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Driving factors of tree biomass and soil carbon pool in xerophytic forests of northeastern Argentina

Silvana María José Sione^{1,2*} , Marcelo Germán Wilson³, Silvia Gabriela Ledesma², Emmanuel Adrián Gabioud³, José Daniel Oszust² and Leandro Javier Rosenberger²

Abstract

Background The conversion of forests into agricultural lands can be a threat because the forests carbon stored could be a source of emissions. The capacity to improve the predictions on the consequences of land use change depends on the identification of factors that influence carbon pools. We investigated the key driving factors of tree biomass and soil carbon pools in xerophytic forests in northeastern Argentina. Based on analyses of forest structure variables and abiotic factors (topography and soil properties) from 18 mature forests, we evaluated carbon pools using uni- and multivariate (redundancy analysis) methods.

Results The total carbon pool was estimated at $102.4 \pm 24.0 \text{ Mg ha}^{-1}$. Soil organic carbon storage is the single largest carbon pool relative to tree biomass, representing 73.1% of total carbon. Tree canopy cover and basal area were positively correlated with biomass carbon pool ($r=0.77$ and $r=0.73$, $p < 0.001$, respectively), proving to be significant drivers of carbon storage in this compartment. Slope, soil clay content and cation-exchange capacity had a better explanation for the variability in soil carbon pools, and all showed significant positive correlations with soil carbon pools ($r=0.64$, 0.60 and 0.50 ; $p < 0.05$, respectively). The vertisols showed a 27.8% higher soil carbon stock than alfisols.

Conclusions The relevance of our study stems from a dearth of information on carbon pools and their drivers in xerophytic forests, and in particular, the importance of this ecosystems' type for Argentina, because they cover 81.9% of native forest area. Basal area and tree canopy cover exert a strong effect on the carbon pool in tree biomass but not in the soil. The results suggests that there is a potentially major SOC accumulation in forests located in slightly sloping areas and soils with higher topsoil clay content, such as vertisols. This could provide an important reference for implementing forestry carbon sink projects.

Keywords Carbon pool, Forest biomass, Soil parameters, Ecosystem services

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Introduction

In the context of weather patterns changes due to the increase in greenhouse gases (GHGs) concentration in the atmosphere, the sustainable management and conservation of forests are key to ensure the provision of the service they provide as carbon (C) sinks (Salas-Macías et al. 2020). Carbon sequestered in forest equate to ~45% of terrestrial carbon stocks (Rodríguez-Veiga et al. 2017). However, warnings are currently being raised about the reduction of capacity forests to supply services of carbon capture and storage due to several anthropogenic disturbances such as deforestation associated to land use change, fires, selective logging and unplanned grazing management that lead to forest degradation (Baccini et al. 2017; Ordway and Asner 2020; Hanan et al. 2021).

The soil and tree biomass are the largest carbon reservoirs of forests (González Roglich et al. 2014; Motharfar et al. 2019). Soil organic carbon (SOC) stocks exceed those in plant biomass in most climatic regions and represent between 30% (tropical forests) and 70% (boreal forests) of total stock (Pan et al. 2011). Despite, there currently remains uncertainty on the SOC stocks, and these have received limited attention from policies of climate change mitigation (Scharlemann et al. 2014).

The size and dynamics of soil and tree biomass carbon pools are influenced by the interacting natural and anthropogenic factors such as climate (Burbano-Orjuela 2018; Joshi et al. 2021), topography (Wiesmeier et al. 2019; Gebeyehu et al. 2019; Sala-Macías et al. 2020; Bohara et al. 2021), forest structure (Aryal et al. 2018; Dimobe et al. 2019; Ordway and Asner 2020; Osei et al. 2022), soil properties, and land use change (Gasparri et al. 2008; Chaplot et al. 2010; Conti et al. 2014; Wiesmeier et al. 2019; Gebeyehu et al. 2019; Saimun et al. 2021; SAGyP 2022).

At a global level, regional climate conditions (e.g., temperature and precipitation) are key drivers of soil carbon storage; however, climate variability at local scales is frequently small, so climatic control of carbon soil storage at a local level is less relevant in contrast to other factors. C input and C stabilization within the soil are most important aspects of SOC storage (Wiesmeier et al. 2019). Several studies in various climatic zones indicated that vegetation type affects SOC stock by controlling both the input and decomposition of C. Even if, significantly different SOC stocks were found between plant functional types due to different C allocation patterns (Jobbágy and Jackson 2000), in forests there is no consensus on the effect of tree species on SOC storage. For example, significant differences in C stocks between conifer and broad-leaf forests were reported by Schulp et al. (2008a, b) while some studies indicate that species-induced differences in C contents are easily and relatively soon seen in forest

floors but much less so in the mineral soil (Dijkstra and Fitzhugh 2003; Vesterdal et al. 2008).

Soil texture is probably one of the most important factors controlling SOC stabilization; therefore, the silt and clay content represents a key indicator (Wiesmeier et al. 2019). Although several studies on the key drivers of carbon stocks can be found, the wide heterogeneity of forest ecosystems makes it difficult to understand interactions between these factors (Ordway and Asner 2020; Ahirwal et al. 2021; Saimun et al. 2021). In addition, drivers of carbon pools in xerophytic forests have been comparatively less studied than in tropical forests. The xerophytic forests cover the largest native forest area in Argentina (81.9%). Although the influence of biotic and abiotic factors on tree biomass and soil C pools is widely recognized, only a few studies have been limited to specific xerophytic ecosystems, as Caldenal, and have analyzed in detail these influences (González Roglich et al. 2014); thus our understanding of drivers of C stocks in xerophytic ecosystems is still limited. Therefore, it is relevant to obtain information on carbon stocks in this type of ecosystems and the factors that influence their dynamics as input to improve the models that simulate carbon storage and to understand the consequences of land use change and forest degradation.

The research presented in this paper aimed to find out the main driving factors of tree biomass and soil carbon pool in xerophytic forests in northeastern Argentina. We defined the following specific objectives: (i) to determine the carbon pool compartmentalization of tree biomass and soil; (ii) to identify the effects of forest structure, topographic factors, and soil properties on biomass and soil carbon pools; and (iii) to assess differences in carbon pools between forests developing on different soil types. In this study, we hypothesize that: (i) forest structure has a stronger effect on carbon pool in tree biomass than in soil, and (ii) forests developing on diverse soil types have different carbon stocks both in biomass and soil.

Methods

Study area

The study was conducted in the Feliciano stream basin (Entre Ríos Province, northeastern Argentina). The basin is located between 30° 15' to 31° 06' SL and 58° 20' to 59° 36' WL. The total area of the basin (Fig. 1) is covered with about 70% (589,800 ha) of forests. The study area corresponds to the Espinal phyto-geographical province (Cabrera 1976). The Espinal woodlands have undergone rapid deforestation for the advance of the agricultural frontier, due to a combination of favorable conditions for agribusiness oriented toward global markets (Bouza et al. 2015; Cherlet et al. 2018). As well, the remaining forests are currently showing signs of degradation due

