



Soil Ecosystem Services in Urban Parks as a Basis for Better Urban Planning: The Case of Mexico City

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Until now, the contribution of soils in urban spaces has been underestimated and, as a result, the services they provide have been severely undervalued in urban planning. This article aims to address this issue through a study of Chapultepec Park in Mexico City. We provide two methodological proposals for the analysis of soil ecosystem services characterized by the interaction of natural and anthropic processes: the morpho-pedological landscapes (MpL), in which we quantify soil carbon sequestration (SOC Mg ha⁻¹) and the comparison of two methods for the analysis of hydraulic conductivity: Pedotransfer functions (PTF) and direct measurement with a double ring infiltrometer. Among the 12 MpL, we found the highest SOC content in slopes with mixed tree vegetation and Phaeozem soils. However, SOC retention decreased by 40%–50% due to sealing surfaces. For infiltration measures, despite the diversity of soils and vegetation, direct measurements values are highly homogeneous, while values calculated using PTFs better reflect the morphopedological landscape heterogeneity. In all the MpLs, the hydraulic conductivity was higher than the maximum rainfall intensity report, indicating that the soils in Chapultepec Park, despite the differences in soils and intensity of use, provide the ecosystem service of infiltration. These results would allow the establishment of a baseline for monitoring these services and provide information to decision makers and urban planners seeking to reduce the construction of gray infrastructure that seals soils and reduces their capacity to provide these ecosystem services.

Keywords: morpho-pedological landscapes, saturated hydraulic conductivity, soil sealing, soil carbon sequestration, nature-based solution

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INTRODUCTION

Urban parks have a strategic importance for the quality of life of our increasingly urbanized society (Bertram and Rehdanz, 2015). These are multifunctional and produce co-benefits such as urban greening for heat mitigation, habitat creation, and human health and wellbeing (Kabisch et al., 2016) and may increase urban resilience to sudden change, disruptions and natural disasters. In these spaces, the soils fulfill essential functions that allow the provision of ecosystem services such as carbon and nitrogen sequestration (Canedoli et al., 2020; Cambou et al., 2018), climate regulation and water infiltration and purification (Jabbar et al., 2022).

Urban parks, as nature-based solutions, should have an adaptive management (Sowinska-Swierkosz and García, 2022), this requires accurate information at an appropriate scale.

Especially in order to incorporate these green spaces into urban planning, it is necessary to more practice-based evidence (Frantzeskaki et al., 2019). Until now the ecosystem services, specially the role of soils is less appreciated (Blanchart et al., 2018), the data on carbon sequestration in these soils is still inconclusive (Baveye et al., 2016) and inconsistently quantified in literature (Cambou et al., 2018; Jones et al., 2022). Incomplete information impedes the understanding of the multiple benefits of urban parks, making it difficult for policymakers to make sustainable decisions.

Usually in urban areas, impermeable materials such as concrete, metal, glass or plastic seal the ground. Soil sealing is one of the most common consequences of urbanization and one of the main threats to soils (van der Putten et al., 2018) as it produces various negative effects, including the impossibility of energy transfer, gas exchange, water movement and the presence of microbial activity (Scalenghe and Ajmone Marsan, 2009). The main impacts of sealing include the loss of vegetation, the alteration of the local microclimate due to the increase in atmospheric temperature (Scalenghe and Ajmone Marsan, 2009), it also reduces water infiltration (Bhaduri et al., 2001), decreases carbon and nutrient content (O'Riordan et al., 2021) and increases surface runoff (Ungaro et al., 2014).

In Latin America, the physical expansion of cities is greater than population growth (Fuchs et al., 2017). Moreover these cities will show in the coming decades the most rapid urban growth with numerous informal settlements and vulnerable places (Bai et al., 2018). Mexico City is no exception, with nearly 9 million people, has a total of 2643 ha of green areas, which means only 2.93 m² green area/person (Ayala-Azcarraga et al., 2023), below the minimum threshold of 9 m²/person recommended (World Health Organization, 2009). However, the steady growth of urbanization threatens the permanence of green spaces, which are continually sealed. While urban planning has long recognized the importance of the green spaces, incorporation of ecosystem services into public policies is still incipient in Latin America because several institutional barriers (Challenger et al., 2018).

Mexico City has few green spaces, which are unevenly distributed and affect marginalized populations (Ayala-Azcarraga et al., 2023). In addition, the ecosystem services of other urban parks are still unknown due to a lack of studies and evaluations. This lack of data is a major disadvantage when deciding on the best use of an area within the city. Urban parks, as NbS, should be based on the theory of change, iterative learning and adaptive management (Sowinska-Swierkosz and García, 2022). In fact, these authors mention that we should not call an effective NbS actions that do not monitor the performance of solutions at the landscape level. However, the soil ecosystem services that underpin urban parks are inconsistently quantified in the literature (Jones et al., 2022). Therefore, there is a need and urgency to assess and monitor them.

In cities, every square meter saved has value. While in urban ecosystems we must make some trade-offs between cultural and environmental ecosystem services, this decision must be based on accurate data and information to maximize the potential of each site. In cities, there is always strong pressure to build on any open space, despite the recognition that green spaces, and especially urban parks, improve the quality of life. However, the

management of these spaces largely determines the provision of ecosystem services, so it is important to establish assessment mechanisms, particularly for soil quality, to provide decision-makers with accurate information to help them understand and clarify the impacts that would result from their loss. In this sense, in the context of climate change and its impact on cities, information on SOC sequestration and infiltration should guide urban planning decisions.

Given Mexico City's significant CO₂ emissions and vulnerability due to water scarcity, coupled with droughts and floods (Zambrano et al., 2017), the government of Mexico City has enacted a Climate Change Mitigation and Adaptation Law, that aims to, among other things, capture carbon and promote water infiltration (Gobierno de la Ciudad de México, 2017).

In light of the above, this study aims to highlight the key ecosystem services of urban park soils, such as carbon sequestration and water infiltration regulation. We believe that assessing the soil ecosystem services of urban parks is crucial for their management and restoration, and ultimately to provide policymakers and planners with relevant information to design a more sustainable city.

METHODS

Study Area

Chapultepec park is in the north western part of Mexico City, at an average altitude of 2355 m.a.s.l. (with an altitude range between 2250 and 2460 masl) (**Figure 1**). The climate is temperate sub-humid with rains in summer (700–1,000 mm/year) and average annual temperature between 12°C and 18°C.

Chapultepec Park is one of the oldest urban parks in the Americas, and its 850 ha represent 32% of Mexico City's green areas. Administratively, the park is divided into four sections. The first two sections (I and II) are located in the lower part of the park, close to the road and public transportation infrastructure. In these sections are the main constructions (museums, parking lots, artificial lakes), whose sealed areas reach 45% and 52%, respectively (Cotler et al., 2021). These sections are also the ones that receive the largest number of visitors: 13 million people per year (PUEC, 2002).

The third section, incorporated in 1974, is located in the upper-middle part of the park, isolated from public transportation infrastructure, with no cultural facilities or parking lots, so its sealed area is only of 14% (Cotler et al., 2021).

The fourth section was the last to be added to this park by the city government (2019). Previously, it was occupied by military installations that sealed 24% of this area.

The soils in the first two sections were intensively managed over the years. They were fertilized with urea until 2019, and from that year on, only foliar fertilization of ornamental plants will be used for reinforcement (about 2-3 sprays per year). On the other hand, compost is regularly added. The soils in the first section are continuously irrigated with treated water (secondary treatment to remove pollutants and odours). The soils around the artificial lakes have received sediment from dredging. Finally, in these sections, the leaves on the bare ground are swept as an aesthetic practice.

