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SOIL CONDITIONS, SIZE AND TREE HEALTH IN URBAN GREEN AREAS

Luis Manuel Morales-Gallegos[2], Tomás Martínez-Trinidad[2*], Armando Gómez-Guerrero[2], Patricia Hernández-de la Rosa[2], Dionicio Alvarado-Rosales[3] and Luz de Lourdes Saavedra-Romero[3]

1 Received on 05.02.2025 accepted for publication on 14.06.2025. Editors: Angeline Martini and Emanoele Lima Abreu.
2 Colegio de Postgraduados - Campus Montecillo, Posgrado en Ciencias Forestales, Texcoco, Estado de México, México. Email: <luis.morales@colpos.mx>, <tomtz@colpos.mx>, <agomezg@colpos.mx> and <pathr@colpos.mx>.
3 Colegio de Postgraduados - Campus Montecillo, Posgrado en Fitosanidad, Texcoco, Estado de México, México. Email: <dionicio@colpos.mx> and <saavedra.luz@colpos.mx>.
*Corresponding author.

ABSTRACT

Urban trees generally grow in soils highly influenced by humans where conditions are unfavorable. A site assessment tool would be useful for arborists to improve species site adaptation. To investigate the problematic above, the goal of this work was to determine the relationship between soil conditions and tree health in 21 green areas of the city of Texcoco de Mora, Mexico. Three soil samples were collected at three depths (0-5, 5-10 and 10-15 cm) in each green area and analyzed for pH, bulk density (BD), total soil porosity (SP), electrical conductivity (EC), total dissolved salts (TDS), organic matter (OM), organic carbon (OC), and soil texture. Growth (diameter at breast height and total tree height), tree health condition (chlorophyll fluorescence), tree visual metrics (TC), typology and management intensity in green areas were evaluated, and the Rapid Urban Site Index (RUSI) was determined. Descriptive and non-parametric statistics were used for the analysis. A total of 549 trees were evaluated. Soil analysis revealed that conditions are generally suitable for tree growth, except for BD that showed high values. The mean values for the soil variables were: pH, 7.04; BD, 1.35 g cm^{-3}; SP, 49.07 %; EC, 0.75 dS m^{-1}; TDS, 482.06 mg L^{-1}; OM, 2.79 %; OC, 1.62 %; sand, 66.19 %; silt, 22.27 %; clay, 11.54 %. The Kruskal-Wallis test found significant differences ($p < 0.05$) at the green area level, indicating that the main variables that can restrict tree growth and health condition are BD and EC due to their high values. The soil properties that significantly changed ($p < 0.05$) along soil depth were OM, OC and pH, which is normal in soils. RUSI indices were significantly correlated to tree growth and health condition ($p < 0.0001$), as well as with the typologies and management intensity ($p < 0.05$) of the green areas analyzed, because the variables have implications on the physicochemical and biological characteristics of the soil.

Keywords: RUSI (Rapid Urban Site Index); Urban trees; Urban soil

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CONDIÇÃO DO SOLO, TAMANHO E SAÚDE DAS ÁRVORES EM ÁREAS VERDES URBANAS

RESUMO Árvores urbanas geralmente crescem em solos altamente influenciados por humanos onde as condições são desfavoráveis. Uma ferramenta de avaliação do local pode ser útil para os gestores de árvores urbanas, possibilitando a seleção de espécies mais adequadas. Para investigar a problemática acima, o objetivo deste trabalho foi determinar a relação entre a condição do solo e a saúde das árvores em 21 áreas verdes da cidade de Texcoco de Mora, México. Três amostras de solo foram coletadas em três profundidades (0-5, 5-10 e 10-15 cm) em cada área verde e analisadas para pH, densidade aparente (BD), porosidade total do solo (SP), condutividade elétrica (EC), sais dissolvidos totais (TDS), matéria orgânica (OM), carbono orgânico (OC) e textura do solo. Crescimento (diâmetro na altura do peito e altura total da árvore), condição de saúde da árvore (fluorescência da clorofila), métricas visuais da árvore (TC), tipologia e intensidade de manejo em áreas verdes foram avaliadas, e o Índice Rápido de Sítio Urbano (RUSI) foi determinado. Estatísticas descritivas e não paramétricas foram utilizadas para a análise. Um total de 549 árvores foram avaliadas. A análise do solo revelou que as condições são geralmente adequadas para o crescimento das árvores, exceto para BD que apresentou valores altos. Os valores médios para as variáveis do solo foram: pH, 7,04; BD, 1,35 g cm^{-3}; SP, 49,07 %; CE, 0,75 dS m^{-1}; TDS, 482,06 mg L^{-1}; OM, 2,79 %; OC, 1,62 %; areia, 66,19 %; silte, 22,27 %; argila, 11,54 %. O teste de Kruskal-Wallis encontrou diferenças significativas ($p < 0,05$) à nível de área verde, indicando que as principais variáveis que podem restringir o crescimento e a condição de saúde das árvores são BD e CE devido aos seus altos valores. As propriedades do solo que mudaram significativamente ($p < 0,05$) ao longo da profundidade do solo foram OM, OC e pH, o que é normal em solos. Os índices RUSI foram significativamente correlacionados com o crescimento e a condição de saúde das árvores ($p < 0,0001$), bem como com as tipologias e intensidade de manejo ($p < 0,05$) das áreas verdes analisadas, pois as variáveis têm implicações nas características físico-químicas e biológicas do solo.

Palavras-Chave: RUSI (Rapid Urban Site Index); Árvores urbanas; Solo urbano

1. INTRODUCTION

Trees established in urban green areas (UGAs) are subjected to a variety of stress-inducing conditions, including poor and compacted soils or those characterized by low water availability, among other factors (Scharenbroch et al., 2017; Chi, 2019; Schutt et al., 2022). Consequently, a considerable proportion of issues related to urban tree development are linked to soil quality (Martins et al., 2018; Saavedra-Romero et al., 2015). Urban soils consist of unconsolidated materials, are generally shallow (< 50 cm), and exhibit substantial heterogeneity, both vertically and horizontally, in their structure (Martins et al., 2018), as well as altered physical, chemical, and biological properties (Chi, 2019; Sefati et al., 2019).

Although the majority of urban soils are capable of supporting tree growth (Bünemann et al., 2018; Scharenbroch et al., 2018), evaluating tree performance and soil quality remains challenging due to the limited availability of effective assessment tools (Scharenbroch et al., 2014; Saavedra-Romero et al., 2020).

Several soil quality indicators have been developed based on physical and chemical properties, which can be quantified numerically (Sefati et al., 2019; Saavedra-Romero et al., 2020). Commonly studied indicators include organic matter (OM), organic carbon (OC), pH, bulk density (BD), and electrical conductivity (EC) (Bünemann et al., 2018). In contrast, biological indicators have received comparatively less attention (Saavedra-Romero et al., 2020), despite the beneficial effects of microorganisms on soil properties (Bünemann et al., 2018). Moreover, most existing indicators have been developed for agricultural systems or forest plantations, limiting their applicability for assessing urban soils (Scharenbroch & Catania, 2012; Scharenbroch et al., 2017).