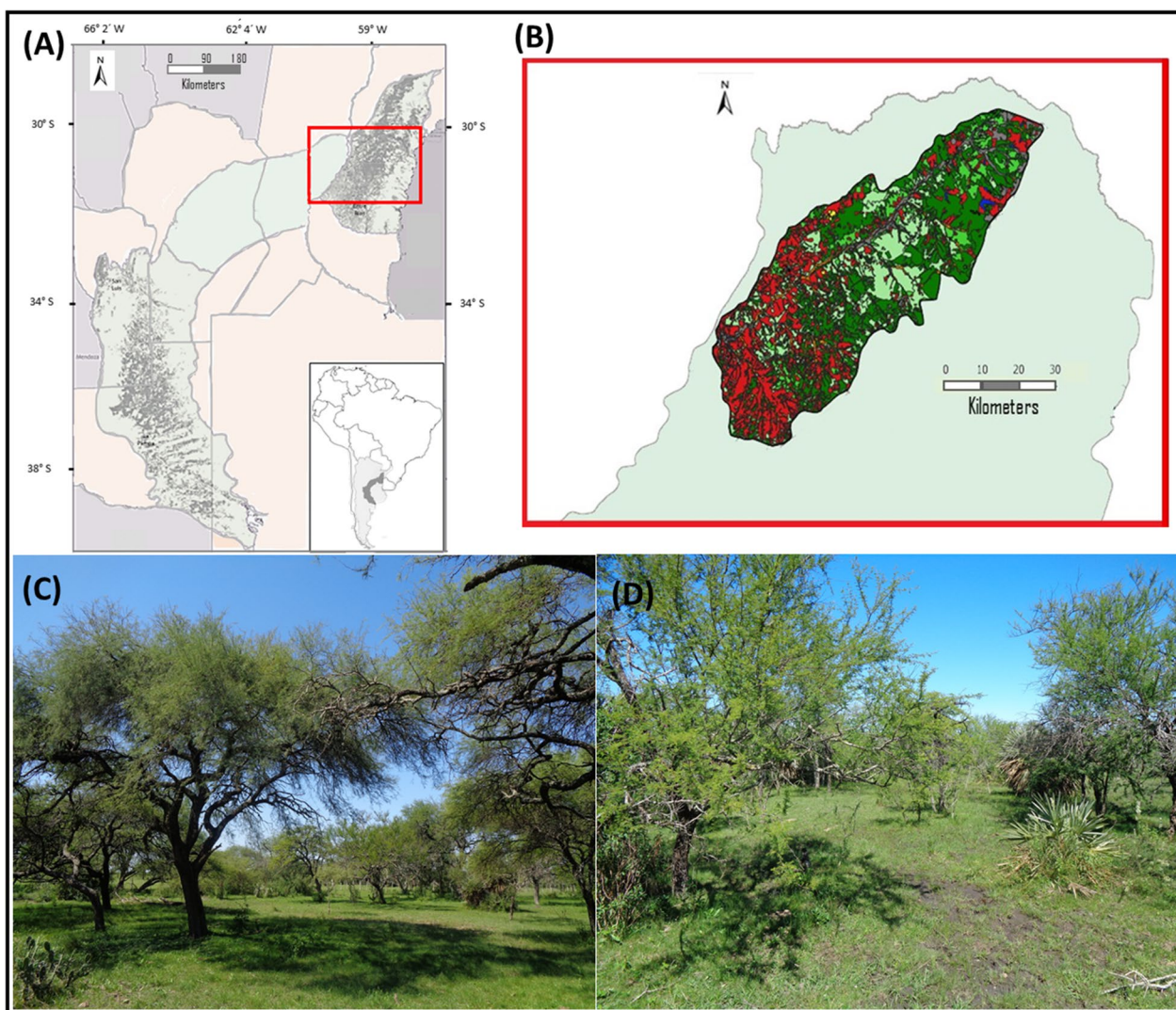


Fig. 1 Study area (Espinal phyto-geographical province, northeastern Argentina): **A** inbox, location of the study area in South America (modified from MAyDS 2020); **B** study area map (Stream Feliciano Basin, Entre Ríos Province) showing the distribution of the three main forest types (ñandubay-espino forests, dark green-shaded area; ñandubay-espino forests which included other species, green-shaded area; and ñandubay open forests, light green-shaded area), and croplands, red-shaded area; **C** and **D** typical Espinal forest landscape, where this study was conducted

to anthropogenic management for economic purposes (selective logging and unplanned grazing management).

The climate is subtropical and humid (1000 mm year⁻¹); the mean annual temperature is 18.5 °C and precipitation is concentrated in summer (37.2%) and spring (32.5%), with a dry season during the winter months (11.2%). The soils at the study area are mainly vertisols and alfisols (Plan Mapa de Suelos 1990; Soil Survey Staff 2014). These soils are a specific soil type characterized by the dominant presence of smectite clays, displaying a strong shrinking–swelling capacity under repeated dry–wet seasonal cycles (Schaeztl and Anderson 2005; Wilson et al. 2013). Vertisols and alfisols developed from same parent material (Hernandarias Formation, e.g.,

calcareous silt material, high clay contents and carbonates presence) but they occupy different positions of the landscape. Alfisols developed mainly in higher and flat landscape positions and slightly undulating areas, with risk of waterlogging; the surface horizon has a depth of approximately 6 to 10 cm, with a low level of organic matter and clay due to leaching. The vertisols are mostly located in slightly sloping terrain (0.5–2.5%) and they are often darker, which are generally attributed to high biological activity and high organic matter content; these soils have clay contents from 35 to 50% (Plan Mapa de Suelos 1990).

Vegetation units include xerophytic forests varying from dense to open, with a single canopy layer. Dominant

species include *Prosopis affinis* Spreng. (commonly named ñandubay), *Vachellia caven* (Molina) Seigler & Ebinger (commonly named espinillo), and *Prosopis nigra* Griseb. (commonly named algarrobo negro), all species are from the Fabaceae family (Burkart 1987). According to the first national native forest inventory (SAyDS 2007), average basal area of these forests is $6 \text{ m}^2 \text{ ha}^{-1}$, and two dominant physiognomic types can be observed: ñandubay-espinillo forests (*P. affinis* and *V. caven* with more than 85% basal area), and ñandubay-espinillo forests which included other species (*P. affinis* and *V. caven* with less than 85% basal area). The latter presents a higher tree density. Other species are *P. nigra*, *Celtis ehrenbergiana* (Klotzsch) Liebm., *Geoffroea decorticans* (Gillies ex Hook. & Arn.) Burkart, *Aspidosperma quebracho-blanco* Schltdl., *Prosopis alba* Griseb. and *Myrcianthes cisplatensis* (Cambess.) O. Berg. It is also common to observe *P. affinis* in open forests, with an average basal area of $2 \text{ m}^2 \text{ ha}^{-1}$ (SAyDS 2007).

Sampling sites

A re-cognisance study was conducted in the xerophytic forest ecosystem of Espinal to gather baseline information and identify possible sampling sites. Based on the forest structure, we selected 18 mature forests corresponding to “ñandubay forests” according to the First National Inventory of Native Forests (SAyDS 2007). “Ñandubay forest” is xerophytic forest representative of Espinal where *P. affinis* or *V. caven* presents a basal area higher than $2 \text{ m}^2 \text{ ha}^{-1}$ and conforms a tree stratum of variable density. In each forest, a 1000 m^2 circular shape plot was located randomly. The minimum distance between sites was 2 km. At each site, we collected data on 11 variables: three were gathered during fieldwork (elevation, slope, tree canopy cover), three were determined through post-fieldwork processing (tree density, basal area, relative dominance of *P. nigra*), and finally, the other variables (soil type, clay content, soil pH, soil C:N ratio and cation-exchange capacity-CEC) were obtained from Soil Charts of Entre Rios Province, Argentina (Plan Mapa de Suelos 1990).

Field data collection and measurements

Geographic coordinates and elevation data were recorded at the center of each plot with Global Positioning System (GPS). Slopes (in percentage) were measured using a clinometer, the Suunto PM-5. At each plot, all trees with a basal diameter (0.3 m aboveground) ≥ 10 cm were identified at species level and measured for diameter and height. The trunk diameter was determined with a Mantax caliper and the height with a telescopic rod. In *C. ehrenbergiana* individuals, the crown area was also determined to estimate the biomass from this variable with allometric function from Conti et al. (2013). For the

estimation of tree canopy cover, five rectangular shape plots of 20 m^2 were located in the middle of the 1000 m^2 circular shape plot and at their N, S, E, and W extremes to reduce the heterogeneity. In each rectangular shape plot, the canopy cover was estimated through ocular estimation (Bunnell and Vales 1990), as the proportion of the forest floor covered by the vertical projection of the tree crowns (Jennings et al. 1999). Relative dominance (RD) was calculated as the proportion of the total basal area of each species.

The average tree density, total basal area, tree canopy cover, and the relative dominance of species within the sampling plots are presented in Table 1. The total number of stems (≥ 10 cm basal diameter) inventoried per plot fluctuated from 130 per hectare to 590 trees per hectare. In the forest sites evaluated, only three species (*P. nigra*, *P. affinis* and *V. caven*) accounted for $94 \pm 8.3\%$ of the total basal area, while *C. ehrenbergiana*, *A. quebracho-blanco*, *P. alba*, and *M. cisplatensis* had relative dominance values of less than 5%.

To determine soil organic carbon (SOC) content, ten soil samples were collected from each extreme and center of the circular plots. Samples were taken at two depths in topsoil (0–10 cm and 10–30 cm) according to IPCC Guidelines (2006). A soil auger was used. The samples for each depth were mixed to obtain a composite soil sample for each plot. The samples were sent to the soil laboratory of the National University of Entre Ríos for further analyses. In addition to changes in the carbon concentration of soil, changes in soil bulk density (BD) should also be considered. The litter is controlled mostly by physical processes like swelling and shrinking (Wendt and Hauser 2013). In vertisol soils of the study area, Wilson et al. (2013) determined volumetric changes greater than 19% as a function of soil moisture content variation. Therefore, it is necessary to define an equivalent mass of soil from a standardized BD value (SBD) to calculate the carbon pool on an area basis (Mg ha^{-1}). For this purpose, soil samples were collected to quantify the soil moisture content (%) and BD (Mg m^{-3}). Three samples at each depth (0–10 cm and 10–30 cm) from different points of the circular plot using a cylinder were taken.

