

## Influence of soil properties on street tree attributes in Singapore

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**Abstract** Soil quality is thought to be a primary driver of street tree performance and thus a major concern for urban forest growth, health and longevity. This research was conducted to evaluate the influence of soil physical, chemical and biological properties on Singapore's street trees. In total, 338 plots, 1014 trees and 32 species across Singapore's five regions were sampled. Singapore's street trees are skewed towards smaller diameters (<50 cm) and largely represented (61 %) by five species, four of which are non-native. Most soil properties in Singapore's streetscapes are likely not limiting for trees: verge (5 to 7 m), bulk density (1.05 to 1.45 Mg m<sup>-3</sup>), P (1.52 to 2.87 mg kg<sup>-1</sup>), organic C (7.8 to 11.4 %), Ca (924 to 1772 mg kg<sup>-1</sup>), Mg (313 to 631 mg kg<sup>-1</sup>), Na (130 to 208 mg kg<sup>-1</sup>), Cr (143 to 212 mg kg<sup>-1</sup>), Pb (55 to 74 mg kg<sup>-1</sup>), Ni (15 to 30 mg kg<sup>-1</sup>) and microbial biomass C (265 to 457 mg kg<sup>-1</sup>). Soil pH (6.04 to 7.63) is not as acidic as the humid-tropical soil commonly found in Singapore. Soil K (23 to 130 mg kg<sup>-1</sup>) was found to be relatively low and potentially limiting. Individual soil properties and multi-factor models were poor predictors of urban tree attributes across Singapore, but models improved when examined at regional scales. Relatively high soil quality, uniformity of streetscape soils and fast growth rates of these trees are proposed as explanations for why soil properties appear to poorly predict street tree attributes in Singapore.

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## Introduction

The concept of soil quality integrates soil biological, chemical and physical attributes, to assess a soil's capacity to function (Karlen et al. 1997) and therefore assessment and improvement of soil quality is imperative for the health and growth of plants. Practical and accurate soil quality indices have been used for many years in agriculture (Doran et al. 1994) and forestry (Amacher et al. 2007); however, a widely-accepted, accurate and practical soil quality index or assessment tool does not exist for urban trees, specifically for street tree landscapes.

Degraded urban soil conditions can and often do, constrain urban tree growth and health (Craul 1992; Watson and Neely 1994; Neely and Watson 1998; Watson et al. 2008). Although the importance of soils for impacting tree performance is widely accepted, very little is known about those soil properties which are most influential in the urban landscape. Due to human influences, the quality of soils in urban landscapes is often impaired. It is not uncommon to find urban soils with high bulk densities, low porosities, poor soil structure, low water percolation rates, altered pH, high salinity, environmental contaminants, reduced organic matter contents, and altered microbial populations (e.g., Short et al. 1986; Craul 1999; Scharenbroch et al. 2005; Scheyer and Hipple 2005; Pouyat et al. 2007). For example, Jim (1998) examined physical and chemical properties of a Hong Kong roadside soil in relation to urban tree growth and found soil depth to be inadequate, possessing poor soil structure, high density, low porosity, low nutrients, low water holding capacity, alkalinity and often contaminated by heavy metals.

Given the strong linkage between site quality and tree growth and health, an urban soil index would have substantial application for urban forestry and arboriculture. For instance, an urban soil index would be an essential tool to aid with the diversification of planting design by better matching species tolerances with site conditions. A soil quality index would also be very useful for the assessment and restoration of degraded urban soils.

Research by Scharenbroch and Catania (2012) identified a minimum data set that included soil texture, bulk density, wet-aggregate stability, pH, electrical conductivity, total and labile organic matter in relation to urban tree performance. This minimum data set had correlated well with attributes of urban street trees, but this research was limited to the western suburban region of Chicago, IL. The researchers concluded that the minimum data set showed promise for use as an urban site index, but needs to be validated across a broader geographic extent with different soil types, climate, management practices, species, etc.

Singapore is a city-state with strong emphasis on urban greening despite of rapid urbanization and limited land resource. Several projects have developed in Singapore on urban environmental studies, but most of them focusing more on the above-ground aspects or are confined to addressing specific regions. Although a few works have been done in Singapore's "natural" areas (Winn et al. 2001, Rahardjo et al. 2004), very little work has been done to assess soil characteristics within the city limits. This study was the first attempt to evaluate the soil quality (physical, chemical and biological) for roadside soils of Singapore.

The primary objectives of the research were to assess the soil quality of Singapore's streetscape soils and to examine if, and which soil properties are correlated to street tree attributes in Singapore's streetscapes; secondarily, to test a few multi-parameter modeling approaches for predicting urban tree attributes across Singapore's street tree landscape. The hypothesis we tested

with this research was that tree attributes would be best correlated with soil properties in the minimum data set of Scharenbroch and Catania (2012). Specifically, tree attributes would be most strongly correlated with bulk density, pH, electrical conductivity, organic C and microbial biomass C. Soil texture was not expected to correlate with street tree attributes in this study since all planting sites had the similar texture class.

## Materials and methods

### Study area

Singapore is located between latitude 1°09'N and longitude 103°38'E at the southern tip of Peninsular Malaysia. The city-state comprises of one major island and some sixty smaller ones, and has a population of approximately four million people over a land area of 700 km<sup>2</sup>. Singapore has a tropical diurnal climate with mean monthly temperatures in the range of 26.4 to 27.8 °C and annual precipitation is around 2400 mm (Watts 1955). Singapore's soils are derived igneous rocks consisting of 'Bukit Timah' granite and 'Gambak' norite in the north and central-north (Public Works Department 1976; Pitts 1984). In the west and south-west soils are from sedimentary rocks of the 'Jurong' formation. Parent material is quaternary deposits of the old alluvium in the east. Recent alluvial deposits of the 'Kallang' formation are distributed throughout the island.

