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Research article

Uso de suelo, propiedades edáficas y almacenes de carbono en el Parque Estatal El Ocotal, México

Land uses, soil properties and carbon storage in *El Ocotal* State Park, Mexico

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Abstract

The *El Ocotal* State Park, located in *Estado de México*, is a priority area for the protection and conservation of local ecosystems, playing a prominent role in the provision of ecosystem services. In addition to being a source of employment through ecotourism, this area faces challenges stemming from historical land-use changes, which have caused significant transformations in the structure and composition of its soil and vegetation cover. However, the extent of these alterations and their implications for the ecosystem services provided by the park remain poorly understood. In this context, the present study focused on estimating the capacity of the park's soil and tree vegetation to preserve and enhance ecosystem services related to carbon capture and storage. Through the analysis of the physical and chemical properties of the soil, mensuration records of the trees, and allometric equations, the capacity of forest communities to store carbon in soils and tree biomass was determined. The largest carbon reservoirs were found in tree biomass, with values ranging from 123 to 330 Mg ha^{-1}, while soils registered between 51 and 128 Mg ha^{-1}. Reforestation with 20-year-old *Pinus pseudostrobus* showed the highest Total Organic Carbon storage capacity, with 406 Mg ha^{-1}. These results underscore the importance of conserving and regulating the use of the park's natural resources to ensure the continuous provision of its ecosystem services.

Keywords: Tree biomass, park, *Pinus pseudostrobus* Lindl., soil properties, reforestation, ecosystem services.

Resumen

El Parque Estatal El Ocotal, ubicado en el Estado de México, es un área prioritaria de protección y conservación de ecosistemas locales, con una función destacada en la provisión de esos servicios. Además de ser un generador de empleo a través del ecoturismo, este espacio enfrenta desafíos derivados de los cambios históricos en el uso del suelo, los cuales han ocasionado transformaciones significativas en la estructura y composición de sus suelos y cubierta vegetal. Sin embargo, la magnitud de tales alteraciones y sus implicaciones en los servicios ecosistémicos proporcionados por el parque siguen siendo poco comprendidas. En este contexto, la presente investigación se enfocó en estimar la capacidad del suelo y la vegetación arbórea del parque como proveedores de servicios ecosistémicos relacionados con la captura y almacenamiento de carbono. A partir del análisis de las propiedades físicas y químicas del suelo, el registro dasométrico de los árboles y de ecuaciones alométricas, se determinó la capacidad de las comunidades forestales para acumular carbono en suelos y vegetación arbórea. Los mayores reservorios de carbono se concentran en la biomasa arbórea con valores entre 123 y 330 Mg ha^{-1}, mientras que en el suelo se registraron entre 51 y 128 Mg ha^{-1}. La reforestación con *Pinus pseudostrobus* de 20 años mostró la mayor capacidad de almacenamiento de Carbono Orgánico Total con 406 Mg ha^{-1}. Los resultados subrayan la importancia de conservar y regular el uso de los recursos naturales del parque para garantizar la provisión continua de los servicios ecosistémicos que ofrece.

Palabras clave: Biomasa arbórea, parque, *Pinus pseudostrobus* Lindl., propiedades edáficas, reforestación, servicios ecosistémicos.

Introduction

Protected Natural Areas (PNA) emerged in North America with their first decree at the end of the 19th century and since then, many countries have incorporated this instrument into their environmental legislation (Chavarría et al., 2019). In Mexico, these spaces are especially important because they are inhabited by communities that depend on the use of their natural resources, so their management requires a balance between the preservation of ecosystems and the reduction of poverty and marginalization of their inhabitants (Arriola et al., 2014).

In the management of the PNAs, strategies have been implemented that include payment for ecosystem services (ES), implementation of productive projects and nature tourism. Tourism in the PNAs must combine the preservation of resources with local economic development and cultural strengthening; however, when practiced in an unregulated manner, it can cause biodiversity loss and deterioration of the environmental quality of its biophysical components and reduction of the ecosystem services they provide to society (Canteiro et al., 2018; Medina-Castro et al., 2019).

To estimate the capacity of the PNA as ES suppliers, it is important to consider the timely monitoring of the biophysical components; in the case of soil, properties and processes that determine its health have been analyzed, so that they can provide a reference to its current condition based on its management or degree of disturbance. Following this line at an international level, tables of quality indicators have been proposed in soils of forest ecosystems in China (Wang et al., 2023), in Mediterranean regions of Central-Eastern Spain (Andrés-Abellán et al., 2019), and coffee agroecosystems in Colombia (Afanador-Barajas et al., 2020).

In Mexico, studies carried out by Álvarez-Arteaga et al. (2020) and Cruz-Flores and Etchevers-Barra (2011) have proposed regional soil quality indicators, which eventually allow the estimation of ES, both in natural spaces and those altered by human activities. In the case of carbon estimation in tree biomass, multiple studies have applied non-destructive methods based on allometric equations with highly efficient results (Canedoli et al., 2020; Ronquillo-Gorgúa et al., 2022).

In regard to the study area of this research in the *El Ocotal* State Park (PEEO), Pérez et al. (2009) qualitatively determined the environmental impact of tourist activities through direct observation methods. The results showed that the continuous flow of visitors generates negative impacts that translate into the deterioration of the vegetation cover, soil sealing and its water erosion. However, they were unable to determine the extent of the impacts. Since the PEEO is a strategic site for the integration of nature tourism, the promotion of ecosystem services, and the mitigation of greenhouse gas emissions, the objective of this research was to estimate the capacity of the soil and tree vegetation in the park to store carbon under different land use conditions.

Materials and Methods

Study area

The PEEO is located in the *Santiaguito Maxdá ejido*, *Timilpan* municipality, in the *Estado de México* (Figure 1), with geographic coordinates LN 19°48’46” and

19°47’52”, and LW -99°45’17” and -99°45’11”, at an average altitude of 2 750 masl and an area of 122 ha (Gobierno del Estado de México, 1999).