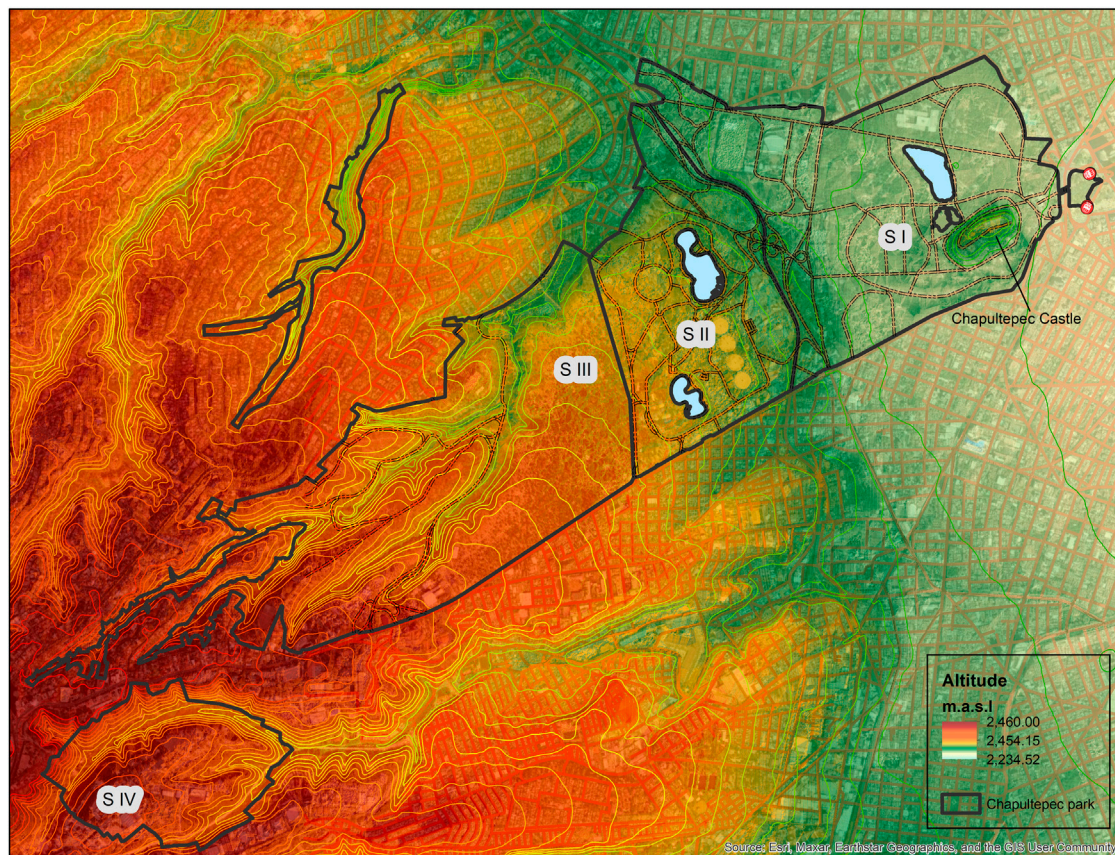


FIGURE 1 | Chapultepec park in Mexico City. S I–S IV: administrative sections.

Morpho-Pedological Landscapes (MpL)

The study of urban soils is challenged by extreme lateral and vertical heterogeneity, and complex interactions between humans and other soil-forming factors (climate, parent material, topography, organisms, time) complicate the definition of a representative set of soil observations (Howard, 2021). In addition, soil characteristics and quality, their distribution and the biogeochemical processes that occur are the result of interactions and retroactions between geological and geomorphological features, landform evolution, parent material type, drainage and plant cover. Therefore, it is more appropriate to think in terms of morpho-pedological landscapes, both spatially and process-wise. These landscape units allow for comprehensive, multidisciplinary approaches that could help unravel the complex spatial patterns of such soils (Delbecque et al., 2022) and thereby select optimal soil sampling sites. In this study, the morpho-edaphological units were defined by superimposing soil-forming factors (relief, geology, vegetation) in a GIS context. The preliminary morpho-pedological map was made with information from a Digital Terrain Model with a resolution.

The field verification of each morpho-pedological landscape (MpL) identified the intensity of visitor use and soil degradation;

this information was incorporated into each MpL because it affects soil quality.

Soil Survey and Analysis

Soil sampling sites were located within each MpL. At each site, pits were dug to investigate soil properties in each soil horizon (Siebe et al., 2016) and to collect soil samples for organic carbon analysis, texture, pH, and bulk density in the laboratory. A total of 28 samples were collected from 8 pits. The soils were classified using USS Working Group WRB (2022) based on field description and laboratory analysis.

Since the first two sections have undergone many changes and their soils contain historical artifacts, the National Institute of Anthropology and History (INAH) gave permission to excavate only one pit in the first two sections. Therefore, there are 8 soil profiles in 12 MpL.

In addition, undisturbed surface soil samples (0–5 cm) were taken with cylindrical soil corers (100 mL) to determine bulk density, sand (%), clay (%), and soil organic carbon (%) (Table 1). The weight of rock (if present) was subtracted to calculate bulk density. Samples were air dried and sieved to 2 mm. These samples were collected in the main MpL of the four sections and were used for indirect estimation of saturated hydraulic conductivity (Ksc).

Soil Carbon Analysis

Carbon content (%) analysis was performed using a CNHS Perkin Elmer 2400 elemental analyzer at a combustion temperature of 975°C and a reduction temperature of 640°C, following the procedure described in Mora and Shimada (2007).

To determine the carbon sequestration potential of each soil horizon, the organic carbon content per hectare (Mg ha⁻¹) was calculated as follows **Equation 1**:

$$\begin{aligned} \text{C content (Mg C ha}^{-1}\text{)} &= \text{C concentration (\%)} \\ &\quad \times \text{soil bulk density (g cm}^{-3}\text{)} \\ &\quad \times \text{horizon depth (dm)} \end{aligned} \quad (1)$$

Finally, the carbon sequestration of the entire park was calculated over an area obtained by subtracting the sealed area reported in Cotler et al. (2021) from the total area of the park.

Bulk density (g cm³) was calculated using the following formula:

$$\text{Bulk Density} = \frac{(\text{Total Dry Mass} - \text{Rock Mass})}{(\text{Total Volume} - \text{Rock Volume})}$$

Texture was determined using the pipette method according (Van Reeuwijk, 2002).

Soil Water Infiltration

In each MpL, soil infiltration capacity and infiltration water volume were evaluated. These analyses had three stages: i) determination of the field saturated hydraulic conductivity (Ks, mm h⁻¹); ii) analysis of the rainfall intensity (mm h⁻¹) and precipitation data (mm); and iii) analysis of the infiltration capacity obtained from the observation and comparison of the two previous points.

A double ring infiltrometer was used for direct measurement of saturated hydraulic conductivity (Ksm). Three samples were taken around each soil profile (N = 24) and the indirect estimate (Ksc) was calculated using pedotransfer functions (PTFs). Both measured and calculated values of soil saturated hydraulic conductivity (mm h⁻¹) were averaged per MpL and per section.

PTFs use readily measured soil properties to derive those that are less easily determined (Wagenet et al., 1991); soil hydraulic properties are the most commonly estimated using this method (Minasni and Mc Bratney, 2002). Here, Ksc was derived from the properties of soil samples (N = 62) collected from the surface horizons of the profiles and from the 0–5 cm samples and measured in the laboratory. The parameters used in the PTF were organic matter (%), clay (%) and sand (%) content from 0 to 5 cm (Ferrer et al., 2004). The authors provide a continuous pedotransfer function for predicting saturated hydraulic conductivity. According to the authors, the PTFs have been calibrated for different land uses and lithological types.

$$K_s = -4.994 + 1.56728 * \textit{sand} - 0.131 * \textit{clay} - 0.0127 * \textit{OM}$$

Rainfall Intensity and Precipitation Data

The analysis used data from the Tacubaya station (19°24'13"N; 99°11'46" W, 2308.6 m.a.s.l.) from 2006 to 2019 National

Meteorological Service database¹. Rainfall intensity (mm/h) and rainfall amount (mm) data were grouped according to the maximum value per day (00:50 to 23:50 h), month and year. Since the data for 2010 were incomplete, the study was limited to the periods from 2006 to 2009 and from 2011 to 2012, during which at least 80% of the daily, monthly and yearly values were available.