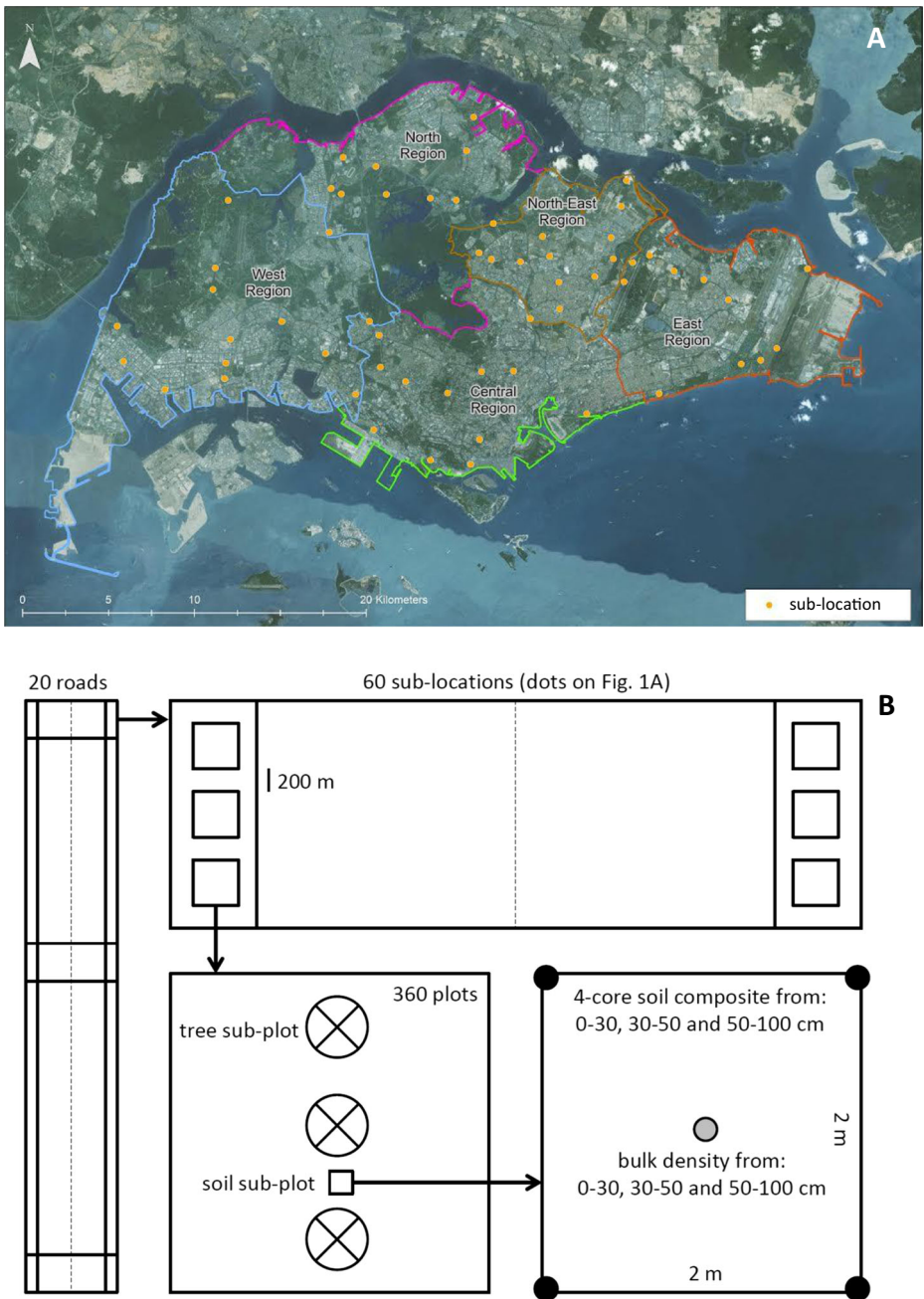
Singapore is comprised of five administrative regions according to Urban Redevelopment Authority (URA) Master Plan 2008: North, North-East, East, Central and West (Fig. 1). The West region is the largest and represents 33 % of Singapore, while the Northeast is the smallest region representing 14 % of Singapore. The important characteristics of these regions are depicted in Table 1.

Nearly 300,000 street trees are relatively evenly distributed throughout these regions (NParks 2014). In total, Singapore maintains over 3400 linear kilometers of roadway, and the adjacent street tree landscape comprises 13.5 % of all managed vegetation and 3.7 % of Singapore's total 716.5 km<sup>2</sup> total land area (Yee et al. 2011; Tan et al. 2013). These land transportation landscapes are a relatively recent product of Singapore's industrialization and urbanization since its independence in 1965 (Yuen 1996).

Road construction guidelines and prescribed tree planting strips that are physically isolated from underground utilities or infrastructure have rooting space of at least 2 m wide and 1 m deep (LTA 2014). Approved soil mix (ASM, 3:2:1 topsoil:compost:sand) from the National Parks Board (CUGE Standards 2013) is commonly used as a growing medium for urban tree plantations (Ghosh et al. 2015). The ASM has the following characteristics: >2 mm (57 %), 1 to 2 mm (25 %), 0.25 to 1 mm (14 %), 0.125 to 0.25 mm (2 %), <0.125 mm (2 %), organic matter (7.6 %), pH (6.45), CEC (8.5 cmol<sub>c</sub> kg<sup>-1</sup>), P (43.1 mg kg<sup>-1</sup>), K (335.6 mg kg<sup>-1</sup>), Ca (1088 mg kg<sup>-1</sup>) and Mg (66.9 mg kg<sup>-1</sup>) (Ghosh et al. 2012). Although the ASM was only formally accepted in 2009, prior tree planting and roadside soil construction was undertaken using similar specifications to the current ASM.

### Sample plots

For this research, four major roads were randomly selected in each of Singapore's five URA regions (Fig. 1a). Three sub-locations (at the point where the road begins, its middle point and at its end) for each of the 20 roads were identified (Fig. 1b). The 60 sub-locations were then further sub-divided into 360 plots, which were located at approximately 200 m intervals along



**Fig. 1** Regions of Singapore city-state according to URA master plan 2008 (a) and sampling protocol (b)

the entire accessible length of the sub-location. Each of the 360 plots contained three trees of identical species and similar age and condition. A soil sub-plot (four m<sup>2</sup>) was located near the plot center. GPS reference points were recorded for each tree and soil sub-plot. Twenty-two of the sample plots were removed from the analyses due to variability in tree age and condition

**Table 1** Important features of regions of Singapore

Factor	Central	East	North	Northeast	West
Parent material	Igneous	Alluvium	Igneous	Alluvium	Sediment
Mean elev. (m)	10.94	8.06	17.75	10.76	11.68
Total area (ha)	13,240	11,115	13,442	10,874	23,629
Total area (%)	18.30	15.41	18.58	15.03	32.67
Agriculture (%)	0.00	0.00	3.82	0.82	1.31
Built greenery (%)	16.78	13.18	41.32	55.54	22.60
Commercial (%)	21.20	33.37	23.06	12.22	41.82
Cemetery (%)	0.70	0.12	0.13	0.00	1.23
Transportation (%)	22.17	31.37	8.30	10.50	12.93
Residential (%)	35.67	18.19	9.90	17.81	10.19
Utility (%)	0.61	1.20	1.99	0.54	3.56
Water (%)	2.87	2.57	11.47	2.58	6.37
Street trees (% of population)	33.26	15.82	14.34	12.17	24.41

(Singapore National Parks Board, personal communication)

within a plot and, or missing tree or soil data. In total, 338 sample plots from Singapore's five regions at a mean density of 17 plots per road were included in this research.

### Soil properties

Five undisturbed soil samples were collected from the four corners and one center point of each 4 m<sup>2</sup> quadrant. Soils were collected with a core sampler (50 mm diameter) from the 0–30, 30–50 and 50–100 cm depths. The four cores per quadrant for each depth were composited and the composite was passed through a 2.0 mm sieve and stored at 4 °C until analyses of physical, chemical and biological properties were undertaken. The fifth core on each quadrant was used to determine bulk density at 0–30, 30–50 and 50–100 cm depths (Grossman and Reinsch 2002).

Soil organic carbon (SOC) was determined by Walkley-Black wet oxidation method (Walkley and Black 1934). Soil pH was measured in 1:5 soil:water suspension using a pH meter (Systronics, Model 1100, Gujarat, India) and the electrical conductivity (EC) of the supernatant suspension was measured using a conductivity bridge (Systronics, Model 304, Gujarat, India) (Sparks et al. 1996). Extractable phosphorus (P) was determined colorimetrically following the ascorbic acid reductant method as outlined by Watanabe and Olsen (1965). Exchangeable sodium (Na), potassium (K), calcium (Ca) and magnesium (Mg) content of the soils were determined by 1 M NH<sub>4</sub>OAc extraction method (Sparks et al. 1996). Soil samples were digested with aqua-regia and the heavy metal [Lead (Pb), Nickel (Ni) and Chromium (Cr)] concentrations were determined using atomic absorption spectrophotometry (Perkin Elmer, Model 2380, Massachusetts, USA). All soil analyses are reported on an oven-dry basis.

