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ESTIMATION OF SOIL CARBON STORAGE IN SHINJUKU GYOEN NATIONAL GARDEN BASED ON LAND USE HISTORY AND SOIL COMPACTNESS PROFILES

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Abstract This study aims to estimate soil carbon storage in Shinjuku Gyoen National Garden, Tokyo Metropolis. Undisturbed soil samples were collected in the Gyoen from regions of different land use using a core cylinder. A modified investigation was used by combining measurement of vertical structure of soil compactness in order to estimate cumulative carbon content without interfering with the park landscape. Softness obtained using a cone penetrometer was converted to soil bulk density (g cm^{-3}) and samples for measurement of total carbon content (g kg^{-1}) were collected using a boring stick. The carbon storage in the Gyoen (0 – 100 cm) was estimated as 316 ± 83.1 t C ha^{-1} in turf areas and 198 ± 61.3 t C ha^{-1} in forest areas, respectively, which are equivalent or slightly larger than the standard values obtained for Andosols and Brown Forest soils, respectively. The large difference in the cumulative carbon storage between turf area and forest area for the entire profile (0 – 100 cm) can be explained by the difference in the pedogenesis process of humus accumulation together with the diagenesis process of humus decomposition, both of which depend on the humus quality of vegetation and land use history. The use of the Softness obtained from measurement of vertical soil compactness was discussed as a proxy of bulk density. It is shown that vertical soil compactness differs in same land use regions in the Gyoen. Although the estimated values of cumulative carbon content had issues with overestimation in some cases, we suggest that the use of the Softness as a substitute for bulk density is applicable for estimating soil carbon storage. Subsurface structure, regulated by land use history and land creating history should be taken into account for the reliable evaluation of soil carbon storage in urban areas.

Key words: soil carbon storage, urban green spaces, soil compactness, land use history

1. Introduction

In recent years, attention has been focused on increasing carbon dioxide in the atmosphere caused by human activities, which leads to global warming. Insulation, capture and storage of carbon dioxide for inhibition of global warming have been studied. Soil is well known for having a higher carbon storage potential than either atmosphere or plants. Efforts to estimate soil carbon storage and capture carbon dioxide

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in forest and agricultural areas have been practiced. In 2009, total greenhouse gas emissions of carbon dioxide were 5.665 million ton in the Tokyo Metropolis. In comparison to other world cities, Tokyo is ranked 30th in the world for carbon dioxide production (Tokyo Metropolitan Government, Environment of Tokyo 2009).

Recently, carbon storage in urban areas is a topic that has gained more attention. Churkrina *et al*. (2010) defined that 10 % of total carbon storage was in human settlements and 64 % of carbon in urban areas was stored in soil. Gough and Elliott (2012) studied how much would continuous human activities affect carbon storage ability, comparing abandoned residential areas and lawns in occupied areas. Beesley (2012) proposed a management strategy for increasing and maintaining the ability of soil to store carbon in newly created and existing urban soils. Lorenz and Kandeler (2005), and Lorenz and Lal (2009) examined carbon and nitrogen circulation from biogeochemical aspect in urban soils. Thus, recent research on carbon storage in urban area worldwide not only examines estimation of carbon storage but also covers the management, maintenance and function of urban soils.

Regarding urban soils in Japan, Takahashi *et al*. (2008) estimated the carbon storage of urban soil in Tokyo. If the evaluation of carbon stock in urban areas is limited to 0 – 30 cm depth, it is insufficient to understand the capacity of the soil carbon sink when compared with agricultural and forest soils. Soil in urban areas is greatly affected by land development and coverage by buildings and pavements. In addition, soil carbon storage alters according to the frequency of land use change or massive land grading in urban areas. The reliability of data is restricted because of the shortage of primary data on soil properties and the survey methods performed in agricultural and forest areas cannot be applied to urban areas. Under such circumstances, a convenient method to estimate carbon storage in soils of urban areas is required.

According to statistics report of Ministry of the Environment (2012), the area of urban parks in Japan reached 110 kha in 2005, which was two times larger than that of urban parks in Japan twenty years ago. Urban parks can be highlighted as one of the main sinks of carbon and bio-philic elements in urban areas (Kawahigashi *et al*. 2012). We investigated Shinjuku Gyoen National Garden (the Gyoen) that is the second largest green space in the central district of Tokyo. Soil profile surveys in the extensive area (58.3 ha) of the Gyoen have been seldom conducted because of the restrictive conditions of park management. This paper discusses the use of the modified sampling methodology for minimizing the disturbance to the park landscape and a method of estimating soil carbon storage based on land use history.

