Journal of Soils and Sediments (2021) 21:2130–2140
https://doi.org/10.1007/s11368-020-02827-5

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Suggested key variables for assessment of soil quality in urban roadside tree systems

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Received: 7 February 2020 / Accepted: 1 November 2020 / Published online: 4 November 2020

Abstract

Purpose Urban roadside soils are important growth media for roadside trees. However, typical assessment variables are limited in describing the characteristics of roadside soils. We assessed the characteristics of roadside soils using the pre- and new suggested variables and recommended optimal soil variables that are representative of roadside tree health.

Materials and methods Seventy-three roadside soils were collected for measurement, while six urban forest soils were prepared as a control. Samples were used to evaluate both pre-suggested and new variables. The former included bulk density, penetration resistance (PR), pH, organic matter (OM), fluorescein diacetate (FDA) activity, and respiration. To improve the pre-suggested variables, we modified the bulk density using PR and investigated the elemental ratios and stable isotopic signatures of particulate organic matter (POM). Two criteria were used to select the variables for urban roadside soils: (1) the variable should identify distinct characteristics of roadside and urban forest soils and (2) the variable should have a high correlation with urban tree health variables: leaf chlorophyll content and tree vigor.

Results and discussion The bulk density measured using the conventional method underestimated soil compaction because obtaining intact cores was challenging. The modified bulk density ($BD_{modified}$) obtained from the soil PR is suggested to better represent soil compaction. The roadside soils were affected by de-icing materials, construction debris, and atmospheric alkali particles, which increased the soil pH. The unexpectedly higher OM contents in the roadside soils, where tree origins are limited, possibly due to soil OM sources such as vehicular emissions, animal excreta, and sewer flooding. These OM sources may alter the C/H ratio (POM-C/H) and the stable isotopic signature of POM, leading to OM quality changes. Soil respiration better reflected the changes in the microbial activity of the roadside soils, rather than FDA activity. The newly suggested soil variables, $BD_{mofieid}$, pH, POM-C/H, and RES, were significantly correlated with leaf chlorophyll content and tree vigor ($P < 0.05$).

Conclusions Using a multiple regression analysis, the newly suggested set of soil variables, including the $BD_{modified}$, soil pH, POM-C/H, and soil respiration, showed high predictive power for the growth of urban roadside trees. Future studies should apply these variables to other cities or broader areas and confirm their predictive ability regarding the health of roadside trees.

Keywords Urban roadside soil · Soil quality variable · Roadside tree health · Soil organic matter quality

1 Introduction

Urban soils in roadside tree systems, which provide a permeable layer next to urban surfaces paved with asphalt and cement, are important as growth media for urban trees, terminal receptors for contaminants, and rainwater filters or reservoirs (Dominati et al. 2010; Guilland et al. 2018). Nevertheless, anthropogenic factors, such as narrow spaces, compaction, waste dumping, and erosion, have severely degraded soil quality in roadside tree systems (Craul 1985; Jim 1998; Scheyer and Hipple 2005; Pouyat et al. 2007; Scalenghe and Marsan 2009; Ow and Ghosh 2017). The challenge of

Responsible editor: Stefan Norra

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growing healthy and stable urban trees in such poor conditions results in trees with shorter lifespans than their biological potential (Patterson 1977; Day and Bassuk 1994; Roman and Scatena 2011). Given the close relationship between soil conditions and tree growth, understanding and assessing soil quality in urban roadside tree systems is necessary to sustain tree growth and health.

Research on urban roadside soils has focused principally on heavy metal contamination, such as by lead, cadmium, and nickel, demonstrating that the main sources of heavy metal are vehicular emissions and industrial activity (Rodrigues et al. 2009; Chen et al. 2010; Zhang et al. 2019). However, in South Korea and other developed countries, the phase-out of heavy metal usage, such as the use of unleaded gasoline, has reduced the levels of heavy metals in urban roadside soils (Kim et al. 2002; Chen et al. 2010; Cheng and Hu 2010). Some studies have used variables previously suggested in the agriculture and forestry sectors, including bulk density, organic matter (OM), microbial biomass/enzyme activity, and total nitrogen (TN) (Rodrigues et al. 2009; Scharenbroch and Catania 2012; Zornoza et al. 2015; Ghosh et al. 2016a). Following the perspectives of agronomy and forestry, these studies reported that soils with optimum bulk density, high OM, and high microbial biomass/enzyme activity were qualitatively superior and promoted urban tree growth.

