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Distribution of Carbon Fractions and Necromass in Forest Soils Across Different Vegetation Types in El Chico National Park, Hidalgo, Mexico

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Abstract

Soils are the most important terrestrial carbon (C) sinks in the biosphere. They play a crucial role in regulating the global carbon cycle, and are key to the provision of ecosystem services. Soil carbon sequestration and accumulation is a useful means to reduce atmospheric CO_2 concentration and mitigate climate change. A study was conducted in El Chico National Park, Hidalgo, Mexico, with the objective of evaluating soil carbon fractions under different vegetation types. Five sampling zones (fir forest, fir-tlaxcal, cedar, fir-oak, pine-oak) were selected under similar edaphic and climatic conditions. The results showed no significant differences ($p<0.05$) among vegetation types in relation to organic matter (OM), organic carbon (Co), total carbon (Ct), oxidizable carbon (Cox), and non-oxidizable or recalcitrant carbon (Cnox). Only the organo-mineral fraction (Cp) presented a significant difference ($p<0.05$). The necromass of the five vegetation types stores an average of 6.60 t C ha^{-1} for both Ct and CO_2, which multiplied by the total area of “El Chico National Park” (PNCh), gives 13,302 Mg of C and 48,818.23 Mg of CO_2. Adding the C stored in the first 20 cm of soil estimates in a total of 237,793.45 Mg C and 872,701.96 Mg of CO_2, with soils under fir vegetation contributing the greatest CO_2 retention.

Keywords

Carbon dioxide, forest soils, necromass, soil carbon storage, soil organic carbon.

Introduction

Soils are the largest terrestrial reservoirs of carbon (C), with approximately 3,200 Pg of C (1 Pg = 10^{15} g) stored as soil organic carbon (SOC) within the top three meters of soils worldwide. Soil contains around 2,344–2,500 Gt of C, of which approximately 1,550 Gt of

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C are stored in organic forms and 950 Gt in inorganic forms (Lal 2004, Stockmann et al. 2013). Forest ecosystems play a crucial role in the carbon cycle, it is estimated that forests globally cover an area of 4.1 billion hectares, storing 861 Pg of C. This carbon storage is distributed as follows: 44% (383 Pg C) is present in the soil up to 1 meter in depth, 42% (363 Pg C) in biomass (both aboveground and belowground), 8% (73 Pg C) in dead wood, and 5% (43 Pg C) necromass. This distribution depends on the type of biome, species composition, and the intensity of land use, with the highest percentage of C accumulation occurring in soil (Dincă et al. 2015, Galicia et al. 2015) . Imaya et al. (2010) reported that andisols worldwide store 29.8 Gt of C and cover an area of 975 × 10^3 km^2.

The accelerated increase in atmospheric CO_2 levels over recent decades has intensified the effects of global warming, such as soil degradation, desertification, and environmental pollution. Therefore, even a small change in the SOC reserve can affect the atmospheric CO_2 cycle, influencing variations in global climate (FAO 2007, Bruun et al. 2013, Stockmann et al. 2013).

Organic matter (OM) is a fundamental component of soil, as it participates in a wide range of physical, chemical, and biological processes. The carbon contained in OM is transformed into inorganic carbon species, mainly CO_2, which is released into the atmosphere (Post and Kwon 2000, Bruun et al. 2013, Willaarts et al. 2016). Consequently, the conversion of natural ecosystems into cropland can lead to the loss of soil carbon, which can contribute to the intensification of global climate change effects and compromise food security (Lal 2004). From 1990 to 2015, a net loss of approximately 129 million hectares of forest was recorded, representing an annual deforestation rate of 0.13%, which corresponds to an annual release of around 546.35 million tons of carbon (FAO 2015).

Broquen et al. (2004), Segura-Castruita et al. (2005) and De Souza et al. (2022) mention that the potential of C stored in soil depends not only on its physical, biological, and chemical properties but is also influenced by the type of vegetation, topographic factors of the area, origin of the soil's parent material, geomorphic characteristics, soil evolution, management practices, mineral composition, texture, depth, bulk density, erosion, deforestation, land use (FAO 2000), and forest fragmentation, all of which have repercussions on the carbon stock (Chaplin-Kramer et al. 2015), as well as climate, among other factors that determine the accumulation and recycling of soil OM.

The organic C reservoir is quite complex and is composed of fractions with different turnover rates that are stabilized or protected against decomposition through three mechanisms: a) physical: by contact with roots (Betancourt-Yanez et al. 1999), encapsulation of OM fragments by clay particles or macro- or micro-aggregates; b) chemical: special bonds between OM and soil constituents, colloids, or clays (FAO 2002); and c) biochemical: considered stabilization due to its chemical composition (recalcitrant compounds such as lignin or polyphenols).

Despite the enormous carbon reservoir in the global soil ecosystem, research efforts on sequestration have mainly focused on geological and plant carbon capture and storage, with less attention given to the role of soil as a viable carbon sink. This situation has been observed in El Chico National Park (PNCh), Hidalgo, Mexico. Razo-Zárate et al. (2013) studied 30.34 hectares that were affected by a forest fire in 1998 in an *Abies religiosa forest*, concluding that 297.33 Mg of C were capture by the regrowth established 12 years after the event. Zamora (2003) estimated the aboveground biomass carbon content at 69 Mg C ha^{-1} in a forest in Michoacán, Mexico, with storage potential for *Quercus* species, 6.58 Mg C ha^{-1}, *Abies* 35.07 Mg C ha^{-1}, and *Pinus* 28.85 Mg C ha^{-1}.

Andisols cover approximately 0.84% of the Earth's surface and accumulate more SOC than other soil orders, accounting for about 5% of global SOC, making them the second most important soil order for C storage (31 kg m^{-2}) after histosols (218 kg m^{-2}) (Óskarsson et al. 2004, Tsui et al. 2013, Galicia et al. 2016).

Little is known about the C dynamics in the soils of El Chico National Park and the mechanisms that regulate the stabilization of organic compounds. For this reason, the objective of the present study is to determine the carbon fractions (Ct: total carbon; Cox: oxidizable carbon; Cnox: non-oxidizable carbon; Cp: carbon in the humic fraction; Cdox: hardly oxidizable carbon) and the carbon content captured in the necromass in soils under different types of vegetation in El Chico National Park, Hidalgo, Mexico, in order to develop strategies for carbon stabilization and to reduce atmospheric CO_2.

