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Soil Dynamics in an Urban Forest and Its Contribution as an Ecosystem Service

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Abstract: Forests embedded in an urban matrix are an important site to investigate the effects of multiple anthropogenic influences that can lead to the modification of biogeochemical cycles and, consequently, of the ecosystem services they provide. In this study, the main soil properties, exchangeable cations, and heavy metal concentrations were measured to assess soil quality and fertility, as well as soil carbon stock (SCS) and CO_2 effluxes (Rs) at the Natural Protected Area Bosque de Tlalpan (BT). Four study zones were considered: strict protection zone (Z1), restricted use protection zone (Z2), extensive public use zone (Z3), and intensive public use zone (Z4) during three climatic seasons (rainy, dry-cold, and dry-warm seasons). The concentration of heavy metals in the BT soil showed that these elements are within the reference limits accepted by Mexican standards and are not considered toxic to the environment, except for mercury, which exceeded the standard with double the concentration. The results revealed significant variations in the SCS and soil organic matter (SOM) among the different sites. The highest mean values of SCS (3.01 ± 0.63 and 4.96 ± 0.19 kg m^{-2}) and SOM ($7.5 \pm 1.01\%$ and $8.7 \pm 0.93\%$) were observed in areas of high protection and extensive public use. CO_2 effluxes showed significant differences between sampling seasons, with fluxes being highest during the rainy season (3.14 ± 1.01 µmol·m^{-2}·s^{-1}). The results suggest that the level of conservation and effective management of the sites played an important role in the carbon storage capacity and in the physicochemical properties of the soil. This not only provided insights into the current state of an urban forest within a large urban area but also emphasized the significance of conserving such ecosystems.

Keywords: CO_2 effluxes; soil carbon stock; soil fertility; land management; urban soils

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Citation: Espinosa Fuentes, M.d.l.L.; Peralta, O.; García, R.; González del Castillo, E.; Cerón Bretón, R.M.; Cerón Bretón, J.G.; Tun Camal, E.; Zavala García, F. Soil Dynamics in an Urban Forest and Its Contribution as an Ecosystem Service. *Land* **2023**, *12*, 2098. https://doi.org/10.3390/land12122098

Academic Editors: Alessio Russo and Giuseppe T. Cirella

Received: 21 October 2023
Revised: 15 November 2023
Accepted: 19 November 2023
Published: 23 November 2023

1. Introduction

Urban forests play a critical role in carbon cycling, with their ability to store carbon in both the short and long term and reduce greenhouse gas emissions. Moreover, the soils of urban forests offer essential environmental services such as flood mitigation, reduction in urban heat island effect, and provision of green spaces vital for physical and mental health. They also significantly contribute to nutrient cycling on a global scale [1–5], assisting the study of biogeochemical cycles [6–9] and the development of crucial ecosystem services [10].

Urban soil provides regulating services such as climate change mitigation through carbon sequestration, pollutant reduction, nutrient supply and retention, organic matter stabilization, greenhouse gas regulation, and biodiversity preservation [11]. These services help to maintain the health and sustainability of urban environments. Ecosystem services are evaluated using soil quality indicators, such as bulk density (BD), electrical conductivity (EC), organic carbon, soil texture (clay and silt), cation exchange capacity (CEC), inorganic nitrogen concentration, pH, and concentrations of potentially toxic elements [12–15].

Carbon sequestration is a crucial soil function that supports vital ecosystem services such as soil fertility maintenance and climate change mitigation [16,17]. Soil fertility, one of the soil properties that determine productivity, is regarded as one of the ecosystem services that soil can provide for the benefit of humans [18] as well as for nutrient maintenance in natural ecosystems [19]. Soil fertility is determined by various factors, including texture, water retention capability, profile depth, nutrient availability, organic carbon content [20], and soil organic matter (SOM) [18,21–23].

Urban forests act as carbon reservoirs, sequestering CO_2 and integrating it as biomass into SOM [24]. Additionally, urban forest soils are subject to significant amounts of heavy metal, organic compounds, and acid compound deposition resulting from atmospheric pollution [2]. The retention of contaminants by soils is largely determined by SOM and pH. Heavy metal adsorption to soil components decreases when organic matter is decreased [25]. The mobility and bioavailability of heavy metals also reduce with an increase in pH as they are removed and taken up by colloids [26]. In addition, pH influences metal transport processes [27].

Urban forest soils with impermeable surfaces can accumulate nutrients, such as metals [28]. Previous studies have investigated urban forests in Mexico City. Fenn et al. [29] determined the concentration of heavy metals in Desierto de los Leones National Park. Santiago-Romero et al. [30] assessed the carbon content stored in above-ground biomass within plant communities in the Bosque de Tlalpan. Similarly, Hernández-Guillen et al. [31] estimated the carbon sequestration within trees in a section of the Chapultepec Forest.

Although urban soils are vital in providing ecosystem services, there has been no integrated evaluation of their quality in Mexico.

The goal of this study was to examine the role of soil as a regulation ecosystem service by comprehensively considering the soil functions that sustain it. To achieve this aim, (1) the soil quality was evaluated through physicochemical parameters, (2) the effect of physical and chemical parameters on the concentration and distribution of heavy metals, cations, and anions was determined, (3) carbon stock and CO_2 efflux were measured in the BT, an urban forest in Mexico City under different management regimes.

2. Materials and Methods

2.1. Study Area

BT is a protected natural area with 253 ha located south of Mexico City (19°17′36″, 99°11′46″). It has an average altitude of 2389 m above sea level and a temperate subhumid climate with an average annual temperature of 15 °C and annual rainfall ranging from 850 to 911 mm. BT is in a volcanic terrain, where lithosols are the primary edaphic unit.

In BT, there are three main types of vegetation: xeric scrub, oak forest, and cultivated forest [32]. Xerophytic scrub is associated with basaltic substrates, shallow soils, and heterogeneous microhabitats that depend on the soil depth, the shading and humidity conditions, the amount of exposed basalt, and the cracks on the rocks [33]. Shrubs and herbs succulents predominate with introduced trees such as *Schinus molle*, *Eucalyptus* spp., *Pinus* spp., and *Cupressus* spp. Oak forests are patches dominated by oak species such as *Quercus rugosa*, *Q. laurina*, *Q. mexicana*, and *Q. crassipes*. Cultivated trees are in reforested areas with *Eucalyptus* spp., *Pinus* spp., *Cupressus* spp., and *Fraxinus uhdei*.

2.2. Sampling Campaign and Classification of Sampling Areas

The sampling campaigns took place in August 2021 (rainy season), January 2022 (dry-cold season), and April 2022 (dry-warm season). The BT study area was separated into four sites (Figure 1A,B) in accordance with the zoning proposed by the 2011 Forest Management Plan [32]. The various zones were determined based on environmental quality, current and potential use, and the impact of human intervention.