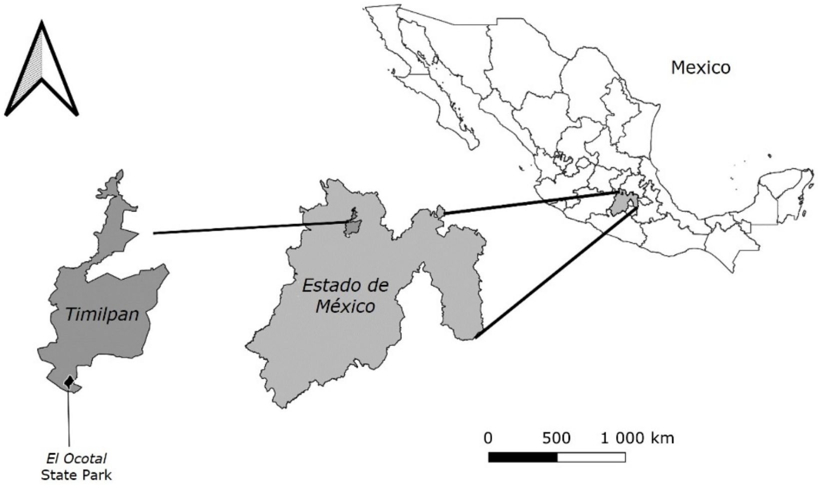


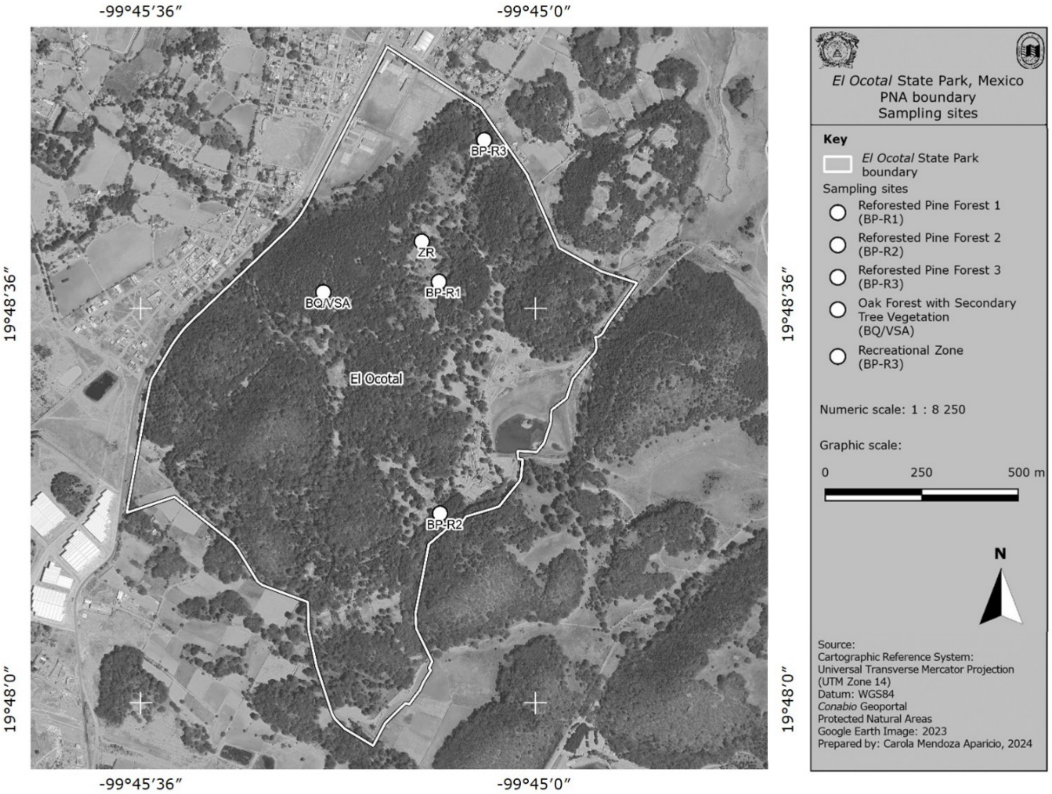
Figure 1. Study area location.

The area is dominated by a temperate subhumid climate with summer rains. The average annual temperature is 16 °C, with an average annual rainfall of 800 mm (Instituto Nacional de Estadística, Geografía e Informática [INEGI], 2016). The dominant soil group is luvic and haplic feozem; the tree association is made up of *Pinus pseudostrobus* Lindl., *P. montezumae* Lamb., *Quercus rugosa* Neé, *Q. laurina* Bonpl. and *Q. crassipes* Bonpl., in association with induced grassland (INEGI, 2016).

The inhabitants indicate that until 40 years ago forest use continued to obtain firewood and charcoal, so much of the current vegetation cover of the park is the result of reforestation with pine species carried out from this period. Tourist services are provided by members of the community, who offer lodging, food, surveillance and maintenance.

Soil and vegetation characterization and sampling

Based on spatial analysis using QGis Version 3.22 software (Geographic Resources Analysis Support System [GRASS], 2022) and satellite images from the Google Earth platform, areas of the park with different land uses and vegetation were delimited. Field surveys were subsequently conducted to verify the information, and five sites representative of the land uses were selected, according to the methodology proposed by Siebe et al. (2016) (Figure 2).



El Ocotal = *El Ocotal* State Park; ZR = RZ (Recreational Zona).

Figure 2. Sampling sites in the study area.

To determine the soil properties of each site, the thickness and condition of the organic layer of the soil were characterized according to the scheme proposed by Chertov and Nadporozhskaya (2018), which identifies the different organic horizons of the soil and their implications on the decomposition of organic remains. Four soil extractions were carried out with a model 301.64 AMS® auger at 20, 50 and 100 cm depth, obtaining 1 kg samples. Additionally, surface samples were collected in triplicate from each point in order to calculate the Apparent Density (*AD*) by the cylinder method. The samples were taken to the Environmental Sciences Laboratory Unit of the Graduate School of Urban and Regional Planning of the *Universidad Autónoma del Estado de México* for preparation and physical and chemical analysis during 2023.