Materials and Methods

Study Area

The present study was conducted within PNCh (2,739 hectares), located in the municipality of Mineral El Chico, Hidalgo, at the western end of the Sierra de Pachuca, part of the physiographic province known as Sierra Madre Oriental. It is situated between the geographic coordinates 20°10’10’’ to 20°13’25’’ N latitude and 98°41’50’’ to 98°46’02’’ W longitude (Fig. 1), at an elevation ranging from 2,320 to 3,090 m (CONANP 2005). The area is located within the geological province of the Trans-Mexican Volcanic Belt, characterized by Tertiary volcanic rocks, extrusive igneous rocks such as volcanic breccia and andesite (Enciso-de la Vega 1992). The climate is classified as Cb(m)(w)(i)gw, corresponding to a temperate sub-humid climate with a cool and long summer, an annual temperature ranging between 12 and 18°C, and a summer rainfall regime with an average annual precipitation of 1,386 mm (García 2004). The predominant soils are Haplic Andosols (FAO 1998) and, according to the Soil Survey Staff (2003), classified as Typic Hapludands. These soils are well-drained, moderately deep to deep, and primarily of sandy loam texture (Acevedo-Sandoval et al. 2008).

Five areas were selected, each representing different vegetation types or associations: i) oyamel forest (*Abies religiosa* (Kunth) Schltdl. & Cham); ii) pine-oak (*Pinus teocote* Schltdl. & Cham. - *Quercus glabrescens Benth*); iii) *oyamel-oak* (*Abies religiosa* (Kunth)

Schltdl. & Cham - *Quercus glabrescens Benth*); iv) white cedar (Cupressus lusitanica Mill); and v) oyamel-Tlaxcal, *Abies religiosa* (Kunth) Schltdl. & Cham - Juniperus monticola Martínez) (Gallina-Tessaro et al. 1974, Zavala-Chavez 1995, Calderón-De Rzedowski and Rzedowski 2005, Hernández-Álvarez et al. 2021), all growing under similar soil and climatic conditions. In each area, 5 soil subsamples were randomly taken at different depths (0-5, 5-20, and 20-60 cm) and homogenized.

Analytical Procedures for Soil Characterization and Carbon Fraction Assessmen

The soil samples were sieved through a 2 mm mesh, and the methods used to determine physical and chemical properties were those described in the Soil Survey Laboratory (2004). The analyzed variables included bulk density (Da), particle size distribution, pH in water, and potassium chloride (1:2.5).

Among the CO fractions, the oxidizable carbon (Cox) was determined using the Walkley and Black technique (NOM-021-SEMARNAT-2000, and the OM content was calculated according to the relationship OM = Cox * 1.724. The SOC or total carbon stored (Cta) was calculated using the equation proposed by González-Molina et al. (2008) SOC (Mg/ha) = Cox (%) * Da (kg m^{-3}) * P (m), where Cox is the oxidizable carbon, Da is the bulk density, and P is the sampling depth. Ct was determined using a Solids TOC Analyzer 1020A, SHIMADZU brand elemental analyzer, and the difference between Ct and Cox was used as an estimate of the non-oxidizable or more recalcitrant carbon (Cnox). Carbon bound to the soil humic fraction (Cp) was determined according to the methodology described by Smith (1994), based on the complexing power of sodium pyrophosphate. Non-complexed, difficult, or slowly oxidizable carbon fractions (Cdox) were calculated as the difference between Cox and Cp; COO corresponds to non-complexed and slowly oxidizable forms and is obtained from the difference between Ct and pyrophosphate-extractable carbon (Cp). The stratification ratio of OM (REmos), an indicator of soil quality, was obtained by dividing the OM content of the upper layer by that of the lower layer (Rodríguez Rodríguez et al. 2004, Martínez H et al. 2008, Dincă et al. 2015, Vásquez-Polo and Macías-Vázquez 2017, SEMARNAT 2022).

To measure the amount of necromass, a 50 x 50 cm frame was used, and six random samples were taken in each vegetation type. The samples were homogenized by area, and a composite sample was collected and placed in a bag. In the laboratory, they were dried in an oven at 75°C for 48 hours to obtain the dry weight. A 20 mg sample was then taken, and the carbon percentage was determined using a Solids TOC Analyzer 1020A, SHIMADZU brand elemental analyzer.

The following equation was used to calculate the fixed CO_2 (Landeta-González 2009), once the carbon content was determined: CO_2 = Kr * C; where Kr is the conversion factor to CO_2 of 3.67, resulting from the ratio of the molecular weights of carbon dioxide (44) and carbon (12).

The analyses were performed in triplicate, and all data were compared using analysis of variance followed by Tukey's multiple comparison test ($p<0.05$), to establish possible statistical differences for the variables related to the type of vegetation

Results and Discussion

The studied soils generally exhibit a bulk density of less than 0.93 Mg m^{-3}, are moderately acidic (average 5.84), and have medium to rich levels of total nitrogen and high organic matter, with the exception of the soil under cedar vegetation, which is considered medium for volcanic soils (SEMARNAT 2022). The C/N ratio, with average 11.43 for the five sites, indicates a moderate mineralization, which is an important indicator for microbial activity, nutrient availability and plant growth and development (Fernández 2004, Vásquez-Polo and Macías-Vázquez 2017). Yang et al. (2020) report that in acidic soils, organic matter is generally stabilized by exchange reactions involving bonds with non-crystalline Fe and Al oxides. Ortíz-Escobar et al. (2004) report that soils with andic properties and acidic pH have high contents of exchangeable aluminum (Al^{+3}). The low bulk density values and the C/N ratio of the surface layer indicate the accumulation of labile organic matter predominantly from slightly decomposed plant residues and suggest the accumulation of organic residues in a recent process (De Souza et al. 2022). Organic matter affects soil reaction (pH) due to active groups that contribute degrees of acidity, exchange bases, and the nitrogen content present in the organic residues contributed to the soil (Aguilera S. 2000, Wong et al. 2000).

In Table. 1, the pH values in water (active acidity) and in KCl (potential acidity) are presented, along with the difference between the two values, delta pH (ΔpH), which is an indicator of the nature of the clays and the index of decomposition and incorporation of OM into the soil. In this study the values range from -0.97 to -1.33, indicating that the soil predominantly has variable charge and therefore has a large amount of colloids and short-range or allophanic minerals (Acevedo-Sandoval et al. 2008).

The Alo+0.5Feo index > 2% (Table 1) shows that soils under different forest vegetation in the PNCh are generally characterized by having andic properties (FAO 1998), with values ranging from 2.16 to 3.41. In this study, the soil with the fir-Tlaxcal forest showed the highest values, while the white cedar forest had the lowest; however, there were no statistically significant differences ($p≤0.05$) between the five sites.

Regarding the relationship of the different forms of C (Table 2), the Ct varied from 3.06% (cedar forest) to 9.44% (mixed fir-Tlaxcal forest), with no statistically significant differences ($p≤0.05$) among the five sites. Vásquez-Polo and Macías-Vázquez (2017) reported that total carbon values around 3% are considered the minimum necessary for adequate soil structural stability, and that values below 3% indicate soils with erosion problems, low cation exchange capacity, and low moisture retention, which are associated with low inputs of organic materials and high rates of organic matter mineralization.

