

Cedrelinga catenaeformis (Tornillo) in natural and agroforestry systems: Dendrometry, soil and macrofauna

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ABSTRACT

Agroforestry and protected areas are alternatives to mitigate the adverse impacts generated by human activities in the tropical forests of the Peruvian Amazon. The aim of this study was to determine the influence of natural and agroforestry systems of *Cedrelinga catenaeformis* (Tornillo) on soil properties. The physical, chemical, and soil macrofauna properties, as well as dendrometric variables of Tornillo aged 140 and 180 years in natural systems and 7, 17 and 37 years in agroforestry systems, were examined. Results revealed variability in soil properties depending on their origin; however, no marked differences were observed due to tree age or natural versus agroforestry condition. Regarding soil macrofauna, greater diversity was noted in the older agroforestry system, while dendrometric variables exhibited a sigmoidal behavior, except for wood volume, which showed a linear increase. Agroforestry systems of Tornillo associated with *Centrosema macrocarpum* (*Centrosema*) maintain soil properties similarly compared to natural systems; however, the soil of the oldest agroforestry system showed higher activity of earthworms *Rhinodrilus lavellei*, *Rhinodrilus pashanasi*, Diptera orders, and Julidae, compared to soils of more recent agroforestry systems and natural systems. It was estimated that dendrometric variables of Tornillo show stagnation in the increase of total height at 150 years, commercial height at 165 years, and DBH at 70 years. Meanwhile, total height and DBH showed very strong and strong positive correlations ($p < 0.05$) with soil N content and CEC in agroforestry systems with 17 and 37 years. Estimating dendrometric variables and understanding the nutritional requirements in the growth and development of Tornillo will contribute to its more effective management in natural and agroforestry ecosystems in the Amazon region.

1. Introduction

The Amazon basin, with an approximate area of 7.5 million km², more than 90 % of which is primarily distributed among Brazil, Peru, Colombia, and Venezuela; this ecosystem harbors 25 % of all known species; of which more than 5081 species of shrubs and trees have been identified (Silva-Souza and Souza, 2020). Despite its biological richness, Amazonian forests face constant threats due to human activities such as tree logging, which are continuously deforesting. The loss of Amazonian forests affects biodiversity, ecosystem services, and the livelihoods of local populations (Nogueira et al., 2018; Rorato et al., 2021).

In Peru, it is estimated that 13.8 % of the Amazonian territory has experienced some degree of deforestation (Rojas Briceño et al., 2020). An analysis of the period between 2001 and 2021 reveals a loss of 2774, 562 ha of Peruvian Amazon, with the most affected regions being Loreto

with 508,028 ha, followed by Ucayali with 506,423 ha, and San Martín with 480,775 ha (MINAM, 2017). The Amazonian forests in these regions have been lost due to the expansion of agriculture, livestock farming, and timber extraction. In the latter case, trees are selectively harvested for their high timber value.

In the Peruvian Amazon, classic and high-value timber species include *Cedrela odorata* and *Swietenia macrophylla*; however, in the 2000s/2010s, overexploitation led these species to the brink of extinction, prompting exploitation to shift towards secondary species such as *Dipteryx micrantha* and *Cedrelinga catenaeformis* (Tornillo) (Putzel et al., 2011). Currently, Tornillo faces particularly intense pressure due to its high timber demand, as its wood exhibits favorable characteristics for compression, flexion, elasticity, and good density (Cruz et al., 2020; Barahona et al., 2021); properties that are ideal for various wood-working, carpentry, and construction applications.

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As deforestation in the Peruvian Amazon advances, the recovery of these areas is slow, often through reforestation with timber species, including Tornillo, typically established in agroforestry systems (Karsten et al., 2014); additionally, protected areas of high diversity have been established (Cusi et al., 2017). However, despite efforts aimed at the creation and preservation of protected areas, studies like that of Miranda et al. (2016) indicate that these areas have not significantly reduced the deforestation rate in the country. In response to this challenge, Law No. 29,763 has been created, which establishes provisions for assigning protected areas to small farmers, with the aim of promoting sustainable management of the Amazonian forest through conservation practices and reforestation in agroforestry systems (SERFOR, 2015; Robiglio and Reyes, 2016).