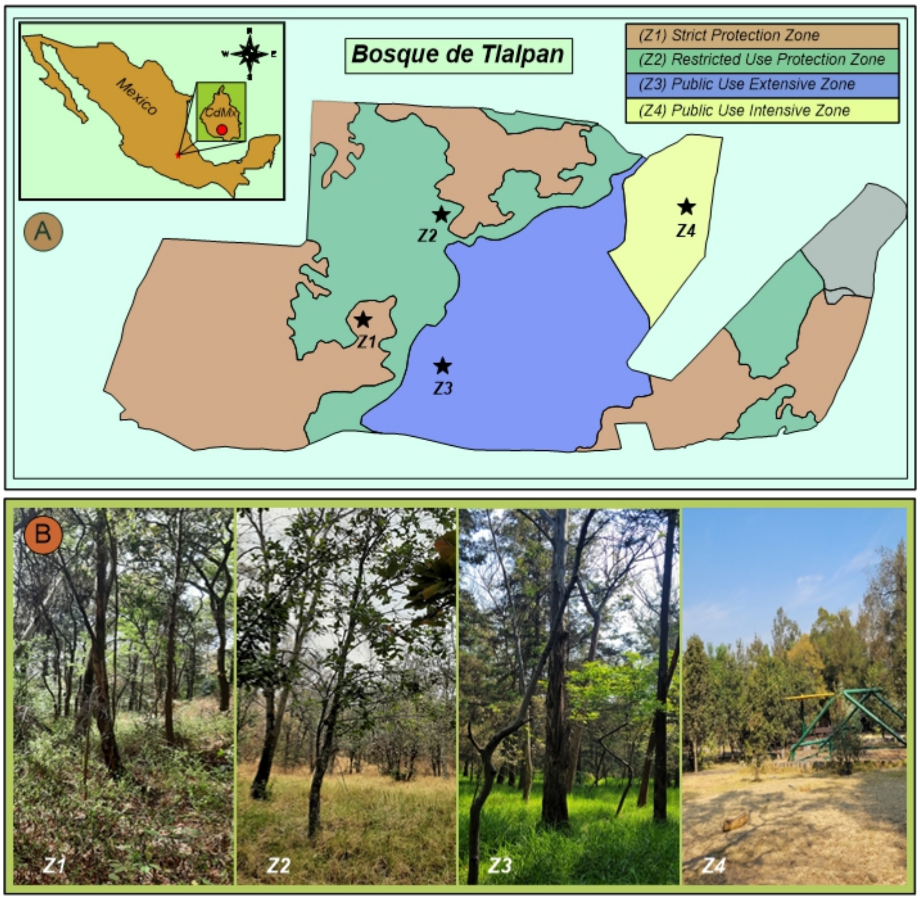


Figure 1. Location of the study area (**A**) and sampling sites (**B**) in the Natural Protected Area Bosque de Tlalpan.

The strict protection zone (Z1) has limited human intervention and consists of habitats with delicate flora and fauna resources that necessitate absolute protection owing to their fragility and high value for maintaining the aquifer's recharge capacity. Z1 spans an area of 97.5 ha and is characterized by scrub and oak trees present in different regions of the forest. On the other hand, the restricted use protection zone (Z2) encompasses an area of 53.66 ha and is composed of oak trees, cultivated trees, and xeric scrub species. Between 1970 and 1975, the area underwent clearance for a football pitch construction and was later utilized as a heliport from 1988 to 1994. Currently, the area is utilized for sporting activities and as a viewing point since it has been reforested. The extensive public use zone (Z3) spans 70.27 ha, introducing various tree species and wildlife. The zone has dense vegetation and grassy terrains with accessible paths and roads. The intensive public use zone (Z4) spans 16.28 ha. The recreational area, with jogging tracks, paths, and a playground, experiences significant anthropogenic influence. The vegetation cover primarily comprises cultivated trees [32].

2.3. Soil Sampling and Analyses

At each site, a 4 × 12 m plot was selected with three sampling points of 1 m^2, at each point, four soil core samples were taken from the shallowest layer (0–10 cm deep) using a core sampler of 193.3 cm^3 to obtain 3 composite samples per site, this procedure was repeated in each campaign giving a total of 36 samples.

After soil extraction, the roots and leaves visible on the label were removed and sealed, and the samples were sent to the laboratory. Each composite sample was air-dried and sieved in the laboratory with a 2 mm stainless steel mesh sieve. Soil moisture (SM) was measured according to Etchevers et al. [34], and soil temperature (Ts) was measured in situ with a Decagon Echo 5-TM sensor. The pH was determined with a HANNA (Instruments electronic) model pH211, with an Extech Instrument electrode. The pH meter was calibrated with two buffer solutions 7 and 4 Merck Certipur (DEU). The EC was measured using a TRANS instrument model HC3010, TDS-Conductivity-Salinity (USA), with an electrode TIPB10-0400 with K = 0.9660 and calibrated with a standard solution of 1.4 mS.

The pH and EC were measured from aqueous extracts and verified in duplicate after 1 min, followed by stirring the samples for 30 s. The aqueous extracts were prepared with deionized water (>18.2 MΩcm) and $CaCl_2$ 0.01 M ACS certified (Japan) ($CaCl_2 \cdot 2H_2O$, Fisher Scientific, Hampton, NH, USA) solution. The determination of soil texture was made following Bouyouco's method [35]. For BD (0–10 cm deep), an undisturbed sample of soil was taken using a steel cylinder (95.4 cm^3). BD was determined from the oven-dried (105 °C) mass of the core and the core volume.

Total organic carbon (TOC) was determined using a Shimadzu TOC-V CSN analyzer with an SSM-5000A solid sample module. The TOC analyzer is an analytical instrument that measures the total amount of organic carbon contained in many solid samples in addition to aqueous samples, including soil, sludge, and sediments. For the TOC analyzer, 20 mg of each soil sample was weighed into sample cups. To calibrate the analyzer, D-glucose Anhidra powder reagent (carbon concentration: 40%) was collected in a sample boat, and its TC was measured [36]. SOM was estimated from the TOC determination using a conversion factor of 1.724 based on the assumption that SOM contains 58% organic carbon [37].

The SCS (kg m^{-2}) was calculated using Equation (1)

$$\text{SCS} = [\text{BD (g cm}^{-3}) \times \text{TOC (\%)} \times \text{SDI (cm)}]/10 \tag{1}$$

where SDI is the soil depth interval (0–10 cm deep).