Table 1 Summary of forest structural and floristic parameters in assessed sites

TD (ind ha^{-1})	BA ($\text{m}^2 \text{ ha}^{-1}$)	TCC (%)	RD (%)		
			<i>P. affinis</i>	<i>P. nigra</i>	<i>V. caven</i>
341.0 (32.0)	11.10 (0.76)	57.0 (5.0)	27.9 (4.3)	45.2 (6.1)	21.0 (4.1)

TD tree density, BA basal area, TCC tree canopy cover, and RD relative dominance of tree species. Values represent means of 18 replicates, with standard errors shown in parentheses

Soil carbon pool determination

Soil moisture content was measured through the oven-dry method at 105 °C (O'Kelly 2004), and BD was determined by the cylinder method (Forsythe 1975). The available water range is the difference between soil water content at field capacity (FC) and soil water near the permanent wilting point (WP). In the study area, soils with a dominant presence of smectite clays (vertisols and alfisols) showed a linear relationship between soil moisture content and BD within the available water range (Wilson and Cerana 2004). Therefore, a linear equation for each soil layer was generated (Eqs. 1 and 2) from the BD and soil moisture content data obtained in this work. The available water range in the 0–10 cm soil layer was between 0.20 g g⁻¹ (WP) and 0.35 g g⁻¹ (FC) (Wilson et al. 2013), while in the 10–30 cm layer, it was between 0.24 g g⁻¹ (WP) and 0.40 g g⁻¹ (FC) (Wilson, pers. comm).

$$\text{SBD (00-10)} = -0.01021x + 1.442 \left(R^2 = 0.30; \quad p < 0.005 \right) \quad (1)$$

$$\text{SBD (10-30)} = -0.005601x + 1.416 \left(R^2 = 0.30; \quad p < 0.007 \right) \quad (2)$$

where SBD: soil standardized bulk density; x : soil water content (%).

We proposed to consider as SBD the BD value with soil water content corresponding to 50% of available water. Using Eqs. 1 and 2, SBD values determined were 1.17 Mg m⁻³ and 1.24 Mg m⁻³ for 0–10 cm and 10–30 cm soil layers, respectively. From these SBD values, the equivalent soil mass in the 0–10 cm layer was estimated at 1166.80 Mg ha⁻¹ whereas, in the 10–30 cm layer, the equivalent soil mass was 2484.20 Mg ha⁻¹. The procedure described requires no bulk density sampling and thus avoids imprecision in its determination that occurs through volumetric changes under repeated dry-wet seasonal cycles.

For SOC determination, samples were oven-dried at temperatures below 40 °C and sieved (2 mm). SOC

content was determined by Walkley and Black method (1934) and was expressed as mass of carbon per unit mass of soil (g kg⁻¹) or percentage. For the calculation of the soil carbon pool on an area basis (Mg ha⁻¹), SBD and soil depth data were used, as follows (Eq. 3):

$$\text{Soil C pool (Mg ha}^{-1}\text{)} = \text{SBD (Mg m}^{-3}\text{)} \times \text{SOC (\%)} / 100 \times \text{Soil depth (m)} \times 10000 \quad (3)$$

where SBD: soil standardized bulk density; SOC: soil organic carbon.

Soil carbon pool at 30 cm was obtained from the sum of the carbon pool at two depths in topsoil (0–10 cm and 10–30 cm).

Tree aboveground biomass (AGB) and carbon pool estimation

To estimate tree AGB, we used functions developed for xerophytic forests of Espinal and Arid Chaco regions (Table 2). For species without models (*P. alba* and *M. cisplatensis*), we applied the general Eq. 4:

$$\text{AGB (kg tree}^{-1}\text{)} = \text{bd (m)} * \text{h (m)} * \text{wd (kg m}^{-3}\text{)} \quad (4)$$

where AGB: aboveground biomass; bd: basal diameter trunk; h: tree high; wd: wood density. We used the wood density data from INTI-CITEMA (2007).

$$\text{Tree biomass C pool (Mg ha}^{-1}\text{)} = \text{AGB (Mg ha}^{-1}\text{)} * \text{CF} \quad (5)$$

where AGB: aboveground biomass; CF = Carbon fraction.

We used an average value of C fraction (0.475) for the Espinal dominant species (Sione et al. 2021). Finally, at each site, the total C pool was calculated from the sum of tree biomass and soil C pools.

Statistical analysis

Redundancy analysis (RDA) was developed to assess how much of the variation in one set of variables (response

Table 2 Allometric functions used to estimate tree AGB

Species	Function	R ²	bd range (cm)	Source
<i>Prosopis affinis</i>	$\ln(\text{AGB}) = -3.23 + 2.61 * \ln(\text{bd})$	0.97	5 < bd < 35	Sione et al. (2019)
<i>Prosopis nigra</i>	$\text{Lln}(\text{AGB}) = -2.86 + 2.60 * \ln(\text{bd})$	0.98	5 < bd < 40	Sione et al. (2020a)
<i>Vachellia caven</i>	$\ln(\text{AGB}) = -3.70 + 2.83 * \ln(\text{bd})$	0.97	5 < bd < 25	Sione et al. (2020b)
<i>Celtis ehrenbergiana</i>	$\ln(\text{AGB}) = -12.5 + 1.28 * \ln(\text{CA})$	0.68		Conti et al. (2013)
<i>A. quebracho-blanco</i>	$\text{AGB} = 0.074 * \text{bd}^{2.59} * e^{-0.15}$	0.97	10 < bd < 60	Gaillard de Benítez et al. (2002)

AGB = aboveground biomass (kg), bd = basal diameter (0.3 m aboveground, cm), CA = crown area (cm²)

variables: tree biomass and soil C pools) can be explained by the variation in another set of variables (explanatory variables: tree density, basal area, tree canopy cover, relative dominance of *P. nigra*, elevation, slope, soil clay content, soil CEC, soil pH, and soil C:N ratio). RDA, a direct extension of multiple regression in that it models the effect of an explanatory matrix X on a response matrix Y , was carried out using R software (vegan package). Pearson's correlation was calculated to assess the relationships between dependent variables (tree biomass carbon, soil carbon, and total carbon stock) and independent variables (forest structure data and abiotic factors). To show the variability of tree biomass and soil carbon pools for each soil type, the coefficient of variation (CV) was calculated (Guerra Dávila 2014). We performed one-way analysis of variance (ANOVA) of tree biomass and soil pools for different types of soils. For these ANOVAs, we employed Tukey's test at $p < 0.05$ to separate means. All statistical analyses were performed using the RStudio software 2023.06.0.

Results

Tree biomass and soil carbon pools

The total carbon pool in the xerophytic forests in study sites was estimated at $102.4 \pm 24.0 \text{ Mg ha}^{-1}$. The carbon stored in the first 30 cm depth of soil accounts for $73.1 \pm 6.6\%$ of total carbon per hectare. Tree biomass carbon pool per unit area varied widely, ranging from a low of 11.0 Mg ha^{-1} to a high of 44.7 Mg ha^{-1} . The soil carbon pool showed a significant positive correlation ($R^2 = 0.25$; $p < 0.05$) with tree biomass carbon (Fig. 2).

Comparison of the carbon pool among forests developing on different soil types

There were large differences in carbon pools among soil orders (Fig. 3 and Additional file 1: Table S1). Vertisols had the greatest soil carbon pool (86.1 Mg ha^{-1}).

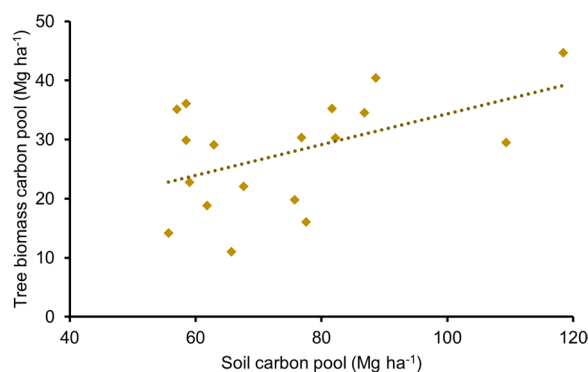


Fig. 2 Relationship between tree biomass and soil carbon pools ($n = 18$)

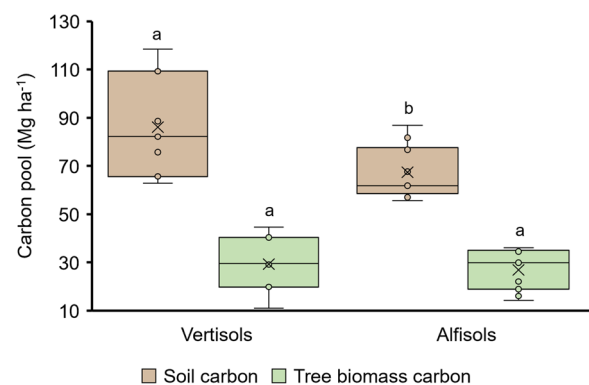


Fig. 3 Carbon pools in soil and tree biomass, among soil types: $n = 11$ for alfisols, and $n = 7$ for vertisols. Different lowercase letters indicate significant differences (Tukey $p < 0.05$) between soil types for the same compartment (tree biomass or soil)

A differential behavior was observed in the variability of the soil carbon pool, resulting in a higher CV in vertisols (24.5%) than in alfisols (16.8%). The tree biomass carbon pool in vertisols also resulted in higher levels than in alfisols (Fig. 3); however, these differences were not significant ($p > 0.05$). The variation coefficients in the mentioned carbon pool were estimated at 39.1% and 30.8% for vertisols and alfisols, respectively.