Field-moist soil samples, stored at 4 °C, were used to determine microbial properties. Chloroform (CHCl<sub>3</sub>) fumigation–extraction method was used to determine microbial biomass C (MBC) (Voroney and Paul 1984). Populations of bacteria, fungi and actinomycetes were enumerated by using standard serial dilution plate techniques (Waksman and Fred 1922).

Some potentially important soil properties have been excluded in these analyses due limited resources. Soil texture impacts a host of other soil properties (e.g., exchange capacity, moisture

relationships), but it was not assessed in this study. Soil texture did not vary across these planting sites due to the uniformity in soil specification of particle size separates. Furthermore, texture is a static soil property and is relatively resistant to change. Soil nitrogen (N) is also potentially important for tree growth and was not measured. However soil N has been shown to be a poor predictor of soil quality due to its temporal instability (Scharenbroch et al. 2005). Soil N is known to be tightly coupled to organic matter and microbial biomass (McGill and Cole 1981; Wardle 1992), properties which we have measured.

### Tree attributes

Three individuals of the same species, centered around each sample point were selected for assessment. That is, the individual tree nearest to the soil sample location provided a center point about which two adjacent neighbouring trees were also selected with one to the right and one to the left. The trees were almost always planted in uniformly spaced, even aged rows of the same species. Tree growth rates were determined by measuring trunk diameter at 1 m above the highest root using a diameter tape (Metric Diameter Tape, Forestry Suppliers Inc., Jackson, MS, USA) and total height was ascertained using a hypsometer (TruPulse 200B, Laser Technology Inc., Centennial, CO, USA) on two separate occasions over six months. Diameter and height growth rates (%  $\Delta$ ) were computed using the formula  $[(t_2 - t_1)/(t_1)] * 100$ , where  $t$  is diameter or height and frequency of measure.

The age class and canopy condition of all trees were assessed visually and assigned categorical scores between zero and three. Tree age was scored as young (0 = 0 to 20 years), semi-mature (1 = 21 to 40 years), mature (2 = 41 to 60 years), or senescent (3 = > 60 years). Growth rings and bud scars are not associated with a fixed time interval in the equatorial tropics. Age classes were determined qualitatively based on typical growth rates. Age class was intended to provide a coarse, first-order age classification of all tree specimens. Tree canopy condition was classified as undamaged (0), degenerated (1), stagnated (2), or resigned (3). Tree vitality was quantitatively assessed by randomly selecting five leaves from distributed areas in the canopy and measuring their light absorbance in the blue (400 to 500 nm) and red (600 to 700 nm) range with the SPAD-502 chlorophyll meter (Konica Minolta, Tokyo, Japan). The leaf color assessment does have some limitations, such as inherent variations due to species and tree age. However, leaf color has been found to be an acceptable surrogate for measuring leaf nutrient content (Chang and Robison 2003) and was chosen due to practicality and also because it is non-destructive sampling technique.

### Statistical analyses

Statistical analyses were conducted using SAS JMP 11.0 software (SAS Institute Inc., Cary, NC). The assumptions of constant variance and independence among residuals were checked with standard diagnostic plots. Normality in the data was checked for using the Shapiro-Wilk  $W$  test. All responses aside from bulk density required data transformation or non-parametric analyses. Tree and soil responses were analyzed for effects of region and depth using one-way ANOVA or Wilcoxon/Kruskal-Wallis (non-parametric). Mean separations were conducted using Tukey's HSD or Steel-Dwass (non-parametric) tests. A Bonferroni adjustment was used to protect for the type I error by adjusting the a priori  $\alpha$  level by dividing by the number of comparisons.

Soil properties were analyzed for their ability to predict street tree attributes using four modeling approaches. First, single soil properties were tested with a fit  $y$  by  $x$  pair-wise test against single tree attributes. The  $F$ -test and  $R$ -correlations values were used to evaluate these

pairwise correlations. A full model (ANOVA standard least squares) that included all independent parameter estimates was created for predicting each tree attribute. The full model was tested as the largest soil data set that might be required to evaluate tree performance in these planting spaces. An expert model included bulk density (Db), pH, electrical conductivity (EC), organic C (OC) and microbial biomass C (MBC) was tested to predict urban tree attributes. The expert model represented a data set that has been identified to predict urban tree performance in street tree landscapes near Chicago, IL (Scharenbroch and Catania 2012). The last modeling approach was a principal component analyses (PCA). The PCA was performed on correlations with varimax rotation. Model comparisons were made using the F-test,  $R^2$  and root mean square error (RMSE) values. The F-test ( $P \leq 0.05$ ) was used to evaluate the null hypothesis that all regression coefficients are equal to zero. The  $R^2$  is a relative measure of fit with values closer to one indicating better fit. The RMSE is an absolute measure of fit, with lower values indicating better fit.

## Results and discussion

### Tree attributes

In total, 338 street trees plots and 1014 individual trees (three trees per plot) were sampled. The street tree plots included 32 tree species (Table 2). Total number of sampled trees was relatively evenly distributed across Singapore's five regions, however species were not. Over half (61 %) of the sampled street tree plot population was represented by five species: *Albizia saman* (29 %), *Peltophorum pterocarpum* (12 %), *Khaya senegalensis* (8 %), *Swietenia macrophylla* (8 %) and *Khaya grandifoliola* (4 %); and, only these five major species were sampled in more than two regions.

The overall mean tree diameter was 34.9 cm and overall mean tree height was 11.9 m. Diameters and heights varied with species (Table 2) and region (Table 3). Diameters ranged from 7.5 cm (*Terminalia catappa*) to 81.8 cm (*Washingtonia robusta*). Tree heights ranged from 3.8 m (*Cordia sebestena*) to 26.1 m (*Washingtonia robusta*). Diameters were greater in the Northeast compared to Central and Eastern regions. Diameters in the North were greater than in the East. Tree height was greater in the North and Central compared to the East. The overall diameter distribution is skewed towards smaller trees with 75 % of the trees <65 cm in diameter and 50 % of trees <47 cm in diameter.

The overall mean diameter and height growth rates were 1.6 %  $\Delta$  and 4.0 %  $\Delta$ , respectively. Diameter growth rate was significantly greater in the East region (2.82 %  $\Delta$ ) compared to the other four regions (Table 3). The greatest diameter growth rate (18.2 %  $\Delta$ ) was found for *Talipariti tiliaceum* in the East (Fig. 2). The lowest diameter growth rate (0.6 %  $\Delta$ ) was for *Albizia saman* in the East. Height growth rate did not differ among Singapore's five regions (data not shown). The greatest and lowest height growth rates measured were for *Dalbergia oliveri* (21.0 %  $\Delta$ ) and *Alstonia angustiloba* (0.85 %  $\Delta$ ), respectively.

Overall mean leaf color was 48.6 SPAD units. Leaf color ranged from 40.2 SPAD units for *Millettia pinnata* to 76.7 SPAD units for *Washingtonia robusta*. The overall mean tree condition rating was 0.32. Tree condition class ranged from 0.0 (14 species) to 1.1 for *Pachira obovata*. Tree age class ranged from 0 (young) to 2 (mature), with means of 1.07 to 1.37 (semi-mature). Neither leaf color, condition nor age class significantly varied among Singapore's five regions.