In each of the sampling plots and once per campaign, the soil CO_2 efflux, here called soil respiration (Rs), was monitored. At each sampling point, at least one week before the Rs measurement, 5 PVC collars (9.1 cm high) were partially inserted into the soil at 5 m intervals. The static closed chamber method was used. The chamber consists of an acrylic cylinder (14.6 cm inner diameter, 24.3 cm height) sealed at one end; a diffusion-based, air CO_2 mole fraction sensor (CARBOCAP GMP 343, Vaisala), and an air temperature and relative humidity sensor (CS215 Campbell Scientific) are attached to the sealed top of the chamber. At the start of the measurement, the open end of the chamber was placed on the collar, enclosing an air volume V of 0.0037 m^3 (the total volume of the chamber minus the volume occupied by the sensors). Due to microbial activity, plant root activity, and possible dissolution of calcium carbonate in the water present in the soil, CO_2 is released from the soil and accumulated in the chamber at a rate $\Delta c/\Delta t$. Water vapor evaporated from the soil also accumulates in the chamber after it is closed, diluting the CO_2 mole fraction c [38]. To account for this dilution effect, a corrected CO_2 mole fraction c' is calculated:

$$c' = \frac{c}{1 - w} \tag{2}$$

where w is the water vapor mole fraction (mol/mol) in the air, computed from the relative humidity reported by the temperature and relative humidity sensor inside the chamber.

The efflux rate Rs from the soil is then estimated as the corrected rate of change using the following equation:

$$Rs = \frac{V}{A} \cdot \frac{\Delta c'}{\Delta t} \cdot \frac{P_0}{\mathcal{R} T_0} \tag{3}$$

where V is the chamber volume, A is the circular area of the chamber, P_0 is the initial atmospheric pressure, T_0 is the initial temperature, and $\Re$ is the universal gas constant. The University Network of Atmospheric Observatories (RUOA) meteorological station, 4 km northeast of BT, measures the atmospheric pressure every minute with a Vaisala PTB110 sensor; these readings are considered P_0. The other variables were measured every 20 s for

10 min. The accumulation of CO_2 increased after 40 s. The *Rs* was calculated with 5 min data to reduce the bias of saturation of the chamber [39,40].

For the preparation of samples, the Official Mexican Standard [41] was followed. The digestion procedures and analytical determination of heavy metals in the soil were carried out according to the standard method of Digestion Procedure for Microwave Extraction for Ambient Filter Samples Method IO-3.1 [42], with control of the pressure and temperature. For the analysis of heavy metals, samples are previously processed for their acid digestion, weighing 0.5 g of soil per sample. A microwave digestion system (CEM MARS-5, Matthews, NC, USA) with Teflon-coated digestion containers was used. Samples were digested using a concentrated acid mixture: 15 mL HNO_3 65%, 2 mL H_2O_2 35% [43]. H_2O_2 was used to enhance the decomposition of organic matter in samples. Samples were digested at 180 °C for 30 min, with a heating rate of 10 °C min^{-1} [43]. After the microwave digestion process, the final solution was diluted to 25 mL with deionized water (>18.2 MΩcm). For the determination of Hg-Total (HgT), the atomic absorption spectrophotometry technique with a cold steam hydride generator (AAS-GH) was applied; for the determination of Cd, Cu, Ni, Pb, and Zn, the inductively coupled plasma optical emission spectrometry (ICP-OES) technique was applied [44]. The ionic species analyzed were Cl^-, $NO_3{}^-$, $PO_4{}^{3-}$, and $SO_4{}^{2-}$ by anion exchange chromatography, and for the determination of cationic species: Na^+, K^+, Ca^{2+}, Mg^{2+}, by cation exchange chromatography, applying the high-resolution liquids chromatography technique (HPLC).

A solution of 45 mmol L^{-1} Na_2CO_3/14 mmol L^{-1} $NaHCO_3$ was used to elute anions and 20 mmol L^{-1} H_2SO_4 to elute cations at a flow rate of 0.25 mL min^{-1}. A 20 µL volume of soil solution was injected into the chromatograph. The chromatographic standard curve was prepared using certified Dionex solutions, whose concentrations ranged from 0.1 to 40 mg L^{-1} for anions and from 0.25 to 100 mg L^{-1} for cations. To verify the validity of the results, we used NIST standard reference materials SRM 1646a (Gaithersburg, MD, USA) and CRM-029 (Sigma-Aldrich, Burlington, MD, USA). The cation exchange capacity (CEC) was calculated by adding the exchangeable Na^+, K^+, Ca^{2+}, Mg^{2+}, and H charge equivalents.

2.4. Statistical Analysis

Statistical analysis was conducted using Statgraphics Centurion 19. The assumption of normality and homogeneity of variances was tested using the Shapiro–Wilk and Levene tests prior to the ANOVA analysis. The purpose of the ANOVA analysis was to determine the variations in soil parameters (such as physicochemical properties, heavy metals, SOM, SCS, and Rs) between sampling sites and monitoring seasons. Tukey's post hoc test was used to separate means where differences were significant ($p < 0.05$).

Pearson's correlation was utilized to determine the relationship between the soil variables. Additionally, a collinearity analysis was undertaken in SPSS to establish the associations between the dependent and independent variables in the soil parameters. This analysis discriminated the highly weighted variables in accordance with the Sarstedt criterion [45]. Furthermore, a principal component analysis (PCA) was conducted on the selected variables after the collinearity analysis.

3. Results

3.1. Environmental Parameters and Physicochemical Properties of the Soil

In 2021, the rainy season extended from May to October (Figure 2A); at the time of the measurement in August 2021, the BT soils had received 92 mm of rain in the previous month and a total of 546 mm since May. Consequently, the SM was highest during the rainy season (36.7 ± 5.7%), particularly at Z1 (Figure 2B), and lowest during the dry-cold season (6.5 ± 2.3%). Despite the long seasonal drought that preceded the dry-warm season measurements, several early rainfall events in the previous week wetted the soil to an intermediate moisture level (20.5 ± 4.2%). Ts varied less between seasons, being highest during the dry-warm season of April 2022 and, on average, only 4 °C less during the cold-dry season of February 2022, when the lowest temperatures were recorded (Figure 2C).