However, the question remains whether the variables commonly used in the agronomical and forestry sectors could explain the characteristics of urban roadside soils, which have unique physical, chemical, and biological attributes. Generally, soils with a high bulk density in urban roadside tree systems result from prolonged compaction by human trampling and the passage of heavy vehicles (Craul 1985; Jim 1998; Scharenbroch et al. 2005; Scharenbroch and Catania 2012; Sefati et al. 2019). Soil compaction destroys the pore structure, causing poor drainage and aeration, which has a negative influence on root respiration and microbial activity (Day and Bassuk 1994; Jim 1998; Fierer et al. 2003; Jim and Ng 2018). However, Yoon et al. (2016) reported relatively low soil bulk density of roadside soils and suggested that collecting intact cores from urban roadside soils was difficult because the soils in roadside tree pits were entangled with gravel, tree roots, or construction debris (cement, concrete, and bricks). Thus, cross-checking of measured bulk density with other physical variables is required to accurately assess the degree of soil compaction in urban roadside soils. Regarding soil organic matter content (OM), Jim (1998) and Li et al. (2013) found significantly lower soil OM in roadside soils ($< 1\%$), which is mainly due to roadside tree pits being filled with sand particles (Jim and Ng 2018). In addition, inputs of tree-derived organic materials to soils, such as fallen leaves and other residues, are very limited as they are immediately removed from the surfaces because of esthetics, pedestrian and vehicular traffic, and hygienic aspects (Jim 1998; Li et al. 2013; Yoon et al. 2016). Nevertheless, some previous studies reported the opposite results: soil OM was similar or sometimes even higher in roadside soils than that in natural forests, agricultural fields, and urban parks. This might be due to atmospheric deposition, sewage sludge, or animal waste (Lorenz and Kandeler 2005; Zhao et al. 2013; Ghosh et al. 2016b; Shetty et al. 2018). These results indicate that the sources of soil organic matter input may be completely different in urban roadside soils from those in other types of ecosystems. However, there is still a lack of research focusing on the qualities of different OM in roadside soils by tracing their sources and input pathways.

In this study, we suggest variables that best represent the characteristics of urban roadside soils to assess soil quality in urban roadside tree systems. The objectives of this study were (1) to assess the characteristics of roadside soils using the pre-suggested soil variables, including bulk density, penetration resistance (PR), total exchangeable cations, pH, OM, TN, total Pb, fluorescein diacetate (FDA) activity, and soil respiration (RES), by comparing these variables in urban roadside soils with those of urban forest soils; (2) to evaluate roadside soils using additional variables to understand the unique characteristics of roadside soils that are difficult to assess using the pre-suggested variables; and (3) to suggest an optimum set of variables that are highly correlated with tree health.

2 Materials and methods

2.1 Study site

In this study, we chose roads A (Toegye-ro) and B (Deogyeong-daero) that run through the center of the metropolitan cities (Seoul and Suwon). Both roads have six car lanes with heavy traffic. On each road, the sections with the highest vehicular and pedestrian traffic were selected as sites A (1.3 km long) and B (3 km long). As our study did not aim to compare the urban roadside soil properties representing two selected cities but to identify a new set of soil variables that best represent the characteristics of urban roadside soils influenced by human activities, we believed that the selection of these two sites with high levels of disturbance would be the best choice. These sites include commercial (motorcycle retailers, pet shops, and parking spaces) and residential (established and under construction) land uses. At sites A and B, the roadside tree pits are mainly filled with sandy soil, intermittently mixed with gravel, tree roots, and construction debris. Pine (*Pinus* spp.) and zelkova (*Zelkova* spp.) trees are planted along sites A and B, respectively. To understand the unique properties of urban roadside soils influenced by anthropogenic stresses, the urban forest adjacent to site B was selected as a control. The urban forest is a mixed forest and has terrain with low altitude (a height of 157.1 m). This urban forest is a typical type of urban remnant forest patch that commonly emerges due to deforestation and fragmentation for urbanization. The urban forest has no vehicular road within a radius of 350 m and only trekking trails, so there is significantly less anthropogenic disturbance compared to the urban roadside areas. In this urban forest, fallen leaves or branches are not removed, and soil management practices are absent.

2.2 Soil sampling and analysis

Soil samples were collected from 49 and 24 measurement points along the transects of sites A and B, respectively. For each measurement point, soil sampling was performed with two replications. Soil samples were collected at a depth of 0–15 cm on May 15, 2018, and May 25, 2019. In the urban forest, soil sampling was performed by dividing the total area into six subareas on the map and randomly collecting three soil cores from each subarea. Soil samples were passed through a 2-mm sieve and air-dried for 2 weeks. Table 1 summarizes the variables used in the analysis.

2.2.1 Measurements of pre-suggested soil quality variables

Soil texture was determined using the hydrometer method (Chen et al. 2015). Soil bulk density ($BD_{measured}$) was determined using a soil core using a manual driving hammer probe (2.5 cm diameter, 35 cm length; AMS Inc., American Falls, ID, USA) and drying the soil at 105 °C for 24 h to determine the soil dry weight contained in the soil volume. To cross-check the degree of compaction in the roadside soils, we measured the PR of the soil surface at a distance of 0.5 m from the tree trunk using a cone penetrometer (DIK-5553, Daiki Co., Japan).

The total exchangeable cations, including Ca^{2+}, Mg^{2+}, K^+, and Na^{2+}, were evaluated by the acetate (pH 2.31) saturation method (Brown 1943). Soil pH was measured using a pH meter (Orion 3 star, Thermo Fisher Scientific, MA, USA) at a 1:2 (*w*/*v*) ratio of soil to deionized water. Soil organic matter (OM) content was determined by the loss on ignition (LOI) method in a muffle furnace at 450 °C for 1.5 h. The LOI (%) was converted to soil OM (%) using the following equation (Nelson and Sommers 1996):

$$\text{OM}\ (\%) = \{\text{LOI}\ (\%) \times 0.7\} - 0.23.$$

The TN was analyzed by combustion analysis using a Carlo Erba NS 1500 analyzer (Carlo Erba, Milan, Italy). The total Pb content in the soils was determined by 0.1 N HCl extraction, as the Korean standard method for soil analysis (Lee et al. 2001; Moon et al. 2010). The extracted solution was analyzed using an inductively coupled plasma mass spectrometer (Agilent 7500cx, Agilent, Santa Clara, CA, USA).