**Table 2** Total and distribution of street tree plots in Central (C), East (E), North (N), Northeast (NE) and West (W) regions of Singapore with mean diameter (cm) and height (m)

<i>Genus species</i>	$\Sigma$	C	E	N	NE	W	Dia. (cm)	Height (m)
<i>Albizia saman</i>	99	9	24	18	27	21	69.4	13.5
<i>Alstonia angustiloba</i>	3	3	-	-	-	-	34.9	10.2
<i>Bismarckia nobilis</i>	6	-	-	6	-	-	35.0	11.5
<i>Buchanania arborescens</i>	1	1	-	-	-	-	12.0	6.40
<i>Callerya atropurpurea</i>	6	-	-	6	-	-	42.0	13.4
<i>Callistemon citrinus</i>	2	-	-	-	-	2	20.5	6.32
<i>Cassia fistula</i>	11	-	11	-	-	-	33.1	12.9
<i>Cocos nucifera</i>	1	-	-	-	-	1	35.0	14.4
<i>Cordia sebestena</i>	6	-	-	-	-	6	7.68	3.81
<i>Dalbergia oliveri</i>	7	-	-	-	7	-	26.6	10.2
<i>Erythrophleum suaveolens</i>	12	-	12	-	-	-	43.7	16.6
<i>Fagraea fragrans</i>	11	11	-	-	-	-	16.7	8.95
<i>Hopea odorata</i>	9	-	-	-	6	3	21.8	9.39
<i>Khaya grandifoliola</i>	13	-	6	-	6	1	39.1	13.0
<i>Khaya senegalensis</i>	28	5	-	5	8	10	77.6	22.1
<i>Lagerstroemia speciosa</i>	1	-	1	-	-	-	31.7	8.43
<i>Maniltoa browneoides</i>	3	3	-	-	-	-	13.1	9.64
<i>Mesua ferrea</i>	2	-	-	2	-	-	46.5	13.2
<i>Millettia pinnata</i>	1	-	-	-	-	1	11.1	4.93
<i>Pachira obovata</i>	6	-	-	-	6	-	17.1	8.08
<i>Peltophorum pterocarpum</i>	41	16	-	18	6	1	40.3	13.5
<i>Roystonea oleracea</i>	7	-	1	-	-	6	30.0	8.56
<i>Sterculia parviflora</i>	1	-	-	1	-	-	23.4	10.6
<i>Swietenia macrophylla</i>	27	3	-	16	2	6	50.6	16.3
<i>Syzygium grande</i>	9	3	-	-	-	6	44.9	13.8
<i>Tabebuia rosea</i>	4	-	-	-	-	4	51.8	19.6
<i>Talipariti tiliaceum</i>	3	-	3	-	-	-	44.0	12.4
<i>Terminalia catappa</i>	3	-	3	-	-	-	7.51	4.21
<i>Terminalia muelleri</i>	2	-	-	-	-	2	40.6	14.2
<i>Terminalia phellocarpa</i>	1	-	-	-	-	1	35.3	10.9
<i>Washingtonia robusta</i>	1	-	-	-	1	-	81.8	26.1
<i>Xanthostemon chrysanthus</i>	11	-	11	-	-	-	35.0	12.3
Total or mean	338	54	72	72	69	71	34.9	11.9

This research was not intended to be a comprehensive survey of street tree landscapes of Singapore. However, it is still useful to add some context to these data by comparing what was observed to the local urban forests. A survey of the urban forest of Guangzhou, China found 120 species in roadside plantings, with ten species representing over 70 % of the population (Jim and Liu 2001). In this study, 32 species were found, with five species representing over 60 % of the population. Jim and Liu (2001) found the roadside forest of Guangzhou, China to be dominated by native broad-leaved trees. Singapore's street tree population is currently dominated by non-native broadleaf trees.

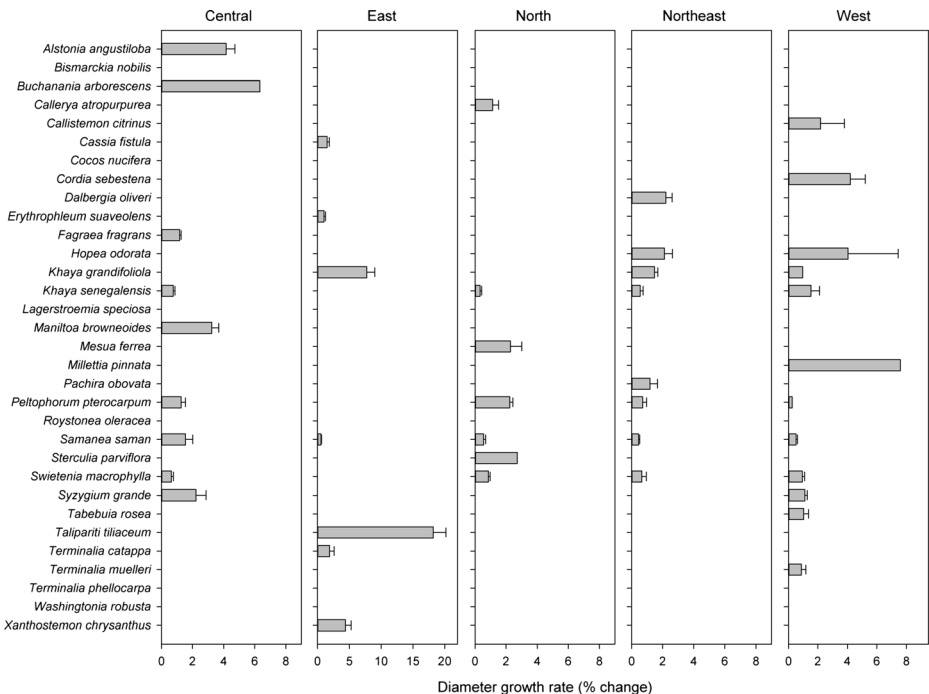


**Table 3** Diameter, diameter growth rate, height, height growth rate, leaf color, condition and age class of street tree landscapes in Singapore’s five regions

Tree attribute	Central	East	North	Northeast	West	Prob > F
Diameter (cm)	43.0bc	41.6c	53.6ab	57.8a	49.9abc	0.0007
Dia. growth (% Δ)	1.60b	2.82a	1.24b	1.02b	1.49b	0.0002
Height (m)	14.6a	12.2b	14.5a	14.3ab	13.2ab	0.0153
Ht. growth (% Δ)	2.86	4.62	3.38	4.39	4.59	0.1384
Leaf color (SPAD)	48.1	49.0	50.6	47.7	47.4	0.1309
Condition class	0.278	0.266	0.243	0.423	0.369	0.0573
Age class	1.07	1.19	1.36	1.37	1.18	0.0533

Footnote: Unique letters identify significant ( $P \leq 0.05$ ) differences across regions using Tukey’s HSD test

Like other urban forests in the region, the diameter distribution of Singapore’s street trees is skewed towards trees with smaller diameters (e.g., Beijing, China) (Yang et al. 2005). However, it is not as heavily skewed as the younger urban forest of Bangalore, India, which had more than 70 % of its trees with diameters <15 cm in DBH (Sudha and Ravindranath 2000). Yang et al. (2005) found 29 % of Beijing’s urban trees to be classified in poor condition. In contrast, the majority of Singapore’s street trees were found to be in good condition with very little damage.