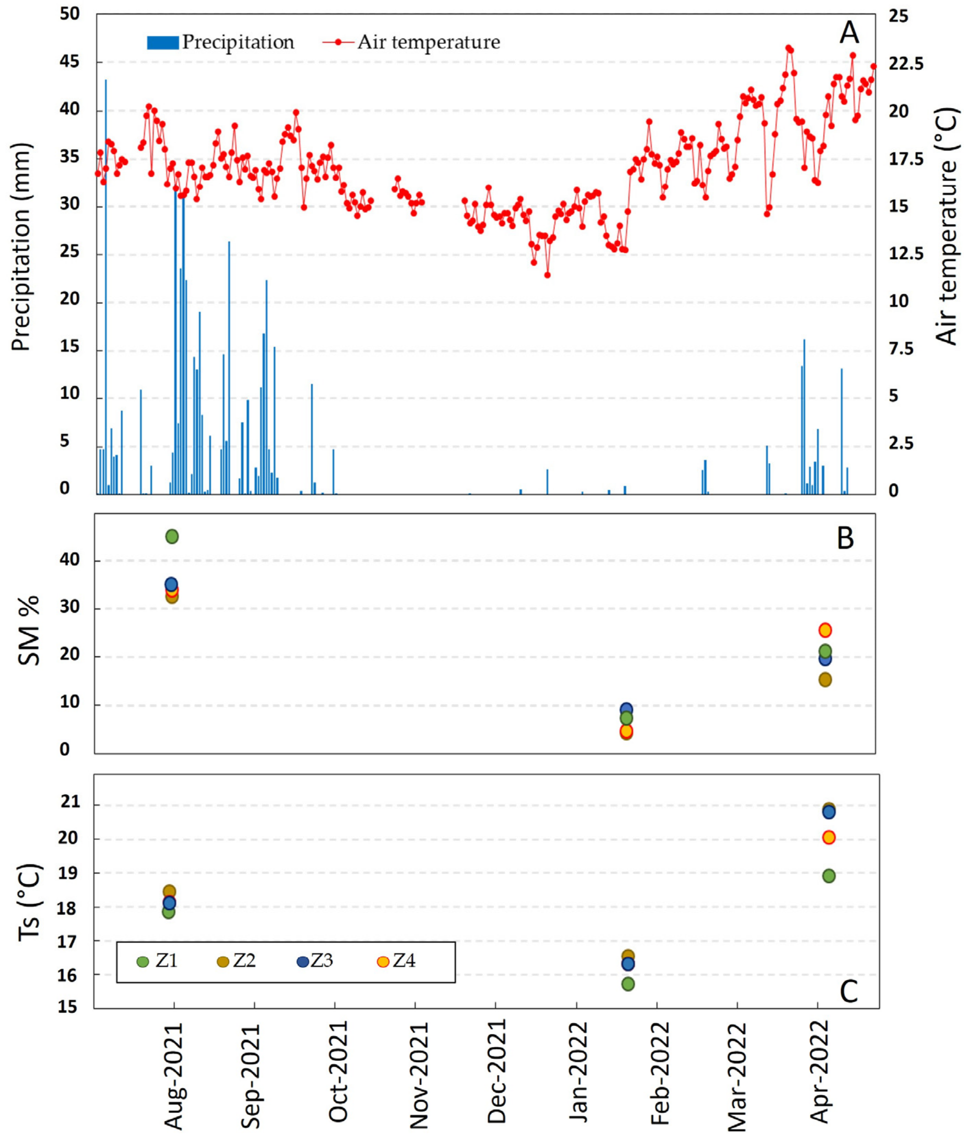


Figure 2. Precipitation and air temperature conditions (**A**), volumetric soil moisture SM% (**B**), and soil temperature Ts °C (**C**) prevalent at the sampling sites (Z1, Z2, Z3, Z4) in different months of the year.

In the study area, sand, clay, and silt ranged from 46 to 67%, 12 to 16%, and 21 to 40% respectively (Figure 3). Based on this, Z1, Z3, and Z4 were categorized as loam soil, and Z2 was categorized as sandy loam.

pH, EC, and BD remained without significant changes in the sampling sites and seasons (Table 1). pH ranged from 5.20 to 6.50, EC values ranged from 0.51 to 0.79 dS cm^{-1}, the BD values ranged from 0.83 to 1.26 g cm^{-3}, the sites with the highest BD values were Z3 (0.96 to 1.01 g cm^{-3}) and Z4 (1.24 to 1.26 g cm^{-3}) indicating more compact soils. The SOM showed differences between sites (F = 42.33; p = 0.0001); the mean values of Z1 and Z3 were 6.27 ± 1.43% and 8.55 ± 0.33%, respectively, Z2 and Z4 showed lower values of 2% in both sites. The CEC in the 0–10 cm horizon ranged from 6.1 to 21.86 Cmol (+) kg^{-1} (Table 1). Z2 had the lowest average values, and Z3 had the highest.

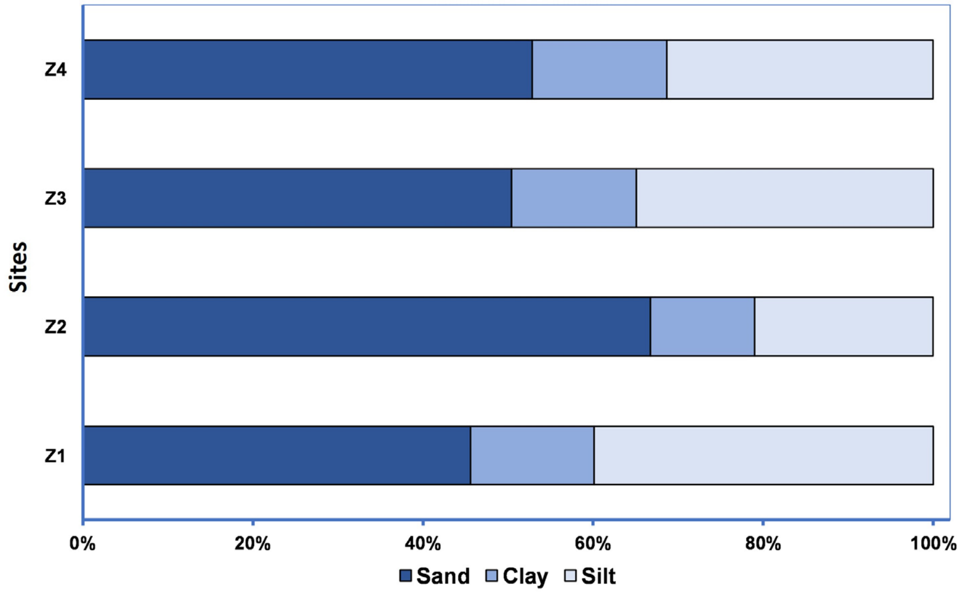


Figure 3. Soil particle size measured as a percentage contribution of sand, clay, and silt at the different BT sites (Z1, Z2, Z3, and Z4).

Table 1. Soil summary values of the soil profile (0 to 10 cm) at different sampling sites and seasons at BT. pH, electrical conductivity (EC), bulk density (BD), soil organic matter (SOM), and cation exchange capacity (CEC). Mean and standard deviation are given. Letters indicate a significant difference between sites ($p < 0.05$) according to Tukey's test.