2. Materials and Methods

Study area and sampling sites

The field study was conducted from May 2010 to July 2012. The study area and sampling sites are shown in Fig. 1. Shinjuku Gyoen National Garden (58.3 ha) has been managed and used for the past 400 years. The Gyoen is located on Yodobashi upland of Shimosueyoshi surface that formed 125 thousand years ago. A small valley erodes the upland from east to west. Soil of the Gyoen area is categorized as ‘Thick Kuroboku soils (Andosols); humic’ in the 1:50,000 soil map (Tokyo Metropolitan Government 1998).

The Gyoen was constructed on the site of a private mansion belonging to Lord Naito (1590 –), a ‘*daimyo*’ of the Edo era, and has been one of the most important gardens since the Meiji era (1868 –). The Naito Shinjuku Research Institute was found in this park in 1872 as a result of public aspiration to promote modern agriculture. In 1906, the Gyoen was completed as an imperial garden. During the Second World War, the Gyoen was used as a field. In 1945, the Great Tokyo Air Raids burnt out buildings in the Gyoen. After the Second World War, the Gyoen was re-designated as a National Garden and opened to the public in 1949. In present arrangement, three formal gardens, the French Formal Garden, the English Landscape Garden, and the Japanese Traditional Garden, are arranged within the 58.3 ha area.

We selected measurement points on the basis of representative land use as shown in Fig. 1. Vertical soil compactness was measured at all 28 points using a cone penetrometer (H-100, Daito Techno Green). Soil sampling was conducted adjacent to these measurement points. Samples were taken at 22 points (P1 – P22) every10 cm below the soil surface until a depth of 90 cm using a 1m long boring stick. Non-destructive samples were also taken every 10 cm below the soils surface until a depth of 1 m using a 100 ml stainless steel cylinder at four points: A – D. Prior to this study, soil surveys were performed in two open pits in turf areas; O1: the French Formal Garden and O2: the Central Rest House in June 2010, where soil samples were collected using core cylinders at each horizon.

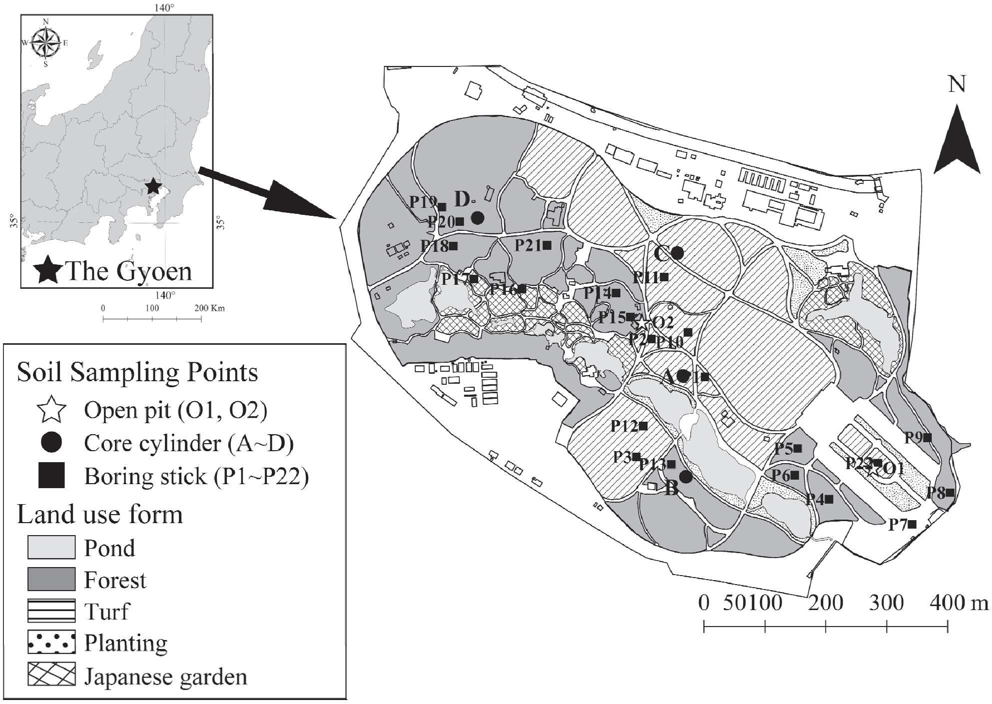

Fig. 1 Location map of the study area (Shinjuku Gyoen National Garden). Measurement of soil compactness was carried out at all sampling points.