Agroforestry systems have been shown to consistently maintain soil properties over time and across different geographic areas, similarly to what is observed in natural systems (Murga-Orrillo et al., 2023a). These systems not only preserve but also enhance soil macrofauna, which play a role in the formation of aggregates that regulate organic matter and nutrient cycling (Rodríguez et al., 2021). Reports such as that of Visscher et al. (2024) have determined that agroforestry systems involving Tornillo exhibit more favorable biological indicators of soil macrofauna compared to other systems.

Soil macrofauna, encompassing organisms ranging in size from 2 to 30 mm, represents the greatest total biomass present in soil and plays a decisive role in the functioning of the soil food web (Gongalsky, 2021). These organisms act as colonizers, shredders, and soil engineers, and their interactions with microorganisms significantly contribute to long-term soil sustainability (Sofo et al., 2020). Furthermore, if soil macrofauna is associated with legumes, they enhance the availability of N, P and K in the soil (Murga-Orrillo et al., 2023b). Despite their importance, understanding the functions and evolution of soil macrofauna over time and space, depending on system design and management, whether natural or agroforestry, remains limited in the scientific literature (Marsden et al., 2020).

In the Peruvian Amazon, ancient Tornillo trees are primarily found in protected areas; on the other hand, Tornillo plantations are found in various stages of growth, typically within agroforestry systems. It is hypothesized that Tornillo plantations in agroforestry systems conserve soil physical, chemical properties, and macrofauna diversity similarly to natural environments. Additionally, it is postulated that the dendrometry of Tornillo varies depending on the age of the trees and the characteristics of the systems, both natural and agroforestry. Therefore, the

aim of this study was to determine the influence of natural and agroforestry systems of Tornillo on soil physical, chemical properties, and macrofauna.

2. Materials and methods

2.1. Location of experimental units

Field and laboratory assessments for this study were conducted from July 2022 to March 2023. The selected experimental plots consisted of Tornillo trees of various ages, among which, 6 trees were in natural conditions, in primary forests within protected areas in the San Martín and Loreto regions, and 30 trees were agroforestry plantations in the Loreto region (Fig. 1).

In natural conditions within protected areas in the San Martín region, province of Lamas, Barranquita district, 3 trees aged 180 years were identified (Fig. 1A and 1D) in the "Cordillera Azul National Park" (coordinates: 6°20'44"S; 76°3'20"W, altitude: 186 masl). Similarly, in the Loreto region, province of Alto Amazonas, Yurimaguas district, 3 trees aged 140 years were selected in the primary forest of the permanent protection area known as Kashimbo (coordinates: 5°39'38"S; 76°10'54"W, altitude: 172.5 masl); the ages of these trees were determined from reports by native communities.

In plantations established in quincunx design, where five trees are planted in a square area, four at the corners and one at the intersection of the diagonals, in agroforestry systems, in the district of Yurimaguas, in experimental areas of the National Institute of Agricultural Innovation (INIA-San Ramon) (coordinates: 5°56'28"S; 76°7'37"W, altitude: 141.0 masl), 9 trees aged 37 years were selected (Fig. 1B and 1D) with a spacing of 10 m x 10 m (181 plants/hectare). Similarly, at the headquarters of the National University of the Peruvian Amazon (UNAP) (coordinates: 5°57'49"S; 76°11'43"W, altitude: 161 masl), 18 trees aged 17 years were selected with a spacing of 14 m x 14 m (181 plants/hectare). Finally, at the campus of the National Autonomous University of the Alto Amazonas (UNAAA) (coordinates: 5°53'46"S; 76°7'46"W, altitude: 159 masl), 3 trees aged 7 years were selected with a spacing of 12 m x 12 m (123 plants/hectare).