Season	Sites	pH	EC ($dS\ cm^{-1}$)	BD ($g\ cm^{-3}$)	SOM (%)	CEC ($C\ mol\ (+)\ kg^{-1}$)
Rainy	Z1	5.91 ± 0.36	0.54 ± 0.02	0.85 ± 0.02	7.49 ± 1.01 (a)	13.29 ± 0.28
	Z2	6.50 ± 0.21	0.67 ± 0.03	0.92 ± 0.01	2.88 ± 0.75 (b)	6.10 ± 0.12
	Z3	5.70 ± 0.21	0.69 ± 0.03	1.00 ± 0.06	8.66 ± 0.93 (c)	15.73 ± 0.36
	Z4	5.22 ± 0.28	0.56 ± 0.03	1.26 ± 0.01	2.91 ± 0.11 (b)	12.74 ± 0.31
Dry-cold	Z1	5.72 ± 0.35	0.75 ± 0.04	0.84 ± 0.01	6.64 ± 1.08 (a)	15.78 ± 0.36
	Z2	6.10 ± 0.68	0.51 ± 0.02	0.95 ± 0.01	2.56 ± 0.46 (b)	10.95 ± 0.36
	Z3	5.50 ± 0.21	0.53 ± 0.04	1.01 ± 0.08	8.18 ± 1.53 (c)	18.29 ± 0.24
	Z4	5.70 ± 0.24	0.60 ± 0.04	1.24 ± 0.01	2.80 ± 0.22 (b)	15.77 ± 0.39
Dry-warm	Z1	5.64 ± 0.58	0.61 ± 0.02	0.83 ± 0.02	4.68 ± 1.47 (a)	17.23 ± 0.58
	Z2	6.10 ± 0.36	0.60 ± 0.04	0.91 ± 0.03	2.78 ± 0.18 (b)	11.18 ± 0.14
	Z3	5.20 ± 0.28	0.79 ± 0.04	0.96 ± 0.02	8.82 ± 1.01 (c)	21.86 ± 0.27
	Z4	5.72 ± 0.48	0.66 ± 0.02	1.25 ± 0.01	2.84 ± 0.49 (b)	15.71 ± 0.25

3.2. Heavy Metals, Cations, and Anions in Soils

Significant differences in the metallic species, Cu ($F = 3.12$, $p = 0.04$) and Zn ($F = 8.58$, $p = 0.007$), were detected between the sampling sites. Cu and Zn were the metals with the highest concentrations in Z3 and Z4. Cd, Pb, and Ni showed similar concentrations at all sites. According to MON [41], the observed heavy metal concentrations are within acceptable limits and do not pose a threat to the environment. The Hg concentrations were high at all sites (46.5 to 62 mg kg^{-1}) and above the MON (23 mg kg^{-1}) [41] and international standards (6.6 mg kg^{-1}) [46] (Figure 4A).

Mg^{2+} concentrations were similar at all sites; K^+, Na^+, and Ca^{2+} showed significant variation between sites ($p < 0.05$). K^+ and Na^+ showed the highest values in Z4 and Ca^{2+} in Z1 (Figure 4B). On the anion side, $PO_4{}^{3-}$ also showed differences between sites ($p < 0.05$), with the Z3 reporting phosphate concentrations of 184 mg kg^{-1}. $SO_4{}^{2-}$, $NO_3{}^{-}$, and Cl^- concentrations were similar at all sites (Figure 4C).

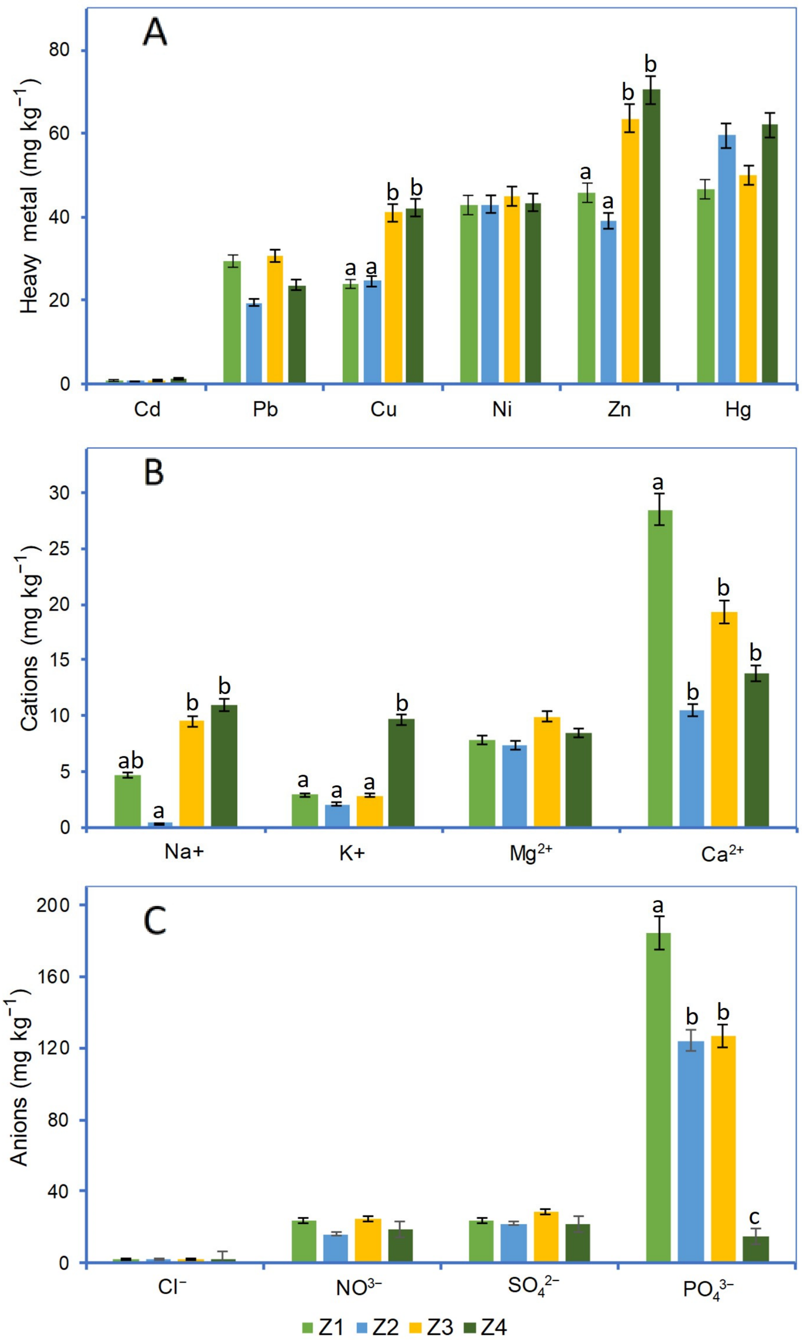


Figure 4. Heavy metals (**A**), cations (**B**), and anions (**C**) concentrations at the different BT sites (Z1, Z2, Z3, and Z4). Different letters above bars indicate statistical significance at $p < 0.05$ between sites according to Tukey's test.