**Fig. 2** Diameter growth rate (% change) of street trees in Singapore by region and species

## Soil properties

In total, 338 plots and 1014 individual soil layers (0–30, 30–50 and 50–100 cm) were sampled. Sixteen of the measured 17 soil properties varied significantly by region (Table 4). Only soil bulk density and organic C varied by depth. Soil bulk density was highest in the 30–50 cm layer ( $1.32 \text{ Mg m}^{-3}$ ), followed by 0–30 cm layer ( $1.21 \text{ Mg m}^{-3}$ ) and lowest in the 50–100 cm layer ( $1.07 \text{ Mg m}^{-3}$ ). Although a significant depth effect was detected for soil organic C, significant differences were not detected with Tukey's HSD among the 0–30 cm, 30–50 cm and 50–100 cm layers.

The tree planting areas (verge) were relatively wide (5 to 7 m) compared to the confined urban tree spaces in many other city centers where the planting space has to be shared with other infrastructure (Table 5). Verge was greater in the Central compared to the Northeast region.

Across all regions, soil bulk densities were relatively low ( $1.05$  to  $1.45 \text{ Mg m}^{-3}$ ) and tended to be lowest in the West region. Soil bulk densities are comparable to similar soils in other urban areas, but lower, than that in sandy soils used in roadside plantings in of Hong Kong (mean of  $1.7$  with a range of  $1.1$  to  $2.6 \text{ Mg m}^{-3}$ ) (Jim 1998). In general, a bulk density above  $1.8 \text{ Mg m}^{-3}$  is regarded as restrictive to tree root growth for sandy soils (Craul and Patterson 1989). Given that bulk density values were relatively low, compaction is unlikely to be a major factor limiting tree growth on these sites.

Soil pH ranged from 6.04 to 7.63, and was highest in the Central and lowest in the North region (Table 5). Acidic soil pH is to be expected in a humid tropical environment and pH values of Singapore's primary and secondary forests (0 to 40 cm) were measured to be between 3.6 to 4.7 (Sim et al. 1992; Grubb et al. 1994). Elevated pH values in these roadside

**Table 4** Prob > F for effects of region (Central, East, North, Northeast and West), depth (0–30, 30–50 and 50–100 cm) and region x depth for soil properties in Singapore's street tree landscapes

Soil property	Region	Depth	Region x Depth
Verge (m)	<0.0001	-	-
Bulk density ( $\text{Mg m}^{-3}$ )	<0.0001	<0.0001	<0.0001
pH (0–30)	<0.0001	0.5290	1.0000
Electrical cond. ( $\text{dS m}^{-1}$ )	0.0087	0.0347	0.2507
Phosphorus ( $\text{mg kg}^{-1}$ )	<0.0001	0.5503	0.6543
Potassium ( $\text{mg kg}^{-1}$ )	<0.0001	0.4443	0.9997
Calcium ( $\text{mg kg}^{-1}$ )	<0.0001	0.7540	0.9743
Magnesium ( $\text{mg kg}^{-1}$ )	0.0008	0.7393	0.6924
Sodium ( $\text{mg kg}^{-1}$ )	<0.0001	0.7163	0.6831
Chromium ( $\text{mg kg}^{-1}$ )	<0.0001	0.5037	0.9723
Lead ( $\text{mg kg}^{-1}$ )	<0.0001	0.8564	0.9994
Nickel ( $\text{mg kg}^{-1}$ )	<0.0001	0.8977	0.6142
Organic C (%)	0.0087	0.0347	0.2507
Micr. biomass C ( $\text{mg kg}^{-1}$ )	<0.0001	-	-
Fungi ( $\text{mg kg}^{-1}$ )	<0.0001	0.9576	0.7249
Bacteria ( $\text{mg kg}^{-1}$ )	<0.0001	0.6328	0.8905
Actinomycetes ( $\text{mg kg}^{-1}$ )	0.2266	0.7692	0.9969

**Table 5** Soil properties by region and depth in Singapore's street tree landscapes

Soil property	Central	East	North	Northeast	West	Prob > F
Verge (m)	7.51a	5.58ab	7.02ab	5.20b	5.67ab	0.0068
Bulk density ( $\text{Mg m}^{-3}$ )						
0–30 cm	1.24a	1.21ab	1.22ab	1.24a	1.14b	0.0136
30–50 cm	1.27bc	1.45a	1.30bc	1.36ab	1.23c	<0.0001
50–100 cm	1.10a	1.05ab	1.11a	1.11ab	1.02b	0.0204
pH (1:1)						
0–30 cm	7.39a	6.56ab	6.04b	6.53ab	7.06a	0.0003
30–50 cm	7.43a	6.59abc	6.15c	6.57bc	7.04ab	0.0005
50–100 cm	7.63a	6.72bc	6.21c	6.68bc	7.09ab	0.0001
Electrical cond. ( $\text{dS m}^{-1}$ )						
0–30 cm	0.193a	0.054c	0.159a	0.099b	0.086bc	<0.0001
30–50 cm	0.188a	0.045b	0.171a	0.080b	0.068b	<0.0001
50–100 cm	0.178a	0.050c	0.132b	0.080c	0.076c	<0.0001
Phosphorus ( $\text{mg kg}^{-1}$ )						
0–30 cm	1.77b	1.56b	2.87a	1.72b	1.52b	0.0004
30–50 cm	1.60b	1.56b	2.61a	1.88ab	1.09b	<0.0001
50–100 cm	1.69ab	1.91a	2.47a	1.77ab	1.00b	<0.0001
Potassium ( $\text{mg kg}^{-1}$ )						
0–30 cm	47.48b	129.60a	27.63b	48.30b	107.15a	<0.0001
30–50 cm	40.98b	122.31a	28.56b	41.78b	96.85a	<0.0001
50–100 cm	44.33b	123.40a	25.67b	42.88b	99.65a	<0.0001
Calcium ( $\text{mg kg}^{-1}$ )						
0–30 cm	1699a	1,132b	1056b	1,442ab	1,326ab	0.0005
30–50 cm	1772a	1,219bc	930b	1,481ab	1,404ab	<0.0001
50–100 cm	1,673a	1,272ab	924b	1,376ab	1,326ab	0.0003
Magnesium ( $\text{mg kg}^{-1}$ )						
0–30 cm	631.1a	450.5ab	312.9b	439.6ab	437.6ab	0.0172
30–50 cm	552.5a	399.4a	412.3a	473.2a	358.8a	0.3394
50–100 cm	491.5a	421.8a	339.3a	512.7a	356.3a	0.0687
Sodium ( $\text{mg kg}^{-1}$ )						
0–30 cm	130.0b	191.7a	193.3a	162.7ab	207.4a	0.0026
30–50 cm	130.2a	186.6a	186.4a	206.3a	203.7a	0.1148
50–100 cm	142.5b	208.4a	208.1a	168.4ab	201.1ab	0.0093
Chromium ( $\text{mg kg}^{-1}$ )						
0–30 cm	174.7b	143.3c	211.5a	202.4a	203.9a	<0.0001
30–50 cm	172.8bc	146.1c	209.2a	191.5ab	194.2ab	<0.0001
50–100 cm	166.8b	144.9b	208.3a	194.1a	201.3a	<0.0001
Lead ( $\text{mg kg}^{-1}$ )						
0–30 cm	57.57a	62.50a	62.39a	74.36a	61.68a	0.0668
30–50 cm	55.01b	63.17ab	62.67ab	73.51a	61.05ab	0.0355
50–100 cm	60.29a	63.33a	64.28a	72.54a	62.17a	0.2375
Nickel ( $\text{mg kg}^{-1}$ )						
0–30 cm	24.37a	27.96a	27.15a	15.36b	27.54a	<0.0001
30–50 cm	24.41a	25.51a	25.71a	15.39b	29.62a	<0.0001