For these reasons, some site quality indicators have been developed, such as the Rapid Urban Site Index (RUSI), which serves as a simple tool to predict the health of urban trees based on site conditions (Scharenbroch et al., 2017). A site assessment tool of this nature can assist arborists in selecting appropriate species according to site characteristics, evaluating the effectiveness of soil management practices, and ultimately enhancing the success of urban tree plantings (Scharenbroch et al., 2017; Scharenbroch et al., 2023). However, further research is needed to determine the accuracy and applicability of RUSI across different tree populations and its relationship with urban tree health (Scharenbroch et al., 2023).

Therefore, the objectives of this study were: (1) to analyze the most common physicochemical properties of soils in Urban Green Areas (UGAs)—such as bulk density (BD), soil porosity (SP), electrical conductivity (EC), total dissolved solids (TDS), organic matter (OM), organic carbon (OC), pH, sand, silt, and clay content—and to assess their relationship with tree health condition; (2) to investigate the relationship between RUSI and the growth and health condition of trees in UGAs; (3) to evaluate the performance of RUSI across different types of UGAs; and (4) to examine the behavior of RUSI in relation to the intensity of management practices implemented in UGAs. The following hypotheses were proposed: (a) the physicochemical properties of urban soils are not suitable for tree development and growth; (b) there is no correlation between the RUSI and the growth and health condition of urban trees; and (c) differences in UGA typology do not affect RUSI values.

2. MATERIAL AND METHODS

2.1 Study area

A total of 21 Urban Green Areas (UGAs) were selected within the city of Texcoco de Mora, State of Mexico, Mexico, and were randomly distributed throughout the urban area (Figure 1). The UGAs were georeferenced and digitized using the Geographic Information System QGIS version 3.28.4 Firenze, with the aid of the "QuickMapServices" plugin for Google Earth©. Satellite imagery from Maxar Technologies© for the year 2021 was used for this purpose. A database was compiled in Microsoft Excel©, including information such as the name, area (m²), and perimeter (m) of each UGA (Table 1), along with data on urban furniture and management intensity, based on previous studies and fieldwork (Saavedra-Romero et al., 2019; Morales-Gallegos et al., 2021). This information was used to develop a typology of the different UGAs. The UGAs were classified into four types: (1) alignment areas (n = 3), corresponding to busy roads, medians, and boulevards; (2) contemplation parks (n = 8), equipped with benches and lighting; (3) sports areas (n = 5), containing courts and playgrounds; and (4) parks (n = 5), which include fountains and kiosks. With regard to management intensity, three categories were identified: intensive management, characterized by daily activities with personnel numbering ≥ 3; intermediate management, defined by weekly and intermittent activity with ≤ 2 personnel; and low management, involving only a few interventions per month, with variable personnel numbers.

As for the study site characteristics, Texcoco is situated at an average altitude of 2,246 meters and has a semi-dry temperate climate, with an average annual temperature of 15.9 °C and average annual precipitation of 686 mm. The soils in the region are classified as Vertisols with a clayey texture and saline-sodic conditions (Gutiérrez & Ortiz, 1999). However, due to significant anthropogenic disturbance, the typical Vertisol profile is often not present in urban areas.

2.2 Soil analysis

Three soil samples were randomly collected from each UGA using a metal auger composed of three consecutive cylinders, which allowed the collection of fractionated samples at depths of 5, 10, and 15 cm. The samples were bagged, labeled, and transported to the laboratory for analysis. Sampling was conducted in the summer and fall of 2022 (Saavedra-Romero et al., 2020; Galle et al., 2021). In the laboratory, the samples were dried at 30 °C until constant weight was achieved, and standardized soil analysis methods were applied (Saavedra-

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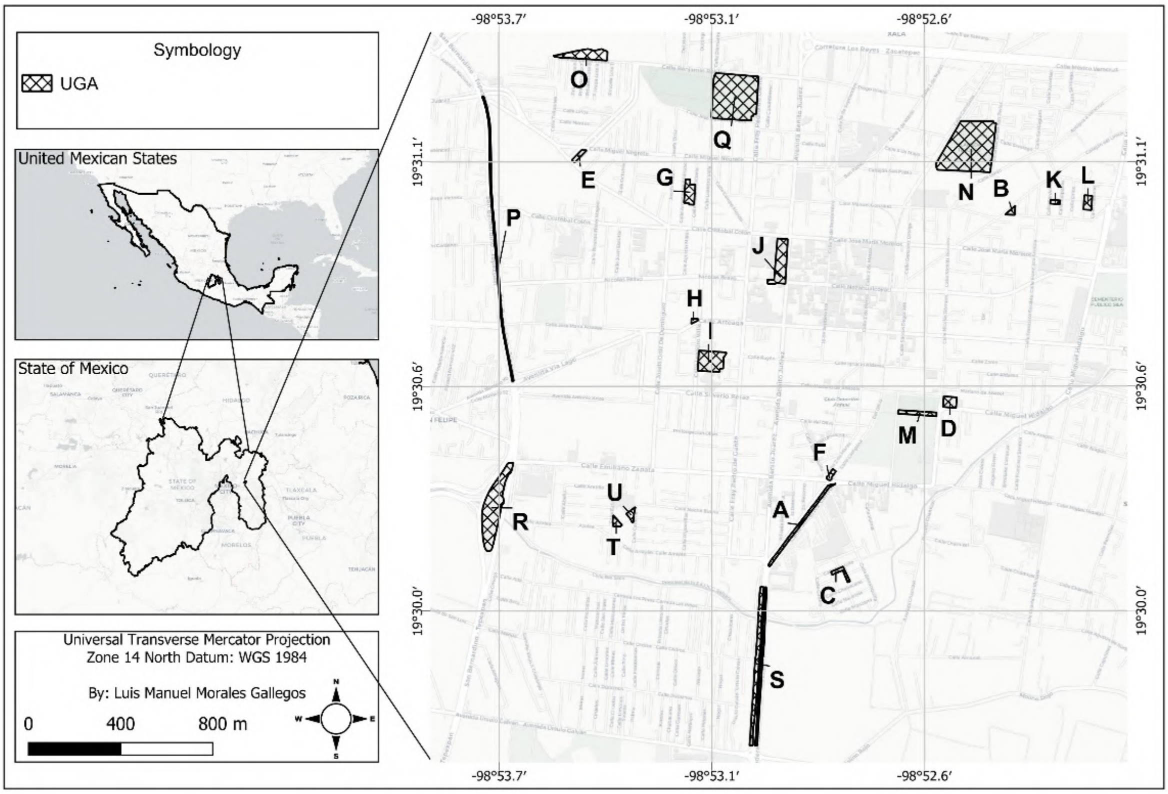

Figure 1. Location of urban green areas in the city of Texcoco
Figura 1. Localização de áreas verdes urbanas na cidade de Texcoco

Table 1. Green areas of Texcoco de Mora, State of Mexico
Tabela 1. Áreas verdes de Texcoco de Mora, Estado do México

ID	Name	Area (m^2)
A	Boulevard Jiménez Cantú	4,687.21
B	Valle de Santa Cruz 2	848.98
C	Jardín San Martín	1,379.92
D	Parque Niños Héroes	2,632.24
E	Parque las Américas	1,123.34
F	Parque del Ahuehuete	876.11
G	Parque Heberto Castillo	4,167.78
H	Parque Arteaga	435.07
I	Parque de la Tercera Edad	9,478.5
J	Jardín Municipal	9,765.82
K	Valle de Santa Cruz 3	717.83
L	Valle de Santa Cruz 1	2,128.93
M	Parque Municipal	2,694.09
N	Alameda Texcoco	43,898.99
O	Parque Xolache	7,436.39
P	Camellón Lechería	7,554.33
Q	Deportivo Silverio Pérez	37,159.45
R	Parque Bicentenario	21,397.46
S	Boulevard Chapingo	16,347.42
T	Las Vegas 1	1,105.62
U	Las Vegas 2	1,173.21

