewski, 2006). Hutyra, Yoon, and Alberti (2011) reported that aboveground carbon stocks in Seattle's urban forests were comparable to those of the Amazon rain forest. Kaye, McCulley, and Burke (2005) measured aboveground net primary productivity in urban lawns and found it was four to five times higher than in nearby agricultural lands and grasslands. Furthermore, Mestdagh, Sleutel, Lootens, Van Cleemput, and Carlier (2005) found that SOC stocks of grassy roadsides, waterways, and railways in urban areas accounted for 15% of the total SOC stocks in a city. The soils beneath impervious surfaces in urban areas offered another, often overlooked, source of SOC (Edmondson, Davies, McHugh, Gaston, and Leake, 2012; Raciti, Hutyra, & Finzi, 2012a).

Urban parks are important natural assets in urban ecosystems and are major components of carbon sequestration strategies (Millward & Sabir, 2011). Urban parks include a large proportion of green space, which can store considerable amounts of SOC (Strohbach, Arnold, & Haase, 2012). In addition, the area of urban parks is expected to expand over time due to increasing urbanization and citizens' desire for a better quality of life. However, little effort has been made to quantify SOC stocks in urban parks.

Due to the lack of quantitative data, the effects of land-use history have rarely been assessed as a determining factor for estimating regional SOC stocks (Schulp & Verburg, 2009). However, historical land-use changes have been shown to affect current SOC stocks in constructed urban parks (Takahashi, Amano, Kuchimura, & Kobayashi, 2008). In fact, many land-use changes are accompanied by anthropogenic belowground disturbances (Raciti, Hutyra, Rao, & Finzi, 2012b). In particular, the construction process can substantially alter natural soil profiles (Chen et al., 2013; Jim, 1998). For example, aggressive land clearing (Neill et al., 1997) and replanting (De Jong, Ochoa-Gaona, Castillo-Santiago, Ramirez-Marcial, & Cairns, 2000; Pongratz, Reick, Raddatz, & Claussen, 2009; Schimel et al., 2001) can affect SOC stocks by changing soil properties and the dominant plant functional types (Hobbie et al., 2007; Palmroth et al., 2006). Constructed urban parks have heterogeneous land cover types such as woody plants, shrubs, lawns, bare land, and ponds. As a result, soil disturbance during park construction is one of the primary reasons for differences in SOC stocks of each land cover type. Therefore, without a detailed investigation of previous land-use and current land management, the SOC budgets of urban parks cannot be accurately predicted for inclusion in the regional carbon databases of urban ecosystems.

In this study, we report SOC stocks for the Seoul Forest Park, which was built in Seoul, South Korea, in 2004. The objectives of this study were (1) to quantify SOC stocks (to a depth of 1 m) in different land-cover types (wetland, forest, lawn, and bare soil) and (2) estimate the changes in SOC concentrations (to a depth of 0.3 m) in different land-use types over a 10 year period (2003–2013). The scientific questions that we addressed included the following: (1) what controls spatial heterogeneity of SOC stocks among different land cover types in the constructed urban park? and (2) how does land use history influence temporal variations in SOC concentrations?

2. Methods

2.1. Site description

This study was conducted in the 115.6 ha Seoul Forest Park, Seoul, Republic of Korea (37.545031◦N, 127.038249◦E). The site has a temperate monsoon climate with a mean annual temperature of 12.5 ◦C and mean annual precipitation of 1450 mm (Korean Meteorological Administration). The parent material of soil in the Seoul Forest Park is underlain by Daebo Granite dating to the Quaternary period. According to the Soil and Environmental Information System of Korea (http://soil.rda.go.kr), the soils in the park are classified to Entisol.

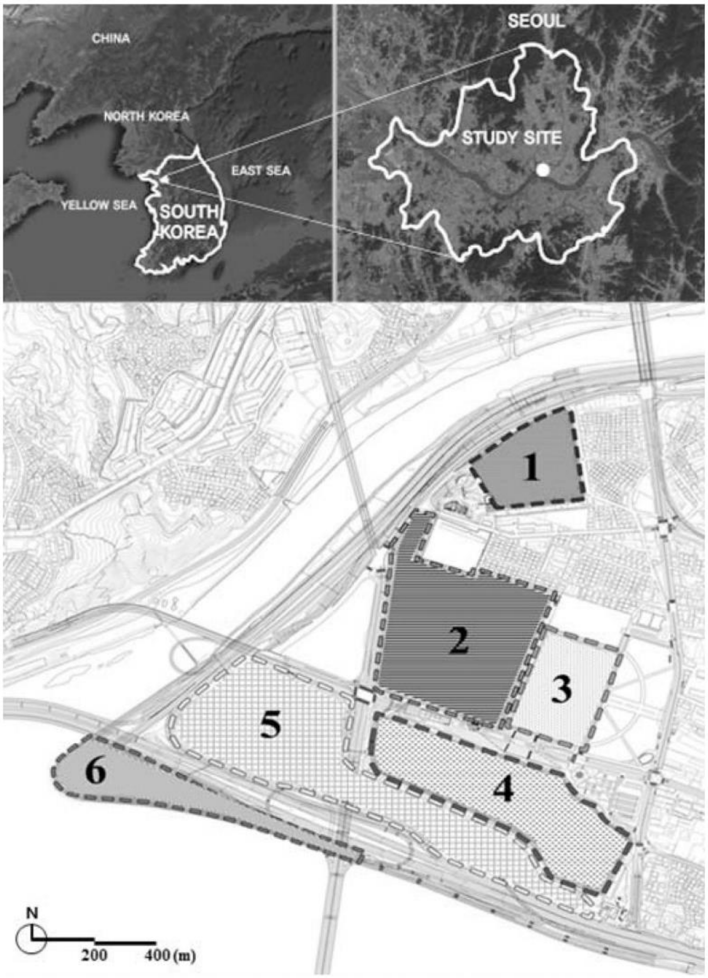

Fig. 1. Location of the Seoul Forest Park, and six districts based on the different land-use types. Both the current and previous land-use types are shown in Table 1.

	Land-use change		**Soil texture (USDA)**	
District	**2003**	**2013**	**2003**	**2013**
1	Retarding basin	Wetland park	Silty clay	Silty clay (50±3%)
2	Golf course and agricultural area	Open space (lawn and forest area)	Silty clay	Sandy clay loam (32±2%)
3	Horse race course	Open space (forest area)	Sand	Sandy clay loam (25±3%)
4	Water purification plant	Water purification plant and industrial facilities	Silty clay	Sandy clay loam (23±2%)
5	Riparian	Deer corral and forest park (forest area)	Sandy clay loam	Silty clay (45±3%)
6	Riverside park	Riverside park	Sandy clay loam	Sandy clay loam (24±2%)

Table 1. Changes in the dominant land-use types and soil texture at a 0–0.3 m soil depth between 2003 and 2013 in the six basic districts. The park was constructed in 2004. Parenthesis in soil texture indicates clay percentages. Error bars indicate 95% CI.

Land-use is defined as a series of operations on land by people. The Seoul Forest Park was a royal hunting ground since the reign of the Joseon Dynasty (1392–1910). In 1908, this historic site was developed into a water purification plant, horse racing course, and golf course. In 2004, the site was converted to an urban park after intensive construction and was opened to the public in June 2005. The current and previous land-use types are shown in Fig. 1 and Table 1. We quantify changes in SOC concentrations of topsoil over the 10 years, according to land-use type.