**Table 5** (continued)

Soil property	Central	East	North	Northeast	West	Prob > F
50–100 cm	24.68ab	25.76a	25.89a	18.49b	27.87a	0.0005
Organic C (%)						
0–30 cm	10.55a	9.98a	10.80a	11.42a	8.68a	0.2132
30–50 cm	10.09ab	9.48ab	6.97b	10.17a	9.16ab	0.0484
50–100 cm	8.92a	10.25a	8.20a	10.03a	7.78a	0.0722
Micr. biomass C (mg kg <sup>-1</sup> )						
0–30 cm	264.9c	285.8bc	272.7bc	457.3a	312.4b	<0.0001
Fungi (mg kg <sup>-1</sup> )						
0–30 cm	2.43a	2.76a	2.69a	1.57b	2.75a	<0.0001
30–50 cm	2.50a	2.56a	2.54a	1.51b	2.94a	<0.0001
50–100 cm	2.50a	2.54a	2.54a	1.82b	2.74a	0.0012
Bacteria (mg kg <sup>-1</sup> )						
0–30 cm	17.54b	14.42c	21.35a	20.43a	20.32a	<0.0001
30–50 cm	17.56b	14.64c	20.93a	19.11ab	19.79ab	<0.0001
50–100 cm	16.75b	14.63b	20.72a	20.51a	20.28a	<0.0001
Actinomycetes (mg kg <sup>-1</sup> )						
0–30 cm	15.76a	16.25a	16.24a	16.18a	16.17a	0.8454
30–50 cm	15.50a	16.32a	16.27a	16.10a	16.11a	0.3892
50–100 cm	16.01a	16.33a	16.43a	16.01a	16.22a	0.8379

Footnote: Unique letters identify significant ( $P \leq 0.05$ ) differences across regions within each soil depth using Tukey's HSD test

plantings, especially in central region might be due to dissolution of calcareous materials (e.g., cement) present in the built environment (Table 1). Jim (1998) reported similar alkalinity in Hong Kong's roadside soils (6.8 to 10). Soil pH values of other urban and streetscape soils range from 3.3 to 7.6 in Baltimore, USA (Pouyat et al. 2007), 7.1 to 8.2 in suburban Chicago, USA (Scharenbroch and Catania 2012) and 6.6 to 8.3 in Kielce, Poland (Gałuszka et al. 2011). We suspect that the majority of these tree species would perform better with a more acidic soil, and it may be that soil pH is a potential limitation to tree performance.

Soil P levels ranged from 1.00 to 2.87 mg kg<sup>-1</sup> (Table 5). Soil P was greatest in the North and lowest in the West region. Concentrations of soil P were much higher than those observed in Singapore's forest soils (0.04 to 0.11 mg kg<sup>-1</sup> via sulfuric acid plus hydrogen peroxide extraction), which are reported to be P deficient (Sim et al. 1992; Grubb et al. 1994). These concentrations of soil P were within similar ranges of streetscape soils in Hong Kong (0.8 to 30.3 mg kg<sup>-1</sup> via Olsen method) (Jim 1998), but lower than those reported in Baltimore, USA (5 to 1154 mg kg<sup>-1</sup> via Mehlich-1 extraction) (Pouyat et al. 2007), suburban Chicago, USA (7.2 to 18.1 mg kg<sup>-1</sup> via Bray method) (Scharenbroch and Catania 2012), Kielce, Poland (400 to 1100 mg kg<sup>-1</sup> via nitric acid plus hydrogen peroxide extraction) (Gałuszka et al. 2011) and also Riga, Latvia (254 to 1044 mg kg<sup>-1</sup> via nitric acid plus hydrogen peroxide extraction) (Cekstere and Osvalde 2013). These streetscape soil P levels would be considered highly productive for growing trees (Wilde et al. 1979) and a soil P limitation is not apparent, though it is often observed in tropical forested systems (Vitousek and Sanford 1986).

Levels of exchangeable K in these soils ranged from 27 to 130 mg kg<sup>-1</sup> (Table 5). Soil K was greater in the East and West compared to North, Northeast and Central regions. Grubb

et al. (1994) reported much higher K concentrations in Singapore's forest soils (810 to 2050 mg kg<sup>-1</sup>) due to high concentration of K in parent rock. Potassium concentrations in these soils are similar to urban soils in Baltimore, USA (12 to 280 mg kg<sup>-1</sup>) (Pouyat et al. 2007) and suburban Chicago, USA (140 to 199 mg kg<sup>-1</sup>) (Scharenbroch and Catania 2012). According to Cekstere and Osvalde (2013), soil K concentrations lower than 200 mg kg<sup>-1</sup> might lead to tree stress. Furthermore, Na might interfere with K uptake and K:Na ratios less than 2.5:1 might be further evidence of K limitation (Cekstere and Osvalde 2013). Our K:Na ratios ranged from 0.14 to 0.67, with a mean of 0.44. Limited availability of K might be a concern for these trees in Singapore's streetscapes, and K fertilization may be considered.

Levels of Ca and Mg in Singapore's streetscape soils were 1056 to 1699 mg kg<sup>-1</sup> and 313 to 631 mg kg<sup>-1</sup>, respectively (Table 5). Calcium and Mg were greatest in the Central and lowest in the North region. Concentrations of Ca and Mg were similar to those reported in Baltimore, USA (18 to 5634 and 21 to 388 mg kg<sup>-1</sup> for Ca and Mg, respectively) (Pouyat et al. 2007) and suburban Chicago, USA (867 to 1190 and 641 to 797 mg kg<sup>-1</sup> for Ca and Mg, respectively) (Pouyat et al. 2007); but, lower than in Kielce, Poland (1600 to 57,600 and 1000 to 4900 mg kg<sup>-1</sup> for Ca and Mg, respectively) (Gałuszka et al. 2011) and also Riga, Latvia (4367 to 50,260 and 1472 to 2960 mg kg<sup>-1</sup> for Ca and Mg, respectively) (Cekstere and Osvalde 2013). We observed an acceptable range of Ca:Mg ratios from 2.5 to 3.4, with a mean of 2.9, and it is unlikely that Ca or Mg concentrations are limiting tree growth in these streetscapes (Wilde et al. 1979).

Sodium concentrations of these streetscape soils were 130 to 207 mg kg<sup>-1</sup>, with the lowest values in the Central region (Table 5). Sodium concentrations were similar to Baltimore, USA (20 to 388 mg kg<sup>-1</sup>) (Pouyat et al. 2007), suburban Chicago, USA (64 to 124 mg kg<sup>-1</sup>) (Scharenbroch and Catania 2012), Kielce, Poland (100 to 800 mg kg<sup>-1</sup>) (Gałuszka et al. 2011) and Riga, Latvia (56 to 1568 mg kg<sup>-1</sup>) (Cekstere and Osvalde 2013). Sodium concentrations in excess of 250 mg kg<sup>-1</sup> might be considered excessive for most trees (Hootman et al. 1994). Although Na concentrations in these soils are relatively high, these soils had low electrical conductivity (< 2 dS m<sup>-1</sup>) and low sodium adsorption ratios (0.002 to 0.005), so are not sodic. This data suggests that soil salinity (Na) may be an issue for street tree growth and the overall tree health in Singapore's streetscapes. Salts are not needed for deicing roads in Singapore and wind-induced salt spray is minimal. We suspect that the source of elevated soil Na levels in these streetscape soils might be from the sand used in these mixes that is dredged from the sea floor.