It is worth noting that all Tornillo agroforestry plantations were associated with *Centrosema* (Fig. 1B and 1C), and the ages of the trees were obtained from the records of the reforestation programs of INIA-San Ramon. Furthermore, the 17-year-old plantations were associated with *Simarouba amara* (marupa), while the 7-year-old plantations were

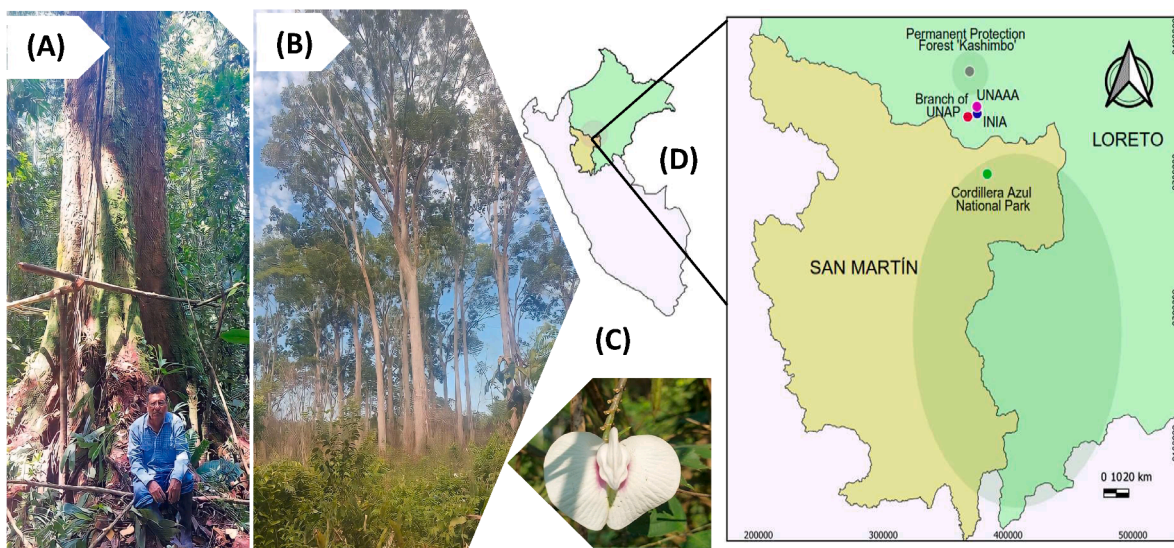


Fig. 1. Tornillo Tree (*C. catenaeformis*), in natural and agroforestry systems. 180-year-old trunk in natural system (A); 37-year-old trees in agroforestry system (B); *Centrosema* (*C. macrocarpum*) flower (C); experimental plot location map (D).

associated with both marupa and *Theobroma cacao* (cacao). In total, 36 trees were counted, encompassing both primary forests within protected areas and agroforestry plantations.

2.2. Soil sampling and analysis

Soil samples were taken at depths of 0–20, 20–40 and 40–60 cm, using an auger (Riverside Brand, Peru). For the 140 and 180-year-old trees, samples were taken at a distance of 5 m from the trunk, while for the 7, 17 and 37-year-old trees, samples were taken at a distance of 1.5 m from the trunk. The total number of soil samples was 108 (36 experimental plots, with 3 depths). The sampling followed the methodology established by the Ministry of the Environment of Peru (MINAM, 2014).

Subsequently, the samples were subjected to air-drying, followed by determining the soil's physical and chemical properties in the laboratory. Organic matter quantification was carried out using the [Walkley and Black method \(1934\)](#), while P determination followed the protocol proposed by [Olsen et al. \(1954\)](#). To assess exchangeable cations (K^+ , Ca^{+2} , Mg^{+2} and Na^+), they were extracted using a 1 N KCl solution and determined using atomic absorption spectroscopy, following the methodology proposed by [Hunter \(1986\)](#). N content was calculated based on the soil's organic matter content, using a factor of 0.045.