Other parameters analyzed were True Density (*RD*) with the pycnometer method, texture by the Bouyoucos method, Soil Organic Carbon (*SOC*) content by the wet oxidation method, pH with the potentiometer method (model 58907 Corning®) in water, Cation Exchange Capacity (*CEC*) and macronutrients (nitrogen, phosphorus and potassium) using a field probe (model 240 v. Fdit®). With the exception of the latter, the methods used are described in van Reeuwijk (2002) and within the NOM-021-RECNAT-2000 (2001).

To characterize the forest cover at each site, the Diameter at Breast Height (*DBH*=1.3 m) of all tree individuals with *DBH*>5 cm was measured using a model 283D/20F Forestry Suppliers® diameter tape. From these data, the composition and structure of the trees, their Basimetric Area (*BA*) and Tree Biomass Carbon (*TBC*) were determined, for which allometric equations specific to temperate forests in Central and Northern Mexico were used (Aguirre-Calderón & Jiménez Pérez, 2011; Bolaños et al., 2017) (Equation 1 and 2).

$$\textit{Quercus rugosa}: B = (0.1033)(DN^{2.39}) \quad (1)$$

Pinus pseudostrobus: $B = 0.3518 \times DN^2$ (2)

Where:

B = Biomass

ND = Normal diameter (cm)

The soil carbon store (Mg ha^{-1}) was estimated at 100 cm depth; *SOC*, *AD* and soil layer thickness were considered and a standard *SOM* (Soil Organic Matter) to *SOC* conversion factor of 0.5 was applied (Etchevers et al., 2005).

Descriptive statistical tests were used to evaluate the variability of soil properties and carbon pools to establish their distribution and behavior with respect to depth. Correlation analyses allowed the identification of significant relationships between the variables used, and key patterns were highlighted that allowed understanding the dynamics of carbon storage in forest ecosystems. Statistical analyses were performed using PASW 18.0 software (Statistical Package for the Social Sciences Inc. [SPSS], 2009).

Results

Characterization of vegetation cover

The general description of the study sites is shown in Table 1. Site BP-R1 (Reforested Pine Forest), 11 years old, is located in a recreation area. The type of mulch overlying the first mineral horizon corresponds to a Moder, characterized by having organic subhorizons thicker than 25 cm due to the slowing down of the decomposition of pine needles.

Table 1. Characterization of sampled sites in *El Ocotal* State Park, *Estado de México*, Mexico.

Point		BP-R1	BQ/VSA	BP-R2	BP-R3	RZ
Reforestation year		2008, 2022	ND	2003	2012, 2022	2022
Altitude (masl)		2 770	2 786	2 750	2 770	2 770
Slope (%)		<1	17.8	0	<1	2
Mulch		Moder	Mull	Mull	Moder	NA
Dominant species		*Pinus pseudostrobus* Lindl.	*Quercus rugosa* Neé	*Pinus pseudostrobus* Lindl.	*Pinus pseudostrobus* Lindl. *Pinus montezumae* Lamb.	NA
			Tree stratum structure			
***DBH* (cm)**	5-10	85	11	0	14	7
	10-30	3	43	47	26	0
	30-50	11	13	32	5	0
	>50	2	0	1	2	0
Total number of individuals in 400 m²		101	67	80	47	7
Basimetric area (m²) in 400 m²		2.20	2.55	5.77	2.60	0.00076
Basimetric area (m² ha⁻¹)		55.10	63.63	144.23	65.08	0.02

BP-R1 = Reforested Pine Forest 1; BQ/VSA = Oak Forest with Secondary Tree Vegetation; BP-R2 = Reforested Pine Forest 2; BP-R3 = Reforested Pine Forest 3; RZ = Recreational Zone; ND = Not available; NA = Not applicable. Moder = Organic horizon with a 2 to 8 cm thickness, slow leaf litter decomposition; Mull = Organic horizon of little thickness or absent.

The BQ/VSA site (Oak Association with Secondary Vegetation) has a thin superficial organic layer (Mull), with a higher rate of decomposition of organic remains than the Moder. The forest cover is dominated by *Quercus rugosa* individuals, with few *Arbutus xalapensis* Kunth specimens. Some particular features of the site were detected, the most evident of which are the presence, although scarce, of epiphytic plants on the trees, signs of sheet and furrow water erosion.

The BP-R2 site (Reforestation with *Pinus pseudostrobus*) is approximately 20 years old. The superficial layer of the soil is covered by needles with a 15 to 25 cm thickness, with a low degree of decomposition and imperceptible fermentation horizon (Moder). Evidence of disturbance caused by gaps was observed, with moderate soil compaction; its effective depth is less than 70 cm.

The BP-R3 site, with *Pinus pseudostrobus* and *P. montezumae* reforestation, is a forest that is over 20 years old. Mulch is 5 cm deep and consists of grass and pine needles. The last site, in a recreational zone (RZ), lacks vegetation cover and the soil is compacted by the passage of visitors and vehicles.

Regarding the structure of the forest communities, in BP-R1 the most recent reforestation is accompanied by isolated trees with *DBH*>30 cm that protect the newly incorporated seedlings. There are few trees with *DBH* between 10 and 30 cm, which indicates spacing in the reforestation and elimination of sick trees. BQ/VSA is considered to be a remnant of the original vegetation prevalent in the region, there are no trees with *DBH*>50 cm, there are predominantly specimens between 10 and 30 cm and there are oak seedlings. In BP-R2, trees with *DBH* between 30 and 50 cm dominate, while in BP-R3, trees with *DBH* between 10 and 30 cm predominate

Physica and chemical characterization of soils

Although medium and coarse textural classes predominate in the surface layer of the PEEO soils, it is important to establish the accumulation pattern of clays because they are the mineral fraction that allows the formation of organomineral compounds that confer stability to the stored carbon in the medium and long term (Rodríguez et al., 2019). Based on the dominant pedogenetic processes of eluviation-illuviation of secondary minerals (clays and iron oxides), a first group is distinguished, represented by site BP-R1, in which an increase in clays is observed at greater depth, denoting the formation of an argillic horizon from 30 cm (Table 2). The second group is formed by sites BQ/VSA, BP-R3 and RZ; in these soils, the existence of a clay accumulation horizon is not observed at least in the first 100 cm deep. The third group corresponds to site BP-R2 where the soils keep clay contents greater than 30 % at all depths and are located in the lower parts of the park.