Soil Cr, Pb and Ni ranged from 143 to 212, 55 to 74 and 15 to 30 mg kg<sup>-1</sup>, respectively (Table 5). Soil Cr tended to be lowest in the East, Ni was lowest in the West, and Pb tended to be highest in the Northeast. As expected these heavy metal concentrations are higher than soils in most natural areas of Singapore (10.3 to 25.6 and 1.1 to 3.9 mg kg<sup>-1</sup> for Pb and Ni, respectively) (Ng et al., 2006). Heavy metal concentrations in Singapore's urban streetscape soils are within similar ranges of those found in other urban areas, such as in Baltimore, USA (8 to 794, 4 to 5652 and 5 to 336 mg kg<sup>-1</sup> for Cr, Pb and Ni, respectively) (Pouyat et al. 2007) or Riga, Latvia (3.3 to 15.0, 18.4 to 118 and 0.5 to 2.0 mg kg<sup>-1</sup> for Cr, Pb and Ni, respectively) (Cekstere and Osvalde 2013). Elevated concentrations of heavy metals in streetscape soils are not surprising given that studies have shown high accumulations in areas of high road density (Linde et al. 2001; Madrid et al., 2004). Due to the neutral soil reaction and high organic matter contents, it is unlikely that these concentrations of Cr, Pb and Ni are deleterious to tree health.

Organic C contents ranged from 6.7 to 11.4 % and did not vary much by region (Table 5). Organic C contents of streetscape soils are high when compared to Singapore's forest soils (1.8

to 8.1 %) (Sim et al. 1992; Grubb et al. 1994). In relation to other streetside plantings, soil organic C in Singapore are higher than in Hong Kong (0.1 to 4.1 %) (Jim 1998), suburban Chicago, USA (2.5 to 3.8 %) (Scharenbroch and Catania 2012) or (0.8 to 10.4 %) Kielce, Poland (Gałuszka et al. 2011). Elevated organic C in Singapore's streetscapes was expected because these are engineered soils and the specification calls for large amounts of compost to be included (CUGE Standards 2013).

Total microbial biomass C, fungi, bacteria and actinomycetes ranged from 265 to 457 mg kg<sup>-1</sup>, 1.5 to 2.8 mg kg<sup>-1</sup>, 14 to 21 mg kg<sup>-1</sup> and 15 to 16 mg kg<sup>-1</sup>, respectively (Table 5). Total microbial biomass was highest in the Northeast and lowest in the Central. Fungi was lowest in the Northeast. Bacteria was lowest in the East and highest in the North. No data is available to compare soil microbial biomass obtained from streetscapes to that of Singapore's forest or natural soils. Soil microbial biomass was within range of streetscapes in suburban Chicago, USA (520 to 760 mg kg<sup>-1</sup>) (Scharenbroch and Catania 2012) and also in street tree planting sites in Moscow, ID and Pullman, WA in USA (317 to 342 mg kg<sup>-1</sup>) (Scharenbroch et al. 2005).

### Modeling tree attributes with soil properties

Correlations among tree attributes and soil properties were strongest with the 0–30 cm soil samples compared to the 30–50 cm, 50–100 cm and total 0–100 cm samples (data not shown). Therefore all modeling with tree attributes and soil properties was conducted on the 0–30 cm soil samples.

Some individual soil properties were significantly correlated with tree diameter growth, height growth and leaf color (Table 6). No soil properties were significantly correlated with tree condition class. Diameter growth was positively correlated with pH, K, Ca, Na; and, negatively correlated with Pb and actinomycetes. Tree height growth was positively correlated with Cr and Fungi. Leaf color was negatively correlated with K. Although some of these correlations were significant, they were relatively weak ( $R^2 \leq 0.09$ ).

Of all soil properties, pH, K, Ca, Na, Pb and actinomycetes appeared to best correlated to tree attributes. Other properties, like verge, bulk density, electrical conductivity and P were unexpectedly not correlated with any tree attributes. It is reasonable to speculate that a property like soil pH was a better predictor of tree attributes compared to other properties like P or bulk density because the latter properties did not appear to be in the range that would potentially limit tree growth. Conversely, soil pH values tended to be substantially higher than the forest soils of Singapore, which presumably would represent conditions to be mimicked for growing trees in the nearby urban environment.

Three modeling approaches were tested to see if tree attributes could be better predicted with a combination of soil properties (Table 7). The full model included all of the soil properties. The expert model tested in this research included five (soil bulk density, pH, electrical conductivity, total organic matter, and microbial biomass) of the seven properties identified by Scharenbroch and Catania (2012). Data was not available for soil texture and wet aggregate stability, therefore was not included in this modeling. The first principal component from the PCA was used as the independent variable for the last modeling approach (Table 7). The first principal component (PC1) explained 21 % and the second (PC2) explained 13 % of the variance in soil properties (Fig. 3). PC1 was most positively loaded with pH, Ca and MBC; and, negatively loaded with Pb, actinomycetes and fungi. Differences in soil properties among Singapore's five regions were not discernible with the PCA. The full, expert and PCA models (Fig. 3) for predicting diameter growth were significant, but not very strong ( $R^2$  of 0.04 to

**Table 6** R-values for pair-wise correlation analyses of soil properties (0–30 cm) and tree attributes from Singapore's street tree landscapes

Soil property	Diameter growth (% $\Delta$ )	Height growth (% $\Delta$ )	Leaf color (SPAD)	Condition Class
Verge (m)	-	-	-	-
Db (Mg m <sup>-3</sup> )	-	-	-	-
pH (1:1)	0.17**	-	-	-
EC (dS m <sup>-1</sup> )	-	-	-	-
P (mg kg <sup>-1</sup> )	-	-	-	-
K (mg kg <sup>-1</sup> )	0.24***	-	-0.15*	-
Ca (mg kg <sup>-1</sup> )	0.20**	-	-	-
Mg (mg kg <sup>-1</sup> )	-	-	-	-
Na (mg kg <sup>-1</sup> )	0.19**	-	-	-
Cr (mg kg <sup>-1</sup> )	-	0.15*	-	-
Pb (mg kg <sup>-1</sup> )	-0.16**	-	-	-
Ni (mg kg <sup>-1</sup> )	-	-	-	-
OC (%)	0.14*	-	-	-
MBC (mg kg <sup>-1</sup> )	-	-	-	-
Fungi (mg kg <sup>-1</sup> )	-	0.16*	-	-
Bact (mg kg <sup>-1</sup> )	-	-	-	-
Actino (mg kg <sup>-1</sup> )	-0.18**	-	-	-

Footnote: \* is  $P \leq 0.05$ , \*\* is  $P \leq 0.01$ , \*\*\* is  $P \leq 0.0001$

0.25; RMSE of 2.44 to 24.6). The full, expert and PCA models were not significant for height growth rate, leaf color nor condition class.

Our hypothesis that tree attributes would be most strongly correlated with bulk density, pH, electrical conductivity, organic C and microbial biomass C was not supported. Of these properties only pH was significantly correlated with tree attributes. Furthermore, for our hypothesis to be supported the expert model would have outperformed the other models for predicting street tree attributes and this was not the case. Our data do not support the minimum data set of soil properties proposed by Scharenbroch and Catania (2012) for predicting urban tree performance.