2.3. Soil macrofauna sampling

Soil samples for macrofauna determination comprised 4 monoliths per experimental plot, with each monolith measuring 25 cm x 25 cm in area and 30 cm in depth. Sampling was conducted at the same distance from the trees as indicated in the "Soil sampling and analysis" section. A total of 144 monoliths were evaluated (4×36 experimental plots).

The monoliths were stratified into litter and soil layers at depths of 0–10, 10–20, and 20–30 cm. The strata were placed in plastic trays, where manual extractions and/or using tweezers (Model: Herford, Brand: Stainless Steel, Germany) of macrofauna individuals were performed. Subsequently, these individuals were preserved in a 4 % formaldehyde solution in water, stored in airtight 50 ml jars. Finally, taxonomic identification, grouping, and weighing of the macrofauna were conducted on an analytical balance (Brand: OHAUS, Model: V11P3T, USA). The resulting data were expressed in units of g/m^2 . In summary, a total of 36 soil macrofauna samples were obtained, representing one sample per experimental plot. This procedure followed the methodology proposed by [Anderson and Ingram \(1994\)](#).

2.4. Dendrometry of Tornillo trees

In the 36 experimental plots, dendrometric variables of the trees were evaluated, such as total height, merchantable height, diameter at breast height (DBH) at an average of 1.3 m above the ground, and wood volume. Total height and merchantable height were determined using a clinometer (Brand: Suunto, model: PM-5/1520, Finland), according to Equation (Eq. (1)), and volume was determined following the methodology of [Korning and Balslev \(1994\)](#) according to Eqs. (2) and 3 (Eq. (2) and Eq. (3)).

$$HT = Do * (Tag\beta) + Ao \quad (1)$$

$$Vol = AB * Hc * Fc \quad (2)$$

$$AB = \frac{\pi}{4} * D^2 \quad (3)$$

Where: HT - height total (m), Do - distance from observer to tree, Ao - observer height (m), Vol - wood volume (m^3), Hc - height commercial (m), β - observation angle, Fc - correction factor (0.5 or 0.6) according to [Cannell \(1984\)](#), D - trunk diameter (m).

To predict dendrometric variables based on the age of Tornillo,

maintaining sigmoidal behavior typical of higher plants, the model (Eq. (4)) proposed by [Schumacher and Hall \(1933\)](#) was fitted.

$$Y = e^{\delta 0 + \delta 1/x} \quad (4)$$

Where: Y - dendrometric variable, e - base of the natural logarithm (2.71828), $\delta 0$ and $\delta 1$ - adjustment coefficients, x - age of Tornillo (years).

2.5. Statistical analysis of data

The historical data of temperature and annual rainfall were analyzed using boxplots. To assess the discrimination between environments by natural system, agroforestry, and tree age, principal component analysis (PCA) was employed. In selecting the most correlated variables (explaining over 70 % of the total accumulated variation), following [Jolliffe's methodology \(1972\)](#). For the variables contributing to the PCA, mean and non-parametric confidence intervals (CI: 95 %) were determined. Non-linear regression analysis of tree dendrometric variables as a function of age was conducted, while wood volume was fitted to a linear regression model. Tornillo dendrometric variables were correlated with soil N, P, K and CEC using Pearson's methodology ($p < 0.05$), where the correlation coefficient (r) was classified as perfect correlation ($|r| = 1$), very strong ($0.8 \leq |r| < 1$), strong ($0.6 \leq |r| < 0.8$), moderate ($0.4 \leq |r| < 0.6$), weak ($0.2 \leq |r| < 0.4$) and negligible ($|r| < 0.2$). All analyses were performed using FactoMineR, factoextra, corplot, ggplot2, tidyverse, and bootstrap packages ([R Core Team, 2021](#)).