Table 2. Physical properties of the soils of the study sites of *El Ocotal* State Park, *Estado de México*, Mexico.

Site	Prof.	Are	Lim	Arc	*AD*	Poro
	cm			%		
BP-R1	1	69.0 (10.5)	20.3 (6.9)	10.7 (3.6)	0.8 (0.1)	52.2 (2.7)
	2	53.7 (2.5)	23.8 (9.8)	22.5 (8.1)	0.9 (0.1)	54.0 (7.6)
	3	45.9 (4.3)	23.8 (4.0)	30.3 (1.3)	1.0 (0.1)	42.3 (23.6)
BQ/VSA	1	48.8 (3.5)	36.7 (2.5)	14.5 (1.0)	0.8 (0.1)	58.7 (4.7)
	2	53.8 (3.0)	32.5 (1.3)	13.7 (3.5)	0.9 (0.1)	51.9 (7.5)

	3	52.0 (3.9)	31.6 (5.6)	16.4 (1.7)	1.0 (0.0)	49.2 (0.5)
BP-R2	1	38.3 (5.3)	30.1 (1.8)	31.6 (6.2)	1.02 (0.0)	47.5 (2.6)
	2	47.6 (24.8)	20.0 (5.9)	32.4 (21.9)	1.07 (0.1)	47.5 (1.5)
	3	49.2 (14.1)	20.6 (4.2)	30.2 (18.4)	1.0 (0.0)	48.9 (0.4)
BP-R3	1	56.7 (8.3)	27.0 (6.5)	16.3 (2.6)	0.8 (0.1)	54.6 (8.0)
	2	51.4 (16.4)	23.5 (1.0)	25.1 (16.1)	0.9 (0.1)	54.5 (3.7)
	3	61.7 (4.7)	21.3 (1.7)	17.0 (3.7)	1.1 (0.1)	48.4 (3.3)
RZ	1	50.6 (5.4)	31.1 (5.3)	18.3 (2.4)	0.84 (0.0)	53.9 (4.4)
	2	46.5 (8.1)	31.3 (3.4)	22.2 (7.9)	0.9 (0.1)	55.6 (2.1)
	3	63.6 (5.3)	17.7 (4.1)	18.7 (2.2)	1.1 (0.1)	50.3 (1.2)

Prof. = Depth 1:0-20 cm, 2:20-50 cm and 3:50-100 cm; Are = Sands; Lim = Silts; Arc = Clays; *AD* = Bulk Density; Poro = Porosity. BP-R1 = Reforested Pine Forest 1; BQ/VSA = Oak Forest with Secondary Tree Vegetation; BP-R2 = Reforested Pine Forest 2; BP-R3 = Reforested Pine Forest 3; RZ = Recreational Zone. * = Surface data. Data in parentheses refer to the standard deviation.

The *AD*, *RD* and porosity values at the sites, except in BP-R2 (whose textural class differs), indicate greater compaction and reduction of the porous space with depth, which tends to decrease the capacity to dislodge water, especially in the rainy season. Porosity in all soils and depths is greater than 50 %, except in BP-R2 (47.5 %), where medium and fine pores predominate (0.2-50 microns).

The pH values (Table 3) show a moderately acidic tendency in the surface horizon, which approaches neutrality in depth. However, this condition should not be a limitation in the mobility of macro and micronutrients.

Table 3. Chemical properties of the soils of the study sites of *El Ocotal* State Park, *Estado de México*, Mexico.

Site	Prof.	pH		*SOC*	N	P	K	*CEC*
	cm	H_2O	KCl	%	mg kg^{-1}			meq 100 g
BP-R1	1	6.0 (0.5)	4.9 (0.3)	3.7 (1.8)	1.0 (1.0)	2.0 (1.0)	4.5 (1.7)	22.5 (2.8)
	2	6.3 (0.1)	5.3 (0.3)	1.3 (0.8)	1.0 (0.0)	1.0 (0.0)	4.0 (0.0)	
	3	6.5 (0.2)	5.0 (0.1)	0.5 (0.2)	3.0 (1.0)	4.0 (1.0)	11.2 (1.2)	
BQ/VSA	1	6.6 (0.3)	5.4 (0.4)	2.1 (2.3)	3.0 (3.0)	4.0 (4.0)	9.5 (9.4)	30.2 (6.1)
	2	6.4 (0.4)	5.2 (0.2)	0.4 (0.1)	1.0 (1.0)	2.0 (1.0)	4.7 (3.0)	
	3	7.0 (0.1)	5.9 (0.3)	0.4 (0.1)	1.0 (1.0)	2.0 (1.0)	1.5 (2.1)	
BP-R2	1	6.1 (0.2)	4.6 (0.3)	1.3 (0.7)	4.0 (2.0)	5.0 (3.0)	12.2 (7.2)	17.5 (2.0)
	2	6.3 (0.1)	4.7 (0.2)	1.3 (0.9)	5.0 (2.0)	7.0 (3.0)	17.0 (7.1)	
	3	6.2 (0.1)	4.6 (0.2)	0.3 (0.1)	7.0 (3.0)	10.0 (4.0)	23.0 (8.4)	
BP-R3	1	6.0 (0.2)	4.7 (0.3)	1.7 (1.4)	1.0 (1.0)	2.0 (1.0)	4.7 (3.0)	21.7 (5.5) *
	2	6.3 (0.1)	5.4 (0.6)	0.6 (0.3)	1.0 (1.0)	2.0 (1.0)	11.5 (13.3)	
	3	6.3 (0.2)	5.1 (0.4)	0.9 (0.8)	2.0 (1.0)	3.0 (1.0)	7.7 (3.7)	
RZ	1	6.4 (0.1)	4.9 (0.1)	0.9 (0.5)	1.0 (1.0)	2.0 (1.0)	5.5 (2.6)	23.2 (3.8)