The Cnox ranged from 4% to 51% relative to Ct, representing the more stable carbon that ensures significant residence times in soils. This fraction is the most effective in functioning as a CO_2 sink (Rodríguez Rodríguez et al. 2004), with soils under cedar vegetation showing the highest C stability (51%) and fir forest soils the lowest (4%). Statistically, there were no significant differences ($p \leq 0.05$) among soils under the five vegetation types (Table 2).

Values greater than 0.10 for the Cnox fraction in forest soils indicate the effectiveness of these soils in capturing carbon (Vásquez-Polo and Macías-Vázquez 2017). The organic carbon contained in this fraction has a very long residence time, ranging from decades to thousands of years. In this study, values ranged from 0.39% (fir forest) to 3.14% (fir-oak forest), indicating that soils under fir-oak forests have more stable forms of carbon in the soil.

The low percentage of Cnox (0.39% in fir forest soils) in this fraction has significant consequences for the soil's ability to retain water, ions, nutrients, contaminants, its integration with biotic activity, and the formation of stable aggregates (Macias et al. 2004).

High Cox values were observed in soils under different types of vegetation, except for soils under cedar, where the mean Cox value was 1.97% (Table 2). Statistically, there were no significant differences ($p \leq 0.05$) among the five sites. Cox varied from 49% to 96% relative to the Ct, with the highest value found in the soil under fir forest (96%). This high Cox content is attributed to the fact that OM in these soils (Andosols) is stabilized by minerals with a low degree of crystallinity (allophane, imogolite, ferrihydrite, etc.), which present a high specific surface area with variable charge, capable of adsorbing organic molecules and/or forming stable metal-humus complexes (Dahlgren et al. 1993, Broquen et al. 2004, Acevedo-Sandoval et al. 2008).

The most stable forms of carbon were higher in soils with mixed forests (fir-oak), functioning as CO_2 sinks; however, there were no statistically significant differences ($p \leq 0.05$) between soils under the five types of vegetation (Table 2). Thus, all five sites can be considered to have a high potential as CO_2 sinks and carbon capture.

The Cp is usually identified with the existing humified carbon; in this study, it ranged from 10.6% (mixed fir-oak forest) to 18.4% (cedar forest) relative to Ct, which is related to the differences in inputs and humification among the five sites. Below the values reported by Vásquez-Polo and Macías-Vázquez (2017) for soils with natural vegetation in the Magdalena Department, Colombia (19 to 31%).

Low Cp values were found in soils under cedar forests (Table. 2), indicating low evolution of OM toward humified forms (Vásquez-Polo et al. 2011) and little formation of organic complexes, apparently due to the predominance of young humus with low capacity for complex formation (Shoji and Fujiwara 1984).

Meanwhile, soils with fir-Tlaxcal showed a higher percentage of more stable organic complexes, with statistically significant differences ($p \leq 0.05$) between soils under different types of vegetation (Table 2). The soils in the PNCh are of volcanic origin and present a high content of aluminum oxyhydroxides and hydroxides, which are associated with humic substances forming stable Al-humus complexes (Broquen et al. 2004, Acevedo-Sandoval et al. 2008, Grand and Lavkulich 2011).

The fraction of hardly oxidizable carbon (Cdox) ranged from 75% to 86% relative to Ct, indicating a higher percentage of stable C in soils with fir and fir-oak forests (86%).

The C in the hardly oxidizable carbon fraction represented 79.7% of the Cox (mean value in the five soils under different vegetation types). This fraction corresponds to C that has escaped biological activity and even the normal oxidative processes in soils. A higher percentage of C was associated with more stable fractions in soils under fir (86.53%), showing statistically significant differences ($p \leq 0.05$) with soils under other types of vegetation. Vásquez et al. (2013) reported 70% and 62% Cdox values for tropical dry forest soils and cultivated soils in the Magdalena Department, Colombia, concluding that the use and management of cultivated soils cause a decline in the more stable forms of C, indicating a higher percentage of C associated with more stable fractions in forest soils than in cultivated soils. The relationship of different forms of C concerning Ct content shows that the highest percentage of Ct consists of labile forms.

Galicia et al. (2016) mentioned that the Andosol soil group has significant SOC accumulation (310 Mg C ha^{-1}), which occurs due to OM stabilization through the formation of organo-metallic and organo-mineral complexes. Pérez-Ramírez et al. (2013) reported for andosol soils in the Monarch Butterfly Biosphere Reserve, 115 to 207 Mg C ha^{-1} in a fir forest and 70 to 136 Mg C ha^{-1} in a pine-oak forest. For the PNCh, the values ranged from 14.41 Mg C ha^{-1} (cedar forest) to 109.59 Mg C ha^{-1} (fir forest), with statistically significant differences ($p \leq 0.05$) among the five sites.

The carbon stock among different vegetation types in the PNCh indicates that soils with high SOC content are associated with high biodiversity (De Souza et al. 2022), making it important to maintain this biodiversity for carbon capture in these soils.

Martínez H et al. (2008) report that the organic matter stratification ratio (REmos) is an indicator of soil quality at the limit of the arable layer; the higher the value, the better the soil quality. In the present study, soils under cedar are of better quality (value 5.12, Table 2), while soils under fir-oak and fir-Tlaxcal showed low values (0.34 and 0.38, respectively). No statistically significant differences ($p \leq 0.05$) were observed among the five sites.

Rodríguez Rodríguez et al. (2004) concluded that the accumulation and stabilization of organic carbon in Andosols and Andean soils of Garajonay National Park (La Gomera, Canary Islands) is related more to the maturity and stability of the ecosystem than to the type of vegetation; Vargas-Larreta et al. (2023) concluded that based on the results, the type of forest does not influence SOC stores, but the type of soil does (Table 3).

Amaguaya Llamuca (2015) reports that the total carbon stored in the soil of native Andean forest from 0 to 30 cm was 252.57 t C ha^{-1}. Vásquez-Polo et al. (2011) reported a total carbon accumulation of 42.4 Mg C ha^{-1} in forested areas of Magdalena, Colombia, at a depth of 20 cm, while Chiriluș et al. (2022) reported 36.19 t ha^{-1} of organic carbon in forest plantations at a depth of 0-10 cm, with greater sequestration and water retention capacity. They concluded that land use and sampling depth influence the physicochemical properties of the soil and increase carbon sequestration capacity.