Land-cover is defined as the physical land type such as vegetation types. To quantify spatial variations of SOC stocks in 2012, we used the land-cover types instead of land-use types because one land-use type may include contrasted land-cover types (e.g. bare land and mixed forest). The proportions of the each land cover type in the Seoul Forest Park were 2% bare land, 14.9% lawn, 27.4% mixed forest, 10% evergreen needle-leaf forest, 17.6% deciduous broadleaf forest, and 4.5% wetland. The dominant plant species included *Zoysia japonica* in lawn, *Quercus acutissima*, *Quercus mongolica*, and *Pinus rigida* in mixed forest, *P. rigida* and *Pinus strobus* in evergreen needle-leaf forest, *Q. acutissima*, *Q. mongolica*, and *Quercus serrata* in deciduous broadleaf forest, and *Phragmites japonica*, *Phragmites communis*, and *Miscanthus sacchariflorus* in wetland.

2.2. Data collection

Soil samples were collected from June 2012 and July 2013. We estimated SOC stocks to a depth of 1 m in the six land-cover types described above. We randomly determined 12 plots (10 × 10 m quadrat) within each land-cover type. At each point, we removed the litter layer, dug out soils to a 1 m depth, and collected four soil samples along the soil vertical profile (0–0.1, 0.1–0.3, 0.3–0.7, and 0.7–1.0 m) using a soil corer (Soil Sampler; Shinill Science Inc., Seoul, Korea) with a 50 mm inner diameter, 51 mm length, and 100 cm3 volume. We also collected six root samples from each vertical soil layer of each land-cover type for a total of 168 root samples collected in June 2012. To quantify the changes in SOC concentrations in the topsoil between 2003 and 2013, we combined a literature survey and field observations. We used data from the soil survey report by the Seoul Forest Development Corporation (2004) to determine the SOC concentration and soil texture of the topsoil before the park was constructed. A total of 22 topsoil samples were collected in six different land-use districts in July 2003. We repeated the topsoil measurements in the same land-use districts by randomly collecting six samples in each district.

To understand plant growths in the park, we estimated the changes of diameter at breast height (DBH) with a diameter tape at a height of 1.3 m between August 2012 and August 2014. The 22 monitoring plots (10 × 10 m square) were distributed randomly in District 2, 3 and 5 which experienced significant land-use changes and plantations (Fig. 1 and Table 1). We selected a total of 690 trees which include seven species such as *Ginkgo biloba* L., *Pinus densiflora* Siebold & Zucc., *Pinus strobes* L., *Metasequoia glyptostroboides* Hu & Cheng., *Acer buergerianum* MIQ., *Zelkova serrata* (Thunb.) Makino., *Quercus palustris* Munchh., *Ulmus davidiana* Planch. var. *japonica* (Rehder) Nakai., *Magnolia kobus* A. P. DC. The sampled trees were mainly planted during park construction. To infer plant growths before 2012, we used the data of the changes in DBH between 2005 and 2012 in the Seoul Forest Park surveyed by the Department of Environment, Gyeonggi Research Institute (Kim, 2012).

2.3. Data processing

Soil texture was determined using the percentages of sand, silt, and clay as determined by the hydrometer method (Gee & Bauder, 1979). The textural classes were determined based on the USDA soil classification scheme (USDA, 2010). The soil samples were oven dried (C-DH; Chang Shin Scientific Co., Pusan, Korea) at 105℃ for 2 days in the laboratory (USDA-NRCS, 1992).We separated dead roots from living roots with tweezers, then washed the fine roots (<2 mm diameter) from the soils and oven-dried the roots at 70 ◦C for 2 days to determine dry weight (Olsthoorn, 1991). The soil samples were strained through a 2 mm standard testing sieve (Chung Gye Sang Gong SA, Seoul, Korea) to remove stones. The bulk density of soil at each depth was determined using the following equation (Adams, 1973):

$$\text{soil bulk density} = \frac{(\text{total dry mass} - \text{rock mass})}{(\text{total volume} - \text{rock volume})} \qquad (1)$$

To estimate the volume of rocks from the rock mass, we assumed rock particle density was 2.65 Mg m^{-3} (Brady & Weil, 2007). SOC concentration was quantified using an Elemental Carbon Analyzer (Flash EA 1112; Thermo Electron, Waltham, MA, USA) at the National Instrumentation Center for Environmental Management (NICEM), Seoul National University.

2.4. Remote sensing data

To understand the relationship between the growth of vegetation and changes in SOC concentrations over 10 years, we used the MODIS normalized difference vegetation index (NDVI; MOD13Q1) (Huete et al., 2002). The NDVI represents vegetation activity (Tucker, 1979; Ryu et al., 2010; Ryu, Lee, Jeon, Song, & Kimm, 2014), and the MOD13Q1 provides the NDVI at a 250 m resolution over a 16 day interval. We only used good-quality data, which were defined as "Good Data—use with confidence" by a MOD13Q1 pixel reliability flag (http://vip.arizona.edu/MODIS ATBD.php). To estimate vegetation activity during the peak growing season (June), we extracted the NDVI values for the twelve pixels that included the park, and then calculated the mean and 95% confidence interval (CI) for NDVI values for each year.

To quantify temporal changes in NDVI for the six land-use districts, we used 30 m resolution images from Landsat 7 ETM+ and Landsat 8 taken under clear sky conditions for path 116 and row 34. As Landsat 7 ETM+ has had a detector striping problem since 2003, we selected one Landsat 7 ETM+ image during a peak growing season in 2002 (day 173 of the year). As Landsat 8 imagery has been available since 2013, we identified one Landsat 8 image for a similar day of the year (day 179) to compare with the earlier image. For the two images, we applied atmospheric correction using the dark object subtraction method (Song, Woodcock, Seto, Lenney, & Macomber, 2001) to remove path radiance effects, and computed red and near-infrared reflectance, and finally the NDVI (Ryu et al., 2014). We quantified the mean and 95% CI for NDVI values in each district for the two years. To investigate land-use changes over the past decade, we used Google Earth V 7.1.2.2041. Over the decade, twelve scenes were available and we chose three scenes in study area taken on 15 February 2002, 12 October 2005 (image copyright: Digital globe 2014) and 16 October 2013 (image copyright: CNES/Astrium2014). Three scenes represent before park construction, just after park opening, and most recent image.

2.5. Statistical analyses

Statistical analyses were conducted using SigmaPlot 12.0 software (Systat Software Inc., Chicago, IL, USA). We used a t-test to compare SOC concentrations of topsoil of each district between 2003 and 2013, to compare DBH between 2012 and 2014, and to assess differences in the NDVI of each district between 2002 and 2013. We used one-way analysis of variance (ANOVA) followed by Tukey's post hoc test or Dunn's multiple comparison test to compare SOC stocks among land-cover types, and to compare SOC concentration, soil bulk density, and fine root mass density among soil depth intervals for each land-cover type. All data are presented as means ± 95% CI unless otherwise specified.