The overall microbial activity was measured using the fluorescein diacetate (FDA) hydrolysis method, which is widely accepted as a proxy for overall microbial activity in soils (Adam and Duncan 2001). As a variable of soil microbial activity, soil respiration (RES) was measured by the release of carbon dioxide (CO_2) from the soil surface using the chamber method at a total of 60 sampling points (Wang et al. 2011). The chamber (6.5 cm in diameter, 13 cm in height) was inserted 5 cm deep at each sampling point. According to the chamber method, the chamber was sealed with caps for 30 min, and gas samples were collected from the headspace of the closed chamber using syringes (BD Luer-LokTip). The CO_2 concentration was detected using gas chromatography (Agilent 7890A, Santa Clara, CA, USA) with a hydrogen flame ionization detector (FID). The CO_2 flux was calculated based on changes in head space concentration over the measured period using the following equation (Troy et al. 2013):

$$\text{Flux} = \frac{\text{dGas}}{\text{dt}} \times \frac{V}{A} \times \frac{P \times 100 \times \text{MW}}{R} \times \frac{273}{T}$$

where dGas/dt is the change in the CO_2 concentration over time, V is the volume of the chamber, A is the surface area covered by the chamber, P is the atmospheric pressure, MW is the molecular weight of CO_2, R is a gas constant, and T is the absolute temperature.

Table 1 Soil physical, chemical, and microbial parameters used for soil quality assessment in this study

	Parameters	
	Pre-suggested	Additional
Physical	Measured bulk density ($BD_{measured}$) Soil penetration resistance (PR)	Modified bulk density ($BD_{modified}$)
Chemical	Total exchangeable cation pH	The C and N contents of particulate organic matter (POM-C and POM-N)
	Soil organic matter (OM)	C/H ratio of particulate organic matter (POM-C/H)
	Total N Total Pb	The C and N stable isotope ratios of soil POM (POM-δ^{13}C and POM-δ^{15}N)
Microbial	Fluorescein diacetate (FDA) activity Soil respiration (RES)	

2.2.2 Measurement of additional variables for assessing soil quality of roadside soils

We suggested using modified bulk density ($BD_{modified}$) to overcome the difficulties of collecting an intact core due to the obstructions posed by gravel, roots, and construction residues in roadside soil environments. The $BD_{modified}$ was converted from the soil PR using the following equation (Hernanz et al. 2000):

$$BD_{modified} = 0.913 \times PR^{0.096} \times d^{-0.061} \left(r^2 = 0.702, P < 0.0001\right),$$

where d is the depth of the soil PR measurement (approximately 1 cm).

To determine the sources and quality of the roadside soil OM, we analyzed particulate organic matter (POM). The POM was separated from the bulk soil by dispersing 10 g of dried soil into 30 mL of a sodium hexametaphosphate solution. The suspensions were shaken at a high speed with a reciprocal shaker for 1 h and then passed through a 53-μm mesh (Wander et al. 1998). The samples on the 53-μm mesh were dried and ground with a mortar and pestle. The ground samples were analyzed by combustion analysis with a Carlo Erba NS analyzer to determine the C, N, and H contents (POM-C, POM-N, and POM-H). The C/H ratio of the POM (POM-C/H) was used as a variable to determine soil OM quality because higher values of the C/H ratio correspond to larger quantities of aromatic compounds and condensation (Chiou and Xing 2004). The increased degree of aromaticity in soil OM is indicative of recalcitrance (Marschner et al. 2008). To investigate the sources of the soil OM, the C and N stable isotope ratios of soil POM (POM-δ^{13}C and POM-δ^{15}N) were determined using a stable isotope ratio mass spectrometer system with an elemental analyzer (Micomass, Ltd., Manchester, UK). The isotope ratios were calculated using the following equation:

$$\delta X\ (‰) = \left(\frac{R_{sample}}{R_{standard}} - 1\right) \times 1000$$

where X is the ^{13}C and ^{15}N isotopes, and R_{sample} and $R_{standard}$ are the ratios of the heavy-to-light isotope in the sample and standard, respectively.

2.3 Criteria for selecting the key variables for soil quality assessment in urban roadside tree systems

There were two main criteria used to select a set of soil quality variables: (1) the values of soil quality variables should sufficiently differentiate the basic characteristics of the roadside soils from those of the urban forest soils to explain the unique soil characteristics in urban roadside tree systems, and (2) soil variables should be highly correlated with urban tree health. On the day of soil sampling, we investigated roadside tree health on the day of soil sampling to determine the relationship between the suggested set of soil variables and tree health. Tree variables were assessed using leaf chlorophyll content at site A and tree vigor at site B. Leaf chlorophyll was extracted using the dimethyl sulfoxide method (Hiscox and Israelstam 1979), and the light absorbance (648 nm and 665 nm) of the extracted solution was measured using spectrometry (Eppendorf Biospectrometer; Eppendorf, Hamburg, Germany). Tree vigor was measured with a Junsmeter (Prum Bio, Suwon, Korea), a portable electrical device used to assess tree health. The Junsmeter was developed by modifying a Shigometer, which is a representative method of measuring tree vitality electro-physiologically using the electric resistance of the tree cambium. The larger values measured by the equipment indicate the greater tree vigor (Kim and Jung 2019).