3.3. Soil CO_2 Efflux (Rs) and Soil Carbon Stock

The average CO_2 efflux was 1.22 μmol·m^{-2}·s^{-1}. Collars measurements ranged from 0.18 to 5.72 μmol·m^{-2}·s^{-1}. Measurements between sampling seasons showed significant differences ($F = 91.57$, $p = 0.000$), with the highest mean effluxes recorded during the rainy season (3.14 ± 1.01 μmol·m^{-2}·s^{-1}) and the lowest during the dry-cold season (0.53 ± 0.34 μmol·m^{-2}·s^{-1}) (Figure 5). Among sites, the highest mean value was observed in Z1 (2.07 ± 0.57 μmol·m^{-2}·s^{-1}) and the lowest in Z4 (1.58 ± 0.93 μmol·m^{-2}·s^{-1}), while sites Z2 and Z3 had mean Rs of 1.88 μmol·m^{-2}·s^{-1} and 1.80 μmol·m^{-2}·s^{-1}, respectively (Figure 5).

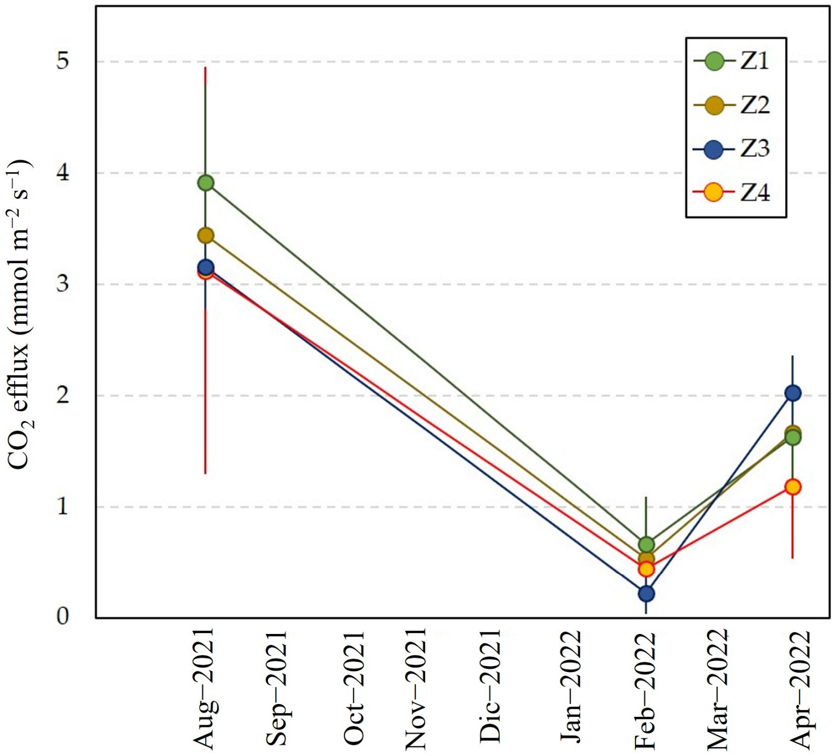


Figure 5. CO_2 efflux at the different periods and sampling sites in BT.

The SCS showed significant differences between sites (F = 42.33, $p = 0.000$), with values ranging from 1.4 to 5.1 kg m^{-2} (0–10 cm depth), with the highest values recorded in Z3, and the lowest values were observed in Z2 and Z4 (1.4 to 2.1 kg m^{-2}, respectively) (Figure 6). Pearson's correlation showed negative but not significant correlations between SCS and sand, pH and BD (Figure 7A).

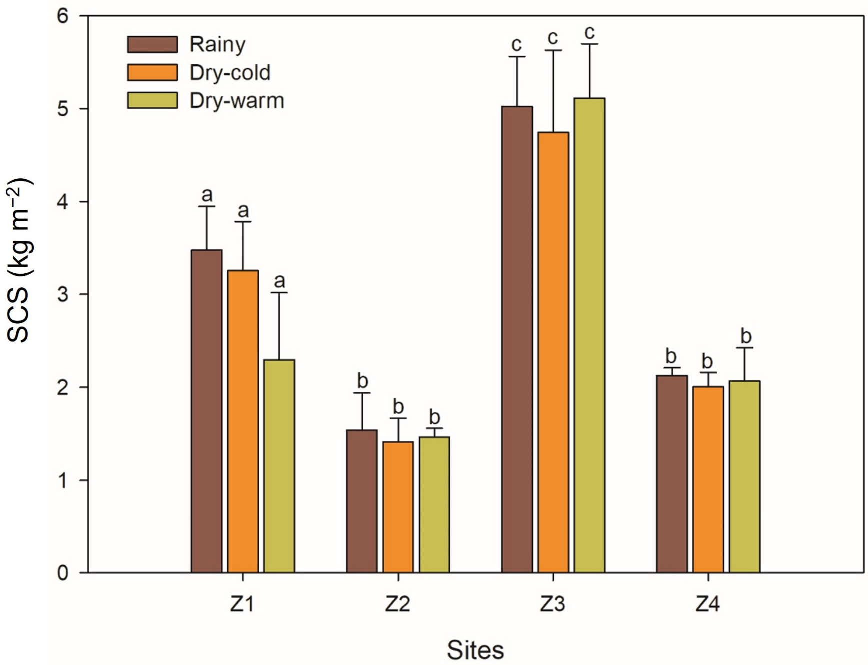
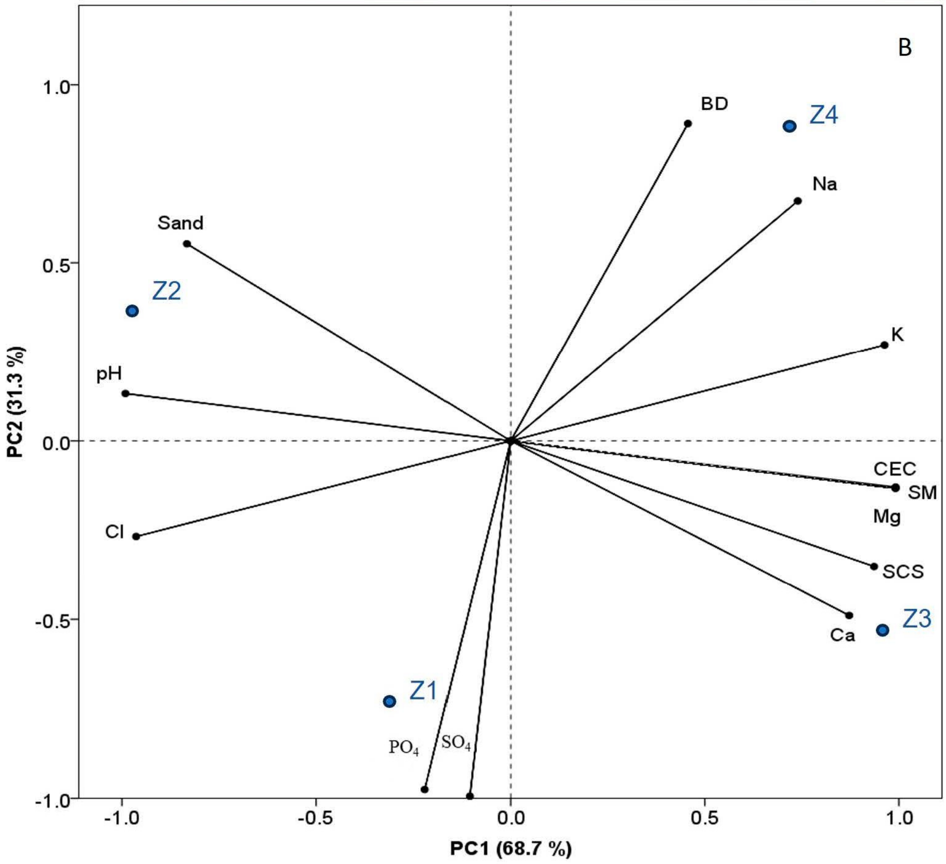