3. Result

3.1. Soil organic carbon concentration

The highest SOC concentration was located at 0–0.1 m soil depth in all of the land-cover types ($P < 0.05$). The SOC concentration decreased with soil depth, except in wetland soils, in which the 0.7–1.0 m depth had a higher SOC concentration than the 0.3–0.7 m depth (Fig. 2f). In wetland soils, the SOC concentration in the topsoil was 68% of that at 1 m depth, whereas in forests, lawns, and bare soils, SOC concentrations were 80%, 91%, and 96%, respectively, of that at 1 m soil depth. In the topsoil layer, lawn soils had a significantly greater reduction in SOC from 0–0.1 m to 0.1–0.3 m (76.58 ± 4.86%) compared to forest soils (mixed: 41.64 ± 8.62%, deciduous broadleaf: 41.71 ± 9.69%, and evergreen needle leaf: 32.75 ± 9.55%), bare soils (47.22 ± 11.32%), and wetland soils (37.64 ± 9.46%).

3.2. Soil bulk density

In forested areas, the soil bulk density increased with soil depth, with the highest bulk density in the bottom layer (0.7–1.0 m depth; Fig. 3). Except for forest soils, the soil bulk density in the first layer (0–0.1 depth interval) was not significantly lower than in the second layer (0.1–0.3 m depth interval; $P > 0.05$). In lawn soils, the soil bulk density in the first layer was significantly higher than in the second layer ($P < 0.05$). In wetland soils, the vertical distribution of the soil bulk density did not significantly differ across the soil depth intervals ($P > 0.05$).

3.3. Soil organic carbon stocks in different land-cover types

A greater than tenfold difference in SOC stocks was observed at 1 m depth across the six different land-cover types (Fig. 4). Wetland soil had significantly higher SOC stocks (13.99 ± 1.05 kg m^{-2}) than forest soil (mixed: 10.19 ± 0.65 kg m^{-2}, deciduous broadleaf: 7.27 ± 0.55 kg m^{-2}, and evergreen needle leaf: 7.27 ± 0.58 kg m^{-2}), lawn soil (3.74 ± 0.75 kg m^{-2}), and bare soil (1.58 ± 0.12 kg m^{-2}). The bottom layer (0.7–1 m depth) accounted for approximately 25% of the SOC stock across the 1 m soil profile in wetlands, which was far greater than the other land-cover types. The mixed forest SOC stocks were significantly higher than those of the other forest types ($P < 0.05$; Fig. 4). No significant difference was detected in SOC stocks of deciduous broadleaf forest and the evergreen needle leaf forest ($P > 0.05$). By multiplying areas and SOC stocks for each land-cover type, we calculated the total SOC stocks in the Seoul Forest Park to a depth of 1 m to be 6,960 ± 574 Mg C.

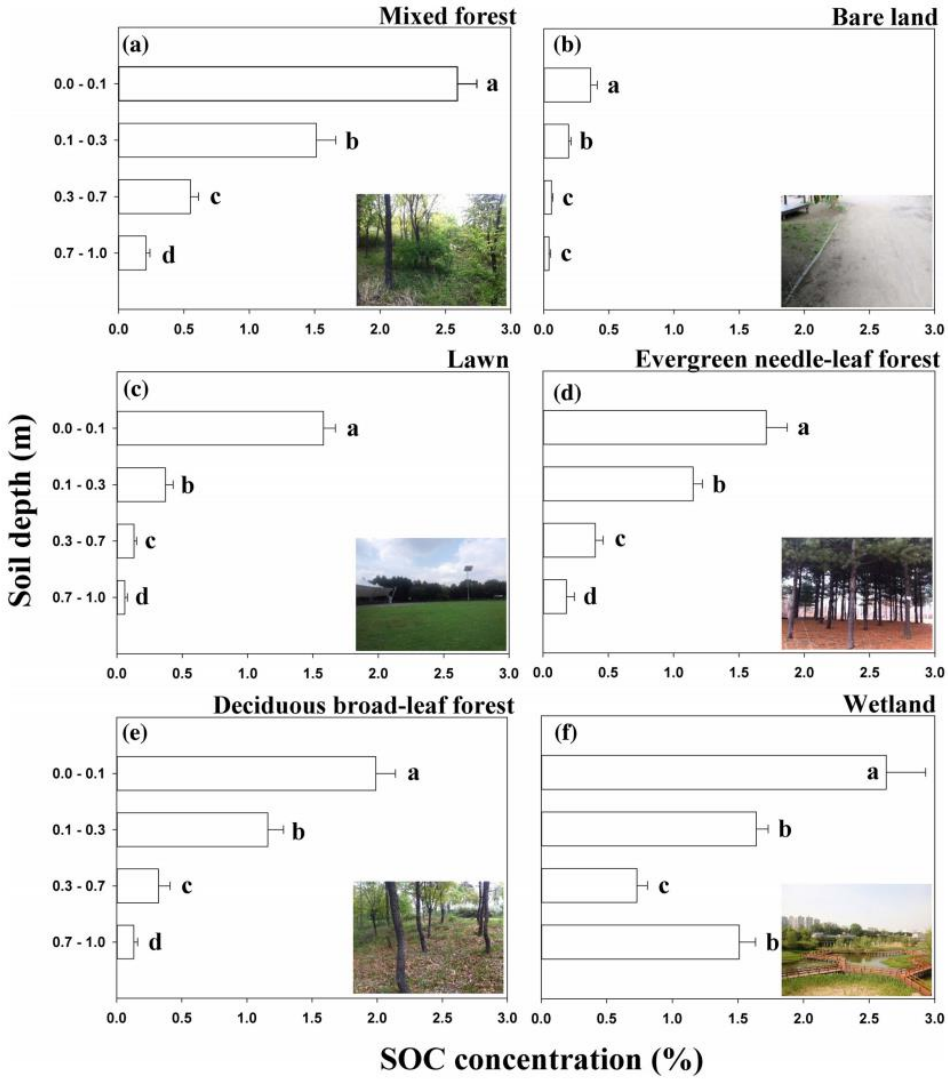

Fig. 2. Vertical distributions of the SOC concentration (%) in different land-cover types. Different letters indicate a significant difference among the soil depth intervals in each of the land-cover types (Tukey test, $P < 0.05$). Error bars indicate 95% CI. The representative site view of each land-cover type appeared at the bottom-right corner.

3.4. Fine root mass density

Fine root mass density (FRMD) decreased with soil depth, with the exception of the second layer (0.1–0.3 m depth) in wetland soils, which had higher values than the first layer (0–0.1 m depth; Fig. 5). In lawn soils, the FRMD in the topsoil accounted for 99% of the entire 1 m soil profile. The ratios of FRMD in the top layer (0–0.1 m) to the entire 1 m profile were 60.4%, 79.6%, 66.1%, and 73.4% for the mixed forest, evergreen needle leaf forest, deciduous broadleaf forest, and wetland soils, respectively.

3.5. Changes in the soil organic carbon concentrations in topsoil between 2003 and 2013

The SOC concentration increased significantly in all districts between 2003 and 2013, with an average increase of 256 ± 130% (t-test, $P < 0.05$). The largest increases in SOC concentration occurred in District 5 (from wasteland to forested land, 611 ± 237%) and District 3 (from bare land to forested land, 320 ± 191%). In contrast, the change in SOC concentration was relatively low in District 4 (89 ± 67%), where the land-use type, a water purification plant (Fig. 8), did not change. Furthermore, we found that the percentage of clay increased substantially in Districts 3 and 5 since 2003 (Table 1).