Analysis of soil samples for carbon storage estimation

Soil samples collected using the 100 ml cylinder were oven dried at 105 °C for 24 h and then, the weight of solid phase (g) was measured using an electronic balance to calculate bulk density. Bulk density is defined as the mass of dry soil divided by its volume, and is expressed in units of gram per cubic centimetre (g cm^{-3}), or in megagram per cubic metre Mg m^{-3}. Total carbon content (g kg^{-1}) was measured for all samples by the dry combustion method using an NC analyzer (NC-22A, Sumika Chemical Analysis Service Ltd.).

Soil compactness

Vertical profiles of soil compactness were obtained by measuring softness (Softness; cm $drop^{-1}$) using a cone penetrometer at a maximum depth of 1 m. The measurement was conducted by dropping a 2 kg weight from a height of 50 cm to penetrate a φ20 mm cone with an angle of 60°. The Softness is described by the depth penetrated (cm) per drop, which can be used practically in planting techniques to evaluate the physical condition and properties of the soil. The critical values for tree and root growth indicated by Research Committee of the Japanese Institute of Landscape Architecture (2000) are:

Softness ≤ 1.0: interference for tree root extension

Softness ≥ 4.0: strength deficiency and water shortage for trees

3. Results and Discussions

Vertical structure of soil compactness

Results of soil compactness at core sampling points are shown in Fig. 2. Sites A and C are located in the center of turf areas and Sites B and D are located in forest areas. There was a consolidated layer at 0 – 50 cm of Site A with a Softness ≤ 1.0 that drastically turned soft (Softness ≥ 2.0) for soil layers below a depth of 50 cm. In contrast, Softness below 1.0 dominated at Site C presenting that it had a continuous compacted layer throughout the profile. Site B had a continuous undeveloped soil structure composed of incompact layer from the surface to the bottom and Site D was characterized with alternate emergence of compacted and soft layers.

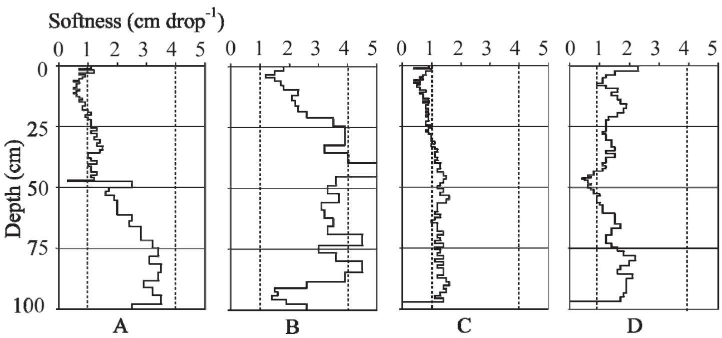

Fig. 2 Representative profiles (A – D) of soil compactness in the Gyoen. Site B is composed of soft layer (Softness ≥ 4.0). Site C is composed of compacted layers (Softness ≤ 1.0). A: turf, B: forest, C: turf, D: forest.

We attempted to clear relationship between land use history and vertical structures of ground on the basis of records and documents provided by the management office of Shinjuku Gyoen National Garden. This revealed that the turf area was uniformly completed in 1908. The forest area of Site D was re-constructed as a nature study forest in 2007. Consequently, it is plausible to consider the difference revealed in the vertical structure of compactness in turf areas resulting from management after land creation in 1908.