3. Results

3.1. Edaphoclimatic conditions of the Tornillo tree

In the study area, during the period from 1990 to 2019, climatic conditions are depicted in [Fig. 2](#). Monthly temperatures reach their lowest values in July and increase in September and October ([Fig. 2A](#)). Regarding monthly precipitation, it increases from September onwards, reaching maximum values in May and decreasing from April, with minimum levels in August ([Fig. 2B](#)). These climatic conditions, along with soil properties ([Table 1 and 2](#)), influenced the Tornillo tree, its dendrometric variables ([Table 3](#)), its geographical distribution, resilience, and adaptability, both in agroforestry systems and natural systems.

The soil properties in both natural and agroforestry systems of Tornillo are observed in [Table 1](#), where it was determined that they mostly exhibit sandy loam texture, with acidic pH attributed to aluminum saturation, and low availability of organic matter due to high mineralization typical of tropical climates. Additionally, prolonged and high precipitation saturates the soil with moisture, consequently leaching nutrients, resulting in low contents of P, K and CEC.

3.2. Soil and macrofauna in different management systems

The physical and chemical properties of the soil, as well as soil macrofauna, show notable similarities in both natural and agroforestry systems of the Tornillo tree ([Fig. 3](#)). Thus, PCA applied to soil variables, explaining 73.3 % of the variability, including texture (sand, silt, and clay), AD, CEC, Al, N, P and K, revealed little differentiation between natural and agroforestry systems ([Fig. 3A](#)). Similarly, PCA applied to soil macrofauna, with a combined explanation of 73.2 % of the variability, addressing the Diptera Order, the Julidae and Geophilidae families, as well as the earthworm species *Pontoscolex corethrurus*, *R. pashanasi*, and *R. lavellei*, did not show marked distinctions between natural and agroforestry systems of Tornillo ([Fig. 3B](#)).

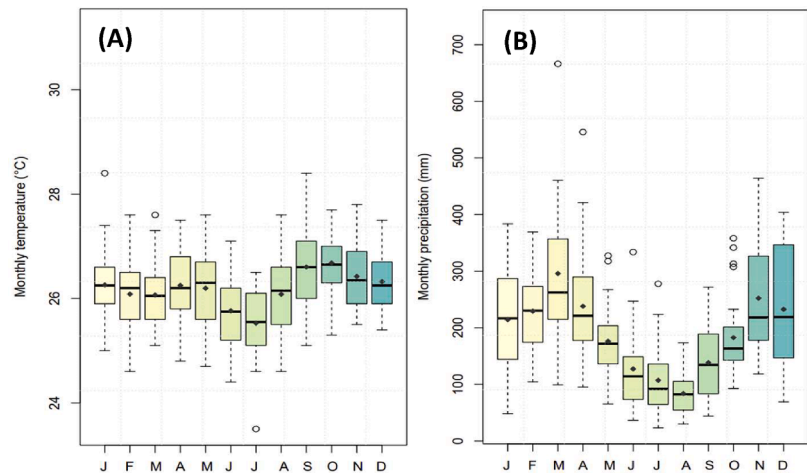


Fig. 2. Historical climatic conditions from 1990 to 2019. Monthly average temperature (A) and monthly rainfall (B) in the areas where Tornillo trees (*C. catenaeformis*) were assessed.

Table 1
Physical and chemical properties of soil with Tornillo trees (*C. catenaeformis*) in natural and agroforestry systems.