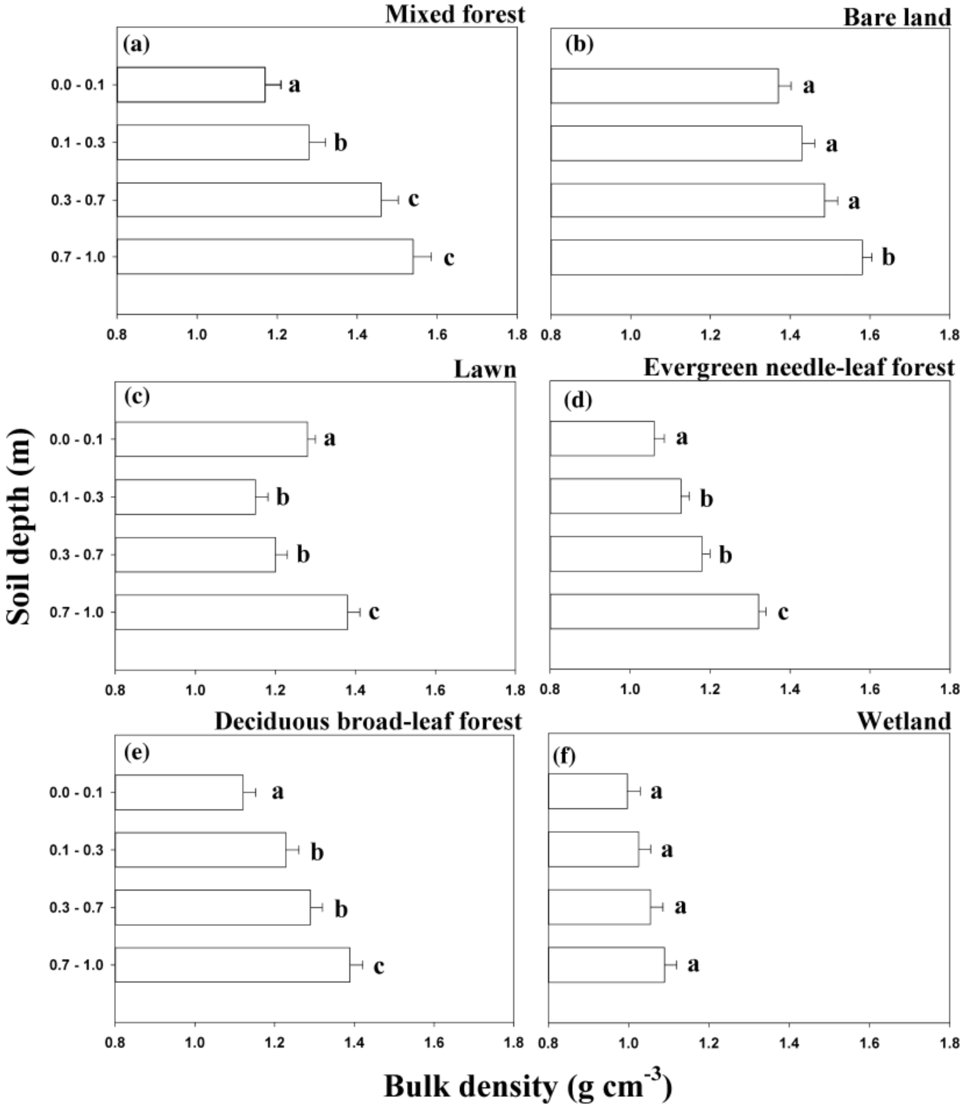

Fig. 3. Vertical distribution of the soil bulk density (g cm^{-3}) in each land-cover type. Different letters indicate a significant difference among the soil depth intervals in each land-cover type (Tukey test, $P < 0.05$). Error bars indicate 95% CI.

3.6. Temporal changes in vegetation activity and land-use types

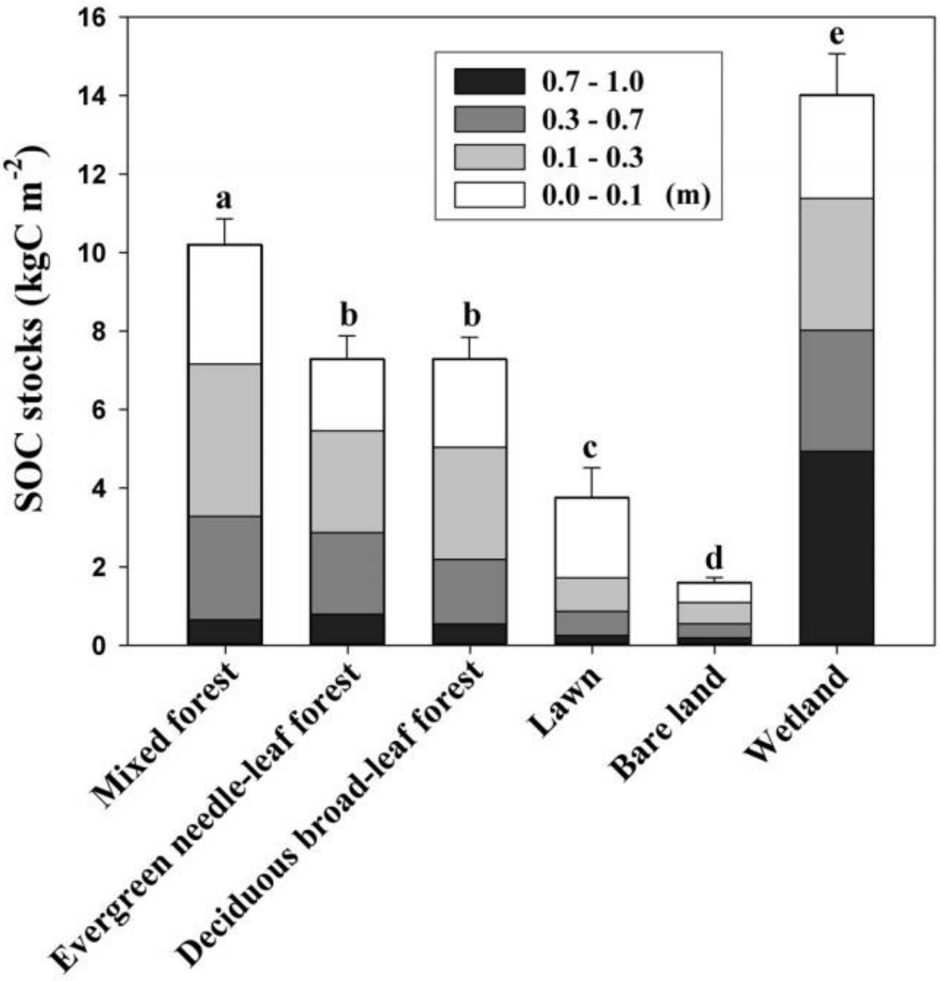

Fig. 4. SOC stocks (kg C m−2) with different land-cover types. Different letters indicate the significant difference across the land-cover types (Dunn'test, $P < 0.05$). Error bars indicate 95% CI of SOC stocks at a depth of 1 m.

To understand SOC accumulation over the 10 year period, we checked the inter-annual variation in the peak growing season mean NDVI values derived from MODIS (Fig. 7a). We found that the NDVI was significantly lower during 2004, when the park was being constructed, than in 2003. However, after the park was established and trees were planted or replanted, the NDVI increased steadily until 2014 (Fig. 7a). Landsat NDVI data enabled us to investigate temporal changes in the NDVI for each land-use district between 2002 and 2013 (Fig. 7b). The largest increase in NDVI appeared in District 5 (from wasteland to forested land) and District 1 (from retarding basin to wetland) (Fig. 8a and b). The smallest increase in the NDVI was in District 2 (from golf course to lawn and forested land) (Fig. 8a and b).