Romero et al., 2020). Textural class (ST), bulk density (BD) from undisturbed soil samples collected using a soil core sampler, and pH (soil:water ratio, 1:2), determined in triplicate using a Beckman® potentiometer, were evaluated. Electrical conductivity (EC) was measured with a conductivity meter at a soil-solution ratio of 1:2, using the soil extract (dS m^{-1}) (Segura et al., 2000), and organic matter (OM) was assessed using the Walkley and Black method (Eyherabide et al., 2014). The variables of percent organic carbon (OC), total soil porosity (SP), and total dissolved salts (TDS) concentration were calculated. The formulas used were: %OC = [0.58 × (%OM)]; %SP = [1 − (BD/Dr)] × 100, assuming a particle density (Dr) of 2.65 g cm^{-3}; and TDS = [640 × (EC)] (Eyherabide et al., 2014; Bunemann et al., 2018; Saavedra-Romero et al., 2020). Finally, since BD is influenced by soil texture, a composite variable (% silt + % clay) was used as a predictor for analysis (Toledo et al., 2021). Finer soil components, such as silt and clay, also serve as indirect indicators of soil fertility and water-holding capacity.

2.3 Rapid urban site index

In the present study, the RUSI was adapted and applied to the UGAs following the methodology proposed by Scharenbroch et al. (2017) (Table 2). The index comprises five factors—climate, urban, soil physical, soil chemical, and soil biological—each with three associated parameters. For the climate factor, the parameters evaluated were precipitation (PPT), growing degree days (GDD), and exposure (EXP). PPT and GDD data for the year 2022 were obtained from weather station 15125, located in the city of Texcoco (19° 30’ 21.60” N, 98° 52’ 55.20” W), covering the period from January 1 to December 31, 2022. GDD was calculated using the average of the daily maximum and minimum temperatures, minus a base temperature of 10 °C—a standard approach for estimating plant growth potential (Scharenbroch et al., 2017). EXP was assessed by counting the number of sides of the tree canopy exposed to sunlight (Schomaker et al., 2007) (Table 2).

For the urban factor, the parameters included traffic (TRAF), infrastructure (INFR), and surface (SURF). TRAF was determined based on the number of traffic lanes adjacent to each UGA. INFR was measured as the distance from the evaluated tree to the nearest building. SURF was evaluated based on the extent of surface coverage over the tree’s root area.

The soil physical parameters included texture (TEXT), structure (STRC), and mechanical resistance (PEN), all evaluated using a relative scale. TEXT refers to the relative distribution of soil particle sizes and was determined through the tactile method, following the field manual of Mery (1980). STRC was assessed according to the methodology proposed by Scharenbroch et al. (2014), while PEN was evaluated based on the depth and ease with which the auger penetrated the soil during sampling, following Saavedra-Romero et al. (2015) and the criteria in Table 2. To reduce variance bias due to soil moisture, measurements were performed under consistent conditions (visibly dry), avoiding drastic changes in moisture content.

The soil chemical parameters included pH, electrical conductivity (EC), and organic matter (OM). These parameters were adapted using the values obtained from laboratory analyses, with scoring ranges adjusted to the local conditions based on recent studies of regional soil characteristics (Saavedra-Romero et al., 2020; Santoyo et al., 2021).

The soil biological parameters included estimated root area (ERA), depth of the A horizon (AHOR), and wet-aggregate stability (WAS). ERA was defined as the area available for root growth (i.e., permeable surface); if a breakout area was present—defined as an adjacent space of at least 50 m² separated by less than 2 m from the rooting zone—the ERA score was increased by one point, up to a maximum of three (Scharenbroch et al., 2017). AHOR was determined via visual inspection by identifying changes in soil color to distinguish the topsoil layer and by assessing the presence or absence of fine roots. Finally, WAS was evaluated by immersing five aggregates (2 to 5 mm in diameter) in water for 30 seconds, placing them on a 1 mm sieve, and shaking vigorously for an additional 30 seconds. The number of aggregates that remained intact after this procedure was scored according to the criteria in Table 2 (Scharenbroch & Catania, 2012; Scharenbroch et al., 2017).

The RUSI value was calculated using the following equation: RUSI = (Σs / 3n) ×

Table 2. Parameters and scores for the Rapid Urban Site Index (RUSI) used in the green areas of the city of Texcoco de Mora, Mexico
Tabela 2. Parâmetros e pontuações para o Índice Rápido de Sítios Urbanos (RUSI) usados nas áreas verdes da cidade de Texcoco de Mora, México

Parameter	Unit	0	1	2	3
PPT	mm $year^{-1}$	< 500	500 - 750	751 - 1000	> 1000
GDD	d	< 1000	1000 - 2500	2501 - 4000	> 4000
EXP	#	0	1 – 2	3 - 4	5
TRAF	n/a	> 4 lanes	2 - 4; without parking	2 - 4; parking	< 2 lanes
INFR	m	< 0.99	1 – 5	5.1 – 10	> 10
SURF	n/a	non-permeable or bare	vegetation patches	thick vegetation	organic mulch
TEXT	n/a	CF > 75 %	CF = 50 - 75 %	CF = 25 - 49 %	CF < 25 %
STRC	n/a	M, SG, PL	ABK	SBK	GR
PEN	cm	< 5 with maximum effort	5 – 20	20 with maximum effort	20 with minimum effort
AHOR	cm	< 1	1 - 5	6 - 15	> 15
ERA	m^2	< 5	5 - 25	26 - 50	> 50
WAS	%	Without aggregates	< 50 % after soaking	< 50 % after shaking	> 50 % after shaking
OM	%	0 - 1.2	1.21 – 2.40	2.41 – 4.2	> 4.2
EC	dS m^{-1}	< 0.05 or >3	0.05–0.1 or 2.001-3	0.101–0.3 or 1.001-2	0.301 to 1
pH	n/a	< 4 or > 9	4 - 4.9 or 8.1 - 9	5 - 5.9 or 6.6 - 8	6 - 6.5

CF = coarse fragment (>=2mm); M = massive; SG = single grain; PL = plastic limit; ABK = angular blocks; SBK = subangular blocks; GR = granular.
CF = fragmento grosso (>=2mm); M = maciço; SG = grão único; PL = limite plástico; ABK = blocos angulares; SBK = blocos subangulares; GR = granular.

100, where s is the score (ranging from 0 to 3) assigned to each parameter, and n is the total number of parameters evaluated (Scharenbroch et al., 2017). The resulting value provides an estimate of site or soil quality for each UGA. These values were subsequently classified into quartiles to categorize UGAs into high and low site quality groups.