Driving factors of carbon pools (tree biomass and soil pools)

Both forest structure variables and abiotic factors showed significant associations with carbon pools in the different compartments (tree biomass and soil pool) at a plot level ($R^2 = 0.86$; adj.- $R^2 = 0.66$; $F = 4.30$; $p = 0.015$). Redundancy analysis (RDA) showed that basal area, canopy cover, relative dominance of *P. nigra*, tree density, slope, soil clay content, soil CEC, elevation, soil pH, and soil C:N ratio were important environmental factors influencing tree biomass and soil carbon pool. The results of the RDA test indicated that the RDA biaxial explained 86.0% of the variation in carbon pools. Axis 1 of the RDA plot explained roughly 73.9% of the variation, while axis 2 explained a further 12.0% (Table 3 and Fig. 4).

Among the environmental factors affecting soil carbon pools, slope, clay content and soil CEC had a better explanation for the variability in soil carbon pools. Among them, slope explained the highest degree, and all showed significant ($p < 0.05$) positive correlations with soil carbon pools (Figs. 4 and 5). Tree biomass carbon pool was found highly significantly positively ($p < 0.001$) correlated with cover canopy and basal area (Figs. 4 and 5).

Table 3 Redundancy analysis (RDA) and biplot scores for explanatory variables

Variable	RDA1	RDA2
SLO	-0.686	0.148
CLC	-0.632	0.223
TCC	-0.565	-0.493
CEC	-0.519	0.148
BA	-0.337	-0.778
ELE	0.278	-0.324
PND	-0.215	-0.407
C:N	0.195	-0.126
Ph	0.175	0.202
TD	0.090	-0.041

pH soil pH, *C:N* soil C:N ratio, *CEC* cation-exchange capacity, *CLC* clay content, *SLO* slope, *ELE* elevation, *PND* relative dominance of *P. nigra*, *TCC* tree canopy cover, *TD* tree density and *BA* = basal area

Discussion

The soil and vegetation have complex interrelations because they develop together over a long period of time (Ahirwal et al. 2021). Soil organic carbon storage is controlled by the balance of carbon inputs from vegetation and outputs through decomposition; so amount organic carbon in the soil affects and is affected by vegetation

(Schlesinger 1977). We found that xerophytic forests of northeastern Argentina contain a total carbon pool (tree biomass + soil for the first 30 cm depth) of 102.4 Mg ha⁻¹. These estimates are within the range of earlier observations of the comparable ecosystems considering aboveground biomass and upper soil profiles (Fig. 6).

The estimated carbon pool in our work is within the range of estimates for seasonally dry Chaco forests, including all aboveground compartments and organic soil profiles up to 1 m depth (Gasparri et al. 2008), and it is similar to the closed semiarid Caldenal forests, considering woody and herbaceous, above- and belowground litter, and deeper organic soil profiles up to 2 m depth (González Roglich et al. 2014). Other work, including carbon in aboveground plant standing biomass and organic soil profiles up to 2 m depth, resulted in 121.3 Mg C ha⁻¹ of total carbon storage (Conti et al. 2014), similar to the ones determined in our study.

According to previous studies, we found that carbon stored in soils to be the single largest carbon pool (74.7 Mg ha⁻¹), representing 73.1% of total carbon per hectare, with more than half the sites falling between 72.1 and 85.7% of total pool. In comparable forests (Fig. 6), such as the Caldenal in semiarid Espinal, and semiarid Chaco forests, between 53 and 63% of total ecosystem carbon stock was in the soil, respectively (Bonino 2006;

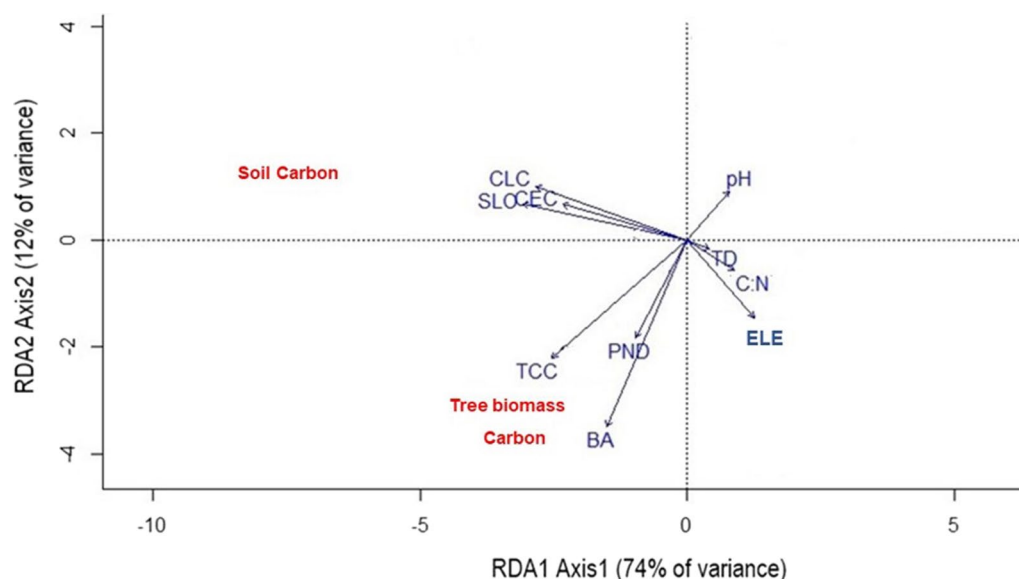


Fig. 4 Redundancy analysis (RDA). Explanatory variables (forest structure and abiotic factors) were indicated by arrows. Arrows pointing toward a response variable (tree biomass and soil carbon pool) indicate a high positive correlation. Arrow lengths indicate the strength of the relationship between carbon pools and explanatory variables. Forest structure data (density, basal area, canopy cover, relative dominance of *P. nigra*) and abiotic factors (elevation, slope, soil clay content, soil CEC, soil pH, and soil C:N ratio) explained 84.0% of the total variance in carbon pools (tree biomass and soil), with 73.9% of the variance on RDA axis 1 and 12.0% on RDA axis 2. *pH* soil pH, *C:N* soil C:N ratio, *CEC* cation-exchange capacity, *CLC* clay content, *SLO* slope, *ELE* elevation, *PND* relative dominance of *P. nigra*, *TCC* tree canopy cover, *TD* tree density and *BA* basal area

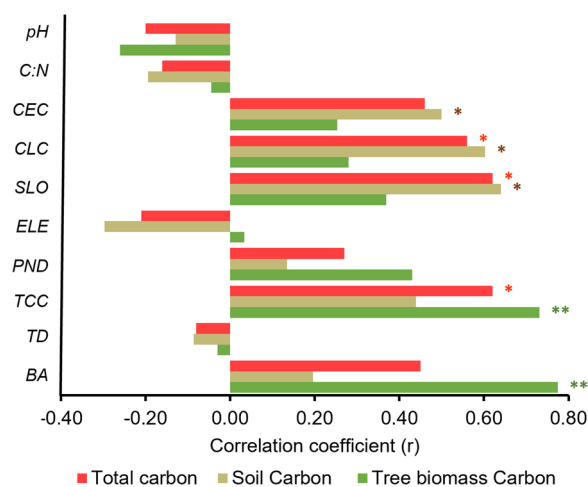


Fig. 5 Correlation coefficient (Pearson's r) of the relationship among carbon pools (tree biomass carbon, soil carbon and total carbon) and different factors. *pH* soil pH, *C:N* soil C:N ratio, *CEC* cation-exchange capacity, *CLC* clay content, *SLO* slope, *ELE* elevation, *PND* relative dominance of *P. nigra*, *TCC* tree canopy cover, *TD* tree density and *BA* basal area. *significant ($p < 0.05$), and **highly significant ($p < 0.01$)

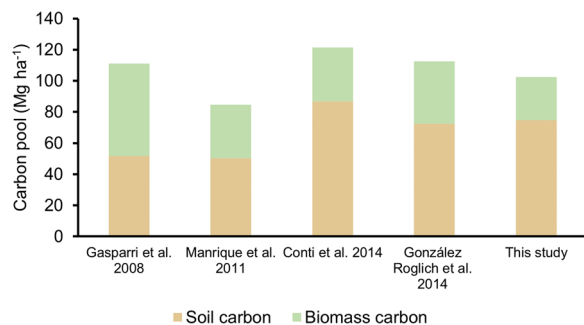


Fig. 6 Comparisons of biomass and soil carbon pool in xerophytic forests of northeastern Argentina with comparable ecosystems. Gasparri et al. (2008): seasonally dry Chaco forests, Manrique et al. (2011) and Conti et al. (2014) for the semiarid Chaco forests, and González Roglich et al. (2014) for closed semiarid Espinal forest (Caldenal)

Gasparri et al. 2008; Manrique et al. 2011; Pan et al. 2011; Conti et al. 2014; González Roglich et al. 2014).