4. Discussion

4.1. What controls spatial heterogeneity of SOC stocks among different land-cover types?

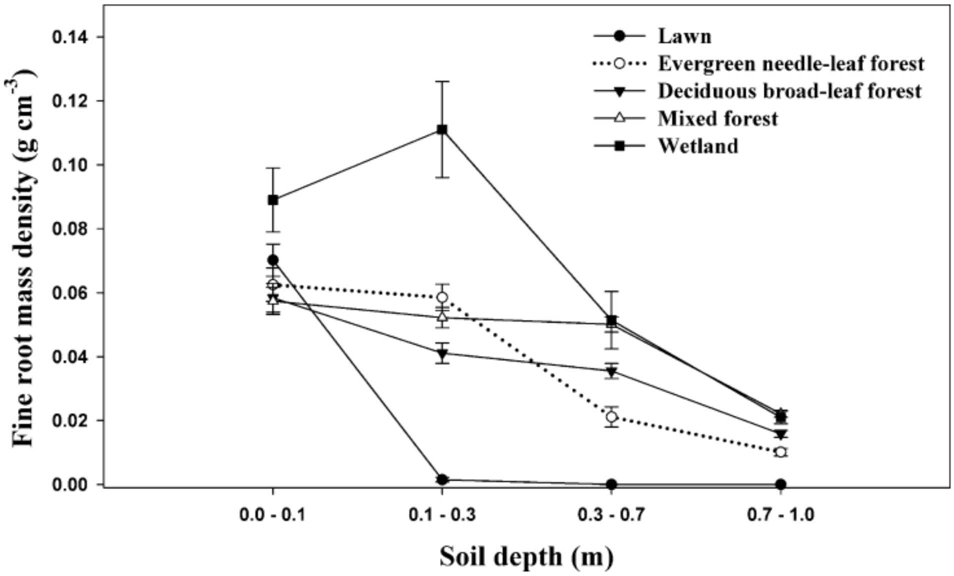

Fig. 5. The vertical distributions of the fine root mass density (g cm^{-3}) in different land-cover types. Error bars indicate 95% CI.

We found a tenfold difference in SOC stocks in the top 1 m of soil among the six different land-cover types in the constructed urban park (Fig. 4). Wetland soils had the highest SOC stocks and the lowest soil bulk density among the six land-cover types (Fig. 3). Higher SOC concentrations in wetland soils mainly determined the highest SOC stocks (see Eq. (1)). It was reported that the carbon accumulation at the topsoil layer in the wetland was greatly affected by continuous flood and soil saturation (Vymazal, 2007). However, the water level of the constructed wetland in the Seoul Forest Park was controlled by water management system. The higher carbon stocks in wetland soils could be explained by two factors. First, the “cultural layer” at 0.7–1 m depth substantially increased SOC concentrations. During park construction, the wetland area was developed through the addition of soil (155,000 m^3) from a nearby construction site (Seoul Metropolitan Government, 2004). The “cut and fill” method, which is typically used in wetland construction, is accompanied by anthropogenic disturbances including a buried A horizon (Chaopricha & Marin-Spiotta, 2014). We found various cans and bottles at 0.7–1 m depth during the soil survey. Given a small amount of FRMD in the “cultural layer” (Fig. 5), we believe the high SOC concentration in the “cultural layer” was related with the buried A horizon. This “cultural layer” has been reported to increase vertical heterogeneity in SOC concentrations, representing anthropogenic disturbance of the soil profiles (Alexandrovskaya & Alexandrovskiy, 2000; Vasenev, Stoorvogel, & Vasenev, 2013). Second, higher FRMD in the wetland soils compared to the other land-cover types could enhance the SOC concentration (Fig. 5). In particular, the FRMD in the topsoil was significantly higher than in the other land-cover types ($P < 0.05$).

Mixed forest had greater SOC stocks than the other two forest types (Fig. 4; $P < 0.05$). The SOC concentration in the topsoil of mixed forest was higher than in deciduous broadleaf and evergreen needle leaf forests ($P < 0.05$). Furthermore, beneath the topsoil, both FRMD and SOC concentration were higher in mixed forest than in deciduous broadleaf or evergreen needle leaf forest ($P < 0.05$), which caused higher SOC stocks at a depth of 1 m in the mixed forest than in the other two forest types. Higher SOC concentrations and FRMD in the mixed forest soils could be explained by two anthropogenic factors. First, the litter layer was well preserved in the mixed forest (Fig. 2a). Typically, mixed forest was far from areas of intensive human activity where litter is regularly removed. While taking soil samples, we observed numerous earthworms only in mixed forest soils. Second, mixed forest was designed for multilayer canopy structure, which includes deciduous broadleaf and evergreen needle leaf trees as well as shrubs. The coexistence of different plant functional types might occupy their own niches through different rooting systems in the soil profile, which could enhance FRMD and SOC concentration (Brassard et al., 2013; De Deyn, Cornelissen, & Bardgett, 2008).

Our results suggest that SOC concentrations were positively correlated with FRMD ($R = 0.789$, $P < 0.05$) in the constructed urban park. Both the SOC concentration and FRMD decreased with soil depth in all of the land-cover types except for the “cultural layer” in wetland soils (Figs. 2 and 5). In particular, lawn soils contained the majority of the carbon in the topsoil layer (Fig. 2c), which corresponds to the large amount of fine roots found in the topsoil layer (Fig. 5). Over 70% of SOC stocks in the lawn were distributed in the topsoil layer. This finding is in agreement with previous studies that reported large amounts of SOC stored in the topsoil layer in both urban and rural grasslands (Gill, Burke, Milchunas, & Lauenroth, 1999; Pouyat, Yesilonis, & Golubiewski, 2009).

Soil bulk density in the topsoil layer was significantly higher in areas with human activities, such as bare land (1.37 ± 0.03 g cm^{-3}) and lawn (1.28 ± 0.03 g cm^{-3}), than in the other land-cover types ($P < 0.05$). This finding is consistent with previous studies that reported unremitting human activities, such as foot and vehicle compaction (Sarah & Zhevelev, 2007), increased soil bulk density in the surface soil layer (Beesley, 2012; Gregory, Dukes, Jones, & Miller, 2006). Approximately 7 million people visit the Seoul Forest Park annually. Various types of human activity, such as recreational uses and mowing occur in the lawn and bare land. Thus, soil compaction by human activities could reduce SOC stocks in the urban park. We found a negative correlation ($R = 0.781$, $P < 0.05$) between the soil bulk density and SOC concentration in the topsoil among land-cover types. In particular, the increase in soil bulk density was overcompensated with a decrease in SOC concentration ($R = 0.982$, $P < 0.05$), which reduced SOC stocks in the lawn. Furthermore, excessive soil compaction disrupts vertical root penetration, which could reduce the movement of the SOC into the deep soil layers (Watson & Kelsey, 2006).

Most surveys of urban SOC have focused on the topsoil (Kong et al., 2009; Liu, Wang, Yue, & Hu, 2013; Takahashi et al., 2008). However, our results indicate that SOC stocks in the topsoil account for only 60% of all SOC stocks in the constructed urban park. Furthermore, accelerated soil disturbance through land-use, land-cover change, and human activities can increase the heterogeneity of the vertical distribution of SOC contents as we found in the "cultural layer." Our results highlight the need for understanding the SOC stocks deeper in the soils (to a depth of at least 1 m) in constructed urban parks.