2	6.4 (0.2)	4.9 (0.1)	0.5 (0.4)	2.0 (1.0)	3.0 (2.0)	6.7 (3.8)
3	6.4 (0.2)	5.1 (0.3)	0.4 (0.3)	2.0 (1.0)	3.0 (2.0)	7.0 (3.9)

Prof. = Depth 1:0-20 cm, 2:20-50 cm and 3:50-100 cm; pH = Hydrogen potential; KCl = Potassium chloride; *SOC* = Soil Organic Carbon; *CEC* = Cation Exchange Capacity; Nt = Total nitrogen; P = Assimilable phosphorus; K = Potassium; meq 100 g = Milliequivalents per 100 g of soil. BP-R1 = Reforested Pine Forest 1; BQ/VSA = Oak Forest with Secondary Tree Vegetation; BP-R2 = Reforested Pine Forest 2; BP-R3 = Reforested Pine Forest 3; RZ = Recreational Zone. Data in parentheses refer to the standard deviation.

SOC decreases with depth, and BP-RI is the site with the highest content (5.5 %). This value does not correlate directly with the concentration of nitrogen, phosphorus and potassium; in contrast, BQ/VSA presents higher values for these indicators. The low availability of *SOC* and macronutrients in RZ coincides with the scarce contribution of organic remains. BQ/VSA stands out for having the highest *CEC* in the system.

The carbon stores in the soil and tree biomass are shown in Table 4. In all sites, except in RZ where forest cover is scarce, the largest carbon reserve is in tree biomass, with values between 123.4 and 329.8 Mg ha^{-1}. This variation is due to the proportion of individuals with *DBH* of 30 to 50 cm per site. In BQ/VSA, natural replacement trees stand out in this segment, absent in the other sites.

Table 4. Carbon stores in biomass and soil (Mg ha^{-1}).

	BP-R1	**BQ/VSA**	**BP-R2**	**BP-R3**	**RZ**
			Mg C ha^{-1}		
		TBC			
		***DBH* (cm)**			
0-10	1.0	1.8	0	2.9	0
10-30	3.9	52.8	102.1	27.0	0

30-50	82.9	98.0	206.4	28.8	0
>50	35.6	0	21.2	89.3	0
Subtotal	123.4	152.7	329.8	147.9	0
			***SOC* (cm)**		
0-20	62.0 (32.5)	29.9 (31.0)	26.7 (14.5)	29.4 (25.9)	14.7 (8.8)
20-50	37.7 (21.2)	13.5 (4.0)	42.2 (31.7)	18.4 (10.4)	13.5 (11.5)
50-100	28.4 (13.3)	7.8 (3.7)	8.0 (3.4)	49.4 (40.9)	24.9 (17.1)
Subtotal	128.1	51.2	76.9	97.3	53.2
TOC	251.5	203.9	406.7	245.2	53.2

TBC = Carbon in Tree Biomass; *SOC* = Soil Organic Carbon; *TOC* = Total Organic Carbon; Mg C ha^{-1} = Megagrams of Carbon per hectare. BP-R1 = Reforested Pine Forest 1; BQ/VSA = Oak Forest with Secondary Tree Vegetation; BP-R2 = Reforested Pine Forest 2; BP-R3 = Reforested Pine Forest 3; RZ = Recreational Zone. Data in parentheses refer to the standard deviation.

The carbon stock in the soil fluctuated between 51.2 and 128.1 Mg ha^{-1}. BQ/VSA showed the lowest value, influenced by the rapid decomposition of leaf litter and erosion. It is important to note that between 30 and 50 % of the *SOC* is found in the first 20 cm deep, which indicates the importance of conserving this surface layer. Based on the total carbon stored in the soil-vegetation system, the composition of the stores can be variable: in BP-R2, 81 % of the carbon is concentrated in the biomass, and reaches the highest *TOC* reserve with 406.7 Mg ha^{-1}, while in BP-R3, it only corresponds to 60 %. In contrast, in RZ, the entire carbon store is located in the soil (53.2 Mg ha^{-1}) (Figure 3).

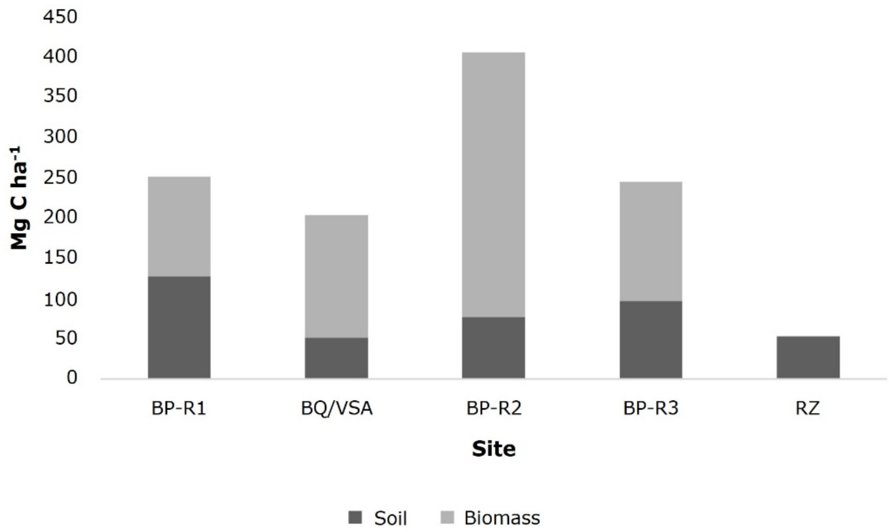


Figure 3. Comparison of carbon stores in tree biomass *vs.* soil, *El Ocotal* State Park, *Estado de México*, Mexico.