Studies carried out in different forest regions of Argentina reported a wide range of tree biomass carbon pools among forest types. For instance, the xerophytic forest of Espinal region stored between 38.9 and 43.9 Mg ha⁻¹ of carbon (Sione et al. 2021 and Ledesma et al. 2021, respectively); the semiarid Chaco forests sequestered up to 43.0 Mg ha⁻¹ (Gasparri and Manghi 2004; Conti et al. 2014; Loto 2021), while a carbon stock of 270.1 Mg ha⁻¹ was determined in the aboveground biomass of Andean-Patagonian forests (Gasparri and

Manghi 2004). The average carbon value estimated in our work was 27.8 Mg ha⁻¹, with half the sites being between 20 and 35 Mg ha⁻¹. These values showed moderate variability (34%). The remaining forests of the study area are heterogeneous in coverage and degradation level due to several anthropogenic disturbances such as selective logging, fires, and unplanned grazing management. Previous studies have found high variability both in biomass carbon pools and in soil organic carbon pools of degraded forests. In the case of Chaco forests, for example, the forest was degraded, its biomass and carbon decreased significantly because of the reduction in density and size of individuals; as a result, total biomass exhibited significant variations among the communities. However, a moderate decrease in soil carbon content with respect to vegetation degradation was observed (Bonino 2006).

Biomass carbon storage depends on many factors, such as the type, density, and diversity of the vegetation. On the one hand, a strong positive correlation between carbon stock in trees was observed, and on the other tree density, size, and height (Aryal et al. 2018; Dimobe et al. 2019). In relation to previous studies (González Roglich et al. 2014; Sheikh et al. 2020; Osei et al. 2022), we found that tree canopy cover and basal area proved to be significant drivers of biomass carbon storage, as well as the total carbon pool stocks of forests. Instead, we did not find a relationship between tree density and these pools. The size of tree species and canopy cover explained more of the variation observed in biomass carbon stocks than in tree density (Gebeyehu et al. 2019). Burrows et al. (2000) indicate that basal area is usually used to estimate biomass carbon pools since it shows a significant relationship with this reservoir, integrates both the number and size of trees, and is easily measurable. Osei et al. (2022) found that basal area explained >88.0% variability in aboveground woody carbon stocks. The significant importance of tree canopy cover on biomass carbon pool could be attributed to the physiognomy of dominant species of Espinal forests. For instance, *P. nigra* and *P. affinis* individuals invest most of their resources in the development of crowns rather than stems (Sione et al. 2019, 2020a), therefore, high tree canopy cover values are associated with higher carbon pools.

An effect of *P. nigra* relative dominance on biomass carbon storage ($r=0.43$) was observed, although it was not significant. Earlier findings revealed that *P. nigra* was associated with the highest biomass and carbon stocks per unit or basal area (Sione et al. 2020a, b). In addition, at the individual tree level, this species stores more carbon per unit of biomass (48%) than other dominant species of forests evaluated (Sione et al. 2021). For instance, applying existing biomass models allows us to know that the aboveground biomass carbon storage in *P. nigra*

individual (with basal diameter of 30 cm) was 45% higher than for *P. affinis* individual (same diameter), even when the latter has higher specific wood density. This implies that forests could have comparable basal area per hectare but higher biomass carbon storage in those with higher relative dominance of these species.

Neither elevation nor slope was significantly associated with carbon pools of tree biomass in our study. Existing literature is not consistent in showing the relationship between topographic factors and carbon stocks: some sources provide evidence that carbon stocks increase gradually with increasing slope and elevation (Gebeyehu et al. 2019; Pragasan 2020; Saimun et al. 2021), others indicate that stocks are reduced (Bohara et al. 2021) or no relation is shown (Salas Macías et al. 2020). Our results showed that slope, soil clay content, and CEC are the principal factors controlling soil carbon pool, as well as total carbon pool stocks of forests, although the correlation between CEC and total pool ($r=0.46$) was not significant. The strong influence of clay content on soil carbon storage is consistent with earlier observations in this same region (González Roglich et al. 2014; SAGyP 2022), reinforcing the previous findings in different ecosystems worldwide. Several authors reported that soil texture plays an important role, as clay content increases, carbon outputs decrease because clay has a stabilizing and protecting impact on soil organic carbon (Paul 1984; Jobbágy and Jackson 2000). A high clay content may cause to clay surfaces adsorb more organic C molecules due to the larger surface area and the presence of polyvalent cation forming organic-mineral complexes to control the protection of SOC from microbial and enzymatic decomposition, increasing SOC storage (Zaffar and Lu 2015; Zhong et al. 2018). It is commonly accepted that SOC binding potential is higher in soils dominated by 2:1 clay minerals (such as montmorillonite, clay type dominant in the soils of study area) than in soils dominated by 1:1 clay minerals. The higher cation-exchange capacity and larger specific surface of 2:1 clay minerals, which would promote organic-mineral complexation and their capacity of these minerals to promote aggregation could explain the higher SOC stabilizing capacity of soils dominated by this type clays (Greenland 1965; Kleber et al. 2007; Fernández-Ugalde et al. 2013). Besides, we did not find a significant relationship between elevation and soil carbon stock. A review of drivers of soil organic carbon at various scales (Wiesmeier et al. 2019) indicates that there is no general agreement on the importance of topographical features for soil carbon storage, due to various scales of observation. Local terrain attributes such as slope and curvature appear to influence soil carbon storage only at small spatial scales, while landscape position may become an important key at larger scales. These authors

indicated that the importance of topographical features for soil carbon storage is due to their contribution to erosional processes because they control water flow paths, water accumulation, and discharge. Sites with steep slopes and convex curvatures lead to higher water discharge, whereas low inclination and concave curvatures favor water accumulation. Fritsch and Fitzpatrick (1994) propose a link between waterlogging and organic matter and clay migration down to the lower horizons. Therefore, SOC and clay loss occurs in surface horizons, which leads to poor soil aggregate stability (Indelángelo et al. 2007; Gabioud et al. 2011). We found that forests developing on diverse soil types have different carbon stocks in soil but not in biomass, partially reinforcing our second hypothesis. The vertisols showed 27.8% higher soil carbon stock than that in alfisols. The observed differences are probably explained by differences in slope, clay content, and CEC. These two soil types, developed from the same parent material, occupy different positions in the landscape. Alfisols develop mainly in higher and flat landscape positions and slightly undulating areas, with a risk of waterlogging while vertisols are mostly located in slightly sloping terrain. However, as was reported by Wiesmeier et al. (2019), different soil carbon pools among soil types could be attributed to the different slopes rather than to the position in the landscape. In our work, 61% of the plots were located on alfisols and 39% on vertisols. All plots located on alfisols were located on slopes less than 1%, whereas around 64% were on areas with higher elevations than 65 m. In vertisols, the elevation of the plots was lower than 65 m and the slope varied between 1 and 2%. In addition, vertisols showed average clay contents of 327.6 g kg^{-1} , which are 16% higher than those determined in alfisols (Additional file 1: Table S1). These outputs indicate that soil type is not independent controlling driving factor but integrates a number of parent materials and topographical situation-related variables, such as soil texture and moisture contents, which directly affect the potential of soils to store C (Wiesmeier et al. 2019).

Previous literature showed controversial results on the importance of slope as a key driver of soil carbon storage. In the semiarid savannahs of Argentina, no statistically significant relationship between slope and soil carbon pool was found (Gonzalez Roglich et al. 2014). However, some studies determined that a significant proportion of soil carbon storage variability was explained by slope gradient (Chaplot et al. 2010) while other studies found that sites on steeper inclination have been found to contain less SOC (Ritchie et al. 2007). Even when our work showed that forest structure variables have no significant effect on soil carbon storage, tree canopy cover was the variable of higher correlation ($r=0.44$), although it was

not significant. Consistent with our results, earlier studies found that stand density (expressed as basal area per hectare) had no significant effect on SOC storage in the whole soil profile (Osei et al. 2022).