In a study by Vela-Correa et al. (2012) to measure total organic carbon levels in the soils of conservation areas in Mexico City, limits were defined for SOC intervals for the 0-30 cm layer to provide a general reference for what are considered high and low values. The established ranges were: low (<50 Mg C ha^{-1}), medium (50-100 Mg C ha^{-1}), high (100-150 Mg C ha^{-1}), and very high (>150 Mg C ha^{-1}). The Ct obtained in the PNCh for the fir forest was 114.40 Mg C ha^{-1}, a value that, according to these authors, would be classified as high, while for the cedar forest (31.60 Mg C ha^{-1}), it would be classified as low.

Cruz-Flores and Etchevers-Barra (2011) concluded that *Pinnus spp.* forests store an average of 148.5 Mg C ha^{-1} in soils formed from pyroclastic materials. Anaya et al. (2016) reported an average of 118±7 Mg C ha^{-1} in cloud forests in Michoacán, Mexico, and in cloud forests in Chiapas, 102 to 461 Mg C ha^{-1} (Jong et al. 1999), and in Oaxaca, 158 to 222 Mg C ha^{-1} (Álvarez-Arteaga et al. 2013). Vela-Correa et al. (2012) reported that the fir forest showed high SOC values of 145.6 Mg C ha^{-1}, due to the fact that these forests are well-conserved.

The total surface area of the PNCh captures approximately 821,638.74 Mg CO_2 in the top 20 cm of soil, with the majority of CO_2 retention occurring in soils under fir vegetation, accounting for 88% of the total. This confirms it as a carbon sink worth considering, making it a strategic area of fundamental interest for mitigating the negative environmental effects (temperature increases and the global greenhouse effect) caused by the rise in atmospheric CO_2. Land use change represents the second largest anthropogenic source of emissions into the atmosphere (Smith et al. 2016). Jones (2006) reported that an increase of one percent in organic carbon in the top 20 cm of soil, with a bulk density of 1.2 g cm^{-3} would represent an increase of 24 t ha-1 of SOC, which is equivalent to 88 t ha^{-1} of CO_2 sequestered from the atmosphere.

Hu et al. (2018) reported that, in an abandoned agricultural soil profile from 0 to 50 cm in the karst regions of southwest China, SOC and nitrogen reserves will recover to primary forest levels in approximately 74 years at a rate of 112.35 g C cm-2 $year^{-1}$ and in approximately 100 years at a rate of 12.07 g N m^{-2} $year^{-1}$, respectively.

MAE, (2015) reported that in Ecuador, gross deforestation emissions from native forests for the year 2014 amounted to 10,523,577 t C, a value representing 38,586,447 t CO_2-eq $year^{-1}$. Deforestation contributes to increased atmospheric pollution.

Pérez-Ramírez et al. (2013) remarked how sustainable management of forest areas contributes to the conservation of large carbon reserves in the soil and the biodiversity that inhabits it. They also reported that well-conserved fir forests store 45-80% of organic carbon in the top centimeters of soil, with similar results observed in PNCh (Fig. 2).

The Ct of the five study areas shows that, with increasing depth, there is a greater carbon content per square meter in soils under fir forest (2.17 kg C m^{-2}, indicating a potential for long-term carbon storage and sequestration). Acosta et al. (2001), Anaya et al. (2016), Yang et al. (2020) and Chiriluș et al. (2022) reported that the vertical distribution of SOC results from land-use change, organic matter inputs, topographical location, slope, necromass composition, decomposition rate, and eluviation. These factors are determined by pedological processes, along with rhizodeposition and microorganisms that establish the distribution at different depths, as well as by the site's climatic conditions.

Schiedung et al. (2019) mentioned that more than 50% of the world's SOC is stored in subsoil, and when radiocarbon testing is conducted, SOC increases with depth, regardless of soil type. Amaguaya Llamuca (2015) concluded that the greatest amount of stored total carbon is found at a depth of 20 to 60 cm in native Andean forest soils, with similar results seen in PNCh. Anaya et al. (2016) concluded that the accumulated SOC content (Mg C ha^{-1}) increases with depth in cloud forest soil in Michoacán, Mexico.

Necromass represents an important carbon sink and is one of the main pathways for carbon to enter forest soils, having a fundamental effect not only in the top centimeters but also at greater depths through its decomposition products (Wang et al. 2013, Hernández et al. 2016). Approximately 5% of the total carbon stored in forest systems is found in the necromass. In the present study, the average carbon concentrations in the necromass were statistically similar between forest types ($p \leq 0.05$); C and CO_2 stores in the necromass per hectare were highest in the fir forest, accounting for 26.47% of the total, while the lowest values were found in the cedar forest, accounting for 15.23% of the total (Table 4). These results show that the amount of biomass contributed to the forest soil is greater in the fir forest than in the cedar forest.

Rodríguez-Laguna et al. (2009) reported that the C content in necromass in a pine-oak forest in the "*El Cielo Biosphere Reserve*", Tamaulipas, was 9.88 Mg C ha^{-1}, a value higher than those obtained in PNCh. Hernández et al. (2009) report a total carbon content present in the necromass of *Eucalyptus dunnii* aged 9 years of 8.4 Mg C ha^{-1} in Uruguay, while Laclau (2003) reported carbon amounts stored in the necromass of *Pinus ponderosa* and *Austrocedrus chilensis* in Patagonia ranging from 6.6 to 8.5 Mg C ha^{-1}. Vargas-Larreta et al. (2023) reported that in temperate forests of Durango, Mexico, carbon stocks in the necromass of pine-oak forests average 8.47 Mg ha^{-1}, a value greater than that found in the pine-oak forest of PNCh (6.43 Mg C ha^{-1}). Cruz-Flores and Etchevers-Barra (2011) mentioned that in the temperate regions of Mexico, necromass contributes 6.91 Mg C ha^{-1} to the soil. In the present study, the average value across the five sites was 6.60 Mg C ha^{-1}. In the study area, the amount of Ct captured in the necromass was 6.60 Mg C ha^{-1}, which, when multiplied by the area under study, estimates in a total of 13,302.63 Mg of C captured in the necromass and 48,840.81 Mg of CO_2. Among the five forest ecosystems, there are no significant differences in the carbon content in the necromass.

Conclusions

The PNCh provides the environmental service of CO_2 capture; the soil in the top 20 cm captured a total of 821,638.74 Mg of CO_2 over an area of 2,015.55 ha. Therefore, it is important to have a forest management program that increases forest biomass and carbon stability in soils to protect the PNCh by reducing deforestation and conducting reforestation, as it is a strategic ecosystem of significant state importance.

The contents of Ct, Cox, Cnox, and REmos did not show statistically significant differences among the types of vegetation. Cnox was present in soils with cedar vegetation (51%), where it would be interesting to study the mechanisms of natural carbon stabilization. Stable organic complexes (Cp) are present in soils with oyamel-tlaxcal, showing significant differences ($p \leq 0.05$) compared to the other soils with vegetation studied.