2.4 Assessment of tree growth and health condition

To evaluate tree growth and health condition, data from a previous study conducted by Morales-Gallegos et al. (2023) were utilized. That study surveyed trees within the same UGAs in 2021, resulting in a database of 1,543 individuals belonging to 53 species. From this dataset, a representative sample of trees with a diameter ≥ 10 cm (a threshold indicating that the trees are established) was selected using simple random sampling at a 95% confidence level, following the sampling formula proposed by Sosa-Martínez et al. (2020). This process yielded a final sample of 549 trees, representing 53 species, with the most frequently occurring families being Cupressaceae, Rosaceae, and Oleaceae.

$$n = \frac{N\,\sigma^2\;Z^2}{(N-1)\,e^2 + \sigma^2\,Z^2} \qquad \text{(Eq. 1)}$$

Where:
n= sample size;
N= population size;
σ= 0.5;
Z= confidence level 1.96 (95 % confidence);
e= permissible limit of error.

To assess tree growth, total height (TH) was measured using a Haglöf ECII D® electronic clinometer, and diameter at breast height (DBH) was recorded using a diameter tape (Forestry Suppliers Inc., Jackson, MS). Trees with a bifurcated trunk below 1.3 m in height were considered as individual trees

(Saavedra-Romero et al., 2019); however, if the trunk split above 1.3 m, measurements were taken at the point where the bifurcation began.

Tree health condition was evaluated through chlorophyll fluorescence (Fv/Fm), an indirect indicator of physiological stress (Morales-Gallegos et al., 2019). For this, five leaves were randomly selected around the crown of each tree and adapted to darkness for 10 minutes. Measurements were then taken using a Pocket PEA portable fluorimeter (Hansatech Instruments Ltd., King's Lynn, UK) with detection parameters of 1 s and light emission at 650 nm with an intensity of 3,500 µmol m^{-2} s^{-1} (Morales-Gallegos et al., 2019). Simultaneously, a visual tree condition assessment (TC) was performed through a 360° visual inspection of each tree. This rapid method, commonly used in urban forestry, assigns a score of: 0 to trees with > 50% dead crown, damaged bark on the main trunk, or that are dead; 1 to trees with < 50% dead crown or severely stunted crown growth; 2 to trees showing growth reduction, chlorosis, or dieback; and 3 to trees exhibiting no apparent stress and a high growth rate (Scharenbroch et al., 2017).

Tree growth and health assessments were conducted between July and August 2022.

2.5 Data analysis

A Microsoft Excel® database was created and organized using the pivot table function to facilitate descriptive statistical analysis. Subsequently, nonparametric statistics were applied to compare soil properties across UGAs, typologies, and management intensity levels using the Kruskal-Wallis test. The kruskal() function (for n > 2) in RStudio was employed to compare group means. To evaluate the relationship between RUSI and tree growth and health condition, linear regression analyses were conducted. All statistical tests were performed at a 95% confidence level. Data analysis and graphical representations were carried out using RStudio software, incorporating the tidyverse, agricolae, stats, dplyr, and ggplot2 packages (RStudio Team, 2021).

3. RESULTS

3.1 Urban soil condition

Tests revealed that the physical and chemical properties of soils in the UGAs are generally suitable for tree development, with the exception of bulk density (BD) and sand content, both of which exhibited high average values.

A horizontal analysis of soil physical and chemical properties showed significant differences ($p < 0.05$), indicating heterogeneous conditions across the UGAs—some of which may be restrictive for tree growth and development (Table 3). Specifically, the highest BD value (1.56 g cm^{-3}) was recorded in Parque Heberto Castillo (G), while the lowest (0.99 g cm^{-3}) was observed in Camellón Lechería (P). For pH, the highest value (8.04) was found in Parque de la Tercera Edad (I), and the lowest (5.79) in Jardín Municipal (J). High electrical conductivity (EC) values were also recorded in Parque de la Tercera Edad (I) and Las Vegas 2 (U), with 2.91 and 4.53 dS m^{-1}, respectively; the same pattern was observed for total dissolved solids (TDS), with values of 1,859.20 and 2,898.13 mg L^{-1}.

In terms of soil porosity (SP), Camellón Lechería (P) exhibited the highest percentage (62.73%), whereas Parque Heberto Castillo (G) had the lowest (41.29%). Significant differences were also found among sand, silt, and clay contents. For instance, Parque Niños Héroes (D) had the highest sand content (78.92%), while Parque del Ahuehuete (F) exhibited the highest clay content (18.41%) (Table 3). Additionally, BD showed a significant inverse relationship ($p < 0.05$) with the sum of fine soil materials (clay and silt) (Figure 2). Regarding vertical variation, only organic matter (OM) and organic carbon (OC) showed significant differences ($p < 0.05$) by depth, with values decreasing as depth increased. In contrast, pH tended to increase with depth.

3.2 UGAs and tree condition

The different UGA types also exhibited significant differences ($p < 0.05$) in their physical and chemical soil properties. Alignment-type areas recorded higher values for organic matter (OM), organic carbon (OC), electrical conductivity (EC), total dissolved solids (TDS), and soil porosity

Table 3. Physical and chemical properties of soils in the 21 urban green areas of the city of Texcoco de Mora, Mexico
Tabela 3. Propriedades físicas e químicas dos solos nas 21 áreas verdes urbanas da cidade de Texcoco de Mora, México

UGAs	BD	pH	EC	TDS	SP	Sand	Silt	Clay
A	1.51^{ab}	7.74^{abc}	0.60^{abc}	382.93^{abc}	43.05^{ab}	68.92^{abc}	24.72^{ab}	6.36^{cd}
B	1.49^{ab}	6.86^{abcde}	0.90^{abc}	574.93^{abc}	43.85^{ab}	60.25^{bc}	24.48^{ab}	15.27^{ab}
C	1.35^{ab}	7.56^{abc}	0.31^{abcd}	198.40^{abcd}	49.23^{ab}	64.92^{abc}	24.24^{ab}	10.84^{abcd}
D	1.26^{ab}	7.19^{abcde}	0.22^{abcd}	137.60^{abcd}	52.50^{ab}	78.92^{ab}	12.00^{b}	9.08^{abcd}
E	1.50^{ab}	7.60^{ab}	0.23^{abcd}	144.00^{abcd}	43.27^{ab}	61.59^{abc}	20.67^{ab}	17.75^{ab}
F	1.54^{a}	6.76^{bcde}	0.17^{abcd}	109.44^{bcd}	41.97^{b}	57.59^{c}	24.00^{ab}	18.41^{a}
G	1.56^{a}	6.50^{de}	0.50^{abcd}	321.07^{abcd}	41.29^{b}	68.92^{abc}	1.57^{ab}	9.51^{abcd}
H	1.27^{ab}	7.41^{abcd}	0.21^{abcd}	134.40^{abcd}	51.94^{ab}	73.59^{ab}	21.39^{ab}	5.03^{d}
I	1.28^{ab}	8.04^{a}	2.91^{abc}	1859.20^{abc}	51.83^{ab}	71.59^{abc}	20.72^{ab}	7.69^{cd}
J	1.38^{ab}	5.79^{e}	0.36^{abcd}	232.53^{abcd}	47.89^{ab}	64.25^{abc}	27.39^{ab}	8.36^{bcd}
K	1.32^{ab}	6.56^{cde}	0.24^{abcd}	154.67^{abcd}	50.35^{ab}	66.25^{abc}	22.05^{ab}	11.69^{abcd}
L	1.33^{ab}	7.22^{abcde}	0.28^{abcd}	177.07^{abcd}	49.94^{ab}	63.59^{abc}	24.72^{ab}	11.69^{abcd}
M	1.28^{ab}	7.07^{abcde}	0.06^{d}	38.40^{d}	51.57^{ab}	68.92^{abc}	16.05^{ab}	15.03^{abc}
N	1.40^{ab}	6.71^{bcde}	0.11^{cd}	69.33^{cd}	47.31^{ab}	56.25^{c}	30.72^{a}	13.03^{abcd}
O	1.50^{ab}	7.19^{abcde}	0.60^{abc}	386.13^{abc}	43.54^{ab}	70.92^{abc}	18.72^{ab}	10.36^{abcd}
P	0.99^{b}	7.25^{abcde}	1.51^{abc}	967.47^{abc}	62.73^{a}	78.25^{a}	14.05^{b}	7.69^{bcd}
Q	1.17^{ab}	6.94^{abcde}	0.35^{abcd}	222.93^{abcd}	55.89^{ab}	64.25^{abc}	24.05^{ab}	11.69^{abcd}
R	1.23^{ab}	6.76^{bcde}	0.16^{abcd}	99.20^{bcd}	53.52^{ab}	68.25^{abc}	19.39^{ab}	12.36^{abcd}
S	1.31^{ab}	6.76^{bcde}	0.33^{abcd}	210.13^{abcd}	50.41^{ab}	56.92^{c}	28.72^{a}	14.36^{abc}
T	1.36^{ab}	6.96^{abcde}	1.26^{ab}	805.33^{ab}	48.52^{ab}	60.25^{bc}	26.05^{ab}	13.69^{abc}
U	1.33^{ab}	7.05^{abcde}	4.53^{a}	2898.13^{a}	49.87^{ab}	65.59^{abc}	22.05^{ab}	12.36^{abcd}