The annual days on which the values of maximum rain intensity exceeded those of Ksc and Ksm were expressed as a percentage (%) of the total number of rainy days in that year. For each MpL and site, the percentage of days with values higher than the Ks values would indicate the moments when water drained or flooded due to soil saturation. Likewise, the infiltration water sheet (mm) was estimated based on the precipitation recorded at the Tacubaya station from 2009 to 2012, without considering 2010 because the database was not complete.

The maximum rain intensity (mm/h) of each rainy day and the values of Ksc and Ksm (mm/h) were plotted; finally, Ksm was plotted only when the values were close to those of rain intensity.

Estimation of Infiltration Water Regulation as a Soil Based Ecosystem Service at Chapultepec Park

Using the values obtained from the infiltration capacity, the volume of infiltrating water in each MpL was estimated in each of the four sections of the park. The volume of water that would have been prevented from infiltrating by sealing the soil was also taken into account. For this purpose, the annual precipitation values (m) obtained for each MpL were multiplied by the corresponding total surface area of that MpL (m²) to obtain the total potential volume of infiltration (m³, equivalent to 1000 L). To obtain the volume of water prevented from infiltration by soil sealing, the annual precipitation amount (m) obtained for each MpL was multiplied by the corresponding sealed area (m²) (Cotler et al., 2021). The effective volume of infiltration water was estimated from the difference between the potential total and the volume prevented by soil sealing.

RESULTS

Morpho-Pedological Landscapes (MpL)

The preliminary morpho-pedological map divided the park into 6 MpL. Incorporation of more precise information on vegetation, intensity of use and soil degradation increases this to 12 MpL. The characteristics of the MpL and their location are shown in **Table 2** and **Figure 2**.

As a result of the various reforestation programs, the dominant tree vegetation in the four sections of the park is fairly homogeneous, with a predominance of *Fraxinus spp*, *Ligustrum sp*, *Eucalyptus sp* and *Cupressus lusitanica*.

On the other hand, in the first two sections, where most of the visitors are concentrated, there are more widespread

¹<https://smn.conagua.gob.mx/es/observatorio-tacubaya>

TABLE 1 | Sampling sites (0–5 cm) in the four sections of Chapultepec Park.

Section	MpL	No samples
1	Recreational arboreal plain	9
	Plain with anthropic mounds	18
	Castle slope	2
2	Recreational use plain	3
	Diverse vegetation plain	3
3	Plateau	10
	Hillslopes	9
4	Plateau	4
	Hillslopes	4
Total		62

degradation features in the form of sealing and compaction, while on the slopes of sections III and IV, with slopes of 15° to 45°, runoff, rills and exposed tree roots are the most common forms of erosion.













Soil Survey

The soils in section I developed on construction waste, are superficial (**Table 3**), with high bulk density values a slightly acid pH and layers of anthropic fragments (brick layer).

Soils in section II are very shallow (**Table 4**). Below 8–13 cm are two horizons with very high stoniness (>60%) mixed with anthropic fragments (of various ages).

The soils on the slopes of Section III (**Table 5**) were formed on volcanic ash and have diverse characteristics. The southeastern slopes have shallow soils (34 cm) with loam to silty loam textures, low bulk densities, and decreasing SOC contents. The soils of the northeastern slopes are deeper (60 cm), with a slightly clayey texture, medium bulk density, and increasing carbon content in the second horizon. The soils of the plateau are shallower, with a more acidic pH, a slightly more clayey texture and a high carbon content in the first horizon.

TABLE 2 | Morphopedological landscape (MpL) characteristics in the four sections of Chapultepec Park.

Section I				
MpL	Area (ha)	Vegetation	Soil degradation	Symbol
Castle slope	12.55	Casuarina equisetifolia, Ligustrum sp., Quercus sp.	Microrelief, pedestals	
Diverse vegetation plain	54.91	Ligustrum sp., Phytolaca dioica, grasses	Compaction, runoff flows, sealing	
Recreational arboreal plain	36.55	Fraxinus sp., Ligustrum sp.	Compaction, rills, exposed tree roots, sealing	
Plain with anthropic mounds	158.91	Fraxinus sp., Ligustrum sp. on grass	Compaction, runoff flows, sealing	
Section II				
MpL	Area	Vegetation-Use	Soil degradation	Symbol
Recreational use plain	66.51	Fraxinus sp., Ligustrum sp. On grass	Runoff flows, exposed tree roots on bare soils, sealing, compaction	
Diverse vegetation plain	87.04	Cupressus lusitanica, Schinus molle, Eucalyptus spp., Ligustrum sp. and turf	Microrelief on bare soils, sealing, compaction	
Section III				
MpL	Area	Vegetation-Use	Soil degradation	Symbol
Hillslope south-west	137.45	Eucalyptus spp., Fraxinus spp.	Runoff flows, exposed tree roots	
Hillslope north-east	143.48	Eucalyptus spp., Cupressus lusitanica	Runoff flows, exposed tree roots, rills	
Plateau	38.38	Eucalyptus spp., Cupressus lusitanica, Buddleja cordata, Cotoneaster spp., Muhlenbergia spp	Microrelief, pedestals	
Alluvial terrace	2.08	Fraxinus spp., Ligustrum sp., Cotoneaster spp.,	Not visible	nd
Section IV				
MpL	Area	Vegetation-Use	Soil degradation	Symbol
Hillslope south west	70.21	Eucalyptus spp., Cupressus lusitanica, Fraxinus spp	Runoff flows, exposed tree roots	
Plateau	29.51	Induced grasslands	Microrelief, pedestals	
Hillslopes barrilaco (west)	12.42	Eucalyptus spp., Cupressus lusitanica, Fraxinus spp., Buddleja cordata	Not visible	