Based on the obtained results, it can be inferred that each forest species in PNCh contributes uniquely with its forest potential in the contribution and capture of organic carbon in the soil.

The significant accumulation of SOC in PNCh is due to the stabilization of organic matter through the formation of organometallic and organo-mineral complexes; this stabilization makes it resistant to decomposition, allowing for greater carbon residence in the soil, thus considering the park as a mitigator of climate change.

The necromass from the five types of vegetation stores an average of 6.60 t C ha^{-1}, which, when multiplied by the total area of PNCh, results in 13,302 Mg of C and 48,818.23 Mg of CO_2. Adding the stored C in the soil yields a total of 237,793.45 Mg of C and 872,701.96 Mg of CO_2.

The importance of evaluating the carbon dynamics present in PNCh, which are transferred at each level from the necromass to the soil, lies in the ability to develop management strategies and actions that enable the capture and maintenance of carbon stored in these areas, thereby preventing its concentration in the atmosphere.

Conflicts of interest

The authors have declared that no competing interests exist.

References

- Acevedo-Sandoval O, Prieto-Garcia F, Gordillo-Martínez a (2008) Identificar las fracciones de aluminio en un andosol del Estado de Hidalgo, México. Revista de la Sociedad Geológica de España 21 (3-4): 125-132.

- Acosta M, Etchevers JD, Monreal C, Quednow K, Hidalgo C (2001) Un método para la medición del carbono en los compartimientos subterráneos (raíces y suelo) de sistemas forestales y agrícolas en terrenos de ladera en …. Universidad Austral de Chile1-15.
- Aguilera S. SM (2000) Importancia de la protección de la materia orgánica en suelos. Simposio Proyecto Ley Protección de Suelo. Repositorio Académico de la Universidad de Chile 1 (14): 77-85. URL: https://repositorio.uchile.cl/handle/2250/121065
- Álvarez-Arteaga G, García Calderón N, Krasilnikov P, García-Oliva F (2013) Almacenes de carbono en bosques montanos de niebla de la Sierra Norte de Oaxaca, México. Agrociencia 47 (2): 171-180.
- Amaguaya Llamuca JL (2015) Determinación de carbono en el suelo de bosque nativo de ceja andina en el sector Guangra, parroquia Achupallas, cantón Alausí, provincia de Chimborazo. Escuela Superior Politécnica de Chimborazo
- Anaya C, Mendoza M, Rivera M, Páez R, Olivares-Martínez LD (2016) Contenido de carbono orgánico y retención de agua en suelos de un bosque de niebla en Michoacán, México. Agrociencia 50 (2): 251-269.
- Betancourt-Yanez P, González-Rios J, Figueroa-Sandoval B, González-Cossio F (1999) Materia orgánica y caracterización de suelos en proceso de recuperación con coberturas vegetatitas en zonas templadas de México. Tierra Latinoamericana 17 (2).
- Broquen PC, Candan F, Lobartini JC, Girardin JL (2004) Relaciones entre el carbono orgánico y propiedades edáficas y del sitio en suelos derivados de cenizas volcánicas, sudoeste de Neuquén (Argentina). Ciencia del Suelo 22 (2): 73-82. URL: https://ri.conicet.gov.ar/handle/11336/72674
- Bruun TB, Elberling B, Neergaard A, Magid J (2013) Organic Carbon Dynamics in Different Soil Types After Conversion of Forest to Agriculture. Land Degrdation &Development 26 (3): 272-283. https://doi.org/https://doi.org/10.1002/ldr.2205
- Calderón-De Rzedowski G, Rzedowski J (2005) Flora fanerogámica del Valle de México. 2. Instituto de Ecología A.C. y comisión Nacional para el Conocimiento y Uso de la Biodiversidad, Michoacán, Mexico.
- Chaplin-Kramer R, Ramler I, Sharp R, Haddad N, Gerber J, West P, Mandle L, Engstrom P, Baccini A, Sim S, Mueller C, King H (2015) Degradation in carbon stocks near tropical forest edges. Nature Communications 6 (1). https://doi.org/10.1038/ncomms10158
- Chiriluș GV, Lakatos ES, Bălc R, Bădărău AS, Cioca LI, David GM, Roşian G (2022) Assessment of Organic Carbon Sequestration from Romanian Degraded Soils: Livada Forest Plantation Case Study. Atmosphere 13 (9). https://doi.org/10.3390/atmos13091452
- CONANP (2005) Programa de Conservación y Manejo Parque Nacional El Chico. Comisión Nacional de Áreas Naturales Protegidas 1 (1).
- Cruz-Flores G, Etchevers-Barra J (2011) Contenidos de carbono orgánico de suelos someros en pinares y abetales de áreas protegidas de México. Agrociencia 45 (8): 849-862. URL: http://www.scielo.org.mx/scielo.php?script=sci_abstract&pid=S1405-31952011000800001&lng=es&nrm=iso&tlng=es
- Dahlgren R, Shoji S, Nanzyo M (1993) Chapter 5 Mineralogical Characteristics of Volcanic Ash Soils. In: Shoji S, Nanzyo M, Dahlgren R (Eds) Developments in Soil Science. 21. https://doi.org/10.1016/S0166-2481(08)70266-6
- De Souza JJLL, Souza BI, Xavier RA, Cardoso ECM, de Medeiros JR, da Fonseca CF, Schaefer CEGR (2022) Organic carbon rich-soils in the brazilian semiarid region and paleoenvironmental implications. CATENA 212 https://doi.org/10.1016/j.catena.2022.106101