Discussion

In response to the increasing loss of integrity of the vegetation cover within the park, reforestation campaigns have led to the introduction of non-native species that coexist with the remnants of oak forests located on the conical hills; this has led to a transition from oak and oak-pine forest to pine in the middle and lower parts of the system (Rosaliano et al., 2022; Torres, 2021).

The study on the structure of the forest communities detects differences in their composition, derived from the recurrent repopulation campaigns to replace dead or sick individuals, as can be seen in sites BP-R1 and BP-R3. A direct consequence of changes in plant composition is the alteration of biogeochemical cycles, especially of carbon (Rodríguez et al. , 2019), because the decomposition rates and quality of organic matter are reduced in this transition, a condition that is observed in the composition and thickness of soil mulch when moving from oak forest (Mull) to pine (Moder), similar to that shown by Chertov and Nadporozhskaya (2018) in the transition from deciduous to evergreen forests in different bioclimatic regions of the world.

The analysis of soil texture at 100 cm revealed the presence of three patterns, defined by the relationship between the proportion of clays, porosity and soil density, which have direct implications on soil carbon storage, but also on the water performance of the soil; this favors the reduction of hydraulic conductivity as the clay content and the proportion of fine pores increase. This situation is mainly evident in areas with lower slopes, conducive to the accumulation of clays, as is the case of sites BP-RI and BP-R2. Chemical analyses indicate that, in general terms, nutrient availability and *CEC* are medium-low in all sites except BP-R2, which is consistently higher even up to 50 cm deep, which could be related to higher vegetation growth rates.

In tree biomass, the highest storage was recorded for BP-R2 (329.76 Mg C ha^{-1}). Compared to the other study sites, it amounted for between 2.2 and 2.7 times more carbon. These differences are attributed to the high density of individuals with *DBH* between 10 and 50 cm that represent the entire tree stratum, but their relationship with greater availability of nutrients in the soil for this site could not be ruled out, as previously mentioned.

The carbon stores in tree biomass and soil were compared with similar studies from different regions and climatic conditions in Mexico (Table 5). Thus, for example, Aguirre-Calderón and Jiménez-Pérez (2011) in a forest community in Northern Mexico, considering a similar age of the plantations with those of the present study, established that the *TBC* content for the PEEO in the sites BP-R1, BP-R2 and BP-R3, is between 3 and 4 times higher than the sites of the study referred to. Compared to the study carried out in *Pinus pseudostrobus* forests in the *Sierra Norte de Oaxaca* (Leyva-Pablo et al., 2021), the *TBC* reserve in the PEEO at site BP-R1 is 1.9 times lower. The differences in both comparisons are ascribed to the prevailing climatic conditions, including the average annual precipitation, since in the location of the state of *Nuevo*

León it is 430 mm, while in the PEEO it is 800 mm and in the case of the state of *Oaxaca* it is 1 100 mm per year. A third study, carried out by Cano-Flores et al. (2020) within the same bioclimatic region as ours, reported a *TBC* reserve in the *El Faro* PNA three times lower than that obtained in this study. In this case, the difference lies in the low average density of tree individuals (227 *versus* 1 400 in this case), which can be attributed to the intensification of management and conservation practices that have been carried out within the PEEO during the last 40 years sponsored by its state PNA decree.

Table 5. Comparison of carbon stores in tree biomass and soil in forest areas of Mexico.

Vegetation	Biomass	Soil	Total	Source
	Mg C ha^{-1}			
Pine-Oak forest	383.9	47.3	431.2	Leyva-Pablo et al. (2021)
	71.7	53.8*	125.6	Cano-Flores et al. (2020)
Oak-Pine forest	-	164.3	164.3	Vargas-Larreta et al. (2023)
	66.6	98.3*	164.9	Cano-Flores et al. (2020)
***Pinus pseudostrobus* Lindl.**	37.0^{1} 95.0^{2} 30.0^{3}	- - -	52.5 95.0 105.9	Aguirre-Calderón and Jiménez-Pérez (2011)
	238.2	30.4**	268.6	Leyva-Pablo et al. (2021)
***Pinus montezumae* Lamb.**	-	76	76	Cruz-Flores and Etchevers-Barra (2011)
***Pinus* spp.**	123.4^{1} 329.8^{2} 147.9^{3}	128.1 76.9 97.3	251.5 406.7 245.2	This study
***Quercus* spp.**	50.5	101.7*	152.2	Cano-Flores et al. (2020)
	199.1	48.7**	247.8	Leyva-Pablo et al. (2021)
***Quercus* spp.**	152.7	51.2	203.9	This study

^{1} = 15-year data with average height of 16 m; ^{2} = 20-year data with average height of 21 m; ^{3} = 13-year data with average height of 16 m. * = *SOC*:0-20cm; ** = *SOC*:0-30cm.

SOC stores fluctuated within the different sites, being significantly higher in BP-R1, in contrast to BQ/VSA. This is mainly explained by slope processes such as sheet water erosion, the presence or absence of surface organic horizons and soil sealing due to vehicle and visitor traffic. As an important fact, it is highlighted that, for all sites, between 30 and 50 % of the *SOC* storage is concentrated in the first 20 cm of depth, so the reduction or elimination of this surface layer implies a substantial loss in carbon reserves and the availability of nutrients necessary for plant development; therefore, it is considered necessary to focus on those areas where signs of erosion were detected to implement soil restoration actions.

Even though the data from this study indicate that reforestations with pine have the highest biomass production and, consequently, accumulate more carbon, it must also be taken into account that these sites tend to be less biodiverse and susceptible to pests and diseases (Gillerot et al., 2021).

By establishing a comparison of the structure and composition between the studied plant communities, it can be inferred that, unlike pine plantations, oak forests still retain part of their integrity and self-regeneration due to the analysis of the tree structure in which they were recorded, a condition that is threatened by the excessive load of visitors, erosive processes in the soil and spatial fragmentation; this implies microclimatic changes and in the composition of plant communities and soil biota, similar to that stated by Pérez et al. (2013) and Canteiro et al. (2018).