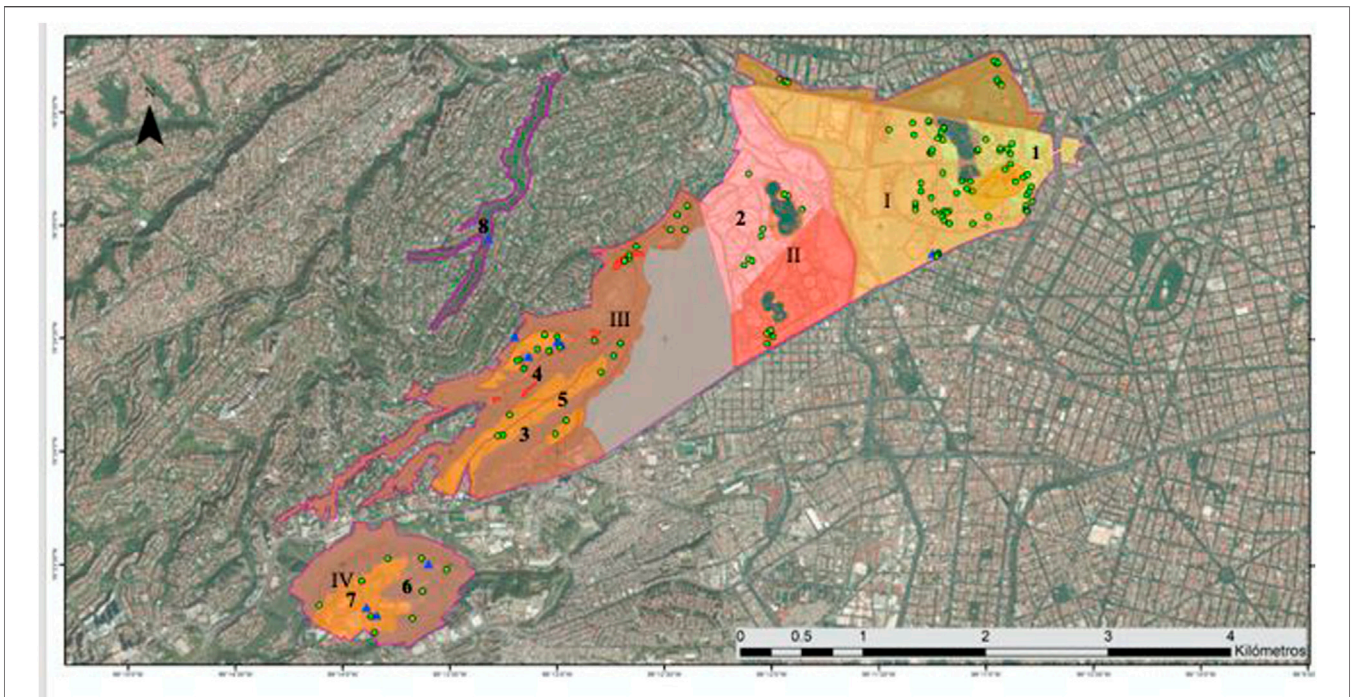



FIGURE 2 | Morphopedological Landscapes (MpL) of Chapultepec park (The gray area is a pantheon). Legend: soil samples 0–20 cm; profiles: 1–8.

TABLE 3 | Soil Profile Characteristics in MpL Plain with anthropic mounds (Section I).

MpL (soil profile)	Horizon	Depth (cm)	pH	Bulk density (g/cm ³)	Texture	Organic C (%)	Structure	Rocks fragments	Porosity	Photo profile
Plain with anthropic mounds with Urbic Technosol (1)	Ah	0–6	6.6	1.4	Loam	4.6	Fine to medium subangular	3% medium gravel	Fine and common vesiculars	
	Cw1	6–32	6.6	1.8	Sandy loam	0.7	Medium Subangular	35% medium gravel	Medium channels, few and fine vesiculars	
	Brick layer Cw2	32–62	6.8	1.4	Clay loam	0.6	Coarse subangular	5% fine gravel	Many and fine vesiculars	

The soils in Section IV occur on a plateau and on two types of slopes (**Table 6**). On the plateau, the soils are moderately deep, with moderate bulk density and little stoniness, while the soil on one of the slopes (SW) is shallow (29 cm), with a silty to loamy clay texture, moderate carbon content, and very little stoniness. The soil of the Barrilaco slope (NW) is deep and developed. It is the only soil that has a mulch layer, which is reflected in a high carbon content in the first horizon that descends along the profile. It has very little stoniness.

Soil Organic Content and Storage Related Ecosystem Service

Soils retain C throughout the depth of the soil profile. The range of potential C stocks varies from 93 to 215.8 Mg ha⁻¹.

The soils of the subsurface horizons of Chapultepec Park had a lower organic carbon content per unit volume than the surface samples (**Table 7**). However, as the thickness of the lower horizons increases, so does the carbon content, especially in phaeozem (III) and leptosol (IV). The average SOC sequestration in the subsurface horizons is 157 MgC ha⁻¹ ±65.4.

SOC stocks were higher in Cambisols and Phaeozems than in Technosols and Leptosols. We found a trend in the concentration of SOC that is presented as: hillslope Barrilaco > hillslope NE > hillslope SW. On the other hand, Plateau with Leptosol and Phaeozem have similar SOC stocks. The lowest SOC values were found in the Technosols.

In Technosols and Leptosols, the SOC stock was higher in the upper horizon (Ah) (except in Hillslope SW of the third section).

TABLE 4 | Soil Profile Characteristics in MpL Diverse vegetation plain (Section II).





MpL (soil profile)	Horizon	Depth (cm)	pH	Bulk density (g/cm ³)	Texture	Organic C (%)	Structure	Rocks fragment	Porosity	Photo profile
Diverse vegetation plain with Leptic Urbic Technosol (2)	Ah	0–8/13	6.9	1.4	Silt loam	5.0	Medium and weak subangular	0%	Fine and common vesiculars	
	C1	8/13–30/37	6.7	n.d	Sandy clay loam	0.9	Medium and weak Subangular	80% medium gravel (anthropic material)	Fine and few vesiculars	
	C2	30/37–43	6.0	n.d	Sandy clay loam	n.d	Medium and weak subangular	60% medium gravel (anthropic material)	Few vesiculars	

TABLE 5 | Soil profile characteristics in MpL of Section III.

MpL (soil profile)	Horizon	Depth (cm)	pH	Bulk density (g/cm ³)	Texture	Organic C (%)	Structure	Rocks fragment	Porosity	Photo profile
Hillslope south-west with Akroskeletal Cambic Phaeozem (3)	Ah1	0–10	6.4	1	Loam	8	Fine to medium subangular	1% fine gravel	Medium and fine interstitial	
	Bw	10–20	6.3	1	Silt clay loam	5.3	Fine to medium subangular	2% fine gravel	Medium and fine interstitial	
	BC	20–34	5.4	1	Silt clay loam	4.3	Medium subangular	10% fine gravel	Many interstitial and few channels	
	C	34–55	6.1	1.6	Silt loam	4.5	--	90% medium gravel	--	
Hillslope north-east with Luvic Phaeozem (4)	Ah1	0–8/10	6.4	1.3	Silt clay loam	6.9	Fine subangular	0%	Many and medium vesicular	
	Ah2	8/10–16	6.3	1.4	Silt clay loam	10.3	Medium subangular	0%	Common interstitial	
	Bw	16–22	6.2	1.4	Clay loam	2.8	Fine to Medium subangular	1% fine gravel	Fine and common vesiculars	
	Bt	22–60	6.2	1.5	Silty clay	-	Coarse subangular	1% fine gravel	Fine and few vesiculars	
Plateau Eutric Leptosol (5)	Ah1	0–8	5.3	1.2	Clay loam	9.6	Cloddy and coarse subangular	0	Fine and common vesiculars	
	Bw	8–18	5.9	1.4	Sandy clay	2.3	Fine and coarse subangular	0	Fine and common vesiculars and channels	
	C1	18–30	-	-	Clay loam	-	-	90%	-	
	C2	30–40	-	-	-	-	-	100%	-	

In phaeozems, SOC was higher in the lower horizons, Ah2, AB and Bw (Figure 3).

SOC content was lower in grass-dominated MpLs, such as the Diverse vegetation plain (section II), than on slopes with mixed vegetation.




The detrimental effect of surface sealing was evident in sections with more construction, such as sections I and II, where the potential for SOC retention was reduced by 40%–50%, while in section III the

loss of C retention was around 14% and in section IV it varied between 14% and 47%.

Water Infiltration and Its Regulation by Soils in the MpL

For all MpL, the value of saturated soil hydraulic conductivity (Ksc) calculated from the PTFs was significantly lower than the Ksm

TABLE 6 | Soil profile characteristics in MpL of Section IV.