Year	Sand%.....	Clay	Silt	AD g/cm ³	pH	OM %	P pmm	K	CEC meq/100 g	SAI %
Natural system in protected areas										
180 (n = 3)	51.01±7.03	18.00±3.00	30.99±4.04	1.45±0.04	5.57±0.08	0.36±0.02	4.41±0.22	35.30±5.43	9.98±2.35	26.59±0.08
140 (n = 3)	52.39±4.96	26.86±2.82	20.75±2.15	1.39±0.03	4.96±0.15	0.07±0.03	10.84±0.41	150.55±28.41	12.29±3.08	56.40±6.93
Agroforestry system										
37 (n = 9)	70.55±9.74	13.69±4.46	15.76±5.40	1.53±0.07	4.93±0.10	0.04±0.01	8.14±1.56	36.45±6.33	4.98±0.98	15.05±11.66
17 (n = 18)	49.74±9.23	27.23±3.93	23.04±7.49	1.39±0.05	5.12±0.13	0.37±0.17	5.92±1.45	64.79±17.96	11.62±2.30	36.17±7.24
7 (n = 3)	72.21±5.67	15.32±3.28	12.47±2.39	1.53±0.05	5.68±0.12	0.03±0.00	13.62±3.29	108.17±67.36	6.65±1.42	11.15±7.94

AD - Apparent density, OM - Organic matter, P - Phosphorus, K - Potassium, CEC - Cation exchange capacity, SAI - Aluminum saturation.

Table 2
Soil macrofauna with Tornillo trees (*C. catenaeformis*) in natural and agroforestry systems.

Year	Pc	Mp	Rl	Rp	Nat	Ants	Ter	Ge	Ju	Gl	Ga	Spider	Dip	He
.....g/m ²														
Natural system in protected areas														
180	42.5 ±	2.5 ±	0.0 ±	0.0 ±	32.0 ±	56.0 ±	629.0 ±	15.5 ±	2.5 ±	2.5 ±	5.5 ±	16.0 ±	0.0 ±	15.5 ±
	42.5	2.5	0.0	0.0	32.0	35.0	149.0	5.5	2.5	2.5	5.5	5.0	0.0	15.5
140	3.3 ± 2.9	3.7 ±	0.0 ±	0.0 ±	26.3 ±	151.0 ±	332.7 ±	19.0 ±	3.3 ±	3.3 ±	1.7 ±	12.0 ±	0.0 ±	10.7 ±
		6.4	0.0	0.0	13.8	36.1	389.5	8.2	2.9	2.9	2.9	13.1	0.0	9.2
Agroforestry system														
37	5.6 ± 6.9	10.3 ±	7.2 ±	2.7 ±	6.7 ±	151.0 ±	311.6 ±	22.7 ±	13.1 ±	0.9 ±	1.3 ±	16.6 ±	16.9 ±	3.6 ±
		12.1	7.6	4.7	8.5	165.4	339.5	12.6	14.1	1.9	3.0	9.1	43.0	1.9
17	104.0 ±	7.1 ±	0.0 ±	0.2 ±	12.7 ±	577.6 ±	258.8 ±	6.7 ±	2.0 ±	2.4 ±	1.3 ±	25.8 ±	0.7 ±	5.6 ±
	48.0	15.2	0.0	0.9	9.2	660.7	356.8	10.9	3.1	4.1	2.7	16.7	1.5	10.7
7	57.3 ±	0.0 ±	0.0 ±	0.0 ±	84.0 ±	240.0 ±	38.7 ±	8.0 ±	4.0 ±	6.7 ±	0.0 ±	25.3 ±	0.0 ±	1.3 ±
	44.2	0.0	0.0	0.0	64.0	299.2	67.0	4.0	0.0	11.5	0.0	6.1	0.0	2.3

Pc- *Pontoscolex corethrurus*, Mp- *Martiodrillus pano*, Rl- *Rhinodrilus lavellei*, Rp- *Rhinodrilus pashanasii*, Nat- native earthworm, Ter- Termites, Ju- Julidae, Ge- Geophilidae, Gl- Glomeride, Ga- Gastropods, Di- Diptera, He- Hemiptera.