- Dincă LC, Dincă M, Vasile D, Spârchez G, Holonec L (2015) Calculating Organic Carbon Stock from Forest Soils. Notulae Botanicae Horti Agrobotanici Cluj-Napoca 43 (2): 568-575. https://doi.org/10.15835/nbha43210141
- Enciso-de la Vega S (1992) Propuesta de nomenclatura estratigráfica para la cuenca de México. Revista Mexicana De Ciencias Geologicas 10 (1): 26-36.
- FAO (1998) FAO/UNESCO Soil Map of the World. Secretaría de Medio Ambiente y Recursos Naturales. Food and Agriculture Organization, Rome.
- FAO (2000) Sistemas de uso de la tierra en los trópicos húmedos y la emisión y secuestro de CO2. 88. Organización de las Naciones Unidas para la Agricultura y la Alimentación, Rome, Italy, 120 pp.
- FAO (2002) Captura de carbono en los suelos para un mejor manejo de la tierra. Organización para la Alimentación y la Agricultura. Food & Agriculture Org., France.
- FAO (2007) Secuestro de carbono en tierras áridas. Organización para la Alimentación y la Agricultura. Organización de las Naciones Unidas para la Agricultura y la Alimentación, Rome.
- FAO (2015) Global forest resources assessment. 2015, Desk reference. Organización para la Alimentación y la Agricultura. Food and Agriculture Organization of the United Nations, Rome.
- Fernández IE (2004) Caracterización química de los suelos del Bosque de Fray Jorge. In: Squeo FA, Gutiérrez JR, Hernández IR (Eds) Historia Natural del Parque Nacional Bosque Fray Jorge. [ISBN 956-7393-21-4].
- Galicia L, Saynes V, Campo J (2015) Biomasa aérea, biomasa subterránea y necromasa en una cronosecuencia de bosques templados con aprovechamiento forestal. Botanical Sciences 93 (3): 473-484. https://doi.org/10.17129/botsci.66
- Galicia L, Gamboa Cáceres AM, Cram S, Chávez Vergara B, Peña Ramírez V, Saynes V, Siebe C, Galicia L, Gamboa Cáceres AM, Cram S, Chávez Vergara B, Peña Ramírez V, Saynes V, Siebe C (2016) Almacén y dinámica del carbono orgánico del suelo en bosques templados de México. Terra Latinoamericana 34 (1): 1-29.
- Gallina-Tessaro .M, González-Romero A, Moutal-Fua RC, Tello-Sandoval GC (1974) Bases para la reestructuración del Parque Nacional El Chico, Hidalgo, México. Universidad Nacional Autónoma de México, México.
- García E (2004) Modificaciones al Sistema de Clasificación Climática de Köppen | Instituto de Geografía. 5. Instituto de Geografía
- González-Molina L, Etchevers-Barra J, Hidalgo-Moreno C (2008) Carbono en suelos de ladera: factores que deben considerarse para determinar su cambio en el tiempo. Agrociencia 42 (7): 741-751. URL: http://www.scielo.org.mx/scielo.php?script=sci_abstract&pid=S1405-31952008000700001&lng=es&nrm=iso&tlng=es
- Grand S, Lavkulich L (2011) Depth Distribution and Predictors of Soil Organic Carbon in Podzols of a Forested Watershed in Southwestern Canada. Soil Science 176 (4): 164-174. https://doi.org/10.1097/SS.0b013e3182128671
- Hernández-Álvarez AG, Reyes-Ortiz JL, Villanueva-Díaz J, Sánchez-González A (2021) Variación en la estructura del bosque de Abies religiosa (Pinaceae), en diferentes condiciones de manejo y disturbio. Acta Botanica Mexicana1-20. https://doi.org/https://doi.org/10.21829/abm128.2021.1752
- Hernández J, Salvo L, del Pino A, Arrarte G (2009) Nutrient export and harvest residue decomposition patterns of a Eucalyptus dunnii Maiden plantation in temperate climate of

Uruguay |. Forest Ecology and Management 258 (2): 92-99. https://doi.org/10.1016/j.foreco.2009.03.050
- Hernández J, Del Pino A, Vance E, Califra Á, Del Giorgio F, Martínez L, González-Barrios P (2016) Eucalyptus and Pinus stand density effects on soil carbon sequestration. Forest Ecology and Management 368: 28-38. https://doi.org/10.1016/j.foreco.2016.03.007
- Hu P, Liu S, Ye Y, Zhang W, He X, Su Y, Wang K (2018) Soil carbon and nitrogen accumulation following agricultural abandonment in a subtropical karst region. Applied Soil Ecology 132: 169-178. https://doi.org/10.1016/j.apsoil.2018.09.003
- Imaya A, Yoshinaga S, Inagaki Y, Tanaka N, Ohta S (2010) Volcanic ash additions control soil carbon accumulation in brown forest soils in Japan. Soil Science & Plant Nutrition 56 (5): 734-744. https://doi.org/10.1111/j.1747-0765.2010.00508.x
- Jones CE (2006) Balancing the greenhouse equation Part IV. Potential for high returns from more soil carbon. Australian Farm Journal55-58.
- Jong B, Cairns M, Haggerty P, Ramírez-Marcial N, Ochoa-Gaona S, Mendoza-Vega J, González-Espinosa I, March-Mifsut I (1999) Land-Use Change and Carbon Flux Between 1970s and 1990s in Central Highlands of Chiapas, Mexico. Environmental Management 23 (3): 373-385. https://doi.org/10.1007/s002679900193
- Laclau P (2003) Biomass and carbon sequestration of ponderosa pine plantations and native cypress forests in northwest Patagonia. Forest Ecology and Management 180 (1): 317-333. https://doi.org/10.1016/S0378-1127(02)00580-7
- Lal R (2004) Soil Carbon Sequestration Impacts on Global Climate Change and Food Security. Science 304 (5677): 1623-1627. https://doi.org/10.1126/science.1097396
- Landeta-González AD (2009) Producción de biomasa y fijación de carbono en plantaciones de teca (Tectona Grandis Linn F.) en la Espol campus "Ing. Gustavo Galindo". Escuela Superior Politecnica del Litoral
- Macias F, Anta RCD, Lado LR, Verde R, Perez XP, Arbestain MC, Macias F, Anta RCD, Lado LR, Verde R, Perez XP, Arbestain MC (2004) El sumidero de carbono de los suelos de Galicia. Edafología 11 (3): 341-376. URL: https://investigacion.usc.gal/documentos/61b44a355f61724497f36983?lang=es
- MAE, (2015) Estadísticas de Patrimonio Natural. Datos de bosques, ecosistémas, especies, carbono y deforestación del Ecuador continental. Gobierno de Ecuador. Ministerio del Ambiente.
- Martínez H E, Fuentes E JP, Acevedo H E (2008) Carbono orgánico y propiedades del suelo. Revista de la ciencia del suelo y nutrición vegetal 8 (1): 68-96. https://doi.org/10.4067/S0718-27912008000100006
- Ortíz-Escobar ME, Zapata-Hernández RD, Sadeghian S, Alvarez HFF (2004) Aluminio intercambiable en suelos con propiedades ándicas y su relación con la toxicidad. Cenicafé 55 (2): 101-110.
- Óskarsson H, Arnalds Ó, Gudmundsson J, Gudbergsson G (2004) Organic carbon in Icelandic Andosols: geographical variation and impact of erosion. CATENA 56 (1): 225-238. https://doi.org/10.1016/j.catena.2003.10.013
- Pérez-Ramírez S, Ramírez MI, Jaramillo-López P, Bautista F (2013) Contenido de carbono orgánico en el suelo bajo diferentes condiciones forestales: reserva de la biosfera mariposa monarca, México. Revista Chapingo serie ciencias forestales y del ambiente 19 (1): 157-173. https://doi.org/10.5154/r.rchscfa.2012.06.042