There is no consensus on the effect of tree species on soil carbon storage in forests (Wiesmeier et al. 2019). For example, tree nitrogen-fixing species have larger effects on forest soils than other species, which include consistent increases in soil organic carbon; this could be attributed to their low C:N ratios, its therefore their relatively fast decomposition rates (Mendoza et al. 2014). On the other hand, soil storage in coniferous forests may be relatively high due to an accumulation of acidic litter in the organic layer (Schulp et al. 2008a, b). However, other studies did not showed significant differences between soil carbon pools among forest types (Vesterdal et al. 2008). Both soil pH and soil C:N ratio were negatively associated with carbon pools in tree biomass and soil, although these correlations were not statistically significant. In dry forests, Gebeyehu et al. (2019) found that moderate levels of soil pH had a positive effect on soil carbon storage, but extreme levels (either low or high) of soil pH caused a decrease in this stock. We found that soil pH values ranged from 5.2 to 7.2, with 89% of sites falling below 6.3 (Additional file 1: Table S1). Soils with these pH values are considered moderately to slightly acid, characteristic of humid regions.

Early findings revealed that soils with C:N ratio in the range of 10 to 12 contribute to slow organic matter decomposition as they require an excess of microbial activities (Landon 1991; Gebeyehu et al. 2019). The 72.2% of sites evaluated in our work corresponded to this range, suggesting slow organic matter decomposition. The main limitation of our study is that we have only quantified carbon storage in aboveground tree biomass and soil in first 30 cm depth. Its therefore, data obtained are likely to be underestimates of carbon stocks in forest of region, carbon emissions from land use change and their CO₂ mitigation potential, as we have not included carbon storage in shrubs, non-woody vegetation and coarse woody debris, belowground biomass, and the carbon stock in the deepest soil layers.

Conclusions

This study contributes to understanding of the key driving factors of carbon pools in xerophytic forests in northeastern Argentina. Its relevance stems from a dearth of information on carbon stocks in this forest type relative to tropical forests, and the importance of xerophytic forests for Argentina, because they cover the largest native

forest area (81.9%). The results suggests that there is a potentially major accumulation of SOC in forests located in slightly sloping areas and soils with higher topsoil clay content. These characteristics determinate to the fact that SOC storage in forests developing on vertisols were higher compared to alfisols.

We found that basal area and tree canopy cover exert a strong effect on the carbon pool in tree biomass but not in the soil, being consistent with our first hypothesis. We also showed that canopy cover is a driving factor of total carbon pool. This suggests that actions to manage tree species can affect the variability of carbon stocks. Management practices that maintain forest cover are essential to conserving carbon in tree biomass. Furthermore, the high association between canopy cover and carbon stock in tree biomass raises challenges for the application of remote sensing to the quantification of carbon stored in tree biomass due to canopy cover being one of the variables that can most easily be measured using this tool. Soil organic carbon stock is the single largest carbon pool in xerophytic forests in northeastern Argentina, accounting for more than 70% of the total pool. These findings reinforce the need to provide certainty on estimates both on soil carbon stocks and emissions from soils, as well as to focus on this carbon pool in climate change mitigation policies. The slope and clay content could provide an important reference for implementing forestry that analyze carbon sink projects. In soils that have higher carbon storage potential, such as vertisols, forests can offer major opportunities for increased carbon stock through sustainable management practices. The information presented here may be especially useful to improve carbon storage models and predictions on consequences of climate change, land use change, and forest degradation, as well as for regional policy development on emissions reduction by deforestation and forest degradation (e.g., REDD+).

Note

A disintegration of the genus *Prosopis* L. has been recently proposed by Hughes et al. (2022) based on molecular phylogeny, and new nomenclatural combination for American species has been published under genus *Neltuma*. Nevertheless, the classification of *Prosopis* by Burkart's (1976) is maintained here due to nomenclatural stability, prevailing current use and disadvantageous changes (Articles 14, recommendation 14A.1; Article 34, recommendation 34A.1; Article 56 recommendation 56A, ICBN (Turland et al. 2018), until acceptance of nomenclatural changes by the International Committee of Nomenclature.

Abbreviations

AGB	Tree aboveground biomass
ELE	Elevation
ANOVA	Analysis of variance
BA	Basal area
BD	Soil bulk density
C	Carbon
CEC	Cation-exchange capacity
CF	Carbon fraction
CLC	Soil clay content
CO ₂	Carbon dioxide
CV	Coefficient of variation
FC	Field capacity
GHGs	Greenhouse gases
GPS	Global positioning system
PCA	Principal component analysis
PND	Relative dominance of <i>P. nigra</i>
RD	Relative dominance of tree species
SBD	Standardized bulk density
SLO	Slope
SOC	Soil organic carbon
TCC	Tree canopy cover
TD	Tree density
WP	Permanent wilting point

Supplementary Information

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Additional file 1: Table S1. Values for variables determined for each sampling site.

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Author contributions

SS: study design, field work, data entry, data analysis and interpretation, writing of original draft, review and editing of subsequent drafts. MW: study design, field work, soil data analysis and interpretation, writing of original draft, review and editing of subsequent drafts. SL: study design, field work, data analysis and interpretation, review and editing of drafts. EG: field work, soil data analysis and interpretation, review and editing of drafts. JO: field work, soil data analysis, review and editing of drafts. LR: field work, review and editing of drafts. All authors read and approved the final manuscript.

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Availability of data and materials

The data generated and analyzed during the present study are available from the corresponding author.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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References

- Ahirwal J, Nath A, Brahma B, Deb S, Kumar Sahoo U, Jyoti Nath A (2021) Patterns and driving factors of biomass carbon and soil organic carbon stock in the Indian Himalayan region. *Sci Total Environ* 770:145292. <https://doi.org/10.1016/j.scitotenv.2021.145292>
- Aryal S, Shrestha S, Maraseni T, Wagle PC, Gaire NP (2018) Carbon stock and its relationships with tree diversity and density in community forests in Nepal. *Int For Rev* 20(3):263–273
- Baccini A, Walker W, Carvalho L, Farina M, Sulla-Menashe R, Houghton A (2017) Tropical forests are a net carbon source based on aboveground measurements of gain and loss. *Science* 358:230–234. <https://doi.org/10.1126/science.aam5962>
- Bohara B, Miya MS, Timilsina S, Gautam D, Regmi S (2021) Biomass and carbon stock variation along slopes in tropical forest of Nepal: a case of Depard Community Forest, Makwanpur, Nepal. *J Multi Appl Nat Sci* 1(2):89–99. <https://doi.org/10.47352/jmans.v1i2.85>
- Bonino EE (2006) Changes in carbon pools associated with a land-use gradient in the dry Chaco, Argentina. *For Ecol Manag* 223:183–189. <https://doi.org/10.1016/j.foreco.2005.10.069>
- Bouza M, Aranda-Rickert A, Brizuela M, Wilson MG, Sasal MC, Sione SMJ, Beghetto SM, Gabioud EA, Oszust J, Bran D, Velazco V, Gaitan J, Silenzi J, Echeverría N, De Lucia M, Iurman D, Vanzolini J, Castoldi F, Hormaeche J, Johnson T, Meyer S, Nkonya E (2015) Economics of land degradation in Argentina. In: Nkonya E, Mirzabaev A, von Braun J (eds) *Economic of land degradation and improvement. A global assessment for sustainable development*. Springer, Heidelberg. https://doi.org/10.1007/978-3-319-19168-3_11
- Bunnell FL, Vales DJ (1990) Comparison of methods for estimating forest over-story cover: differences among techniques. *Can J For Res* 20:101–107. <https://doi.org/10.1139/x90-014>
- Burbano-Orjuela H (2018) El carbono orgánico del suelo y su papel frente al cambio climático. *Rev Cienc Agr* 35(1):82–96. <https://doi.org/10.22267/rcia.183501.85>
- Burkart A (1976) A monograph of the genus *Prosopis* (Leguminosae subfam. Mimosoideae). *J Arnold Arbor* 57:450–525
- Burkart A (1987) Leguminosae. In: Troncoso NS, Bacigalupo NM (eds) *Flora Ilustrada de Entre Ríos (Argentina)*, vol 6. Colección Científica del INTA, Buenos Aires, pp 442–738
- Burrows WH, Hofmann MB, Compton JF, Back PV, Tait LJ (2000) Allometric relationships and community biomass estimates for some dominant eucalypts in Central Queensland woodlands. *Aust J Bot* 48:707–714. <https://doi.org/10.1071/BT99066>
- Cabrera AL (1976) Regiones Fitogeográficas Argentinas. In: Kugler WF (ed) *Enciclopedia argentina de agricultura y jardinería*, vol 2, 2nd edn. ACME, Buenos Aires, pp 1–8
- Conti G, Enrico L, Casanoves F, Díaz S (2013) Shrub biomass estimation in the semiarid Chaco forest: a contribution to the quantification of an underrated carbon stock. *Ann For Sci* 70(5):3–12. <https://doi.org/10.1007/s13595-013-0285-9>
- Conti G, Pérez-Harguindeguy N, Quetier F, Gorné LD, Jaureguiberry P, Bertone GA, Enrico L, Cuchietti A, Díaz S (2014) Large changes in carbon storage under different land-use regimes in subtropical seasonally dry forests of southern South America. *Agric Ecosyst Environ* 197:68–76. <https://doi.org/10.1016/j.agee.2014.07.025>
- Chaplot V, Bouahom B, Valentin C (2010) Soil organic carbon stocks in Laos: spatial variations and controlling factors. *Glob Chang Biol* 16:1380–1393. <https://doi.org/10.1111/j.1365-2486.2009.02013.x>