MpL (soil profile)	Horizon	Depth (cm)	pH	Bulk density (g/cm ³)	Texture	Organic C (%)	Structure	Rocks fragment	Porosity	Photo profile
Plateau with Haplic Phaeozem (6)	Ah1	0–2	6.4	1.1	Silt clay loam	0.2	Fine subangular and single grain	0%	Many interstitial, medium channels	
	AB	2–13/15	7.3	1.2	Clay loam	7.9	Medium and coarse subangular	1%	Many interstitial, fine channels	
	CB1	13/15–28	6.3	1.2	Silty loam	0.4	Medium and fine subangular	2%	Many fine interstitial	
	CB2	28–53		1.2	Silty loam	-	Medium and fine subangular	3%	Common interstitial	
Hillslope SW with Eutric, Mollic, Leptosol (7)	Ah	0–6.5	6.6	1.2	Silty loam	5.2	Medium subangular	3%	Many fine interstitial, common tubulars	
	Bw	6.5–14/29	6.5	1.2	Clay loam	5.4	Medium and fine subangular	10%	Many fine interstitial, common tubulars	
Hillslope Barrilaco with Eutric Cambisol (8)	O	7–0					decomposing eucalyptus leaves			
	Ah1	0–14	6.3	0.9	Sandy loam	10.4	Medium and fine subangular	1% gravel	Many fine interstitial, common tubulars	
	Ah2	14–25	6.6	1.0	Clay loam	3.8	Coarse subangular	4% gravel	Many fine interstitial, common fine tubulars	
	AB	25–30	6.6	1.2	Clay loam	2.6	Medium subangular	3% gravel	Common interstitial, Medium tubulars	
	BC	30–62	6.7	1.3	Sandy clay	0.7	Coarse subangular	3% gravel	Many fine interstitial	

measured with the double ring infiltrometer, and the former have more variability than those measured with the PTF (**Table 8**).

In all sections, the Ksm values were higher than the reported maximum rainfall intensity. In Section I, the Ksm values, infiltration in these MpLs was estimated to be 100%, corresponding to 4,948.0 mm of rain for the periods 2006–2009 and 2011–2012 (**Figure 4**). The lowest Ksc was for the Recreational Arboreal Plain (21.7 mm/h) and the highest was 25.6 mm/h on the Castle Slope. This calculated value of 25.6 mm/h was exceeded six times by measured rainfall events, of which an estimated 99.1% (4,907.7 mm) infiltrated into the ground and the remaining 0.9% (40.3 mm) ran off.

In Section II, Ksm values were even higher than the reported maximum rainfall intensity (55.6 mm/h), with 60.0 mm/h for the recreational use plain and 140.0 mm/h for the Diverse vegetation plain (**Figure 4**). Infiltration was estimated to be 100% (4,948.0 mm) for these MpLs.

In section III, the highest Ksc value was for the hillslope (27.5 mm/h) (**Figure 4**), which gave an estimate of 98.9% infiltration. The lowest Ksc (18.1 mm/h) was for the plateau and gave an estimate of 96.9% (4,790.5 mm) infiltration. Therefore, this was the MpL with the most runoff: 3.1% (157.5 mm).

Finally, in section IV (**Figure 4**), a Ksc value of 25.5 mm/h for the Hillslopes suggested an infiltration of 98.9% (4,893.5 mm), with 1.1% of the rain being drained or flooded.)

By comparing the distribution and central tendency of the hydraulic conductivity values for each evaluated MpL (**Figure 5**), it was determined whether land use affected the infiltration capacity of the soil.

In Sections I and II, there was no significant difference in Ksc values between MpLs, although Ksc was higher for the Diverse Vegetation Plain than for the Recreational Arboreal Plain. In section III, the value was significantly higher ($p = 0.004$) for the hillslopes than for the plateau. In Section IV, a slightly higher Ksc in the Hillslopes was not significant.

The lack of statistically significant differences precluded any conclusions about the effect of land use on infiltration capacity. Nevertheless, the Recreational Arboreal Plain had a slightly lower infiltration capacity than any other MpL in Sections I and II. In Section I (**Figure 6**), the Ksc values suggested that the greatest volume of infiltration per MpL during the study (~4,549 thousand m³) had occurred in the Diverse vegetation plain; within the section, this was the MpL with the most extensive surface area but with 41.5% of it sealed so that the volume of runoff (~3,227.2 thousand m³) was also the greatest.

In section II (**Figure 6**), 36.9% of the surface of the Diverse Vegetation Plain was sealed, while in the Recreational Arboreal Plain 65.2% was sealed. Nevertheless, the Ksc values indicated that the Diverse Vegetation Plain (Ksc 32.9 mm/h) had the

TABLE 7 | Amount of soil organic carbon (SOC) present in each of the horizons of the 8 profiles described in the Chapultepec park.

Section	MpL (soil profile)	Horizon	Depth	Corg	Bulk density	SOC	Potential stock	Real stock	Loss
			(cm)	%	g/cm ³	(Mg ha ⁻¹)	(Mg ha ⁻¹)	(Mg ha ⁻¹)	%
I	Plain with antropic mouths with Urbic Technosol (1)	1Ah	6	4.6	1.4	38.6	9,674	5,672	41.4
		2CB	26	0.7	1.8	32.7	8,202	4,808	
		Bricks							
	3B(t)	26	0.6	1.4	21.84	5,468	3,205		
	Total				93.1				
II	Diverse vegetation plain with Leptic Urbic Technosol (2)	1Ah	10.5	5	1.4	73.5	11,285	5,735	49.2
		2C	23	0.9	1.6	33.12	5,085	2,584	
		3C	20						
	Total				151.4				
III	Hillslope South-west with Akroskeletal Cambic Phaeozem (3)	Ah	10	8	1.0	80.0	22,956	19,747	14.0
		Bw	24	4.9	1.0	117.6	33,746	29,028	
		C	21	4.5	1.6	151.2	43,388	37,325	
		Total				197.1			
	Hillslope North-east with Luvic Phaeozem (4)	Ah1	9	6.9	1.3	80.7	23,166	19,927	14.0
		Ah2	7	10.3	1.4	100.9	28,965	24,916	
		B	6	2.8	1.4	23.5	6,749	5,805	
		Bt	38	-	1.5				
	Total				205.1				
Plateau Eutric Leptosol (5)	Ah	8	9.6	1.2	92.1	3,537	3,058	13.5	
	B	10	2.3	1.4	32.2	1,235	1,068		
	Rw1	12	-	-					
	Total				124.3				
IV	Plateau with Haplic Phaeozem (6)	Ah	2	n.d					47.0
		AB	12	7.9	1.2	113.7	3,357.0	1,779.2	
		CB1	14	0.4	1.2	6.7	198.3	105.1	
		CB2	10	--	1.2				
		Total				120.4			
	Hillslope SW with Eutric, Mollic, Leptosol (7)	Ah	6.5	5.2	1	33.8	2,372	2,029	14.5
		AB	7.5/22.5	5.4	1.2	123.1	8,643	7,392	
		Total				127.7			
Hillslopes Barrilaco with Eutric Cambisol (8)	O eucalyptus leaves	7							
	Ah1	14	10.4	1	145.6	3,995	not sealed		
	Ah2	11	3.8	1.2	50.1	1,376			
	AB	5	2.6	1.2	15.6	428			
	Bw	5	0.7	1.3	4.5	124			
	Total				215.8				

Numbers in bold correspond to totals.

greater volume of infiltrating water during the study period (2710.4 thousand m³), with 1,585.2 thousand m³ of runoff. For the Recreational arboreal plain (Ksc 27.7 mm/h), the estimates were 1,129.3 thousand m³ of infiltration water and 2119.5 thousand m³ of runoff.

In Section III (Figure 6), the Ksc values indicated that the Hillslopes had the highest volume of infiltration water (12,079.0 thousand m³) and the highest volume of runoff (1963.3 thousand m³) during the study period. For the plateau, the estimated infiltration volume was 1,589.5 thousand m³ and the runoff volume was 249.1 thousand m³. For the alluvial terraces, the estimated infiltration was 97.8 thousand m³ and the runoff was 3.4 thousand m³.

In Section IV (Figure 6), the MpL hillslopes had 14.5% of its total area sealed; Ksc values suggested that the volume of infiltration water had been 12,079.0 thousand m³ and runoff had been 497.2 thousand m³ (Figure 6). For the Plateau, with 47% of its total surface sealed, the estimates were 747.6 thousand

m³ of infiltration water and a relatively high volume of runoff because of sealing (663.0 thousand m³).