- Post WM, Kwon KC (2000) Soil carbon sequestration and land-use change: processes and potential. Global Change Biology 6 (3): 317-327. https://doi.org/10.1046/j.1365-2486.2000.00308.x
- Razo-Zárate R, Gordillo-Martínez A, Rodríguez-Laguna R, Maycotte-Morales CC, Acevedo-Sandoval O (2013) Estimación de biomasa y carbono almacenado en árboles de oyamel afectados por el fuego en el Parque nacional "El Chico", Hidalgo, México. Madera y bosques 19 (2): 73-86.
- Rodríguez-Laguna R, Jiménez-Pérez J, Aguirre-Calderón Ó, Treviño-Garza E, Raz-Zárate R (2009) Estimación de carbono almacenado en el bosque de pino-encino en la reserva de la biosfera el cielo, Tamaulipas, México. Revista Científica Ra Ximhai 5 (3): 317-328. https://doi.org/10.35197/rx.05.03.2009.06.rr
- Rodríguez Rodríguez A, Arbelo Rodríguez CD, Notario del Pino JS, Mora JL, Guerra García JA, Armas Herrera CM (2004) Contenido y formas de carbono orgánico en andosoles forestales: aproximación a su dinámica. Edafología 11 (1): 67-102.
- Schiedung M, Tregurtha C, Beare M, Thomas S, Don A (2019) Deep soil flipping increases carbon stocks of New Zealand grasslands. Global Change Biology 25 (7): 2296-2309. https://doi.org/10.1111/gcb.14588
- Segura-Castruita M, Sánchez-Guzmán P, Ortiz-Solorio C, Gutiérrez-Castorena MdC (2005) Carbono orgánico de los suelos de México. Terra Latinoamericana 23 (1).
- SEMARNAT (2022) Norma Oficial Mexicana NOM-021-SEMARNAT-2000 que establece las especificaciones de fertilidad, salinidad y clasificación de suelos, estudio, muestreo y análisis. Secretaría de Medio Ambiente y Recursos Naturales.
- Shoji S, Fujiwara Y (1984) Active aluminum and iron in the humus horizons of andosols from Notheastern Japan their forms, properties, and sifnificance in clay weathering. Soil Science 137 (4). URL: https://journals.lww.com/soilsci/abstract/1984/04000/active_aluminum_and_iron_in_the_humus_horizons_of.2.aspx
- Smith BFL (1994) Characterization of poorly ordered minerals by selective chemical methods. In: Wilson MJ (Ed.) Clay Mineralogy: Spectroscopic and Chemical Determinative Methods. URL: http://link.springer.com/10.1007/978-94-011-0727-3_9 [ISBN 978-94-010-4313-7].
- Smith P, House J, Bustamante M, Sobocká J, Harper R, Pan G, West P, Clark J, Adhya T, Rumpel C, Paustian K, Kuikman P, Cotrufo MF, Elliott J, McDowell R, Griffiths R, Asakawa S, Bondeau A, Jain A, Meersmans J, Pugh TM (2016) Global change pressures on soils from land use and management. Global Change Biology 22 (3): 1008-1028. https://doi.org/10.1111/gcb.13068
- Soil Survey Laboratory (2004) Methods Manual. Soil Survey Investigations Report 42, US Department of Agriculture, Washington DC. Natural Resources Conservation Service.
- Soil Survey Staff (2003) Keys to Soil Taxonomy. United States Department of Agriculture.
- Stockmann U, Adams M, Crawford J, Field D, Henakaarchchi N, Jenkins M, Minasny B, McBratney A, Courcelles VdRd, Singh K, Wheeler I, Abbott L, Angers D, Baldock J, Bird M, Brookes P, Chenu C, Jastrow J, Lal R, Lehmann J, O’Donnell A, Parton W, Whitehead D, Zimmermann M (2013) The knowns, known unknowns and unknowns of sequestration of soil organic carbon. Agriculture, Ecosystems & Environment 164: 80-99. https://doi.org/10.1016/j.agee.2012.10.001
- Tsui C, Tsai C, Chen Z (2013) Soil organic carbon stocks in relation to elevation gradients in volcanic ash soils of Taiwan. Geoderma 209-210: 119-127. https://doi.org/10.1016/j.geoderma.2013.06.013

- Vargas-Larreta B, Amezcua Rojas M, López-Martínez JO, Cueto-Wong JA, Cruz-Cobos F, Nájera-Luna JA, Aguirre-Calderón CG, Vargas-Larreta B, Amezcua Rojas M, López-Martínez JO, Cueto-Wong JA, Cruz-Cobos F, Nájera-Luna JA, Aguirre-Calderón CG (2023) Estimación de los almacenes de carbono orgánico en el suelo en tres tipos de bosque templado en Durango, México. Botanical Sciences 101 (1): 90-101. https://doi.org/10.17129/botsci.3094
- Vásquez JR, Macías F, Menjivar JC (2013) Respiración del suelo según su uso y su relación con algunas formas de carbono en el Departamento del Magdalena, Colombia. Bioagro 25 (3): 175-180.
- Vásquez-Polo JR, Macías-Vázquez F, Menjivar-Flores JC (2011) Formas de carbono orgánico en suelos con diferentes usos en el departamento del Magdalena (Colombia). Acta Agronómica 60 (4): 369-379.
- Vásquez-Polo JR, Macías-Vázquez F (2017) Fraccionamiento químico del carbono en suelos con diferentes usos en el departamento de Magdalena, Colombia. Terra Latinoamericana 35 (1): 7-17.
- Vela-Correa G, López-Blanco J, Rodríguez-Gamiño MdL (2012) Niveles de carbono orgánico total en el Suelo de Conservación del Distrito Federal, centro de México. Investigaciones Geográficas18-30. https://doi.org/10.14350/rig.31007
- Wang H, Wang J, Zuomin S (2013) Dynamics and speciation of organic carbon during decomposition of leaf litter and fine roots in four subtropical plantations of China. Forest Ecology and Management43-52. https://doi.org/10.1016/j.foreco.2012.12.015
- Willaarts B, Oyonarte C, Muñoz-Rojas M, Ibáñez JJ, Aguilera P (2016) Environmental Factors Controlling Soil Organic Carbon Stocks in Two Contrasting Mediterranean Climatic Areas of Southern Spain. Land Degradation & Development 27: 603-611. https://doi.org/10.13039/501100011011
- Wong MTF, Gibbs P, Nortcliff S, Swift RS (2000) Measurement of the acid neutralizing capacity of agroforestry tree prunings added to tropical soils. The Journal of Agricultural Science 134 (3): 269-276. https://doi.org/10.1017/S0021859699007388
- Yang Q, Zheng F, Jia X, Liu P, Dong S, Zhang J, Zhao B (2020) The combined application of organic and inorganic fertilizers increases soil organic matter and improves soil microenvironment in wheat-maize field. Journal of Soils and Sediments 20 (5): 2395-2404. https://doi.org/10.1007/s11368-020-02606-2
- Zamora C (2003) Estimación del contenido de carbono en biomasa aérea en el bosque de pino del ejido “La Majada” municipio de Peribán de Ramos, Michoacán. Universidad Michoacana de San Nicolás de Hidalgo, Michoacán, Mexico.
- Zavala-Chavez F (1995) Encinos Hidalguenses. Universidad Atónoma de Chapingo, Mexico, 133 pp.