4.2. How does land-use history influence the temporal variations of the SOC concentrations?

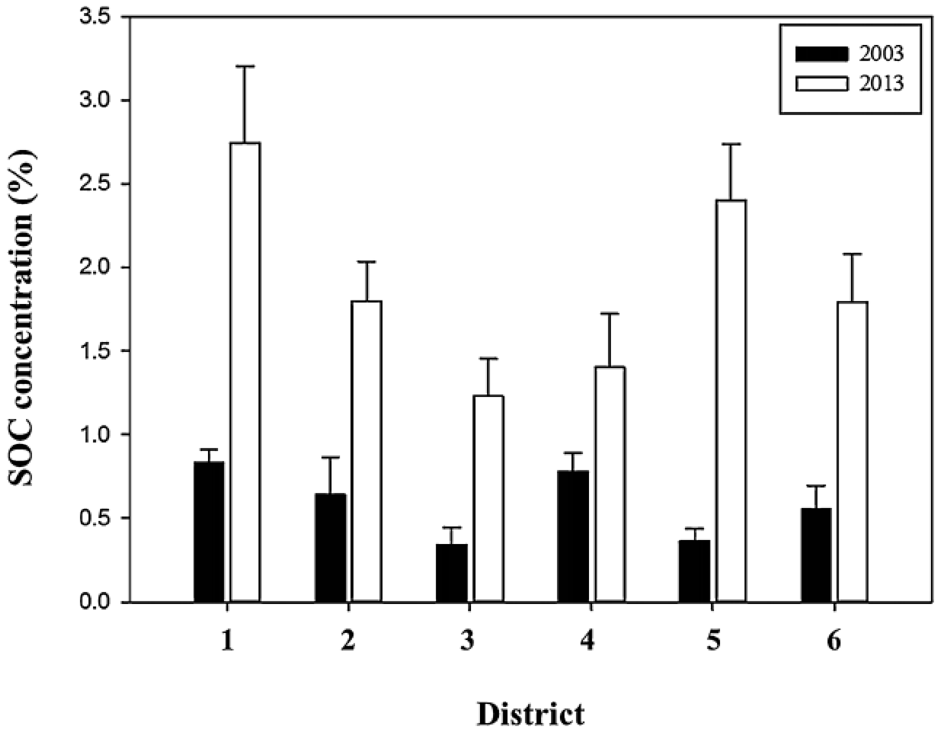

Fig. 6. Comparing the SOC concentrations (%) at a 0–0.3 m depth between 2003 and 2013 in the six land-use districts. The districts are shown in Fig. 1. Error bars indicate 95% CI.

The concentrations of carbon in the topsoil significantly increased in all land-use districts (Fig. 6; $P < 0.05$). The relative increase in the carbon concentration of topsoil ranged from 89% to 611%. The land-use districts represent different intensities of anthropogenic disturbance and land-cover change. Our results indicate that the different land-use history was the primary factor determining the temporal variation of the SOC contents in the constructed urban park.

The spatial variability of increase in topsoil SOC contents could be explained by different land-use histories in the six districts. The largest increase in SOC concentrations was observed in District 5 (611 ± 237%), which was converted from wasteland to forested land (Fig. 8). Landsat NDVI revealed the largest increase in this district (Fig. 7b). Soil texture in District 5 was converted from sandy clay loam to silty clay, indicating an increase in clay content (Table 1). As soil organic matter and clay particles interact to retard the decomposition process (Rice, Anderson, & Coats, 2002), soils with higher clay contents have the potential to hold more SOC. Although the trees and lawn have been planted around the industrial facilities over the years which was captured by an increase in Landsat NDVI and satellite image, the increase in SOC concentration was relatively low in District 4 (89 ± 67%), where the land-use type, a water purification plant, did not change over the 10 years. District 1 was converted from a retention basin to wetland. Visual inspection of satellite image revealed that the retention basin was covered by short green patches with impervious surfaces.

The constructed wetland includes lush vegetation with deck platforms, which prevent soil compaction by human activities. Landsat NDVI showed a twofold increase between 2002 and 2013 in District 1, resulting from intensive plantation activities and vegetative growth. Consequently, the SOC concentration in topsoil increased threefold over the decade in District 1.

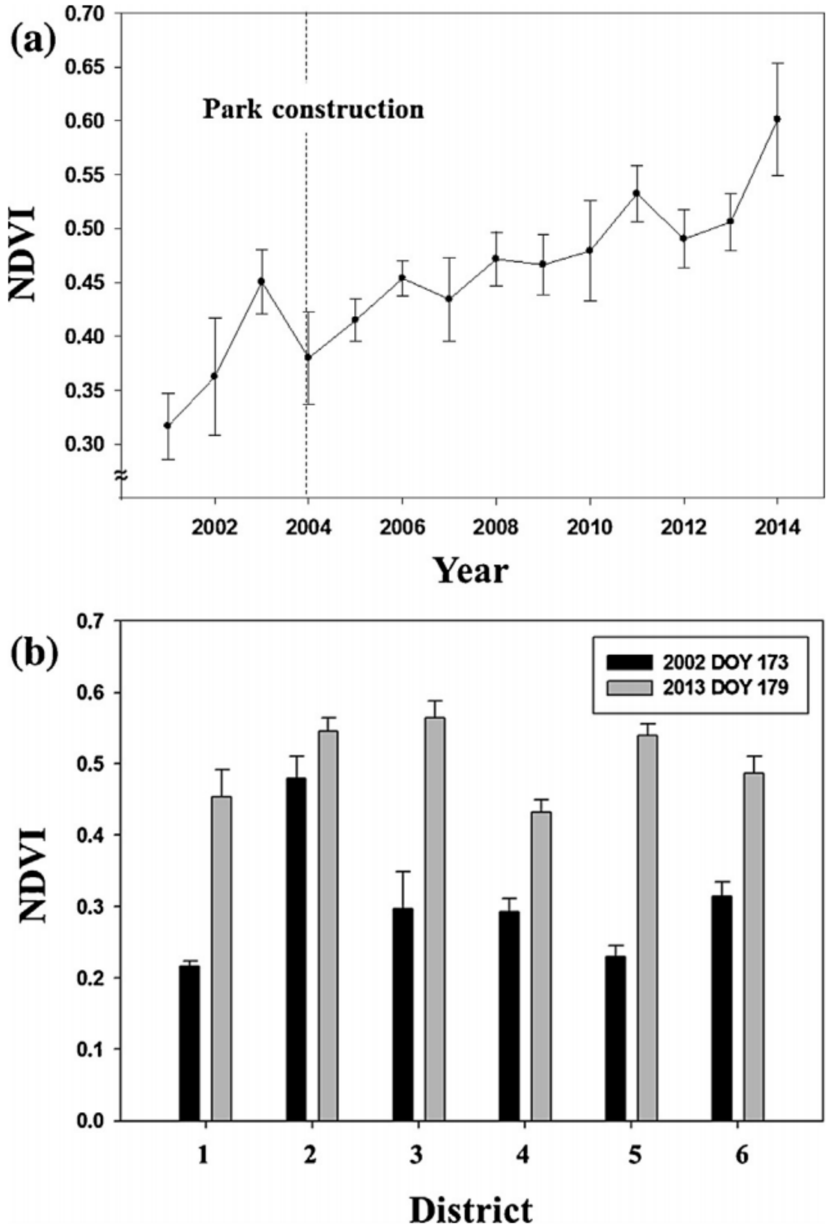

Fig. 7. (a) The inter-annual variation of the mean MODIS NDVI during the peak growing season (June) in the Seoul Forest Park. (b) Comparing Landsat NDVI between 2002 and 2013 in the six land-use districts. The districts are shown in Fig. 1. Error bars indicate 95% CI.