Conclusions

The historical processes of occupation of the territory within the *El Ocotal* State Park have determined changes in the structure and composition of plant communities, which affects the carbon storage capacity in both tree biomass and soil. The transition from oak to pine plant communities has implications for the availability and quality of nutrients in the soil, due in part to the reduction in the decomposition rates of organic matter accumulated in the soil mulch. The largest carbon reservoirs were located in the tree biomass, with values between 123 and 330 Mg ha^{-1}, while in the soil they were recorded between 51 and 128 Mg ha^{-1}; the 20-year-old reforestation with *Pinus pseudostrobus* showed the greatest capacity for total organic carbon storage with 406 Mg ha^{-1} and had the highest density of individuals with *DBH*>30 cm. Between 30 and 50 % of the *SOC* is located in the first 50 cm of depth, so the loss of the surface layers of the soil implies a loss of substances from the soil carbon stores. It is considered of great importance not only to estimate carbon content but also to understand the current state of these reservoirs based on the analysis of the properties and processes that involve their incorporation and permanence in forest systems.

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Conflict of interest

The authors declare that they have no conflict of interest.

Contribution by author

Carola Mendoza Aparicio: field work, laboratory, preparation and correction of the manuscript in the different stages of review; Gustavo Álvarez Arteaga: review and correction of the manuscript in the different stages; Miguel Martínez Tapia: field work, preparation of the manuscript; María Antonieta Reyes Zuazo: laboratory work and review of the manuscript.

References

Afanador-Barajas, L. N., Coca P., D. A., Vargas G., A. F., Bautista M., M. F., Mendoza H., A., y Vallejo Q., V. E. (2020). Evaluación de la calidad de suelos en agroecosistemas de Colombia a través de la selección de un conjunto mínimo de datos. *Colombia Forestal*, *23*(1), 35-50. https://doi.org/10.14483/2256201X.14856

Aguirre-Calderón, O. A., y Jiménez-Pérez, J. (2011). Evaluación del contenido de carbono en bosques del Sur de Nuevo León. *Revista Mexicana de Ciencias Forestales*, *2*(6), 73-84. https://doi.org/10.29298/rmcf.v2i6.575

Álvarez-Arteaga, G., Ibáñez-Huerta, A., Orozco-Hernández, M. E., y García-Fajardo, B. (2020). Regionalización de indicadores de calidad para suelos degradados por actividades agrícolas y pecuarias en el altiplano central de México. *Quivera, Revista de Estudios Territoriales*, *22*(2), 5-19. https://doi.org/10.36677/qret.v22i2.13302

Andrés-Abellán, M., Wic-Baena, C., López-Serrano, F. R., García-Morote, F. A., Martínez-García, E., Picazo, M. I., Rubio, E., Moreno-Ortego, J. L., Bastida-López, F., & García-Izquierdo, C. (2019). A soil-quality index for soil from Mediterranean forests. *European Journal of Soil Science*, *70*(5), 1001-1011. https://doi.org/10.1111/ejss.12798

Arriola P., V. J., Estrada M., E., Ortega-Rubio, A., Pérez M., R., y Gijón H., A. R. (2014). Deterioro en áreas naturales protegidas del centro de México y del Eje

Neovolcánico Transversal. *Investigación y Ciencia*, *60*, 37-49. https://www.redalyc.org/pdf/674/67431160005.pdf

Bolaños G., Y., Bolaños G., M. A., Paz P., F., y Ponce P., J. I. (2017). Estimación de carbono almacenado en bosques de oyamel y ciprés en Texcoco, Estado de México. *Terra Latinoamericana*, *35*(1), 73-86. https://doi.org/10.28940/terra.v35i1.243

Canedoli, C., Ferrè, C., El Khair, D. A., Comolli, R., Liga, C., Mazzucchelli, F., Proietto, A., Rota, N., Colombo, G., Bassano, B., Viterbi, R., & Padoa-Schioppa, E. (2020). Evaluation of ecosystem services in a protected mountain area: Soil organic carbon stock and biodiversity in alpine forests and grasslands. *Ecosystem Services*, *44*, Article 101135. https://doi.org/10.1016/j.ecoser.2020.101135

Cano-Flores, O., Vela-Correa, G., Acevedo-Sandoval, O. A., y Valera-Pérez, M. Á. (2020). Concentraciones de carbono orgánico en el arbolado y suelos del área natural protegida El Faro en Tlalmanalco, Estado de México. *Terra Latinoamericana*, *38*(4), 895-905. https://doi.org/10.28940/terra.v38i4.757

Canteiro, M., Córdova-Tapia, F., & Brazeiro, A. (2018). Tourism impact assessment: A tool to evaluate the environmental impacts of touristic activities in Natural Protected Areas. *Tourism Management Perspectives*, *28*, 220-227. https://doi.org/10.1016/j.tmp.2018.09.007

Chavarría O., Y., Martínez G., A. L., Ortíz C., E., y Goyenechea, I. (2019). Evolución en la selección de áreas protegidas en el continente americano: el caso de Estados Unidos, México y Costa Rica. *Boletín Científico del Instituto de Ciencias Básicas e Ingenierías*, *7*(13), 47-53. https://doi.org/10.29057/icbi.v7i13.3433

Chertov, O. G., & Nadporozhskaya, M. A. (2018). Humus forms in forest soils: Concepts and classifications. *Eurasian Soil Science*, *51*, 1142-1153. https://doi.org/10.1134/S1064229318100022

Cruz-Flores, G., y Etchevers-Barra, J. D. (2011). Contenidos de carbono orgánico de suelos someros en pinares y abetales de áreas protegidas de México. *Agrociencia*, *45*(8), 849-862. https://www.scielo.org.mx/pdf/agro/v45n8/v45n8a1.pdf

Etchevers B., J. D., Monreal, C. M., Hidalgo M., C., Acosta M., M., y Padilla C., J. (2005). *Manual para la determinación de carbono en la parte aérea y subterránea de* *sistemas de producción en laderas*. Colegio de Posgraduados. https://catalogosiidca.csuca.org/Record/UCR.000624421/Details

Geographic Resources Analysis Support System. (2022). GRASSGIS, Bringing advanced geospatial technologies to the world (Version 3.22) [Software]. Open Source Geospatial Foundation. https://grass.osgeo.org/

Gillerot, L., Grussu, G., Condor-Golec, R., Tavani, R., Dargush, P., & Attorre, F. (2021). Progress on incorporating biodiversity monitoring in REDD+ through national forest inventories. *Global Ecology and Conservation*, 3K2, Article e01901. https://doi.org/10.1016/j.gecco.2021.e01901

Gobierno del Estado de México. (1999). *Programa de Manejo del Parque Natural de Recreación Popular El Ocotal*. Secretaría de Ecología, Comisión Estatal de Parques Naturales y de la Fauna y Universidad Autónoma del Estado de México-Facultad de Geografía.