Overall, these modeling approaches performed relatively poorly for predicting urban street tree attributes across Singapore's five regions. However, both relative and absolute measures of fit improved substantially when Singapore's regions were examined separately (Table 8). For example,  $R^2$  values for full model diameter growth rate increased from 0.18 (all regions) to 0.44 (Central) and to as high as 0.63 in the Eastern region. Because soil models improved substantially when examined at the regional level, soil limitations to tree growth in streetscapes might vary by region, and are unlikely to be consistent across the entire city-state of Singapore. For example, soil bulk density was highest in Northeast region, the Northern region had the lowest concentrations of soil K and soil pH was highest in the Central region.

Similar studies have been conducted in other urban areas attempting to use soil properties for predicting street tree growth (Scharenbroch and Catania 2012; Cekstere and Osvalde 2013). Soil properties in Singapore appear to be less influential on street tree attributes compared to these other studies. We propose that Singapore's street trees are less influenced by soil quality due to

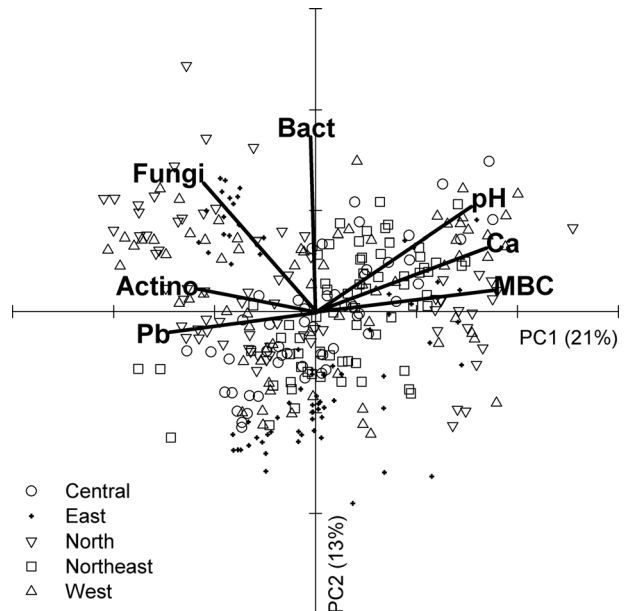
**Table 7** Soil property (0–30 cm) models for predicting diameter, diameter growth rate, height, height growth rate, leaf color, condition and age of Singapore’s street tree landscapes

Tree attribute	Prob > F	R <sup>2</sup>	RMSE	Parameters
<b>Full model</b>				
Dia. growth (% Δ)	<0.0001	0.18	2.50	All
Ht. growth (% Δ)	0.2033	0.09	4.39	All
Leaf color (SPAD)	0.3859	0.09	7.40	All
Condition class	0.3518	0.08	0.40	All
<b>Expert model</b>				
Dia. growth (% Δ)	0.0273	0.05	2.61	Db, pH, EC, OC, MBC
Ht. growth (% Δ)	0.8949	0.01	4.40	Db, pH, EC, OC, MBC
Leaf color (SPAD)	0.7352	0.01	7.58	Db, pH, EC, OC, MBC
Condition class	0.3745	0.02	0.41	Db, pH, EC, OC, MBC
<b>PCA model</b>				
Dia. growth (% Δ)	0.0008	0.04	2.44	pH, Ca, Na, MBC, Pb, Actino, Fungi
Ht. growth (% Δ)	0.1833	0.01	4.36	pH, Ca, Na, MBC, Pb, Actino, Fungi
Leaf color (SPAD)	0.2910	0.00	7.71	pH, Ca, Na, MBC, Pb, Actino, Fungi
Condition class	0.9306	0.00	0.41	pH, Ca, Na, MBC, Pb, Actino, Fungi

three primary reasons: (1) relatively high soil quality in Singapore’s streetscapes, (2) uniformity of Singapore’s streetscape soils and (3) the relatively fast growth rates of trees in tropical climates.

The study by Scharenbroch and Catania (2012) found that street tree growth was well correlated with many soil properties and the model they developed included physical, chemical and biological properties. The soils in suburban Chicago, USA, had finer textures, lower

**Fig. 3** Principal component 1 and 2 and loading factors for soil properties (0–30 cm) of street trees in Singapore by region





**Table 8** Soil property (0–30 cm) models for predicting diameter growth rate by five regions of Singapore’s street tree landscapes

Diameter growth	Prob > F	R <sup>2</sup>	RMSE	Parameters
<b>Full model</b>				
All regions	<0.0001	0.18	2.50	All
Central	0.0937	0.44	1.25	All
East	<0.0001	0.63	3.04	All
North	0.0056	0.48	0.83	All
Northeast	0.0029	0.57	0.75	All
West	0.0028	0.53	1.68	All
<b>Expert model</b>				
All regions	0.0273	0.05	2.61	Db, pH, EC, OC, MBC
Central	0.0075	0.28	1.23	Db, pH, EC, OC, MBC
East	0.0401	0.17	4.08	Db, pH, EC, OC, MBC
North	0.0068	0.24	1.25	Db, pH, EC, OC, MBC
Northeast	<0.0001	0.47	0.72	Db, pH, EC, OC, MBC
West	0.1350	0.14	2.00	Db, pH, EC, OC, MBC
<b>PCA model</b>				
All regions	0.0008	0.04	2.44	pH, Ca, Na, MBC, Pb, Actino, Fungi
Central	0.6904	0.00	1.40	pH, Ca, Na, MBC, Pb, Actino, Fungi
East	0.0054	0.11	4.10	pH, Ca, Na, MBC, Pb, Actino, Fungi
North	0.0001	0.22	0.88	pH, Ca, Na, MBC, Pb, Actino, Fungi
Northeast	0.0004	0.21	0.85	pH, Ca, Na, MBC, Pb, Actino, Fungi
West	0.0836	0.05	2.04	pH, Ca, Na, MBC, Pb, Actino, Fungi

organic matter contents, poor drainage and high pH values; making them difficult substrates for growing street trees. It is likely that the soil properties were more tightly linked to tree attributes in these other studies (Scharenbroch and Catania 2012; Cekstere and Osvalde 2013) because soils in Chicago, USA and Riga, Latvia were generally poor in quality. In comparison, Singapore’s streetscape soils have low bulk densities, high organic matter and microbial populations and adequate nutrient concentrations. Aside from a slightly alkaline soil pH and a potential deficiency in K, Singapore’s streetscape soils are well-suited for growing trees.

Overall, variation in soil properties by depth and across Singapore’s streetscapes was minimal, as evidenced by non-discernible regional differences in the PCA. Although significant regional differences were detected with some soil properties, the differences in soil properties across regional scales are likely of little biological relevance. For example, soil bulk density was greater in the Northeast compared to the West, but the difference is a drop of  $0.08 \text{ Mg m}^{-3}$ , and not near a range in which it would negatively impact on tree growth. Singapore’s extensive streetscape plantings are overseen by the National Parks Board. The homogeneity of Singapore’s streetscape soils are likely a result of the widespread use of a uniform planting substrate and specification (CUGE Standards 2013).

Singapore is a tropical climate with high temperatures and abundant moisture; and thus, trees grow relatively quickly (Prentice et al. 1992). Therefore, we surmise that soil conditions might not have as much control on tree growth in Singapore as compared to street trees in temperate regions. Similarly, Toledo et al. (2011) studied the Bolivian tropical lowland forests

and concluded that climate is a strong driver of tree growth when compared to soil or disturbance.

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