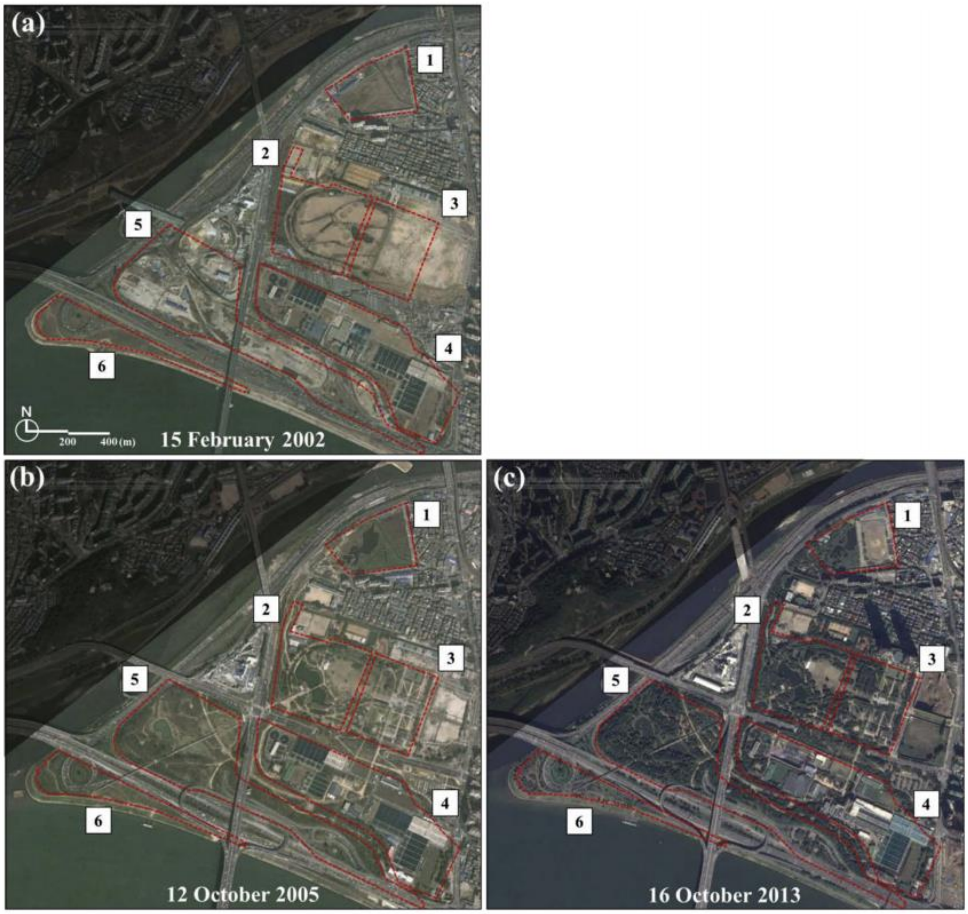

Fig. 8. Land-use changes shown by Google Earth, Digital globe 2014 and CNES/Astrium services image on (a) February 2002, (b) October 2005 and (c) October 2013. Park construction was started in April 2004 and finished in June 2005. The numerical values in the photographs represent each land-use types (Table 1).

Canopy photosynthesis determines carbon inputs to the ecosystems (Baldocchi, 2008; Hogberg et al., 2001; Ryu et al., 2011), and mainly controls carbon inputs to the soils through root exudations and litter fall (Litton, Raich, & Ryan, 2007). We assume the increase in SOC concentration in topsoil might be explained by the increase in carbon inputs to the soils through enhanced canopy photosynthesis. After the intensive park construction in 2004, which involved clearing and grading the surface, a series of plantings have been conducted by Seoul City, private companies, and citizens. In particular, mature trees were intensively planted in the initial stage to provide shade to park users. Since 2011, mature trees have only been planted to replace dead mature trees (personal communications with Hyunhee Kang, Seoul Forest Park Office). The MODIS NDVI time series reflected planting activities in the park, which showed an abrupt decrease in 2004 and then a steady increase (Fig. 7a). The Google Earth images clearly showed the expansion in planted areas before and after the park construction (Fig. 8a and b). The plant growths in the park over the years serve as another evidence in increased canopy photosynthesis (Fig. 9). Previous studies reported there is tight positive correlations between canopy photosynthesis and aboveground biomass increment (Litton et al., 2007).

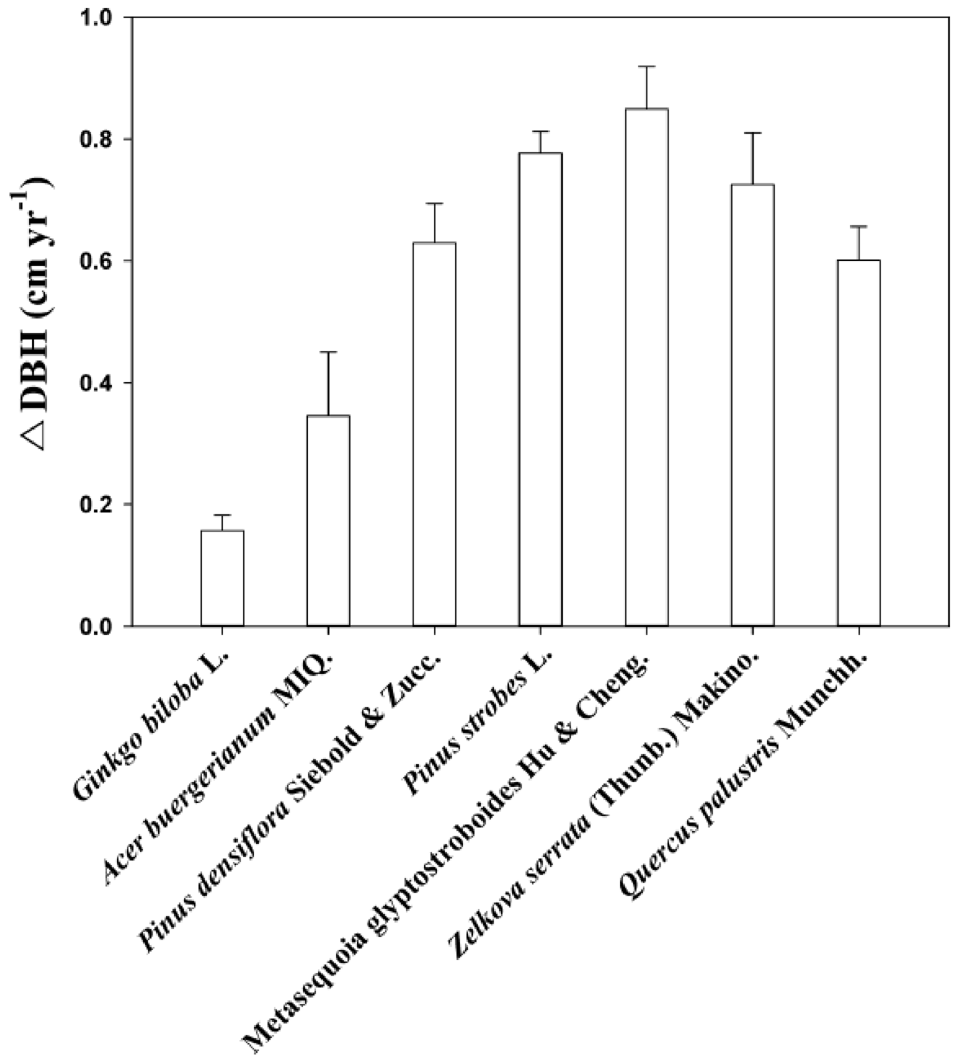

Fig. 9. Change of diameter at breast height (DBH) between 2012 and 2014 for dominant woody species. Error bars indicate 95% CI.