Cumulative carbon content

Cumulative carbon content was calculated by multiplying bulk density (g cm^{-3}) and layer thickness (cm) with T-C (g kg^{-1}) for 4 sites in turf area (A, C, O1, O2) and 2 sites in forest area (B, D). The results are shown in Fig. 3. The cumulative carbon content of the surface soil (0 – 8 cm) was 44.0 t C ha^{-1} in the turf area and 39.4 t C ha^{-1} in the forest area. For 0 – 20 cm depth, it was 150.0 t C ha^{-1} in the turf area and 100.1 t C ha^{-1} in the forest area, and for 0 – 100 cm depth, it was 316 ± 83.1 t C ha^{-1} in turf area and 198 ± 61.3 t C ha^{-1} in forest area. The values of cumulative carbon content tended to show a clear difference between the turf and forest areas. The forest soils tended to show a decrease in carbon content with depth. Soil carbon up to 1 m depth had been previously estimated at approximately 240 t C ha^{-1} for moist Brown forest soil and 315 t C ha^{-1} for Andosols in Japan (Fujimori 2000). Soil carbon storage in the Gyoen was equivalent or slightly larger than these values for Brown forest soil and Andosols in Japan.

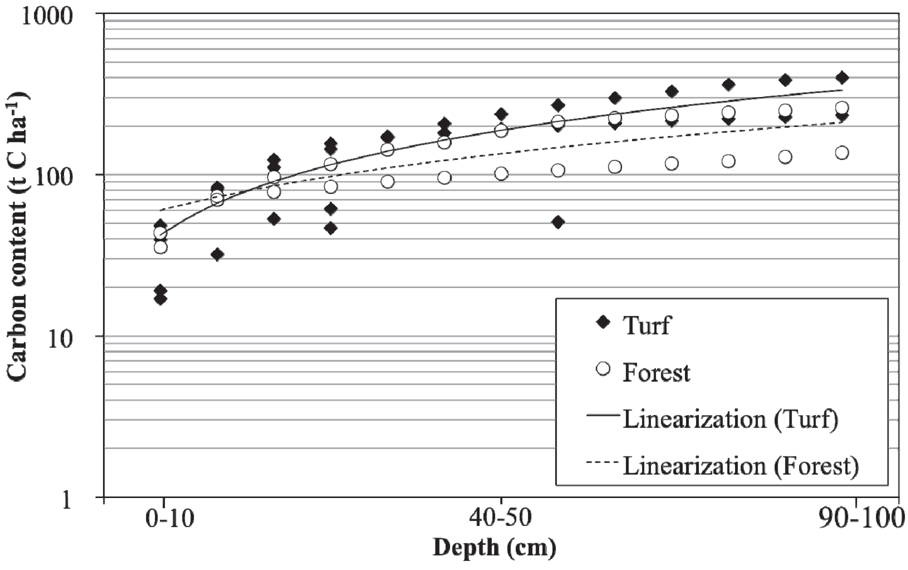

Fig. 3 Cumulative soil carbon content (t C ha^{-1}). Regression curves of accumulate soil carbon content (t C ha^{-1}) are for two points (B, D) in the forest area and four points (A, C, O1, O2) in the turf area.

Takahashi *et al*. (2008) reported soil carbon content from the surface to 30 cm depth in parks and green spaces in Tokyo that also were distinguished based on land use. Table 1 shows a comparison of soil carbon storage values obtained in Takahashi *et al*. (2008), and this study. The values in this study were obtained in taking the average of soil carbon content from 0 – 30 cm depth. The value for turf areas in the Gyoen was 117.3 ± 26.8 t C ha^{-1} (n = 9), while Takahashi *et al*. (2008) observed values of 82.1 ± 37.4 t C ha^{-1}. The value for forest areas in the Gyoen was 80.7 ± 26.0 t C ha^{-1} (n = 11), while those for tree planting areas were 78.9 ± 32.8 t C ha^{-1} and coppice areas were 120.3 ± 34.8 t C ha^{-1} in Takahashi *et al*. (2008). The soil carbon storage of 0 – 30 cm depth for turf area in the Gyoen was larger than the average of Tokyo area and for the forest area in the Gyoen showed agreement with the results in previous studies.

The large carbon storage in turf areas compared to that in forest areas in surface layers (0 – 30cm) can be generally explained by the increase in soil bulk density in turf areas due to intense soil compaction by the treading of park visitors. The large difference of cumulative carbon storage between turf area and forest area for the entire soil profile (0 – 100 cm) can be explained by the difference in the pedogenesis process as a result of humus supply together with the diagenesis process of humus decomposition, both of which depend on the soil humus quality and land use history.