3.3. Soil and macrofauna across different management ages

When soil properties are classified considering the ages of Tornillo trees, PCA (Fig. 4A) shows marked differences without maintaining a pattern based on tree age, suggesting that these differences are due to the geographical origin of the soil. In Dim 1 of the PCA with 52.8 % explanation of variability, soils with trees of 180 and 17 years old present higher values of CEC and silt, contrasting with soils with trees of 7 and 37 years old which exhibit higher values of sand and bulk density. In Dim 2 of the PCA with 20.5 % explanation of variability, soils with trees of 140 years old show higher values of N, P and K in contrast to soils with trees of 7, 17, 37 and 180 years old. In more detailed analyses, with 95 % confidence intervals (CI: 95 %), significant differences are presented:

soils with trees of 180 and 17 years old with higher values of silt (Fig. 4B), lower values of N and P (Fig. 4G and 4H); compared to soils with trees of 7 and 37 years old showing higher values of sand, N, and P (Fig. 4D, 4G and 4H), while soils with trees of 140 years old show wider CI: 95 % ranges for CEC, N, K and Al (Fig. 4F, 4G, 4I and 4K). On the other hand, when soil macrofauna is classified based on the age of Tornillo trees, PCA shows marked differences primarily with higher values for soils of trees aged 37 years in agroforestry systems compared to the macrofauna of soils of trees aged 7 and 17 years in agroforestry systems, or of trees aged 140 and 180 years in natural systems (Fig. 5A). Analysis with 95 % confidence intervals (CI: 95 %) corroborates significant differences for the earthworm *R. lavellei* with higher values (Fig. 5E) and higher means for Diptera, Julidae, and

Table 3
Mean values of dendrometric variables of the Tornillo tree (*C. catenaeformis*) at different ages and systems.

System	Age Year	DBH m	CH m	TH m	Vol m ³
Natural	180 (n = 3)	1.67 ±0.06	28.40 ±1.68	33.55 ±2.00	7.85 ±0.99
	140 (n = 3)	1.30 ±0.12	29.29 ±3.38	38.27 ±2.89	4.83 ±0.55
	37 (n = 9)	0.79 ±0.12	16.84 ±2.24	30.64 ±4.59	1.03 ±0.31
Agroforestry	17 (n = 18)	0.48 ±0.07	8.24±1.56	21.57 ±3.20	0.20 ±0.08
	7 (n = 3)	0.14 ±0.03	11.22 ±0.66	13.62 ±0.48	0.02 ±0.01

DBH - Diameter at breast height, CH - Commercial height, TH - Total height, Vol - Wood volume.

R. pashanasii (Fig. 5B, 5C and 5F) in soil with trees aged 37 years in agroforestry system. Additionally, the soil with 37 years under agroforestry management presents mean values >60 % in sand (Fig. S1A) and >1.5 g/cm³ in bulk density Fig. S1D) in the 0–20 cm, 20–40 cm and 40–60 cm strata, these values being higher than those in soils in natural and agroforestry systems with younger Tornillo trees (Fig. S1).

3.4. Dendrometry of the Tornillo tree

The variation in the ages of Tornillo trees exerts a notable influence on dendrometric characteristics of the tree, including trunk diameter, total and commercial height, and volume; these relationships have been modeled using both nonlinear and linear regressions, according to the nature of the variable (Table 2 and Fig. 6).

For total tree height (Fig. 6A), an average increase of 17.3 cm/year is recorded. The highest average increments are observed in the first 10 years, with an increase of 182 cm/year. As the age progresses, this growth progressively decreases, reaching an increase of <1 cm/year