We measured DBH, a proxy of aboveground biomass, of the same trees in 2012 and 2014, and found DBH in all tree species increased over the two years from 0.16 cm yr^{-1} to 0.85 cm yr^{-1} (Fig. 9). This finding is consistent with the previous study conducted in the park that reported increase of DBH between 2005 and 2012, ranging 0.25 cm yr^{-1} to 0.48 cm yr^{-1} (Kim, 2012). Thus, expansion of planted areas and growth of plants might explain, at least partially, the increase in topsoil SOC concentrations over the years.

Park management is assumed to promote the carbon concentrations of topsoil in the park. In 2005, an initial soil conditioner up to 15 kg m^{-2} (25% organic matter, C:N < 50) was applied to approximately 40% of the current green space in the park within the tree planting and replanting areas (Seoul Metropolitan Government, 2004). The park was also regularly irrigated. Litter layers removed by park managers were used to make compost, which was added back to the planted areas. Providing nutrients, compost, and moisture to the soils might explain the increase in SOC concentrations across the park (Conant, Paustian, & Elliott, 2001; Pouyat et al., 2009).

We admit the interpretation of increase in topsoil SOC concentrations requires further studies. First, soil respiration, which determines SOC release to the atmosphere, should be considered. Changes in topsoil SOC concentrations are the balance between carbon input (root exudations, carbon transfers to microbes, and litter fall) and output (soil respiration) to the soils. Due to the lack in soil respiration data, we only focused on carbon input. Second, we compared topsoil SOC concentrations between 2003 (before park construction) and 2013. Thus, it is unclear how much the construction process changed the topsoil SOC concentrations. We measured topsoil SOC concentration in 2014 (results not shown) where SOC stock was measured in the six land-cover types in 2012, and compared topsoil

SOC concentrations between 2012 and 2014. We found 9.31 ± 4.4% increase, which was however not statistically significant (*t*-test, $P > 0.05$), probably owing to the short time interval (2 years). District 6 did not undergo park construction process thus has kept same land-use type and soil texture (Fig. 8, Table 1). However, District 6 showed threefold increase in topsoil SOC concentration and 60% increase in NDVI. Thus we assume the park construction process alone is unlikely to explain the increase in topsoil SOC concentration. To better understand temporal changes in topsoil SOC accumulation, repeating regular soil surveys in the future will be essential.

5. Conclusion

Urban parks account for a large proportion of green space in urban areas, and the area of urban parks is expected to increase due to increasing urbanization and citizens' desire for a better quality of life. Thus, understanding the carbon cycle in urban parks is imperative to mitigate greenhouse gas emissions in urban regions. Here, we presented SOC stocks in different land-cover types in 2012, and changes in SOC concentration between 2003 and 2013 for Seoul Forest Park in Seoul, Republic of Korea. We found a tenfold difference in SOC stocks among different land-cover types, highlighting that the choice of land-cover types in planning urban parks could significantly impact SOC stocks in the park. A threefold increase in SOC concentration over the decade implies that urban park soils might serve as a carbon sink. In particular, land-use history and park management have played important roles in the temporal variation of the SOC concentration. The findings in this study will be helpful in carbon management programs in cities through landscape planning and managements.

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Abstract (Korean)

본 연구는 시민들을 위한 도시 공원의 생태적 가치와 기능의 중요성이 강조되는 현대 사회에서, 서울시의 대표적 대형 공원인 서울 숲 공원을 대상으로 토양 탄소 저장량의 시공간적 변화를 탐구하였다. 우선, 서울 숲 공원이 조성된 2003년과 10년 후인 2013년의 토양 내 유기 탄소 저장량의 변화를 정량화하였다. 그 결과 10년 사이 3배 이상의 토양 탄소 증가가 표토에서 확인하였으며, 이러한 토양 탄소 증가의 원인을 파악하고자 과거 토지 이용 목적과 증가한 식생을 MODIS와 Landsat 위성탐사 데이터를 활용하여 분석하였다. 더불어, 오늘날의 서울 숲 공원을 6 종류의 대표 식생 타입(침엽수림, 활엽수림, 혼효림, 잔디, 습지, 나지)으로 분류하여, 총 1 m 깊이 내 4개의 토양층(0−0.1, 0.1−0.3, 0.3−0.7, 0.7−1.0 m)을 대상으로 탄소 저장량의 수직적 분포의 이질성을 분석하였다. 가장 높은 유기 탄소 저장량은 습지에서 나타났으며(13.99±1.05 kg m^{-2}), 숲 지역, 잔디, 나지 순으로 정량적 차이를 확인하였다. 이러한 차이는 식생 타입에 따른 뿌리의 영향으로 주로 표토에서 발생되었지만, 그 중 습지의 높은 탄소 저장량은 과거 공원이 조성될 때 동반된 인위적 교란에 따른 심토의 문화적층이 기여한 것으로도 파악되었다. 본 연구는 저탄소 사회와 탄소거래제도에 대비하여 도시 공원이 탄소를 얼마나 어디에 저장할 수 있는지를 정량적으로 평가한 것에 의미가 있으며, 향후 추가 분석을 통해 도시 녹지 내 탄소의 시공간 분포를 평가할 기초 자료로 사용될 것이라 기대된다.

주요어 : 토지 피복 변화, 토지 이용 변화, NDVI, 토양 탄소, 도시 공원

학번 : 2012-21136

Acknowledgements

Firstly, I would like to thank my advisor Ryu Youngryel. The door to Prof. Ryu office was always open whenever I run into a trouble or had a question about my research. He consistently steered me in the right direction whenever I needed it. The chairman and member of the committee, Lee Dongkun and Kang Junsuk encouraged me continuously and gave me insightful comments and questions to broaden my knowledge. Also thankful to Dr. Donggill Kim for his comments on sampling design and statistical analysis. Without their passionate participation and effort, this paper could not have been successfully conducted.

Also thankful to my fellow lab members, Juwon, Jongmin, Yorum, Ben, Yulin, Yunah, Hyungsuk, Seungjoon, Chongya, Yan, Jane, and Soyoun thank you for providing a great work environment, aiding my field works, and discussions with chats. From their help and care, I could finally submit my manuscript to an LUP journal. Finally, I must express my very profound gratitude to my parents, brother and to my lovely wife and son, Hyemin and Jaeyoon, for providing me with unfailing support and continuous encouragement throughout my years of study. This accomplishment would not have been possible without them. I love you, more than you think.

Portions of this dissertation have been reprinted, with permission, from previously published paper, Landscape and Urban Planning, Elsevier. I thank their permission. This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2012R1A1A1004065) and the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP) (2009- 0083527). English editing was supported by the Research Institute for Agriculture and Life Sciences, Seoul National University.