Table 1 Cumulative carbon content (t C ha^{-1}) in surface soil (0 – 30 cm)

Average of cumulative carbon content (t C ha^{-1})			
The Gyoen		Average of parks and green spaces in Tokyo by Takahashi et al. (2008)	
Turf (n=9)	117.3 ± 26.8	Turf (n=17)	82.1 ± 37.4
Forest (n=11)	80.7 ± 26.0	Tree-planting area (n=17)	78.9 ± 32.8
		Coppice (n=13)	120.3 ± 34.8

Mean±SD

Relationship between the bulk density and Softness

In general, carbon content in soil is determined by carbon weight per oven dried soil weight (g C kg^{-1}). Cumulative carbon storage in soil has a definition as carbon weight per volume, which is determined by carbon weight per area per depth (t C ha^{-1} m^{-1}). Practically, carbon content (g C kg^{-1}) is converted to carbon weight per soil volume (kg C m^{-3}) using soil bulk density (oven dried soil weight, g cm^{-3}). Calculating soil carbon content at a particular depth is possible by multiplying bulk density to carbon content (g kg^{-1}). However, it is not feasible to obtain many core samples from open soil pits in well-managed parks or developed urban area. Under such circumstances, a proxy is required to estimate soil bulk density. The Softness (cm $drop^{-1}$) from the cone penetrometer is compatible with soil compaction values (mm) measured by a Yamanaka cone penetrometer (Hasegawa 2008).

In this study, we examined the relationship between the Softness measured using a cone penetrometer and the bulk density in order to discuss the validity of estimating soil carbon storage from Softness. Site data: bulk density and Softness for every 10cm depth, were obtained at four representative profiles: A (turf, n = 13), B (forest, n = 13), C (turf, n = 13) and D (forest, n = 13). As there was no significant correlation between the two parameters among all site data ($y = -1.6x + 3.0$, $R^2 = 0.08$, $n = 52$), the following formula were separately obtained for sites A – D, where y represents the bulk density, x represents the Softness, and R is correlation coefficient.

Site A: $y = -0.92x + 2.12$ ($R^2 = 0.23$) ……………….. (1)

Site B: $y = -7.65x + 7.57$ ($R^2 = 0.53$) ……………….. (2)

Site C: $y = -1.33x + 1.81$ ($R^2 = 0.49$) ……………….. (3)

Site D: $y = -0.72x + 1.81$ ($R^2 = 0.30$) ……………….. (4)

The correlation coefficient of formulae (2) and (3) were significant at a high level; $0.001 < P < 0.01$ (degrees of freedom $v = 11$), while formula (1) and (4) had low significance level; $0.05 < P < 0.1$.

Then the regression formulae were selected from the four types (A – D) on basis of the patterns of vertical distribution of soil compactness. T-C (g kg^{-1}) was obtained using samples collected every 10 cm until a depth of 90 cm using a soil boring stick (φ = 20 mm). The average value of Softness for every 10 cm depth was obtained from the vertical profile of soil compactness. Then, bulk density was calculated using the relevant formulae (1) – (4) mentioned above.

The property of bulk density in urban soils was initially mentioned by Craul (1985). The density of soil particles themselves is approximately 2.65 Mg m^{-3} and an ideal soil has a bulk density of 1.33 Mg m^{-3}, indicating that it has about approximately 50 % pore space. Many top soil layers will have a bulk density near this value or lower. Because of changes in texture and structure with depth, the bulk density increases with soil depth. Subsoil density values may range from 1.6 to 1.8 Mg m^{-3}. Soils with well-developed structure will have low density values (1.1 Mg m^{-3}) whereas poorly structured soils will have high bulk density values approaching 1.8 Mg m^{-3}, or greater. Shober and Denny (2010) reported that bulk density may range from normal, approximately 1.4 g cm^{-3}, to extremely packed, 2.2 g cm^{-3}, in urban soils.

The calculated values of soil bulk density in this study were examined by comparing calculated values to the acceptable range of bulk density for urban soil, which was defined as 0.2 – 2.2 g cm^{-3}. Some of the calculated values were outside this range. The results are shown in Table 2. Eleven points of a total of 22 (50 %) conformed to the acceptable range of 0.2 – 2.2 g cm^{-3}. The 11 points resulted to be out in this range were likely to have drastic change in vertical soil compactness or a continuous undeveloped soil structure, which were excluded from further analysis that calculated cumulative carbon content.