2.4 Statistical analysis

Analysis of variance was performed using the MIXED procedure from SAS 9.4 (SAS Institute Inc., Cary, NC, USA) on the pre-suggested and additional variables for soil physical, chemical, and microbial properties. Least-square means were used to test for significant differences at a 5% probability level. To investigate the relationship between each soil variable and plant health, Pearson's correlation analysis was conducted using SAS 9.4. Finally, we performed a multiple regression analysis using SAS 9.4 to determine the degree of correlation between the new set of soil variables and roadside tree health. We validated that the newly suggested set of soil variables could account for leaf chlorophyll content and tree vigor. To test multi-collinearity among the newly suggested soil variables, we analyzed the variance inflation factor and tolerance.

3 Results and discussion

3.1 Assessment of the pre-suggested soil quality variables

The soil $BD_{measured}$ in the roadside soils was lower than or similar to that in the urban forest, and it was positively correlated with leaf chlorophyll content ($r = 0.4131$; $P = 0.0017$) and tree vigor ($r = 0.3031$; $P = 0.1035$) (Table 2; Table 3). The lower soil $BD_{measured}$ contradicted the original hypothesis that roadside soils were more compacted than urban forest soils. Moreover, the positive correlation found between soil $BD_{measured}$ and tree health was unexpected because, in general, high soil bulk density destroys soil structural stability, damaging the water adsorption system and root respiration of plants (Day and Bassuk 1994; Jim and Ng 2018). These odd results may have arisen from the difficulty of obtaining intact cores from the small-sized pits in the roadside soils. The core was easily contaminated with gravel, tree roots, and construction debris (cement, concrete, and bricks), which were intertwined with the soils (Lorenz and Kandeler 2005; Cekstere and Osvalde 2013; Li et al. 2013). Hernanz et al. (2000) reported that it is difficult to measure the soil bulk density with the traditional method in sandy, dry, and hard-compacted soils without significant disturbance. Hence, we conclude that soil variables other than BD would be necessary for the evaluation of soil compaction in urban roadside tree systems. Soil PR was significantly higher in all of the roadside soils than in the urban forest (Table 2). In particular, the soils near motorcycle retailers at site A and parking spaces at site B had a soil PR level similar to that in compacted agricultural fields (589–1270 kPa at 0–5 cm depth) (Materechera and Mloza-Banda 1997; Celik et al. 2010). Traffic from vehicles such as motorcycles and cars appear to have resulted in excessive soil compaction (Craul 1985; Jim 1998; Scharenbroch et al. 2005; Scharenbroch and Catania 2012; Sefati et al. 2019). Although the significance was low, soil PR was negatively correlated with leaf chlorophyll content ($r = -0.2116$; $P = 0.1209$) and tree vigor ($r = -0.2433$; $P = 0.1950$) (Table 3). Therefore, soil PR is likely to be more suitable for representing the degree of soil compaction in urban roadside tree systems.

The total exchangeable cation content and soil pH were significantly higher in the roadside soils than in the urban forest, which showed the highest values in the soils near motorcycle retailers, parking spaces, and under construction residential districts (Table 2). The high cation (Na^+, Mg^{2+}, and Ca^{2+}) content in the roadside soils might be due to the inputs of de-icing materials, calcareous construction debris, and alkali particles via atmospheric deposition, rainwater runoff, and vehicular traffic, which can eventually promote soil alkalization in roadside tree systems (Craul 1985; Jim 1998; Truscott et al. 2005; Cekstere and Osvalde 2013; Li et al. 2013; Neher et al. 2013). Soil pH higher than 6.5 could cause a deficiency in the available P and micronutrients, inhibiting nutrient absorption by tree roots (Rosolem and Tavares 2006; Amacher et al. 2007; Cekstere and Osvalde 2013; Li et al. 2013; Bühler et al. 2017). Both total exchangeable cation content and soil pH had a negative correlation with leaf chlorophyll content and tree vigor; however, a significant difference was only identified between soil pH and tree health variables ($P < 0.05$) (Table 3). Hence, soil pH may be a useful variable to represent unfavorable chemical conditions in urban roadside soils.