DISCUSSION

In heterogeneous environments such as urban parks, where natural and anthropic processes interact, soil survey requires methods that allow the unification of soil-forming factors, while disentangling the complex spatial patterns of soils (Delbecque et al., 2022). As an urban green space it was also important to consider the intensity of use and its impact on soil erosion. The integration of these factors into morphoedaphological units has allowed us to stratify the landscape, creating homogeneous and representative areas for sampling.

SOC storage and depth distribution are influenced by environmental conditions such as climate, vegetation, and land use, as well as by soil management in urban areas (Cambou et al., 2018). In Chapultepec Park, SOC stocks were higher in Cambisols

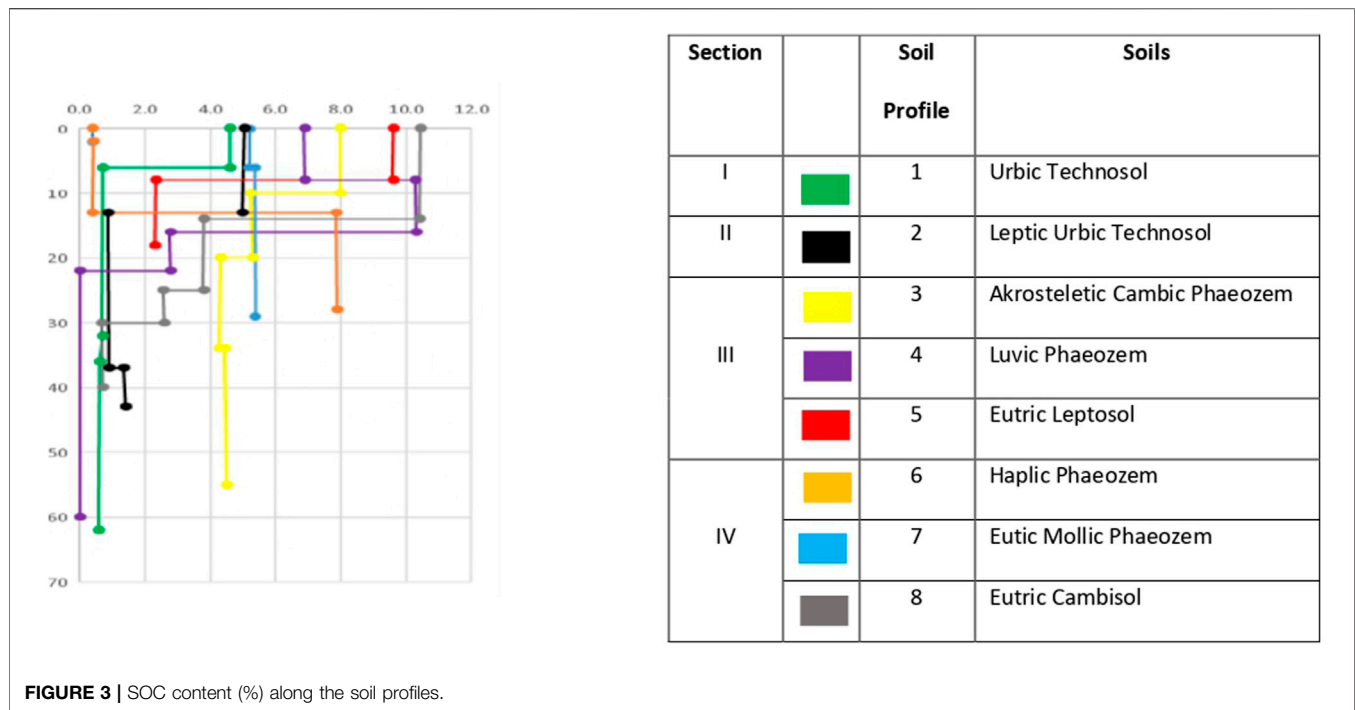


FIGURE 3 | SOC content (%) along the soil profiles.

TABLE 8 | Average, minimal and maximal K_{s_c} and K_{s_m} values obtained per MpL for each Chapultepec park section. K_{s_m} : measured hydraulic conductivity, K_{s_c} : calculated hydraulic conductivity, n : number of observations.