BD = bulk density; EC = electrical conductivity; TDS = total dissolved salts; SP = total soil porosity. Different letters in the columns indicate statistically significant differences ($p < 0.05$). Variables such as organic matter (OM) and organic carbon (OC) did not show significant differences ($p > 0.05$) among UGAs.
BD = densidade aparente; EC = condutividade elétrica; TDS = sais dissolvidos totais; SP = porosidade total do solo. Letras diferentes nas colunas indicam diferenças estatisticamente significativas ($p < 0,05$). Variáveis como matéria orgânica (MO) e carbono orgânico (CO) não apresentaram diferenças significativas ($p > 0,05$) entre UGAs.

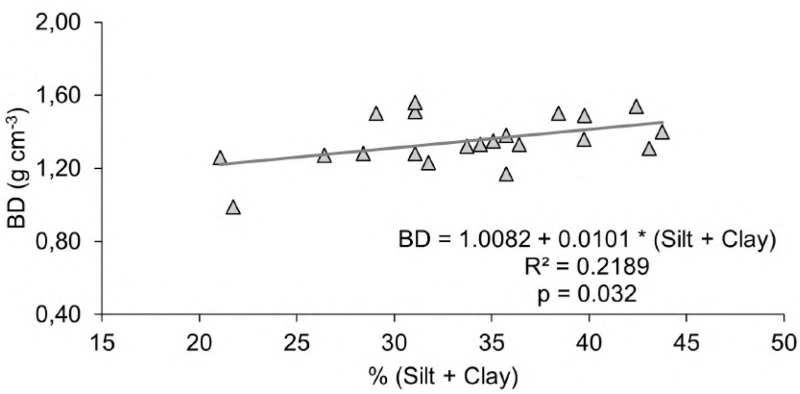

Figure 2. Relationship between BD and the percentage of Silt + Clay in the 21 UGAs analyzed. The p-value < 0.05 indicates a significant correlation between the variables
Figura 2. Relação entre BD e a porcentagem de Silte + Argila nas 21 UGAs analisadas. O valor de p < 0,05 indica correlação significativa entre as variáveis

(SP). In contrast, contemplation areas were characterized by a higher clay percentage, whereas sports areas showed a higher sand content. Parks exhibited high bulk density (BD) values, similar to those in contemplation areas, although the difference between them was not statistically significant. Additionally, parks showed the lowest pH values among the UGA types (Figure 3). The regression analysis revealed

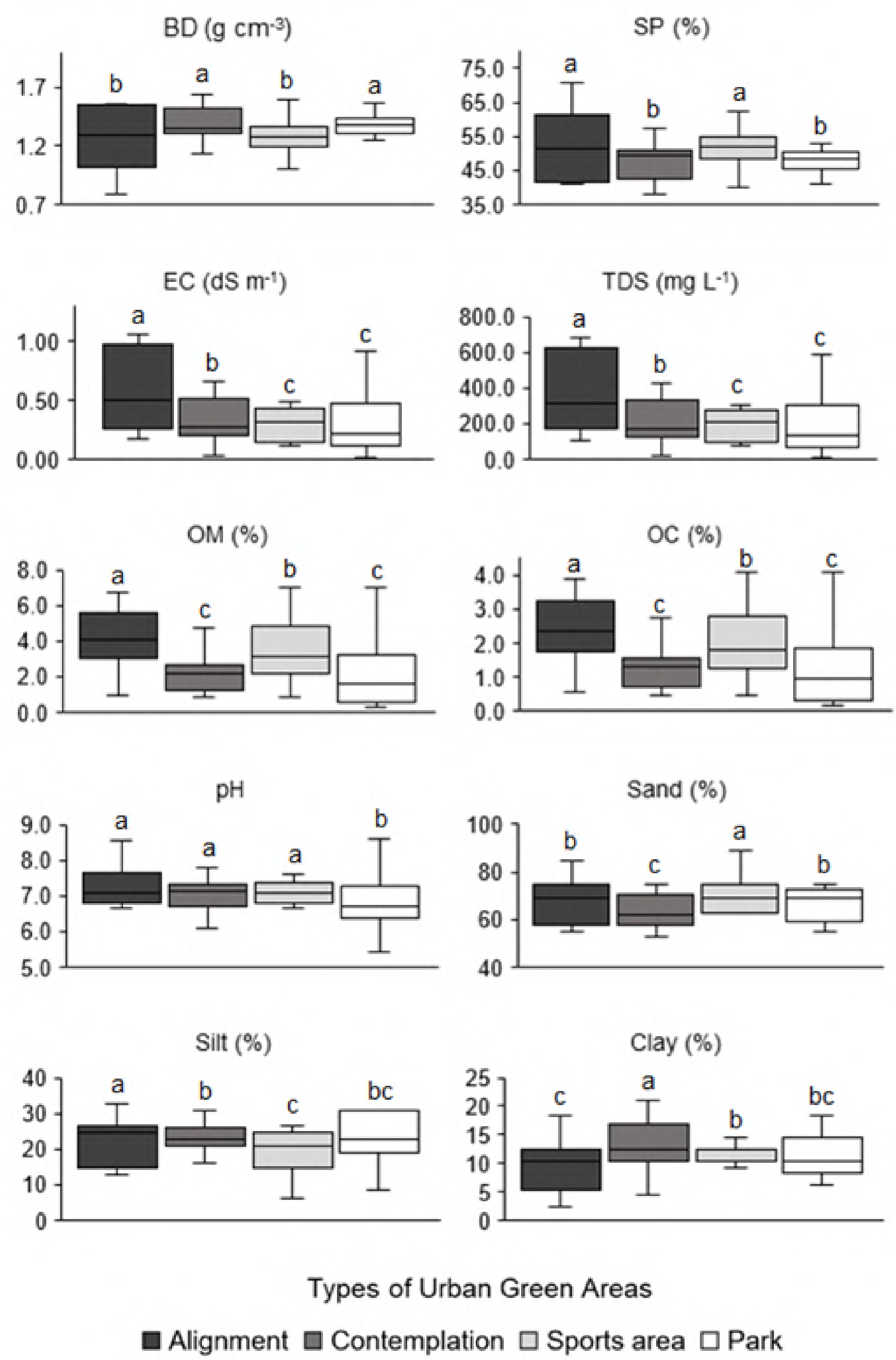

Figure 3. Physical and chemical properties of soils by type of urban green area. BD = bulk density; EC = electrical conductivity; TDS = total dissolved salts; SP = total soil porosity; OM = organic matter; OC = organic carbon; Different letters indicate statistically significant differences ($p < 0.05$)