- Cherlet M, Hutchinson C, Reynolds J, Sommer HJ, von Maltitz G (2018) World atlas of desertification: rethinking land degradation and sustainable land management. Publication Office of the European Union, Luxembourg
- Dijkstra FA, Fitzhugh RD (2003) Aluminum solubility and mobility in relation to organic carbon in surface soils affected by six tree species of the north-eastern United States. *Geoderma* 114:33–47
- Dimobe K, Kuyah S, Dabr  Z, Ouedraogo A, Thiombiano A (2019) Diversity-carbon stock relationship across vegetation types in W National park in Burkina Faso. *For Ecol Manag* 438:243–254. <https://doi.org/10.1016/j.foreco.2019.02.027>
- Fern ndez Ugalde O, Barr  P, Hubert F, Virto I, Girardin C, Ferrage E, Caner L, Chenu C (2013) Clay mineralogy differs qualitatively in aggregate-size classes: clay mineral based evidence for aggregate hierarchy in temperate soils. *Eur J Soil Sci* 64:410–422. <https://doi.org/10.1111/ejss.12046>
- Forsythe W (1975) F sica de suelos: manual de laboratorio. IICA, San Jos 
- Fritsch E, Fitzpatrick RW (1994) Interpretation of soil features produced by ancient and modern processes in degraded landscapes. I. A new method for constructing conceptual soil-water-landscapes models. *Aust J Soil Res* 32:889–907
- Gabioud EA, Wilson MG, Sasal MC (2011) Aplicaci n del m todo de Le Bissonnais para el an lisis de la estabilidad de agregados. *Ciencia Del Suelo* 29(2):129–139
- Gaillard de Ben tez C, Pece M, Ju rez de Gal ndez G, Maldonado A, Acosta VH, G mez A (2002) Biomasa a rea de ejemplares de quebracho blanco (*Aspidosperma quebracho-blanco*) en dos localidades del Parque Chaque o Seco. *Quebracho* 9:115–127
- Gasparri I, Manghi F (2004) Estimaci n de volumen, biomasa y contenido de carbono de las regiones forestales argentinas (Informe Final). Unidad de Manejo del Sistema de Evaluaci n Forestal. Secretar a de Ambiente y Desarrollo Sustentable. Ministerio de Salud y Ambiente. 26 p
- Gasparri N, Grau H, Manghi E (2008) Carbon pools and emissions from deforestation in extra-tropical forests of northern Argentina between 1900 and 2005. *Ecosystems* 11:1247–1261. <https://doi.org/10.1007/s10021-008-9190-8>
- Gebeyehu G, Soromessa T, Bekele T, Teketay D (2019) Carbon stocks and factors affecting their storage in dry Afromontane forests of Awi Zone, northwestern Ethiopia. *J Ecol Environ* 43:7. <https://doi.org/10.1186/s41610-019-0105-8>
- Gonz lez Roglich M, Swenson JF, Jobb gy EG, Jackson RB (2014) Shifting carbon pools along a plant cover gradient in woody encroached savannas of central Argentina. *For Ecol Manag* 331:71–78. <https://doi.org/10.1016/j.foreco.2014.07.035>
- Greenland DJ (1965) Interaction between clays and organic compounds in soils. Part I. Mechanisms of interaction between clays and defined organic compounds. *Soils Fert* 28:415–532
- Guerra D vila T (2014) Bioestad stica, 1st edn. UNAM, FES Zaragoza, M xico
- Hanan NP, Milne E, Aynekulu E, Yu Q, Anchang J (2021) A role for drylands in a carbon neutral world? *Front Environ Sci* 9:786087. <https://doi.org/10.3389/fenvs.2021.786087>
- Hughes CE, Ringelberg JJ, Lewis GP, Catalano SA (2022) Disintegration of the genus *Prosopis* L. (Leguminosae, Caesalpinioideae, mimosoid clade). *PhytoKeys* 205:147–189. <https://doi.org/10.3897/phytokeys.205.75379>
- Indel ngelo N, Wilson MG, Tasi HA (2007) Indicadores de calidad para dos suelos con caracter sticas v rticas de Entre R os (Argentina). *Cadernos Do Laboratorio Xeol gico Do Laxe* 32:111–125
- INTI-CITEMA (2007) Listado de densidades secas de maderas. Buenos Aires (Argentina): INTI. http://www.inti.gov.ar/citema/densidad_cientifico.pdf
- IPCC (2006) Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme. In: Eggleston HS, Buendia L, Miwa K, Ngara T, Tanabe K (eds). IGES, Jap n. <https://www.ipcc-nggip.iges.or.jp/public/2006gl/>. Accessed 16 Jun 2023
- Jennings SB, Brown ND, Sheil D (1999) Assessing forest canopies and understorey illumination: canopy closure, canopy cover and other measures. *Forestry* 72(1):59–74. <https://doi.org/10.1093/forestry/72.1.59>
- Jobb gy EG, Jackson RB (2000) The vertical distribution of soil organic carbon and its relation to climate and vegetation. *Ecol Appl* 10:423–436. [https://doi.org/10.1890/1051-0761\(2000\)010](https://doi.org/10.1890/1051-0761(2000)010)
- Joshi VC, Negi VS, Bisht D, Sundriyal RC, Arya D (2021) Tree biomass and carbon stock assessment of subtropical and temperate forests in the Central Himalaya, India. *Trees For People* 6:100147. <https://doi.org/10.1016/j.tfp.2021.100147>
- Kleber M, Sollins P, Sutton R (2007) A conceptual model of organo-mineral interactions in soils: self-assembly of organic molecular fragments into zonal structures on mineral surfaces. *Biogeochemistry* 85:9–24. <https://doi.org/10.1007/s10533-007-9103-5>
- Landon J (1991) Booker tropical soil manual: a handbook for soil survey and agricultural land evaluation in the tropics and subtropics. Routledge, New York
- Ledesma SG, Sione SM, Oszust JD, Rosenberger LJ (2021) Estimaci n del contenido y captura potencial de carbono en la biomasa arb rea de bosques nativos del Espinal (Entre R os, Argentina). *FAVE Secc Cienc Agrar* 20(1):331–345. <https://doi.org/10.14409/fa.v20i1.10274>
- Loto D (2021) Ciclo de carbono en biomasa de bosque con relaci n al r gimen de disturbios en el Chaco seco argentino. Tesis Doctoral, Santiago del Estero, p 128
- Manrique S, Franco J, N nez V, Seghezzo L (2011) Potential of native forests for the mitigation of greenhouse gases in Salta, Argentina. *Biomass Bioenerg* 35:2184–2193. <https://doi.org/10.1016/j.biombioe.2011.02.029>
- MAYDS. Ministerio de Ambiente y Desarrollo Sustentable de la Naci n Argentina (2020) Segundo Inventario Nacional de Bosques nativos. Informe regional Espinal y Delta e Islas del R o Paran 
- Mendoza C, Gallardo Lancho JF, Ace olaza PG, Turri n MB, Pando V (2014) Temporal evolution of litterfall and potential bio-element return in a successional forest sequence of the Espinal Ecoregion, Argentina. *For Syst* 23(3):411–424. <https://doi.org/10.5424/fs/2014233-05007>
- Motharfarid E, Mahdavi A, Iranmanesh Y, Jafarzadeh AA (2019) Effect of land uses on aboveground biomass and carbon pools in Zagros Forests, Iran. *Ecopersia* 7(2):105–114
- O'Kelly B (2004) Accurate determination of moisture content of organic soils using the oven drying method. *Dry Technol* 22:1767–1776. <https://doi.org/10.1081/DRT-200025642>
- Ordway EM, Asner GP (2020) Carbon declines along tropical forest edges correspond to heterogeneous effects on canopy structure and function. *PNAS* 117(14):7863–7870. <https://doi.org/10.1073/pnas.191442011>
- Osei R, del R o M, Ruiz-Peinado R, Titeux H, Bielak K, Bravo F, Collet C, Cools C, Cornelis JT, Dr ssler L, Heym M, Korboulewsky N, L f M, Muys B, Najib Y, Nothdurft A, Pretzsch H, Skrzyszewski J, Ponette Q (2022) The distribution of carbon stocks between tree woody biomass and soil differs between Scots pine and broadleaved species (beech, oak) in European forests. *Eur J For Res* 141:467–480. <https://doi.org/10.1007/s10342-022-01453-9>
- Pan YD, Birdsey RA, Fang JY, Houghton R, Kauppi PE, Kurz WA, Philips OL, Shvidenko A, Lewis SL, Canadell JG, Ciais P, Jackson RB, Pacala SW, McGuire AD, Piao S, Rautiainen A, Sitch S, Hayes D (2011) Large and persistent carbon sink in the world's forests. *Science* 333:988–993. <https://doi.org/10.1126/science.1201609>
- Paul EA (1984) Dynamics of soil organic matter. *Plant Soil* 76:275–285
- Plan Mapa de Suelos, Convenio INTA Gobierno de Entre R os (1990) Carta de Suelos de la Rep blica Argentina, Dpto La Paz, Entre R os. Tomos I y II. Serie Relevamiento de Recursos Naturales 7, 321 p
- Pragasana LA (2020) Tree carbon stock and its relationship to key factors from a tropical hill forest of Tamil Nadu, India. *Geol Ecol Landsc* 6(1):32–39. <https://doi.org/10.1080/24749508.2020.1742510>
- Ritchie JC, McCarty GW, Venteris ER, Kaspar TC (2007) Soil and soil organic carbon redistribution on the landscape. *Geomorphology* 89:163–171. <https://doi.org/10.1016/j.geomorph.2006.07.021>
- Rodr guez-Veiga P, Wheeler J, Louis V, Tansey K, Balztre H (2017) Quantifying forest biomass carbon stocks from space. *Curr For Rep* 3:1–18. <https://doi.org/10.1007/s40725-017-0052-5>
- SAyDS. Secretar a de Ambiente y Desarrollo Sustentable de la Naci n (2007) Primer Inventario Nacional de Bosques Nativos: informe regional Espinal. Segunda Parte (1  ed.)
- SAGyP, Ministerio de Econom a (2022) Reporte nacional. Estimaci n de las reservas de carbono org nico del suelo con plantaciones forestales y otros usos de la tierra, en distintas regiones de Argentina. Programa Nacional Forestales-INTA
- Saimun SR, Karim R, Sultana F, Arfin-Khan MAS (2021) Multiple drivers of tree and soil carbon stock in the tropical forest ecosystems of Bangladesh. *Trees For People* 5:100108. <https://doi.org/10.1016/j.tfp.2021.100108>
- Salas Mac as C, Montes Escobar K, S nchez Sac n G, Alc var Ch vez W, Murillo Choez A, Vera Cede o F, Bolcato Bolcato D, Iglesias-Abad S (2020) Influencia del gradiente altitudinal sobre la estimaci n del carbono almacenado