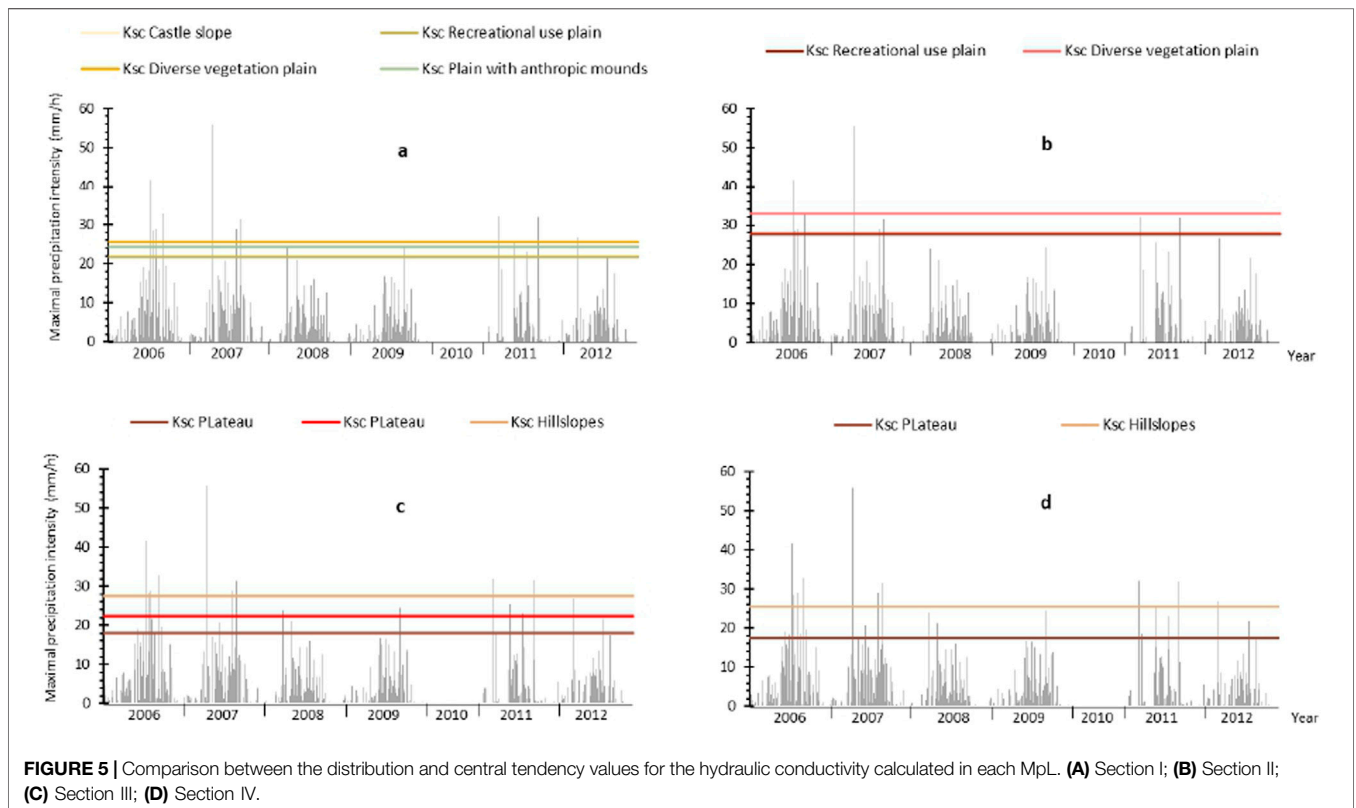
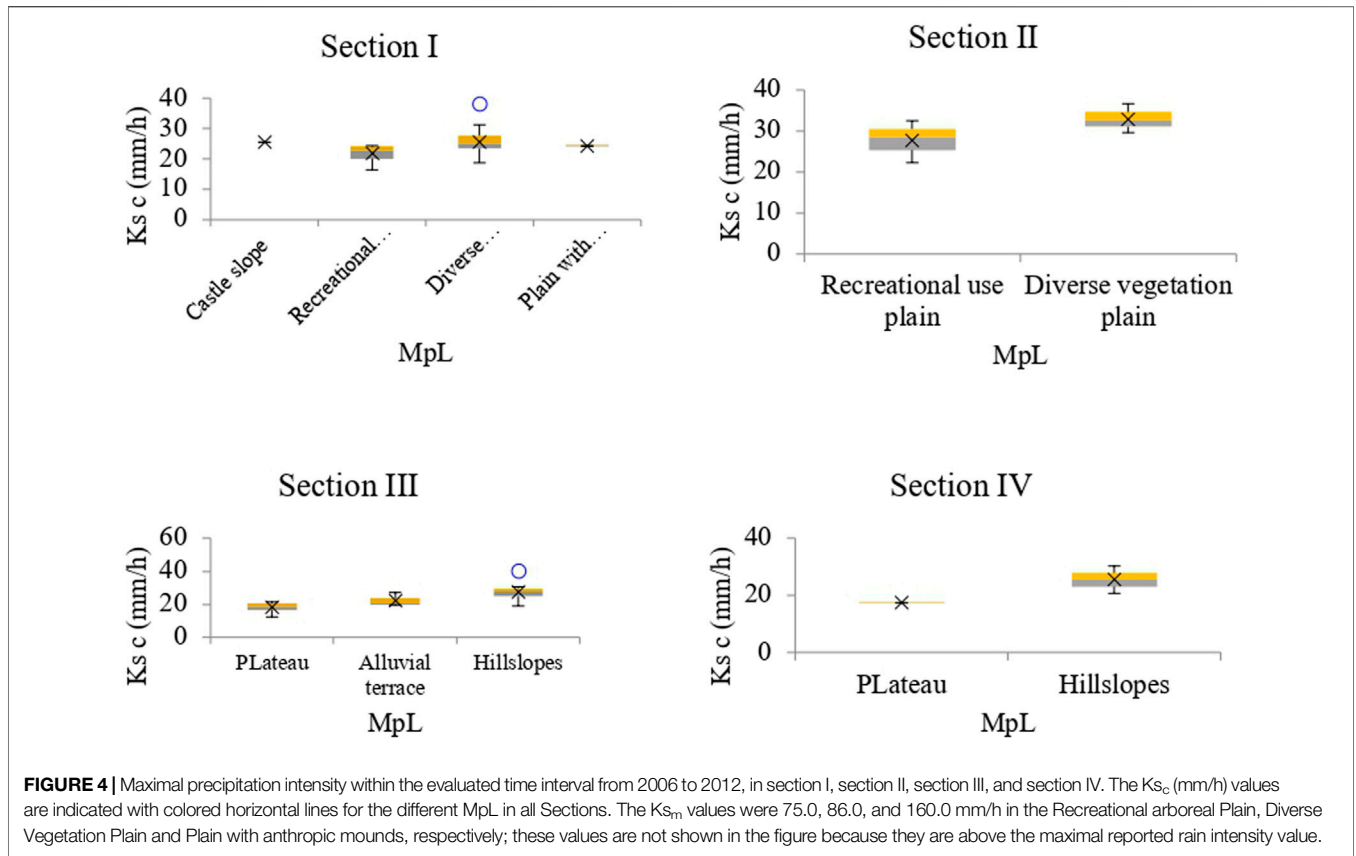
Section	MpL	K_{s_c} (mm/h)				K_{s_m} (mm/h)			
		Average	Min	Max	n	Average	Min	Max	n
I	Castle slope	25.6	-	-	1	-	-	-	-
	Recreational arboreal plain	21.7	16.4	24.4	6	75	60	120	4
	Diverse vegetation plain	25.5	18.7	38.1	22	86	30	180	15
	Plain with anthropic mounds	24.3	24.2	24.4	3	160	120	180	3
II	Recreational use plain	27.7	22.3	32.5	3	60	60	60	1
	Diverse vegetation plain	32.9	29.6	36.7	3	140	120	180	3
III	PLareau	18.1	12.4	21.5	6	-	-	-	-
	Alluvial terrace	22.4	19.6	27.2	3	-	-	-	-
	Hillslopes	27.5	19	40.1	11	164.7	28	480	6
IV	Plateau	17.4	17.3	17.4	2	-	-	-	-
	Hillslopes	25.5	20.7	30.3	2	-	-	-	-

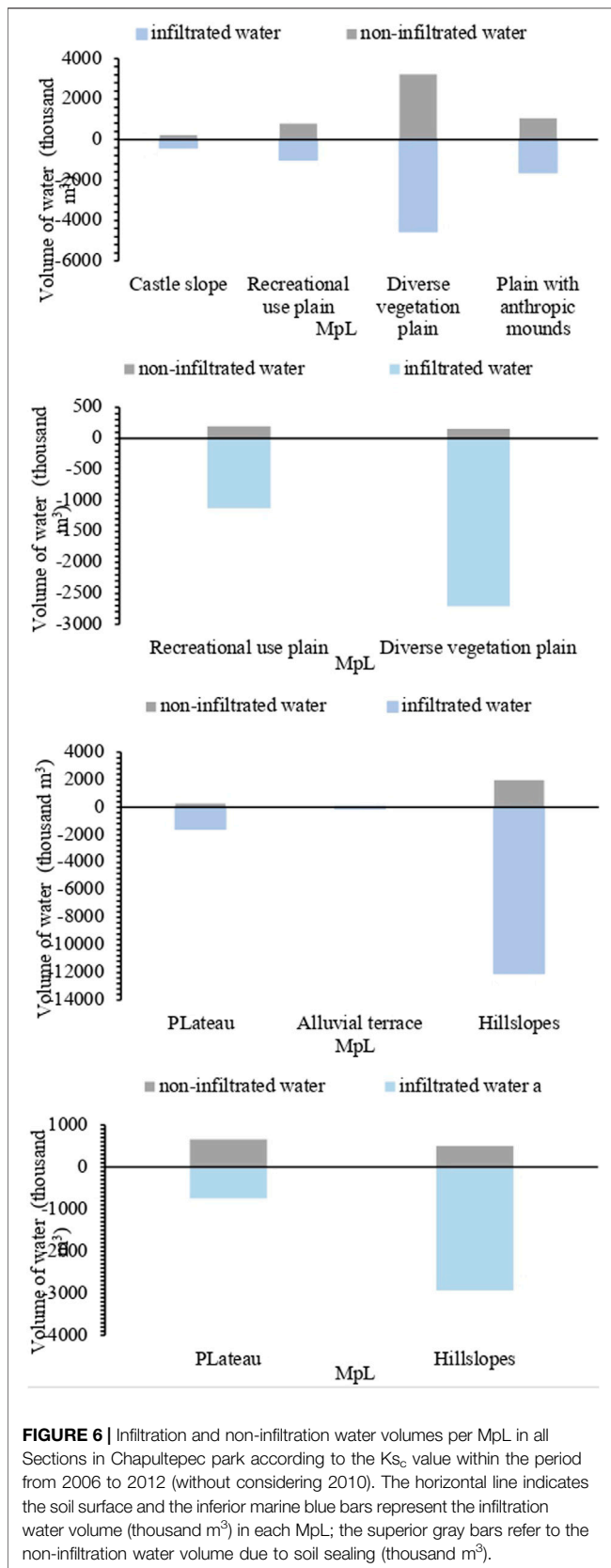
(197 Mg ha⁻¹) and Phaeozems (205 Mg ha⁻¹) than in Technosols (93–151 Mg ha⁻¹) and Leptosols (124–127 Mg ha⁻¹) in subsurface horizons and in general. The role of vegetation was crucial, as the SOC content was higher in the mixed vegetation than in the grassland-only area. Because vegetation community structure may affect the size of the SOC pool by altering both the microenvironment and soil characteristics (You et al., 2014). Also trees can impact the characteristics of the soil beneath them, with various species influencing factors such as soil pH, carbon (C) and nitrogen (N) content, as well as altering the composition of microbial communities (Mitchell et al., 2010).