Figura 3. Propriedades físicas e químicas dos solos por tipo de área verde urbana. BD = densidade aparente; CE = condutividade elétrica; SDT = sais dissolvidos totais; SP = porosidade total do solo; MO = matéria orgânica; CO = carbono orgânico; Letras diferentes indicam diferenças estatisticamente significativas ($p < 0,05$)

that RUSI was positively associated with both tree health condition and growth variables ($p < 0.0001$). However, in all cases, the explained variance was low, indicating that while the relationships were statistically significant, RUSI accounted for only a small portion of the variation in these variables (Figure 4).

3.3 Rapid Urban Soil Index

Regarding the RUSI values evaluated by UGA type, the range of scores obtained was between 40 and 70 points. The mean RUSI values for each UGA type indicated that parks had the highest average index (65.79 ± 7.75), while sports areas recorded the lowest average (55.84 ± 7.99) (Figure 5A). Management intensity in the UGAs had a significant effect on RUSI values ($p < 0.05$), with areas under high-intensity management showing a higher average index (62.64 ± 8.52) compared to areas with intermediate or low management levels (Figure 5B).

4. DISCUSSION

4.1 Analysis of soil physicochemical properties

The average values of the physical and chemical properties of the soils, with the exception of bulk density (BD) and sand content, suggest suitability for urban tree development and are comparable to those reported for soils in the San Juan de Aragón Forest (BSJA) in central Mexico (Saavedra-Romero et al., 2020). This similarity may be attributed to their shared location within the lacustrine area of the Valley of Mexico.

The mean pH value was near neutral (pH = 7.04), aligning with findings from studies on both forest and urban soils, which report an optimal pH range for tree growth between 5.2 and 7.0 (Martins et al., 2018; Saavedra-Romero et al., 2020). Specifically, a research at the BSJA (Galle et al., 2021) recorded an average pH of 7.2, closely matching the value obtained here. However, given the inherent spatial variability characteristic of urban soils (Galle et al., 2021), the horizontal analysis revealed significant differences ($p < 0.05$) across the 21 UGAs studied (Table 3). Spatial variability revealed pH values > 8 (i.e., I; Parque de la Tercera Edad), possibly due to the presence of alkaline compounds, such as concrete, which are characteristic of urban construction waste but may also originate from rainwater runoff, vehicle traffic, and other sources (Kim & Gayoung, 2020). In

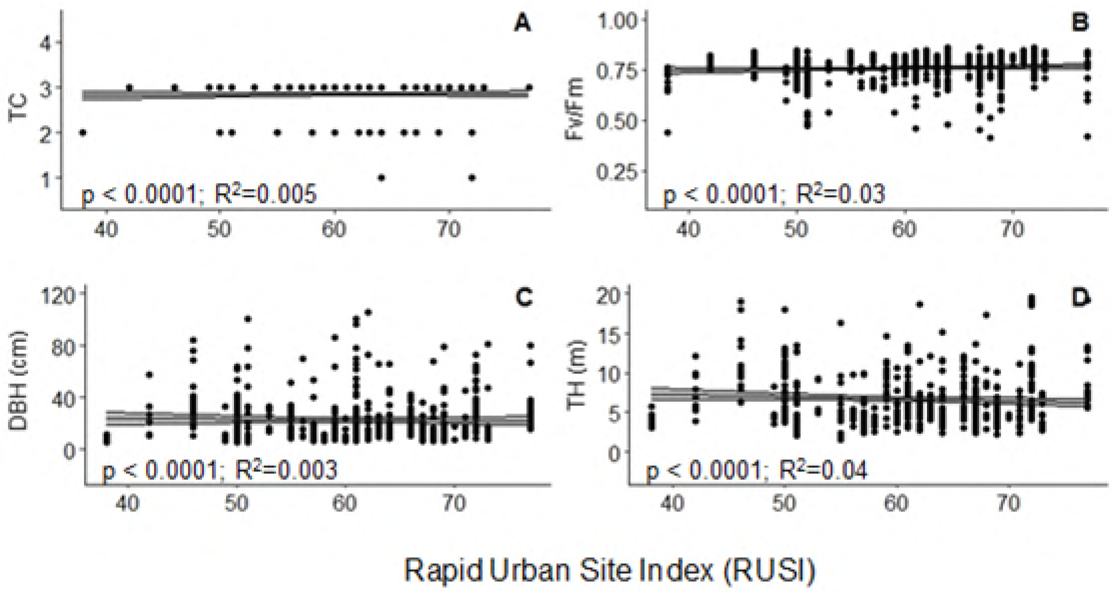

Figure 4. Linear regressions and 95 % confidence intervals for RUSI and tree visual metrics (TC), chlorophyll fluorescence (Fv/Fm), tree diameter (DBH) and height (TH) in 21 urban green areas (N = 549)

Figura 4. Regressões lineares e intervalos de confiança de 95% para RUSI e métricas visuais de árvore (TC), fluorescência da clorofila (Fv/Fm), diâmetro das árvores (DBH) e altura (TH) em 21 áreas verdes urbanas (N = 549)