- en biomasa aérea viva y en suelos del “Bosque y vegetación protector El Artesan—Ecuadorian Hands”. *Joa Jipijapa. Ecosistemas* 29(2):1973. <https://doi.org/10.7818/ECOS.1973>
- Schaetzl R, Anderson S (2005) *Soils genesis and geomorphology*. Cambridge University Press, Cambridge
- Scharlemann J, Tanner EV, Hiederer R, Kapos V (2014) Global soil carbon: understanding and managing the largest terrestrial carbon pool. *Carbon Manag* 5(1):81–91. <https://doi.org/10.4155/cmt.13.77>
- Schlesinger WH (1977) Carbon balance in terrestrial detritus. *Ann Rev Ecol Syst* 8:51–81
- Schulp CJE, Nabulans GJ, Verburg PH, de Waal RW (2008a) Effect of tree species on carbon stocks in forest floor and mineral soil and implications for soil carbon inventories. *For Ecol Manag* 256(3):482–490. <https://doi.org/10.1016/j.foreco.2008.05.007>
- Schulp CJE, Nabulans GJ, Verburg PH, de Waal RW (2008b) Effect of tree species on carbon stocks in forest floor and mineral soil and implications for soil carbon inventories. *For Ecol Manag* 256(3):482–490
- Sheikh MA, Kumar M, Todaria NP, Pandey R (2020) Biomass and soil carbon along altitudinal gradients in temperate *Cedrus deodara* forests in central Himalaya, India: implications for climate change mitigation. *Ecol Indic* 111:106025. <https://doi.org/10.1016/j.ecolind.2019.106025>
- Sione SM, Andrade-Castañeda HJ, Ledesma SG, Rosenberger LJ, Oszust JD, Wilson MG (2019) Aerial biomass allometric models for *Prosopis affinis* Spreng. in native forests of Argentina. *Rev Bras De Eng Agricola e Ambient* 23:467–473. <https://doi.org/10.1590/1807-1929/agriambi.v23n6.p467-473>
- Sione SM, Ledesma SG, Rosenberger LJ, Oszust JD, Andrade HJ, Maciel GO, Wilson MG, Sasal MC (2020a) Allometric equations of aerial biomass for *Prosopis nigra* (Griseb.) Hieron “algarrobo negro” (Fabaceae) in forests of Entre Ríos (Argentina). *Agron Ambiente UBA* 40:63–76
- Sione SM, Ledesma SG, Rosenberger LJ, Oszust JD, Andrade HJ, Maciel GO, Wilson MG (2020b) Biomass allometric models for *Vachellia caven* Mol. Molina in native Espinal forests (Argentina). *Quebracho* 28:20–33
- Sione SM, Andrade HJ, Wilson MG, Rosenberger LJ, Sasal MC, Ledesma SG, Gabioud EA (2021) Reducción de emisiones de carbono por deforestación evitada en bosques del Espinal (Entre Ríos, Argentina). *Colomb For* 24(2):39–51. <https://doi.org/10.14483/2256201X.16166>
- Soil Survey Staff (2014) *Keys to soil taxonomy*, 12th ed. United States Department of Agriculture, Natural Resources Conservation Service, Washington, DC
- Turland NJ, Wiersema JH, Barrie FR, Greuter W, Hawksworth DL, Herendeen PS, Knapp S, Kusber WH, Li, DZ, Marhold K, May TW, McNeill J, Monro AM, Prado J, Price MJ, Smith GF (2018) International code of nomenclature for algae, fungi, and plants (Shenzhen Code) adopted by the Nineteenth International Botanical Congress Shenzhen, China. *Regnum Vegetabile* 159. Glashütten: Koeltz Botanical Books. <https://doi.org/10.12705/Code.2018>
- Vesterdal L, Schmidt IK, Callesen I, Nilsson LO, Gundersen P (2008) Carbon and nitrogen in forest floor and mineral soil under six common European tree species. *For Ecol Manag* 255(1):35–48. <https://doi.org/10.1016/j.foreco.2007.08.015>
- Walkley A, Black I (1934) An examination of the Degtjareff method for the determining soil organic matter and proposed modification of the chromic titration method. *Soil Sci* 37:29–38
- Wendt JW, Hauser S (2013) An equivalent soil mass procedure for monitoring soil organic carbon in multiple soil layers. *Eur J Soil Sci* 64:58–65. <https://doi.org/10.1111/ejss.12002>
- Wiesmeier M, Urbanski L, Hobbey E, Lang B, von Luetzow M, Marin-Spiotta E, van Wesemael B, Rabot E, Liess M, Garcia-Franco N (2019) Soil organic carbon storage as a key function of soils: a review of drivers and indicators at various scales. *Geoderma* 333:149–162. <https://doi.org/10.1016/j.geoderma.2018.07.026>
- Wilson M, Cerana J (2004) Mediciones físicas en suelos con características vérticas. *Rev Cient Agrop* 8:11–22
- Wilson M, Sasal MC, Caviglia O (2013) Critical bulk density for a Mollisol and a Vertisol using least limiting water range. *Geoderma* 192(1):354–361. <https://doi.org/10.1016/j.geoderma.2012.05.021>
- Zaffar M, Lu SG (2015) Pore size distribution of clayey soils and its correlation with soil organic matter. *Pedosphere* 25:240–249
- Zhong Z, Chen Z, Xu Y, Ren C, Yang G, Han X, Ren G, Feng Y (2018) Relationship between soil organic carbon stocks and clay content under different

climatic conditions in Central China. *Forests* 9(10):598. <https://doi.org/10.3390/f9100598>

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