The contents of OM and TN, the typical soil fertility indicators, were the same or even higher in the roadside soils than in the urban forest (Table 2). Despite the limited input of tree-derived OMs, the average contents of OM and TN were threefold and twofold higher in the roadside soils than in the urban forest, respectively. The unexpected results of higher OM in the roadside soils might be due to the different sources of soil OM, such as atmospheric deposition, rainwater runoff, animal excreta, and sewer flooding (Lorenz and Kandeler 2005; Zhao et al. 2013; Shetty et al. 2018). However, soil OM and TN content showed either insignificant or negative correlations with leaf chlorophyll content and tree vigor (Table 3). These results are contradictory to the concepts prominent in agronomy and forestry, specifically, that higher OM in soils significantly increases soil fertility and plant growth (Zornoza et al. 2015). Therefore, we conclude that the soil OM quality variables are more necessary than the OM quantity variables to assess soil fertility in urban roadside soils. We further investigated potential input pathways of soil OM and OM qualities, which are discussed in Section 3.2.

Only the soils of the motorcycle retailer at site A exhibited total Pb content that was significantly higher than that in the

Table 2 Soil physical, chemical, and microbial properties in the roadside tree soils and urban forest analyzed by the pre-suggested soil parameters

	Roadside soils						Urban forest
	Site A			Site B			
	Commercial		Residential	Commercial	Residential		
	Motorcycle retailer	Pet shop		Parking space	Under construction	Established	
$BD_{measured}$ (g cm^{-3})	0.74 b	0.55 a	0.49 a	1.16 d	1.25 d	1.04 c	1.21 d
PR (kPa)	824 c	132 b	172 b	646 c	412 bc	261 b	32 a
Total exchangeable cation (cmol$_c$ kg^{-1})	24.61 c	11.54 b	10.27 b	20.90 c	21.63 c	10.07 ab	4.55 a
pH	8.0 de	6.3 c	5.9 b	7.5 d	7.6 e	6.5 c	4.7 a
OM (%)	2.14 b	5.53 c	7.45 c	2.79 b	1.03 a	2.36 b	1.23 ab
TN (%)	0.08 b	0.15 cd	0.17 d	0.14 c	0.04 a	0.08 b	0.06 ab
Total Pb (mg kg^{-1})	78.76 c	45.35 b	35.70 ab	38.59 ab	22.45 a	35.44 ab	28.72 ab
RES (mg m^{-2} min^{-1})	3.02 a	2.15 a	2.21 a	3.79 ab	5.49 bc	6.19 c	11.88 d
FDA activity (mg fluorescein g^{-1})	6.13 b	7.59 bc	9.50 c	4.48 ab	1.48 a	2.63 a	4.09 ab

Different letters indicate significant differences among the roadside soils and urban forest soils at a 5% level ($n = 54$)

Table 3 Pearson's correlation coefficients between the tree health and the pre-suggested soil parameters. The numbers in parentheses are *P* values

		Pre-suggested parameters								
		$BD_{measured}$	PR	Total exchangeable cation	pH	OM	TN	Total Pb	RES	FDA activity
Tree health	Leaf chlorophyll	0.4131** (0.0017)	−0.2116 (0.1209)	−0.1662 (0.2253)	−0.3133** (0.0198)	−0.1074 (0.4350)	−0.2077 (0.1281)	−0.2492* (0.0666)	0.4438** (0.0007)	−0.2036 (0.1360)
	Tree vigor	0.3031 (0.1035)	−0.2433 (0.1950)	−0.1988 (0.2923)	−0.4087** (0.0249)	−0.5414** (0.0020)	−0.2172 (0.2490)	−0.1988 (0.2922)	0.6317** (0.0002)	0.1971 (0.2965)

Asterisks dictates significant correlation between parameters as follows: $^{**}P < 0.05$ and $^{*}P < 0.10$

urban forest soil (Table 2), showing that a significant negative correlation between total Pb and leaf chlorophyll was present only in site A ($r = -0.2492$; $P = 0.0666$) (Table 3). This indicates that the motorcycle retailer is the definite Pb source during operation and repair, and that Pb must have been deposited to adjacent roadside soils. However, the total Pb content in the urban forest and other roadside soils was lower than that of the criterion of 100 mg kg^{-1} as defined by the Korean Soil Environment Conservation Act (Choo et al. 2005). The overall lower soil Pb levels have been attributed to the phase-out of heavy metal usage since 1993 and the management of heavy metal contaminated soil (Kim et al. 2002; Choo et al. 2005). Thus, heavy metals, such as Pb, should be monitored intensively in soils with distinct sources, rather than being analyzed over a large area.