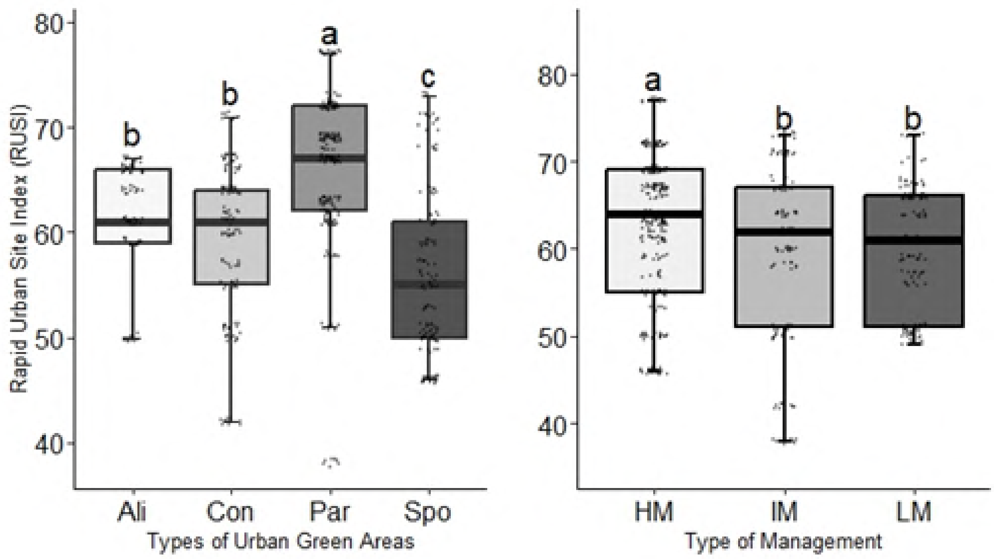

Figure 5. Box plot between RUSI and UGA types. Ali = alignment, Con = contemplation park, Par = park, Spo = sports area; B. Box plot between RUSI and UGA management. HM = high management, IM = intermediate management, LM = little management. Different letters indicate statistically significant differences ($p < 0.05$)
Figura 5. Diagrama de caixa entre os tipos RUSI e UGA. Ali = alinhamento, Con = parque de contemplação, Par = parque, Spo = área esportiva; B. Diagrama de caixa entre a gestão RUSI e UGA. HM = alta gerenciamento, IM = gerenciamento intermediária, LM = pouco gerenciamento Letras diferentes indicam diferenças estatisticamente significativas ($p < 0,05$).

contrast, low pH values < 6 were found (i.e., J; Jardín Municipal), indicating acidity (Table 3), which can alter chemical processes and hinder the solubility and availability of macro- and micronutrients (Martins et al., 2018). The current acidic condition in UGAs differs from that found in urban soils in the cities of Seoul and Suwon, South Korea, where pH values range from 7.5 to 8.0 (Kim & Gayoung, 2020). Some sources of acidity in urban soils include atmospheric pollution, soil impermeabilization, or the absence of vegetation cover, among others (Martins et al., 2018). Additionally, soil pH is involved in various physicochemical processes, such as weathering, humification, microbial activity, and nutrient release into the soil, which directly impacts the health of urban trees (Martins et al., 2018). However, pH tends to decrease due to the decomposition of organic matter, respiration, mineralization, leaching, and the uptake of basic cations (Scharenbroch et al., 2018).

One of the main problems in UGAs is soil compaction (Martins et al., 2018; Chi, 2019), which is caused by the constant circulation of pedestrians and maintenance activities that sometimes involve the use of vehicles and/or machinery (Sefati et al., 2019). However, it may also result from high sand content in the soil (Toledo et al., 2021). Bulk density (BD) is an indicator of compaction, porosity, gas exchange capacity, and infiltration; thus, an acceptable condition offers roots less mechanical resistance to penetration, promoting better development (Scharenbroch et al., 2018; Galle et al., 2021). In this context, UGAs exhibited a high average BD value (1.35 g cm^{-3}); some authors consider the range between $1.2 \geq BD \leq 1.33$ g cm^{-3} to be acceptable for tree development (Hagan et al., 2012; Martins et al., 2018; Saavedra-Romero et al., 2020). Values close to 1.44 g cm^{-3} indicate moderately compacted soils, which affect soil porosity (macropores > 50 µm), and consequently alter plant-available water and gas exchange (Sefati et al., 2019). Green area planning, environmental education, and improved urban development policies can help mitigate this issue.

As for SP, its average value (49.07%) was below the optimum threshold (> 50%). A high SP percentage offers less resistance to root growth, promotes a greater abundance of microorganisms, and consequently improves

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tree health (Jim & Ng, 2018). However, the horizontal analysis showed significant differences ($p < 0.05$) in BD and SP values (Table 3), which can be mainly explained by the influx of users, as walking through these areas generates soil compaction. In this regard, the park-type area exhibited characteristics of higher user influx due to its central location, compared to alignment-type areas, which are located along roads with limited or difficult access (Figure 4). The study by Hagan et al. (2012) reported similar BD values in some U.S. cities, ranging from 1.01 to 1.52 g cm^{-3}, while the study by Scharenbroch et al. (2018) in urban soils in Boston, USA, found values ranging from 0.45 to 1.44 g cm^{-3}, without representing a limiting factor for tree growth.

Some of the study areas are located on the shores of what was originally a saltwater lake (López-Acosta et al., 2019). This condition may be reflected in EC and TDS values, which provide insight into the salinity condition of the soil (Scharenbroch & Catania, 2012; Santoyo et al., 2021). Soils in the UGAs exhibited average values of EC = 0.75 dS m^{-1} and TDS = 482.06 mg L^{-1}, slightly higher than those found in a study conducted in the BSJA, where soils share the same origin (0.51 dS m^{-1} and 327.20 mg L^{-1}, respectively) (Saavedra-Romero et al., 2020). In this context, EC and TDS values < 2.0 dS m^{-1} or 450 mg L^{-1} are considered non-saline or slightly saline (Scharenbroch et al., 2018). Conversely, soils with more than 600 mg L^{-1} of salts are considered salt-affected, and those with more than 1000 mg L^{-1} are considered severely salt-affected (USDA, 2006; Saavedra-Romero et al., 2020). Some of the UGAs showed high salinity values (> 600 mg L^{-1}) (Table 3). A high concentration of salts reduces water uptake by vegetation due to osmotic inhibition (López-Acosta et al., 2019), alters enzymatic processes, and induces toxicity, which restricts tree growth and development. Irrigation helps reduce surface soil salinity; therefore, areas with low irrigation frequency may have higher salt concentrations than those with more frequent irrigation (Santoyo et al., 2021), which may explain the higher EC and TDS values observed in alignment-type areas (Figure 3).

Regarding OM, the average value in the UGAs was acceptable (2.79%); according to the USDA (2006), soils with < 2.3% have a low organic matter content, while those with > 5.4% are considered excellent. Scharenbroch et al. (2018) note that values between 1.4% and 17% are acceptable for urban tree growth.

No OC deficiency was found in UGA soils. OC is a major component of OM and an indicator of soil health, as it improves structural stability by promoting aggregate formation and serves as an energy source for microorganisms (Gómez-Guerrero & Doane, 2018). Moreover, OM and OC showed no significant differences ($p > 0.05$). OM can be positively related to soil moisture content, which results in a greater amount of water available for vegetation and, consequently, better photosynthetic rates and vitality. These factors, combined with acceptable OC levels, contribute to improved soil conditions for tree establishment. The analysis by UGA type revealed that alignment-type areas had high values of OM and, consequently, of OC. This finding is consistent with that of Kim & Gayoung (2020) for trees located along roads, where OM percentages were found to be higher than those in parks. This may be due to contributions of organic material from green space maintenance (i.e., fertilizers or treated water), as well as animal waste, among other sources (Galle et al., 2021). However, management in alignment areas is often limited and may allow the accumulation of organic material derived from trees (i.e., leaves, flowers, fruits, branches, and animal waste) over a prolonged period, leading to its incorporation into the soil and subsequent mineralization, as occurs in forest soils (Gómez-Guerrero & Doane, 2018). Despite this, the high OM values in alignment areas contrast with those reported by Li et al. (2013) in Hubei Province, China, where values < 1% were observed. This was attributed to the constant removal of organic waste derived from tree management for aesthetic purposes, which reduces soil fertility in the long term.