Figure 6. Soil carbon stock (SCS) at the different BT sites (Z1, Z2, Z3, and Z4) and seasons at 0–10 cm depth. Different letters above the bars indicate statistical significance of $p < 0.05$ between sites according to Tukey's test.

A

Variable	BD	SCS	Sand	SM	pH	Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	PO_4^{3-}	SO_4^{2-}
SCS	-0.17											
Sand	0.01	-0.63										
SM	-0.12	0.45	**-0.97***									
pH	-0.30	-0.84	0.80	-0.62								
Na^+	0.72	0.50	-0.60	0.44	-0.87							
K^+	0.93	-0.27	-0.19	0.16	-0.28	0.70						
Ca^{2+}	-0.51	0.52	-0.86	0.91	-0.46	0.11	-0.26					
Mg^{2+}	0.34	0.84	-0.42	0.18	-0.87	0.77	0.14	0.07				
Cl^-	-0.46	-0.01	0.73	-0.77	0.48	-0.64	-0.73	-0.46	-0.06			
PO_4^{3-}	**-0.98***	0.33	-0.20	0.29	0.11	-0.58	-0.89	0.65	-0.21	0.34		
SO_4^{2-}	-0.28	**0.97***	-0.47	0.29	-0.72	0.35	-0.43	0.42	0.81	0.20	0.40	
CEC	0.34	0.80	-0.82	0.65	**-0.99***	0.89	0.34	0.46	0.85	-0.54	-0.15	0.67



1.00 to 0.80 | 0.80 to 0.60 | 0.60 to 0.40 | 0.40 to 0.20 | 0.20 to 0.00

Figure 7. Pearson's correlation coefficients between soil variables (**A**) and principal component analysis of the most highly correlated variables according to the different sampling sites (**B**). * = Correlation significant at $p < 0.05$ (2-tailed). Z1, Z2, Z3 and Z4, are the different sampling sites.

3.4. Principal Component Analysis

The first two components of the PCA explained 100% of the variance, 68.7% for PC1 and 31.3% for PC2. The PCA showed that the soils of BT represent ensembles related to the soil characteristics of each sampling site (Figure 7B). In PC1, the most important factors with contributions between 10.38% and 11.1% were K^+, Mg^{2+}, and Cl^- ions, including CEC, SM, and pH (Table 2).

Table 2. Loadings and contribution of variables to the principal components.

Variable	PC1		PC2	
	Loadings	Contribution (%)	Loadings	Contribution (%)
Sand	−0.833	7.77	0.553	7.52
SM	0.991	11.00	−0.133	0.43
pH	−0.991	11.00	0.133	0.43
BD	0.457	2.33	0.890	19.46
SCS	0.936	9.81	−0.352	3.04
K^+	0.963	10.38	0.270	1.79
Ca^{2+}	0.872	8.51	−0.489	5.89
Mg^{2+}	0.991	11.00	−0.133	0.43
Cl^-	−0.964	10.39	−0.268	1.76
CEC	0.992	11.01	−0.129	0.41
$PO_4{}^{3-}$	−0.220	0.54	−0.975	23.39
$SO_4{}^{2-}$	−0.105	0.12	−0.994	24.30

Several factors contributed to the separation of the plots along PC2. The factors with the largest contribution (19.46% to 24.30%) were BD, $SO_4{}^{2-}$, and $PO_4{}^{3-}$ (Table 2). The PCA showed that the nutrient status of the soils was the most important factor for the separation of the plots according to the different sampling sites.

4. Discussion

4.1. Soil Physicochemical Properties and Its Quality and Fertility

The soils had a loamy and sandy loam texture of sand > silt > clay. Soil texture influences the CEC for the retention and exchange of the cations Na^+, K^+, Ca^{2+}, and Mg^{2+} [47,48]. The highest CEC values were observed at sites where silt and clay predominated (Z1 and Z3); this condition has been observed in other studies [49–52]. According to MON [53], the CEC found in BT are soils with an acceptable exchange capacity, which is reflected in the concentrations of cations that ensure the availability of nutrients for plants. In this study, the presence of macronutrients such as K^+, Ca^{2+}, and Mg^{2+} and micronutrients like Cu and Zn can reflect the natural fertility of the soil by defining the potential of soil to provide these mineral elements [54].

According to Legout et al. [19], soil fertility in forest ecosystems is defined as the capacity of the soil to retain nutrients associated with organic matter and clay content to ensure the proper functioning of the soil-plant system, providing an ecosystem service of regulation. Ca^{2+}, Mg^{2+}, and Na^+ were dominant at all sites in the BT. Ca^{2+} is a function of soil properties; Mg^{2+} is attributed to a hydration ratio that is retained less than Ca^{2+} [55]. The presence of $NO_3{}^-$, $SO_4{}^{2-}$, and $PO_4{}^{3-}$ also indicates a high organic load.