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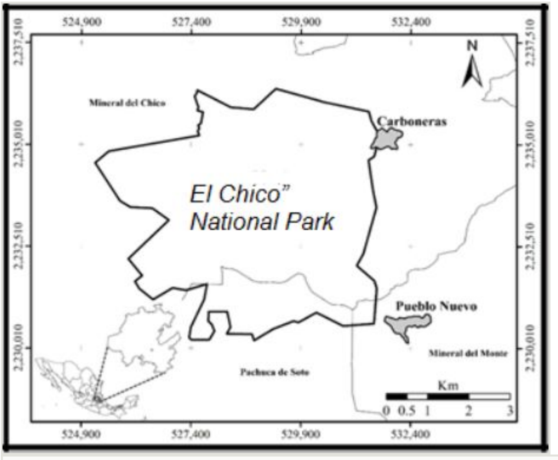

Figure 1.

Geographic location of “El Chico” National Park, Hidalgo.

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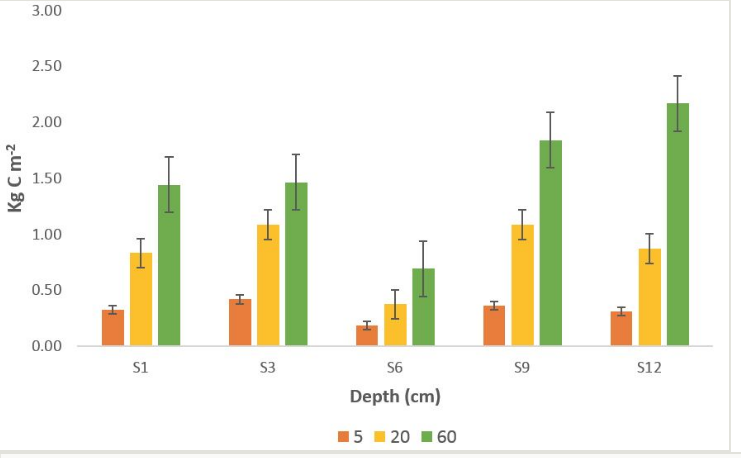

Figure 2.

SOC content by depth under different types of vegetation; S1, Pine-oak; S3, Fir-oak; S6, Cedar; S9, Fir-Tlaxcal; S12, FiYangr.

Table 1.

Some physical and chemical properties of the soil as a function of vegetation type (average values 0-60 cm).

Properties	S1	S3	S6	S9	S12
Da (Mg m-3)	0.93	0.75	0.93	0.69	0.71
Clay (%)	15.67	10.44	20.83	7.67	6.16
pH (clay 1:2.5)	5.57	6.33	5.84	5.58	5.89
pH (KCl 1:2.5)	4.24	5.28	4.69	4.58	4.92
∆pH	-1.33	-1.05	-1.14	-1.00	-0.97
Nt (%)	0.38	0.53	0.17	0.64	0.70
C/N	11.74	11.30	10.26	12.01	11.86
Alo+0.5Feo (%)	2.79	2.74	2.16	3.41	3.21

S1, Pine-oak; S3, Fir-oak; S6, White cedar; S9, Fir-Tlaxcal; S12, Fir; Da: bulk density; Nt: total nitrogen; Alo: oxalate-extractable aluminum; Feo: oxalate-extractable iron; CIC: cation exchange capacity.

Table 2.

Average carbon content in soils (0-60 cm) under different types of vegetation.

Fractions	S1	S3	S6	S9	S12
Ct (%)	6.20a	9.14a	3.06a	9.44a	8.48a
Cox (%)	4.46a	6.00a	1.97a	7.37a	8.09a
Cnox (%)	1.74a	3.14a	1.10a	2.26a	0.39a
Cp (%)	0.83ab	0.83ab	0.49b	1.43a	1.11ab
Cdox (%)	3.62ab	5.17ab	1.48a	5.75ab	6.97b
SOC (Mg C/ha)	45.07b	69.94ab	14.41b	93.66a	109.59a
COO (%)	5.36a	8.31a	2.58a	8.01a	7.37a
REmos (%)	1.93a	2.01a	5.12a	1.13a	1.18a

S1, Pine-oak; S3, Fir-oak; S6, Cedar; S9, Fir-Tlaxcal; S12, Fir; OM, organic matter; Ct, total carbon; SOC, soil organic carbon; Cox, oxidizable carbon; Cnox, non-oxidizable or recalcitrant carbon; Cp, pyrophosphate carbon; Cdox, hard-to-oxidize carbon; SOC, soil organic carbon; COO, non-complexed and slowly oxidizable forms; REmos, organic matter stratification ratio; CO 2 , carbon dioxide; letters in the same row are statistically significant ($p \leq 0.05$).

Table 3.

Area occupied by the types of vegetation studied in PNCh and total carbon and CO2 storage in the soil in the top 20 cm.

Type of Vegetation	*Area (Ha)	Ct Mg/ha at 20 cm depth	Total Mg C/ area	CO2 Capture at 20 cm depth Mg CO2
S1	23.88	94.09	2,246.86	8,223.51
S3	106.62	83.10	8,860.12	32,428.04
S6	31.75	31.60	1,755.77	6,426.14
S9	127.90	111.36	14,242.94	52,129.17
S12	1,725.40	114.40	197,385.76	722,431.88
Total	2,015.55	-	224,491.45	821,638.74

**Source: CONANP, 2005, Ct, total carbon; S1, Pine-oak; S3, Fir-oak; S6, Cedar; S9, Fir-Tlaxcal; S12, Fir.*

Table 4.

Average total carbon content in necromass and CO_2 capture estimation under different types of vegetation in PNCh, Hidalgo, Mexico.

Vegetation type	Biomass carbon (Mg C/ha)	CO_2 (Mg CO_2/ha)
S1	6.43 a	23.59 a
S3	6.76 a	24.80 a
S6	5.03 a	18.46 a
S9	6.06 a	22.24 a
S12	8.74 a	32.07 a
Average	6.60	24.23

S1, Pine-oak; S3, Fir-oak; S6, Cedar; S9, Fir-Tlaxcal; S12, Fir; identical letters in the same column are statistically significant (p≤0.05)