The UGAs exhibited a sand proportion > 50%, with significant spatial variability ($p < 0.05$). These results are similar to those found in the neighboring municipality of Atenco, Mexico, with values ranging from 60% to 68% (Gutiérrez & Ortiz, 1999), a condition that can alter several physical, chemical, and biological processes affecting soil quality and productive capacity, such as permeability, moisture retention, fertility, irrigation, and drainage, among others. It was also observed that many *Quercus* species are susceptible to leaf chlorosis when high sand percentages are combined with pH < 6.5 (Schutt et al., 2022). Information on sand content in soils can assist decision-makers responsible for green areas in determining which species are suitable for specific planting sites, thereby increasing the success rate of tree survival. Castellanos et al. (2017), in studying soil physical processes through various characteristics, pointed out that sand percentages higher than 50% may favor the propagation of herbaceous vegetation but not of trees and shrubs. Conversely, tree survival in forest soils increases when high precipitation is combined with sandy soils (Gómez-Guerrero & Doane, 2018). Finally, the spatial variability observed in sand, silt, and clay reaffirms the heterogeneous origin of urban soils.

4.2 Vertical analysis of soil physicochemical properties

The vertical analysis revealed that the variables BD, SP, EC, and TDS did not show significant differences ($p > 0.05$) across the 0–15 cm gradient. This may be attributed to the origin of urban soils, which provide an unfavorable environment for the proper development of trees. This finding contrasts with that reported for the BSJA, where BD increased with depth, while SP was higher at the surface and decreased with depth (Saavedra-Romero et al., 2020). Similarly, Scharenbroch et al. (2018) found that EC varied with depth (0–100 cm) in urban soils in Boston, Massachusetts, USA. These variations were attributed to factors such as irrigation, drainage, and precipitation. The same study also observed a reduction in OM with increasing depth, with higher content at the surface and decreasing values at greater depths (Scharenbroch et al., 2018). Conversely, the proportion of sand, silt, and clay did not show differences with depth, which may indicate a lack of soil development, as the clay illuviation process is associated with soil formation (Scharenbroch et al., 2018).

Regarding pH, a significant difference was observed ($p < 0.05$), with higher values at the surface, possibly due to the presence of compounds derived from urban construction (Chi, 2019), which can interfere with nutrient absorption by tree roots. In contrast, the BSJA study reported uniform pH values across different depths, likely due to the area's size and limited infrastructure development (Saavedra-Romero et al., 2020).

For OM and OC, a gradual decrease with depth was observed, which is typical in soils (Scharenbroch et al., 2018).

Finally, the composition of the mineral fraction showed no significant differences at the three evaluated depths, reflecting the artificial origin, management, and dynamic environmental conditions characteristic of urban soils (Saavedra-Romero et al., 2020).

4.3 Linear regressions between RUSI and tree health condition and growth

The RUSI values obtained were positively correlated ($p < 0.0001$) with both growth variables and both health condition variables (Figure 4). However, despite low R^2 values ($R^2 < 0.5$), a significant trend in tree growth and health may still be present and should be interpreted with caution, as the predictive capacity of the current analysis is limited. In contrast, a study conducted in eight cities in the United States found that RUSI was positively correlated with tree health condition variables (i.e., TC), but not with growth variables (i.e., DBH) (Scharenbroch et al., 2017). The authors suggest that this discrepancy may be due to bias arising from subjective assessments of health status—primarily visual evaluations—and a limited sample size. Therefore, increasing the sample size could enhance both the explained variance and the accuracy of the evaluation.

The present study used a health condition variable susceptible to bias (TC), but with a larger number of samples (549 trees) and a wider range of species (53 species), along with a variable with reduced bias (Fv/Fm), both of which were statistically significant. In contrast to the study conducted in the eight cities, where the RUSI model did not accurately predict average DBH growth, the present work found significant correlations between RUSI and both DBH and TH. This suggests that species diversity and sample size may be key factors in improving predictive models. In this regard, Scharenbroch et al. (2017) argue that it is possible—though unlikely—that diameter growth may be insignificant in urban trees due to constant competition for resources, which may favor increases in leaf mass and height rather than stem diameter.

4.4 RUSI analysis by UGA typology and management

It was found that park-type areas had a significantly higher RUSI value ($p < 0.05$) than the other three types (Figure 5A). This may be due to the fact that parks provide designated spaces for users, such as walkways and benches, thereby largely preventing soil disturbance. Scharenbroch et al. (2017) identified ERA, STRC, and WAS as some of the most important parameters in the RUSI model; these are directly related to soil volume available to trees and soil compaction—variables that influence the physicochemical and biological characteristics of the soil (Scharenbroch et al., 2023). Low-quality soils present several restrictions to root development, particularly regarding infiltration, permeability, and water retention processes (Martins et al., 2018; Sefati et al., 2019).

As for alignment and contemplation areas, no significant differences were observed ($p > 0.05$). Sports areas, however, presented the lowest RUSI values (Figure 5A). It is important to note that these spaces exhibited evident soil disturbance, primarily compaction, due to the nature of activities carried out (e.g., playing outside designated areas and recreational use of green zones). This supports the idea that soil physical properties carry significant weight in the RUSI model, and thus, proper management and care of green areas have direct implications for urban soils and, consequently, for tree health (Chi, 2019).

Management practices also differ among UGAs, with some activities including irrigation and weed removal. For example, alignment areas (e.g., medians) typically receive less maintenance due to limited accessibility. In contrast, park-type areas are subject to intensive management, as they are centrally located and experience a higher influx of users, resulting in distinct soil conditions and, therefore, higher RUSI values (Figure 5B). Some studies have shown that areas under intensive management tend to have reduced water infiltration capacity (Scharenbroch & Catania, 2012), which decreases soil quality and can negatively affect the health of urban trees. Clearly marked areas, improved UGA design, and adequate signage can help reduce soil compaction. Understanding the RUSI value can support enhanced maintenance practices—particularly those focused on soil conditions—as these are the most modifiable variables within the RUSI model.

5. CONCLUSION

The analysis of the physicochemical properties of the soil revealed that, in general, conditions are appropriate for tree growth (DBH and TH). However, specific variables such as BD, EC, and sand content may restrict tree growth and health, corroborating the heterogeneous nature of urban soils. In this regard, the vertical analysis of the soil further confirmed this heterogeneity, revealing little or no profile development and alterations in soil components—features characteristic of urban soils. On the other hand, RUSI index values were positively correlated with both growth and health condition variables. Furthermore, UGA typology influenced the RUSI values, as the functions and usage patterns of each space differed. Finally, management activities in the UGAs impacted the RUSI, with intensively managed areas exhibiting higher values (RUSI > 65) and better soil conditions, which directly affect tree growth and health in the green areas of Texcoco. The use of site indices such as RUSI supports improved decision-making in urban tree management.

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AUTHOR CONTRIBUTIONS

L.M.M.-G.: Conceptualization, methodology, formal analysis, investigation, writing -original draft preparation, writing—review and editing, visualization, project administration. T.M.-T.: Conceptualization, methodology, validation, formal analysis, investigation, writing -original draft preparation, writing—review and editing, visualization, project administration, funding acquisition. A.G.-G.: Conceptualization, methodology, validation, formal analysis, writing—review and editing, supervision. P.H.-d.l.R.: Investigation, writing—review and editing. D.A.-R.: Writing—review and editing. L.d.L.S.-R.: Writing—review and editing.

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