The RES in the roadside soils was significantly lower than that in the urban forest and had a significantly positive correlation with leaf chlorophyll content ($r = 0.4438$; $P = 0.0007$) and tree vigor ($r = 0.6317$; $P = 0.0002$) (Table 2; Table 3). In general, soil temperature and moisture are the primary factors that alter soil respiration (Luo and Zhou 2006). Roadside soils, which are surrounded by asphalt and concrete, suffer from heatwaves and droughts caused by the heat island effect. This is likely the reason for the lower RES observed in roadside soils compared to urban forest soils (Oke 1989; Salmond et al. 2016). Soil compaction by human trampling and vehicular traffic can further reduce the soil RES in roadside soils because of the lack of sufficient oxygen and water being provided to the soil (Grable 1971; Kemper et al. 1971; Day and Bassuk 1994; Beyer et al. 1995; Jim 1998). Soil RES is affected not only by abiotic factors but also by soil OM (USDA 1996; Dilly 2003; Graham and Haynes 2006; Li et al. 2007, 2009). Therefore, soil respiration is generally used as an early sign to evaluate the process of OM decomposition by soil microbes (Laishram et al. 2007). In this study, lower RES in the roadside soils implies that it may be more difficult for soil microbes to decompose OMs in roadside soils because anthropogenic-derived OM such as sewage sludge and anthropogenic-derived dusts (Kong and Jo 2000; Lorenz and Kandeler 2005). Among the anthropogenic-derived OMs, highly toxic substances such as polycyclic aromatic hydrocarbons, benzoic acids, and phenols from roads, buildings, and air pollutants may enter the roadside soils, likely leading to adverse effects on microbial activity (Helmreich et al. 2010; Peng et al. 2012; Zhao et al. 2013; Liu et al. 2019). However, the FDA activity, which is generally used as another key variable to assess soil microbial activity, did not significantly differ between the roadside soils and urban forest soils (Table 2). It was also not significantly correlated with leaf chlorophyll content or tree vigor ($P > 0.10$) (Table 3). As a sufficient substrate for microbial hydrolysis was added when analyzing FDA activity, FDA activity was used as a proxy for evaluating potential microbial activities (Sánchez-Monedero

Table 4 Modified soil bulk density ($BD_{modified}$), and the C and N contents and C/H ratio of particulate organic matter (POM-C, POM-N, and POM-C/H) in the roadside sites and urban forest

	Roadside soils						Urban forest
	Site A			Site B			
	Commercial		Residential	Commercial	Residential		
	Motorcycle retailer	Pet shop		Parking space	Under construction	Established	
$BD_{modified}$ (g cm^{-3})	1.58 c	1.41 b	1.44 b	1.58 c	1.52 bc	1.46 b	1.24 a
POM-C (g kg^{-1})	1.73 bc	3.72 d	5.16 e	2.53 c	0.82 ab	1.46 b	0.23 a
POM-N (g kg^{-1})	0.09 b	0.17 c	0.20 c	0.18 c	0.05 ab	0.08 b	0.02 a
POM-C/H	15.50 d	7.98 c	7.79 c	15.39 d	2.63 b	3.73 b	0.63 a

Different letters indicate significant differences among the roadside soils and urban forest soils at a 5% level ($n = 54$)

et al. 2008; USDA 2010). We found that soil RES better reflected the changes in the microbial activity of the roadside soils, rather than the variables used to assess potential microbial activity, such as the FDA activity. Therefore, soil RES can be suggested as a variable for assessing microbial activity in urban roadside soils.

3.2 Improvement of soil quality variables with a new methodology

In the previous section, it was discussed that soil PR could be a useful variable for representing the degree of soil compaction in urban roadside tree systems. However, compared with the soil bulk density, the values and units of soil PR are more difficult to define and interpret intuitively, even for soil experts. Thus, we modified the bulk density ($BD_{modified}$) with PR using the empirical equation reported by Hernanz et al. (2000). The $BD_{modified}$ in the roadside soils was 1.41 to 1.58 g cm^{-3}, which was significantly higher than that in the urban forest soils (1.24 g cm^{-3}) (Table 4). In the roadside soils, the range of $BD_{modified}$ was higher than that of $BD_{measured}$ (0.49 to 1.25 g cm^{-3}) (Table 2; Table 4). In particular, the soils near the motorcycle retailers at site A and the parking spaces in site B had $BD_{measured}$ values that were close to the limit at which root growth may be inhibited (Jim 1998; Jim and Ng 2018). These results indicate that soil $BD_{modified}$ can be used as a soil variable to overcome the underestimated degree of soil compaction due to the difficulty of obtaining an intact core from roadside soils. Moreover, the soil $BD_{modified}$ was negatively correlated with leaf chlorophyll content ($r = -0.4726$; $P = 0.0003$) and tree vigor ($r = -0.4031$; $P = 0.0272$) (Table 5). Therefore, these results strongly supports that the soil $BD_{modified}$ may be a good variable for assessing soil compaction in urban roadside tree systems.

Consistent with the soil OM, the POM-C and POM-N contents were from eightfold to fortyfold higher in the roadside soils compared to those in the urban forest (Table 4). Previous studies have reported that increased OMs in roadside soils, where natural OM input is limited, indicates that there may be other sources, such as atmospheric deposition of particulate organic pollutants (Craul 1985; Zhu et al. 2004; Truscott et al. 2005; Neher et al. 2013; Ghosh et al. 2016b). The POM-C/H was significantly higher in the roadside soils than in the urban forest (Table 4). The higher values of POM-C/H were closely related to POM containing less-biodegradable compounds, such as polycyclic aromatic hydrocarbons, benzoic acids, and phenols (Lorenz and Kandeler 2005; Zhao et al. 2013). These materials are mainly contained in petroleum, usually flowing into roadside soils through the deposition and runoff from adjacent roads (Peng et al. 2012; Anyika et al. 2015; Liu et al. 2019). Particularly, the POM-C/H was significantly higher in the soils near the motorcycle retailers at site A and

Table 5 Pearson's correlation coefficients between the tree health and additional soil parameters: modified soil bulk density ($BD_{modified}$), and the C and N contents and C/H ratio of particulate organic matter (POM-C, POM-N, and POM-C/H). The numbers in parentheses are P values