Instituto Nacional de Estadística y Geografía. (2016). *Anuario estadístico y geográfico por entidad federativa 2016*. INEGI. http://internet.contenidos.inegi.org.mx/contenidos/Productos/prod_serv/contenidos/espanol/bvinegi/productos/nueva_estruc/AEGPEF_2016/702825087357.pdf

Leyva-Pablo, T., de León-González, F., Etchevers-Barra, J. D., Cortés-Pérez, M., Santiago-García, W., Ponce M., A. y Fuentes-Ponce, M. H. (2021). Almacenamiento de carbono en bosques con manejo forestal comunitario. *Madera y Bosques*, *27*(4), e2742421. https://doi.org/10.21829/myb.2021.2742421

Medina-Castro, Y. E., Roldán-Clarà, B., y Leyva A., J. C. (2019). Impactos del turismo en dos Parques Nacionales y áreas aledañas de Baja California, México: el caso de Sierra de San Pedro Mártir y Constitución de 1857. *Sociedad y Ambiente*, *7*(19), 165-194. https://revistas.ecosur.mx/sociedadyambiente/index.php/sya/article/view/1940

NOM-021-RECNAT-2000. (2001, 14 de agosto). NORMA Oficial Mexicana NOM-021-RECNAT-2000, Que establece las especificaciones de fertilidad, salinidad y clasificación de suelo. Estudios, muestreo y análisis. *Diario Oficial de la Federación*, Segunda Sección, de 31 de diciembre de 2002. https://www.ordenjuridico.gob.mx/Documentos/Federal/wo69255.pdf

Pérez L., P., López B., F., García O., F., Cuevas-Reyes, P., y González-Rodríguez, A. (2013). Procesos de regeneración natural en bosques de encinos: factores facilitadores y limitantes. *Biológicas*, *1*, 18-24. https://www.biologicas.umich.mx/index.php?journal=biologicas&page=article&op=view&path%5B%5D=148&path%5B%5D=pdf

Pérez R., C., Zizumbo, L., y González V., M. (2009). Impacto ambiental del turismo en áreas naturales protegidas; procedimiento metodológico para el análisis en el Parque Estatal El Ocotal, México. *El Periplo Sustentable*, (16), 25-56. https://rperiplo.uaemex.mx/article/view/5038/3628

Rodríguez B., P. C., González R., H., Cantú S., I., Pando M., M., Marmolejo M., J. G., Gómez M., M. V., y Lazcano C., J. (2019). Modelos de degradación de la hojarasca en bosques de encino y de pino en Nuevo León. *Revista Mexicana de Ciencias Forestales*, *10*(55), 39-55. https://doi.org/10.29298/rmcf.v10i55.548

Ronquillo-Gorgúa, N., Razo-Zárate, R., Rodríguez-Laguna, R., Acevedo-Sandoval, O. A., Hernández-Ortiz, J., & Manzur-Chávez, N. (2022). Carbon storage during the development stages of *Pinus patula* Schiede ex Schltdl. & Cham. in the Sierra Alta of Hidalgo. *Revista Chapingo Serie Ciencias Forestales y del Ambiente*, *28*(3), 483-497. https://doi.org/10.5154/r.rchscfa.2022.02.009

Rosaliano E., R., Ávila-Akerberg, V., Franco-Maass, S., Valencia A., S., y López M., L. A. (2022). Estructura y diversidad arbórea en bosques de encino del centro de México. *Madera y Bosques*, *28*(2), Artículo e2822449. https://doi.org/10.21829/myb.2022.2822449

Siebe, C., Jahn, R., y Stahr, K. (2016). *Manual para la descripción y evaluación ecológica de suelos en el campo* (3ra Ed.). Instituto de Geología de la Universidad Nacional Autónoma de México. https://es.scribd.com/document/686053151/Manual3Siebe-1

Statistical Package for the Social Sciences Inc. (2009). PASW Statistics for Windows (Version 18.0.) [Software]. SPSS Inc. https://www.ibm.com/support/pages/how-cite-ibm-spss-statistics-or-earlier-versions-spss

Torres R., J. M. (2021). Factores ambientales y físicos que afectan la supervivencia de siete especies forestales en el Estado de México. *Revista Mexicana de Ciencias Forestales*, *12*(64), 66-91. https://doi.org/10.29298/rmcf.v12i64.831

van Reeuwijk, L. P. (Comp.). (2002). *Procedures for soil analysis*. International Soil Reference and Information Centre. https://www.isric.org/sites/default/files/ISRIC_TechPap09.pdf

Vargas-Larreta, B., Amezcua R., M., López-Martínez, J. O., Cueto-Wong, J. A., Cruz-Cobos, F., Nájera-Luna, J. A., & Aguirre-Calderón, C. G. (2023). Estimating soil organic carbon stocks in three temperate forest types in Durango, México. *Botanical Sciences*, *101*(1), 90-101. https://doi.org/10.17129/botsci.3094

Wang, L., Guo, J., Liu, X., Li, K., Ma, L., Tian, Y., Wang, J., Zhang, Q., Tian, Y., Li, C., & Lu, M. (2023). Assessment of soil quality in an arid and barren mountainous of Shandong province, China. *Scientific Reports*, *13*, Article 19966. https://doi.org/10.1038/s41598-023-46136-6