These results support previous reports that SOC is higher under mixed vegetation than under grass (Takahashi et al., 2008) and also that mixed forest stands are better for storing SOM (Zhou et al., 2020).

The highest SOC content is found in the first 20 cm of soil, with the exception of Phaeozem (III) and Leptosol (IV), where the greater thickness of the subsurface horizons increases the C. Results are similar to Swift (2001) and Rumpel and Kögel-Knabner (2011), who mention that more than 50% of the SOC reserves are found in subsurface horizons below 30 cm depth.

Compared to the SOC sequestration potential of temperate forest soils in Mexico (327 Mg ha⁻¹) (Monreal et al., 2005), which could be equivalent to the native vegetation of Chapultepec Park, Chapultepec soils have 28%–62% of this potential. The difference could be explained by the presence of exotic vegetation, intensive use and management practices. Also in a initial study, López-López et al. (2018) quantified a reservoir of 3,067.4 Mg ha⁻¹ C in the first section of Chapultepec Park. However, this previous





study may have underestimated C sinks because it included plants but excluded soils.

There is no standardized method to describe and characterize urban soils, especially in terms of sampling depth, and even the formula to calculate SOCS is not harmonized, which limits the ability to compare results between urban parks (Cambou et al., 2018). However, a global average SOC content of 127 Mg ha⁻¹ has been reported in urban soils, with a very high variability of values within each city, ranging from 3 to 1,348 Mg ha⁻¹ (Scharenbroch, et al., 2017), which is consistent with what was found in Chapultepec Park.

A recent review by Vasenev and Kuzyakov (2018) found that SOC content in urban soils can be higher than in natural soils and, combined with C accumulation through the soil profile to 100 cm, resulted in total C stocks 3–5 times higher than in natural soils. Similarly, urban park soils in Milan were found to have higher SOC stocks (0–40 cm) than agricultural soils in the region and were comparable to other non-urban soils in the region (Canedoli et al., 2020). This highlights the importance of urban soils and the need to limit their sealing and adopt practices that improve SOC retention in soils.

The distribution of SOC in the soils of Chapultepec is evidence of a natural in C dynamics, with little human intervention, unlike what Cambou et al. (2018) mention for parks in NYC and Paris, which have suffered from interventions in the form of fertilization and irrigation.

For infiltration measurements, the comparison between field sampling and the use of PTF shows that the values of the first method are very homogeneous, despite the diversity of soils, which is a major weakness of this method, since it does not take into account several soil properties that determine infiltration. However, although the hydraulic conductivity of urban soils differs from that of other soils, there has been no comprehensive, consistent assessment of the hydraulic conductivity of urban soils (Shuster et al., 2021).

Vegetation type affects infiltration. The MpLs with the least disturbed vegetation have the highest hydraulic conductivity values. Living and decaying roots create a network of interconnected channels in the soil (macropores). Flow through these macropores can be up to several hundred times faster than flow through the soil matrix. Several studies have shown that vegetation cover significantly influences the hydrological response (Bosch and Hewlett, 1982; Gallart and Llorens, 2003). Gonzalez-Sosa et al. (2010) also found higher saturated hydraulic conductivity in areas of broadleaf forest and small woodland than in permanent pasture and cultivated land.

Sealing urban green spaces has a number of negative impacts. These include the inability to sequester carbon and allow infiltration (van der Putten et al., 2018; Scalenghe and Ajmone Marsan, 2009). In our study area, particularly in the first two sections, sealing reduces the ability to sequester carbon and allow infiltration by 40%–50%, thereby increasing runoff.

Urban planning can play an important role in supporting the implementation of NBS and in managing trade-offs and conflicts. However, it is well known that urban decision-makers and planners are often faced with conflicting or incomplete information about the effectiveness of urban parks, particularly their ability to provide a range of co-benefits (Jones et al., 2022).

In recent years, the Chapultepec: Nature and Culture has been implemented, investing nearly \$600 million in infrastructure to increase connectivity within the park with bridges, walkways, and the construction of new museums and an art school². This initiative demonstrates that gray infrastructure policies continue to dominate in the area of trade-offs, with little recognition of ecosystem services.

In this context, accurate information on the ecosystem services provided by soils becomes more relevant for better decision making, not only in the management of this urban park, but also in urban planning decisions.

CONCLUSION

This study proposes two methodological approaches for the analysis of urban park soils, which are characterized by the interaction of natural and anthropic processes. On the one hand, the importance of comprehensively capturing and analyzing soil-forming factors, land use and soil degradation processes in morpho-pedological landscapes. On the other hand, the advantage of using pedotransfer functions (PTFs) for the analysis of water infiltration, incorporating properties that determine this process, instead of direct measurement with a double ring infiltrometer.

To highlight the importance of soil ecosystem services in urban parks, SOC reserves and water infiltration were analyzed. This information would allow the establishment of a baseline for monitoring these services and provide information to decision makers and urban planners seeking to reduce the construction of gray infrastructure that seals soils and reduces their capacity to provide these ecosystem services.

We found that the SOC stock was higher in Cambisol and Phaeozem than in Technosols and Leptosols; other trends in SOC concentration were Hillslope SW > Hillslope NE > Hillslope Barrilaco >> Hillslopes in Leptosols > Plateau and Plains with Technosols. In Technosols and Leptosols, the SOC stock was higher in the upper horizon (Ah) (except the hillslopes above Leptosols in section 4). In phaeozems, the SOC stock was higher in the lower horizons, Bw or Cw. Especially in Phaeozem, SOC (%) increased at 10–20 cm depth.

SOC retention in the subsurface horizons was similar to that of natural forests. The role of vegetation was crucial, as the SOC content was higher in the mixed vegetation than under grass. However, the sealing of soils for construction reduces the chances of SOC retention by as much as 40%–50% in the first two sections of the park.

Despite the diversity of soils and vegetation, Ksm values are highly homogeneous, while values calculated using PTFs better reflect this heterogeneity.

Between 2006 and 2012, only a few annual precipitation events exceeded Ksc values in all MpLs, suggesting that the soils of Chapultepec Park infiltrate the most precipitation.

Although the intensity of use of some MpLs, such as the Recreational Arboreal Plain in Sections I and II, compacts the soils and reduces their macroporosity, which influences the low hydraulic conductivity values, one of the main determinants of increased runoff is surface sealing.

The results show that the soils of Chapultepec Park play an important role in capturing C and infiltrating most of the rainfall. The conservation of this park - decreasing sealed areas - will be vital for the sustainability of Mexico City.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

HC and SC participated in the design and implementation of the study. HC delineated the morphopedological landscapes and participated in the interpretation of soil profiles. SC analyzed the organic soil carbon results. BP implemented the pedotransfer functions and did the hydraulic conductivity calculations. VP participated in the reading of soil profiles and their description. LL helped with data analysis. All authors contributed to the article and approved the submitted version.

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CONFLICT OF INTEREST

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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²<https://www.obras.cdmx.gob.mx/proyectos/complejo-cultura-bosque-de-chapultepec>

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontierspartnerships.org/articles/10.3389/sjss.2024.13398/full#supplementary-material>

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