		Pre-suggested parameters					
		$BD_{modified}$	POM-C	POM-N	POM-C/H	POM-δ^{13}C	POM-δ^{15}N
Tree health	Leaf chlorophyll	-0.4726^{**} (0.0003)	−0.2238 (0.1005)	-0.2242^{*} (0.0998)	-0.2693^{**} (0.0468)	−0.1283 (0.3507)	-0.3127^{**} (0.0201)
	Tree vigor	-0.4031^{**} (0.0272)	-0.3262^{*} (0.0785)	−0.2713 (0.1470)	-0.3338^{*} (0.0714)	0.0073 (0.9697)	0.0094 (0.9605)

Asterisks dictates significant correlation between parameters as follows: $^{**}P < 0.05$ and $^{*}P < 0.10$

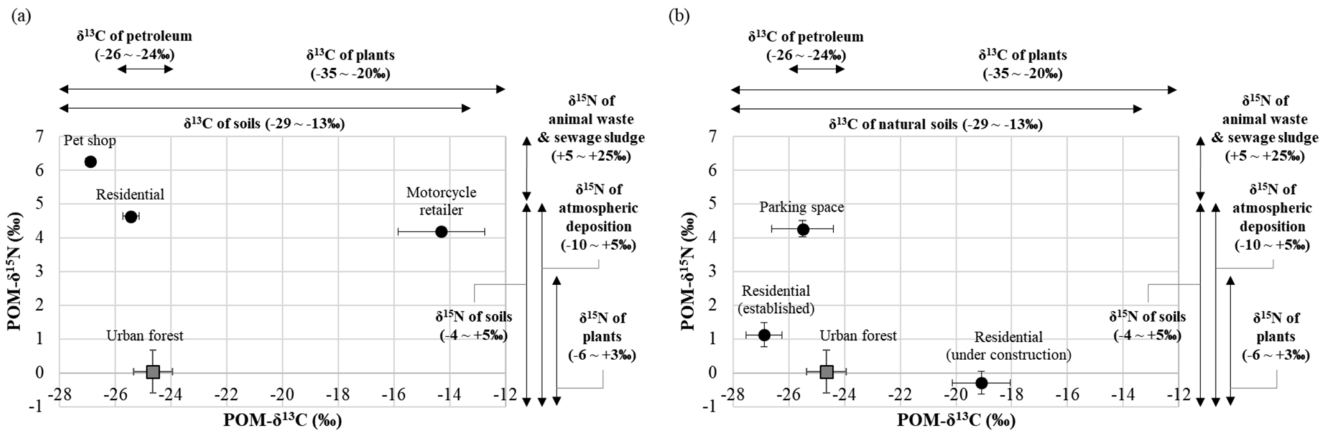
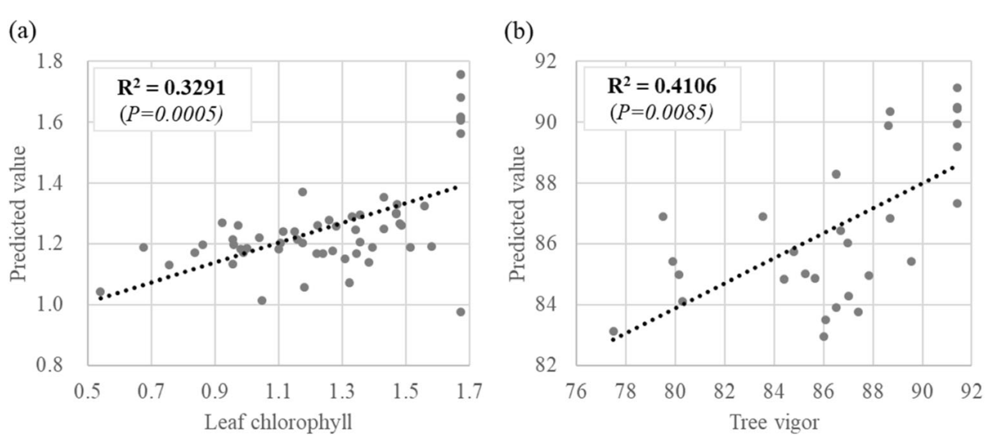


Fig. 1 C and N stable isotope ratios of soil POM (POM-δ^{13}C and POM-δ^{15}N) in the roadside site A (**a**), roadside site B (**b**), and urban forest. Vertical and horizontal bars represent standard errors for ^{13}C and δ^{15}N, respectively

the parking spaces in site B compared with other roadside soils (Table 4). This result might be due to the high input of vehicular emissions and road dust at the sites where motorcycles and automobiles directly cross the roadside soils. Hence, the soils near the motorcycle retailers and the parking spaces had noticeably dark colors and contained a large amount of particulate soot and dust. The high POM-C/H values due to vehicular emissions and traffic were consistent with the high cation content and soil pH in the soils near the motorcycle retailers and parking spaces (Table 2). Moreover, the POM-C/H showed a significantly negative correlation with leaf chlorophyll content ($r = -0.2693$; $P = 0.0468$) and tree vigor ($r = -0.3338$; $P = 0.0714$) (Table 5). Therefore, POM-C/H could be a soil variable for assessing the biodegradability of OM in urban roadside soils.