Table 2 Adaptability of regression formulae

Point	Profile type	Regression formula	Compatibility
P1	A	–	×
P2	D	A, D	○
P3	C	A, C, D	○
P4	A	–	×
P5	C	–	×
P6	D	A, D	○
P7	D	–	×
P8	D	A, D	○
P9	B	–	×
P10	D	A, D	○
P11	D	A, D	○
P12	D	A, D	○
P13	D	–	×
P14	D	D	○
P15	A	–	×
P16	B	–	×
P17	D	A, D	○
P18	D	–	×
P19	D	A, C, D	○
P20	D	A, D	○
P21	A	–	×
P22	C	–	×

Symbols of regression formula are given by adaptable formula (A to D) or none (–) and circles indicate compatible points under condition of bulk density; 0.2 – 2.2 g cm^{-3}.

Cumulative carbon content was obtained for the above applicable 11 points using estimated values of bulk density. The calculation procedure of cumulative carbon content is the same as the procedure mentioned previously. A comparison of cumulative carbon with the estimated values and measured values is shown in Fig. 4. The cumulative carbon content obtained using estimated values was larger than the actual measured value. This tendency was more apparent in the upper layers than in the lower layers, and in the turf area than in the forest area.

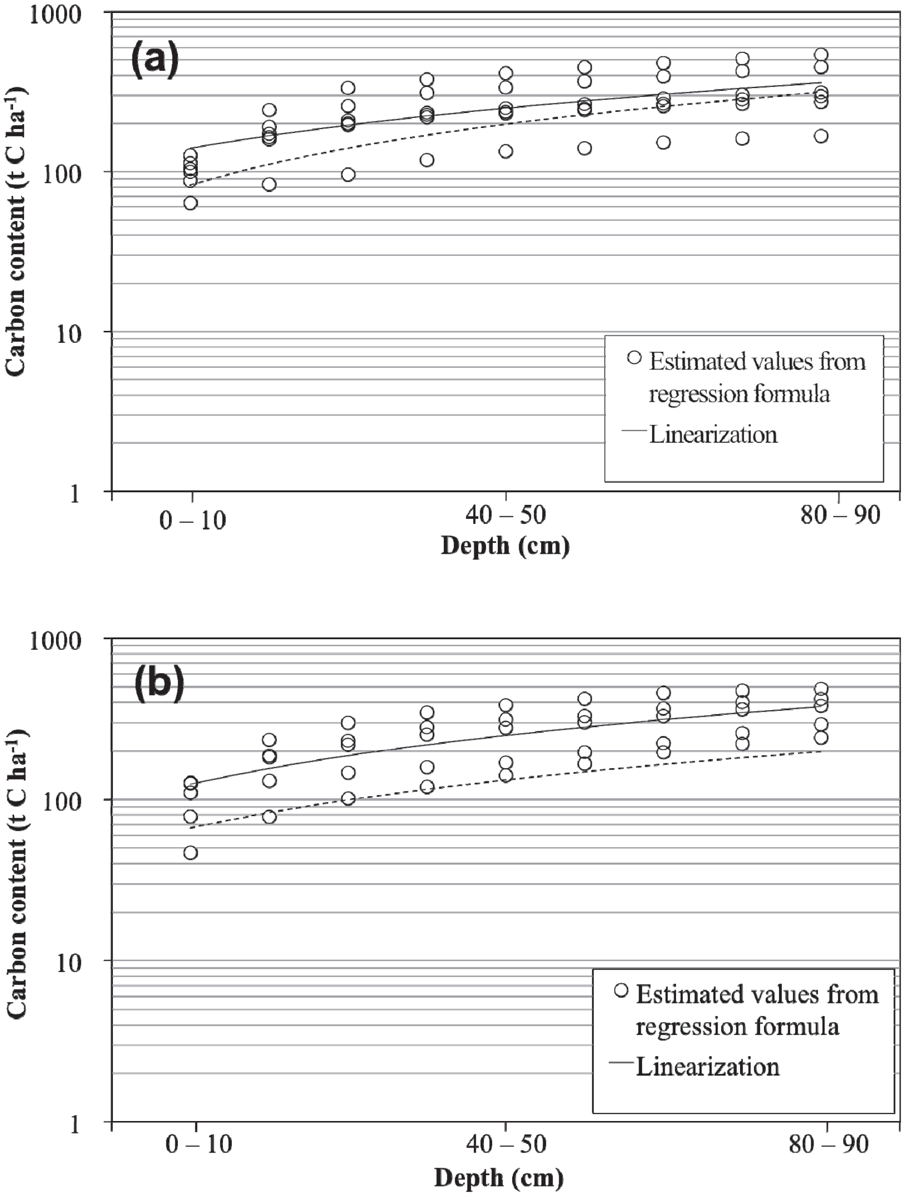

Fig. 4 Estimated cumulative Carbon content (t C ha^{-1}) in the Gyoen; (a): Turf, (b): Forest. Regression curves in dotted line are the measured cumulative carbon content taken from Fig. 3.

Figure 5 shows the comparison of estimated bulk density from Softness obtained using regression formulae with measured bulk density at 2 open pits O1 and O2. According to the vertical profile pattern of Softness, regression formula C and D was applied to O1 and O2, respectively. From the results, the estimated soil bulk density using Softness was confirmed to become approximately 25 % larger than measured bulk density. However, we may conclude that the use of the Softness as a proxy of bulk density can be applicable, particularly when used to evaluate compressed soil profiles.