Concentrations of heavy metals in the soil were lower than at MON and were not considered toxic to the environment [53], except for Hg, which was twice the standard concentration. In the BT, Hg probably originates from anthropogenic activities and is trapped by organic matter enriching the surface layers of the soil [56]. The results show a strong relationship between heavy metals and SOM because organic matter can retain metals [57]. Chen et al. [58] suggest that the increase in trace elements is related to urbanization, which may be the case for BT.

BD is a dynamic soil property associated with texture and SOM [59]. The observed BD values are similar to those found by Saavedra-Romero et al. [60] in urban soils from the San Juan de Aragón forest, Mexico City (0.87 to 1.14 g cm^{-3}) and by Chávez-Aguilar et al. [61] (0.52 to 0.77 g cm^{-3}) in the temperate forest of Nevado de Toluca, Mexico. In urban parks, the BD is higher, reflecting soil compaction due to the influence of regular mowing and human trampling [62]. Studies in urban parks in other locations report mean values of 1.39 and 1.73 g cm^{-3} [63], 1.29 g cm^{-3} [64], and 0.97 g cm^{-3} [62], similar values to Z4. The compaction observed in Z2 and Z4 is due to the continuous human activity and the passage of people.

Sites with anthropogenic disturbance have low SOM values (Z2 and Z4). According to the MON [53], these sites are classified as very low class (<4%). Protected sites (Z1 and Z3) have SOM in the medium class (6.1 to 10.9%), indicating good soil quality.

4.2. Variability of Soil CO_2 Efflux

Soil CO_2 efflux, or Rs, is an important pathway in the global carbon cycle [65]. A number of physical (soil and air temperature, soil moisture) and biological (plant cover, plant phenology, and carbohydrate substrate supply from photosynthesis) factors have been recognized as regulators of Rs [66,67]. However, most process-based and analytical models only include the influence of Ts and SM as significant controls; typically, the effect of Ts on CO_2 efflux is modeled as an exponential function, with SM as an additive or multiplicative term. In this study, Rs did not differ between sampling sites, but there were differences between sampling periods, with higher values during the rainy season and lower values during the dry cold season. The sensitivity of Rs to SM, which modulates—and sometimes overrides—the effect of Ts, has been documented for a variety of water-limited environments such as deserts, Mediterranean ecosystems, and tropical dry forests [68–70]. A rapid increase in water availability leads to microbial reactivation, resulting in a pulse of root respiration and organic matter decomposition [71], carbon mineralization, and nutrient availability [72].

4.3. Influence of Management Type of BT on Soil Carbon Stock

The soils of BT are of volcanic origin, with lithosol and leptosol. They have an average depth of 25 cm, with stones of different sizes, so their potential to store carbon is limited.

The SCS in the study area shows a high variability between sites, ranging from 1.4 to 5.1 kg m^{-2} (0–10 cm). High spatial variability in carbon storage in urban forests and parks (0–10 cm) has also been found in other studies from New Zealand (2.7 to 4.8 kg m^{-2}) [73], Boston, MA, USA (2. 29 to 5.67 kg m^{-2}) [74], Baltimore, MD, USA (6.0 to 8.0 kg m^{-2}) [75], Republic of Korea (2.8 kg m^{-2}) [76], and Milan, Italy (0.75 to 6.48 kg m^{-2}) [64]. All these studies support the hypothesis that differences in management and land use within cities and land use types can explain the observed large intra-urban variability. SCS can regulate climate and influence other soil properties [77,78]. SOC is correlated with soil texture, SM, and CEC. The SCS was higher in soils with a clay texture, such as Z1 and Z3, so these sites are better adapted to sequester carbon [79,80].

Z1 showed the highest SCS, probably because it is the most protected site with very little anthropogenic influence, which is positive for soil and carbon dynamics. Z2 and Z4 had the lowest SCS, both sites having been historically degraded by anthropogenic activities such as recreational use and lawn mowing [32], which is reflected in the high sand content (53–67%) used to fill sites prior to reforestation and consequently higher soil compaction. These results are consistent with other studies that mention that soil compaction by human activities can reduce SCS reserves in urban forests [81,82].

Xu et al. [83] demonstrated that historical land use can have long-term effects on critical ecosystem processes, such as SCS accumulation. Therefore, the land use pattern is one of the most important determinants of SCS at the city or urban forest scale [64,76].

5. Conclusions

The physicochemical properties showed that the BT soil was of high quality, with fertile soils suitable for biomass production, based on SOM, pH, and soil texture as the most critical determinants of soil fertility since these parameters promote the solubility of Cd, Cu, Zn, Pb, Ni, and Hg, providing cations, anions, and nutrients.

The Rs values were higher during the rainy season, associated with higher soil moisture. Sites with high SCS were the least disturbed, so they have important long-term effects on forest carbon accumulation and storage processes.

The results of this study indicate that urban forests can act as carbon sinks if their soils are kept in good condition and under good conservation management. This can lead to the maintenance of the ecosystem services provided by the forest.

Author Contributions: Conceptualization, M.d.l.L.E.F. and E.G.d.C.; methodology, M.d.l.L.E.F., R.G., F.Z.G. and E.T.C.; software, F.Z.G. and E.T.C.; validation M.d.l.L.E.F., O.P. and E.G.d.C.; formal analysis, M.d.l.L.E.F., R.G., E.G.d.C., R.M.C.B. and J.G.C.B.; investigation, M.d.l.L.E.F., R.G., E.G.d.C. and O.P.; resources, M.d.l.L.E.F.; data curation, M.d.l.L.E.F., O.P. and F.Z.G.; writing—original draft preparation, M.d.l.L.E.F., O.P., R.G., E.G.d.C., R.M.C.B., J.G.C.B., F.Z.G. and E.T.C.; writing—review and editing, M.d.l.L.E.F., O.P., R.G., E.G.d.C., R.M.C.B., J.G.C.B., F.Z.G. and E.T.C.; visualization, M.d.l.L.E.F. and O.P.; supervision, M.d.l.L.E.F., O.P., R.G., E.G.d.C., R.M.C.B. and J.G.C.B.; project administration, M.d.l.L.E.F.; funding acquisition, M.d.l.L.E.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Project DGAPA-UNAM, PAPIIT IA102321 "Dinámica de los ciclos biogeoquímicos derivada de los impactos antropogénicos en un bosque urbano".

Data Availability Statement: Data are contained within the article.

Acknowledgments: The authors are grateful for the support of the administrators of the Tlalpan Forest for the facilities provided. The authors also thank María Isabel Saavedra, José Manuel Hernández Solis, and Moises López Carrasco for their assistance during laboratory analysis.

Conflicts of Interest: The authors declare no conflict of interest.

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