The POM-δ^{13}C values for all roadside soils and urban forest soils were in the δ^{13}C range of soils (− 29 to − 13‰) (Fig. 1). The δ^{13}C of plants ranges from − 35 to − 20‰ (Michener and Lajtha 2008), and that of fossil fuels, especially in the Korean market, ranges from − 26 to − 24‰ (Heo et al. 2012). These results indicate that the δ^{13}C range of fossil fuels is fully contained within the range for plants. Thus, it is nearly impossible to distinguish between the anthropogenic-derived and naturally derived OM using POM-δ^{13}C. The POM-δ^{13}C also had no significant correlation with the tree health variables ($P > 0.10$) (Table 5). On the other hand, the average of POM-δ^{15}N in the roadside soils was + 3.8‰, which was higher than that in the urban forest soils (+ 0.0‰) (Fig. 1). The δ^{15}N of soils (− 4 to + 5‰) generally overlaps with the δ^{15}N of plants (− 6 to + 3‰) and atmospheric deposition (− 10 to + 5‰) (Michener and Lajtha 2008; Lee et al. 2013). The δ^{15}N of animal waste and sewage sludge varies from + 5 to + 25‰ (Kendall 1998; Rock and Mayer 2006; Lee et al. 2013). These results indicate that roadside soils can obtain soil OM from various sources, including urban animal urine/feces, sewage sludge, and urban dust deposition (Lorenz and Kandeler 2005; Zhao et al. 2013). In particular, POM-δ^{15}N at site A was higher than that at site B (Fig. 1). In Seoul, where site A is located, 50.4% of the sewage pipes are aged more than 30 years (Korean Ministry of Land, Infrastructure, and Transport). Sewage leaking in urban areas is considered as the main reason for the release of large amounts of organic matter to the surrounding soil and groundwater (Eiswirth and Hötzl 1997; Hua et al. 2003). Although the POM-δ^{15}N is useful for differentiating between the soil OM sources in roadside tree systems, it had a significant negative correlation only with leaf

Fig. 2 Scatter plot of the multiple regression analysis between the suggested set of soil parameters (the modified bulk density, $BD_{modified}$; pH; the C/H ratio of particulate organic matter, POM-C/H; and soil respiration, RES) and tree health (leaf chlorophyll content in site A (**a**) and tree vigor in site B (**b**))



chlorophyll content at site A ($r = -0.3127$; $P = 0.0201$) (Table 5). This result indicates that POM-$\delta^{15}N$ may only be highly correlated if there is an anthropogenic-derived OM, such as sewage sludge, as in site A.

3.3 Suggestion for a set of soil quality variables for roadside tree systems

Following the criteria for selecting a set of soil quality variables, we found that soil $BD_{modified}$, pH, POM-C/H, and RES were useful variables for assessing the quality of roadside tree soils. According to the multiple regression analysis, we found that the newly suggested set of soil quality variables had a high correlation with leaf chlorophyll content and tree vigor (Fig. 2). The correlation coefficients (r^2) were 0.3291 ($P = 0.0005$) and 0.4106 ($P = 0.0085$) at sites A and B, respectively. As a result of the multi-collinearity test, the variance inflation factor was < 10 and the tolerance was > 0.1, indicating that there was no collinearity problem among the suggested soil variables. Therefore, we suggest that the set of soil variables that included soil $BD_{modified}$, soil pH, POM-C/H, and soil RES as the best soil variables for representing the soil characteristics in roadside tree systems.

4 Conclusions

Urban roadside soils have unique physical, chemical, and microbial characteristics. The small-sized pits were excessively compacted with tree roots, gravel, and artifacts, thereby disrupting the sampling of an intact core. To overcome the limitations of the conventional method, we modified the soil bulk density ($BD_{modified}$) using soil PR to obtain a potentially more useful variable for evaluating roadside soils because it can represent the degree of compaction without any physical constraints. Roadside soils are likely to be affected by de-icing materials, construction debris, and atmospheric alkali particles, which result in an increased soil pH. The unexpected results of higher OM in the roadside soils, wherein the tree-derived soil OM is limited, are likely due to vehicular emissions, animal urine/feces, sewage sludge, and atmospheric deposition. In particular, petroleum-derived organic particles can increase the POM-C/H value in roadside soils because these materials are less biodegradable. Thus, POM-C/H can be used to assess the soil OM quality of roadside soils. The soil RES better reflected the changes in the microbial activities of the roadside soils, rather than the variables used to evaluate potential microbial activity, such as FDA activity. Finally, according to a multiple regression analysis, the set of soil variables, including the $BD_{modified}$, pH, POM-C/H, and RES, were shown to be good predictors of the health of urban roadside trees. Future studies should apply these soil variables to other cities or broader areas to confirm their predictive capabilities regarding roadside tree health.

Funding This work was conducted with the support of the Korea Environment Industry & Technology Institute (KEITI) through its Urban Ecological Health Promotion Technology Development Project and funded by the Korea Ministry of Environment (MOE) (2020002770001).

Compliance with ethical standards

This article does not contain any studies involving human participants and animals performed by any of the authors.

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