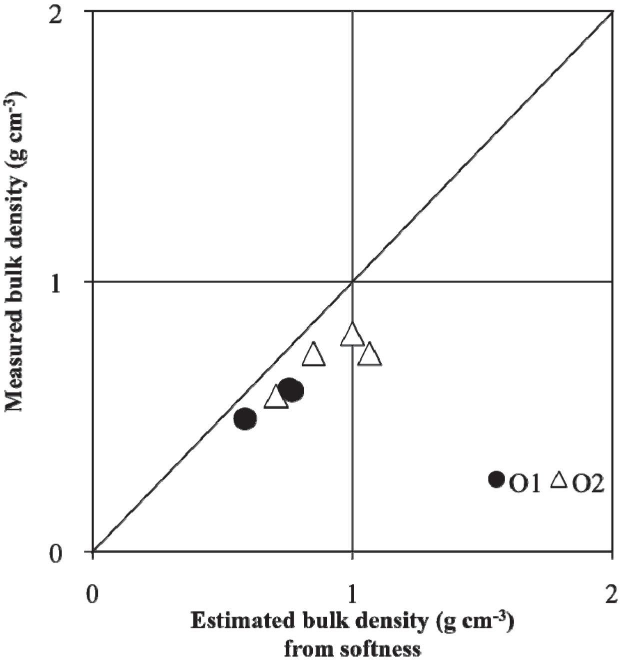

Fig. 5 Comparison of measured bulk density (g cm^{-3}) using core samples and estimated bulk density (g cm^{-3}) using regression formula, at open pit points (O1, O2).

4. Conclusions

The carbon storage in Shinjuku Gyoen National Garden in 0 – 100 cm was estimated as 316 ± 83.1 t C ha^{-1} in turf areas and 198 ± 61.3 t C ha^{-1} in forest areas, which was recognized to be equivalent to that in Andosols and Brown forest soil, respectively.

A modified investigation and sampling method was used to estimate cumulative carbon content without disturbing the park landscape in this study. The use of the Softness obtained from measurement of vertical soil compactness was discussed as a proxy of soil bulk density. Although the estimated values of cumulative carbon content tended to be overestimated in cases, we suggest that the use of the Softness as a substitute for soil bulk density is compatible to estimate carbon storage. However, the method is inapplicable for sites where vertical soil compactness change drastically or sites that have undeveloped soil structure with incompact layers. Further studies to improve regression curves and discussions on their representativeness are required.

It has been shown that vertical soil compactness differs at different sites with the same land use in the Gyoen. Soil bulk density of turf area may also alter, which is dependent on management and disturbance for land creation. In addition, soil carbon storage depends on past soil development. The evaluation of soil carbon storage based on current land use or landscape is not appropriate in urban areas. Subsurface structure, which is a function of land use history and land creating history, should be taken into account for the evaluation of soil carbon storage in urban areas.

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