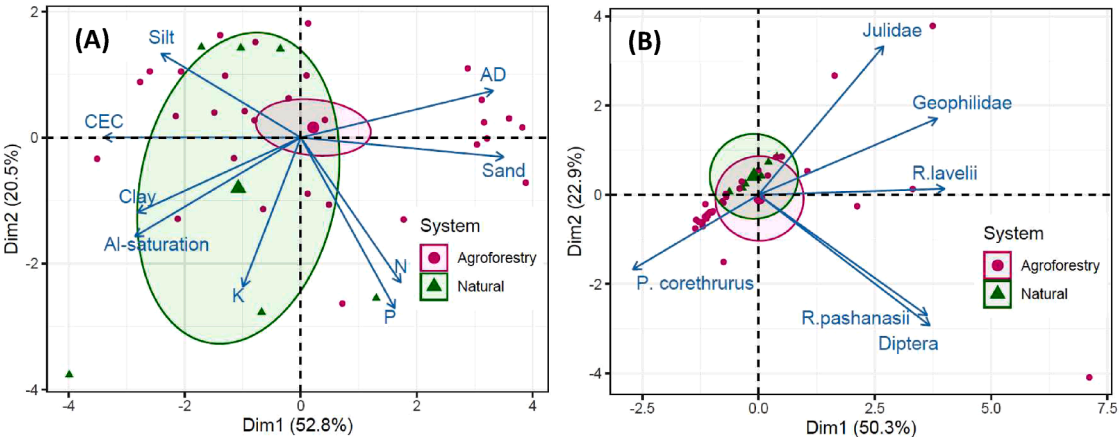


Fig. 3. Principal Component Analysis. Physical and chemical properties of the soil (A), and soil macrofauna (B) in natural and agroforestry systems of Tornillo trees (*C. catenaeformis*).

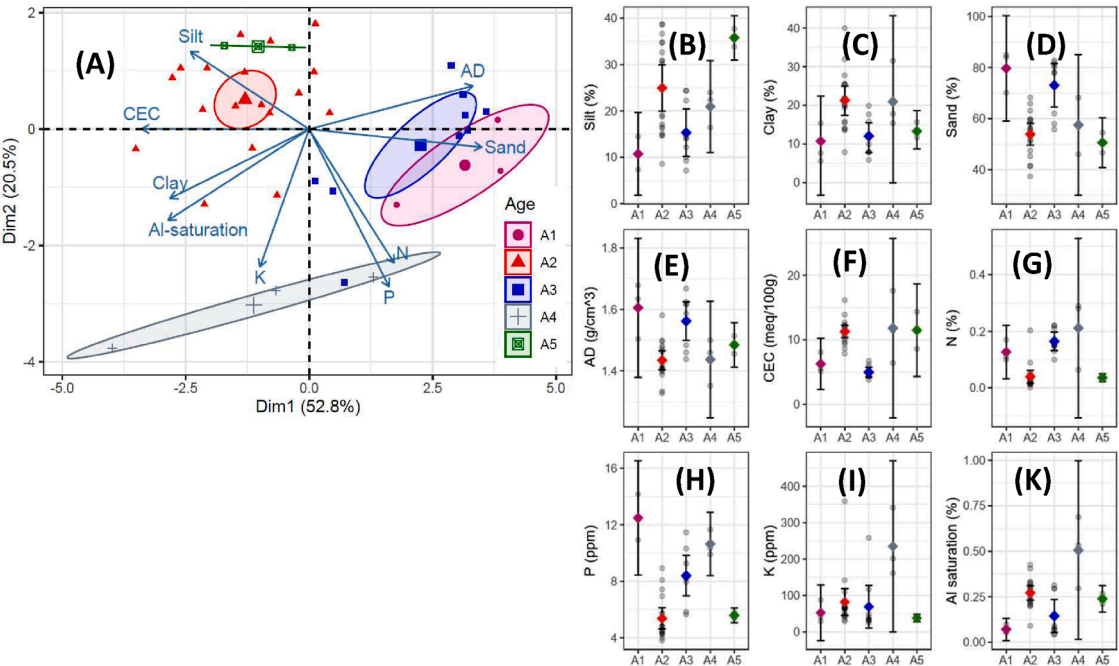


Fig. 4. Principal component analysis (A), and confidence intervals (CI: 95 %) of the physical and chemical properties of the soil (B-K) in natural and agroforestry systems of Tornillo trees (*C. catenaeformis*) of A1- 7, A2- 17, A3- 37, A4- 140, and A5-180 years of age.

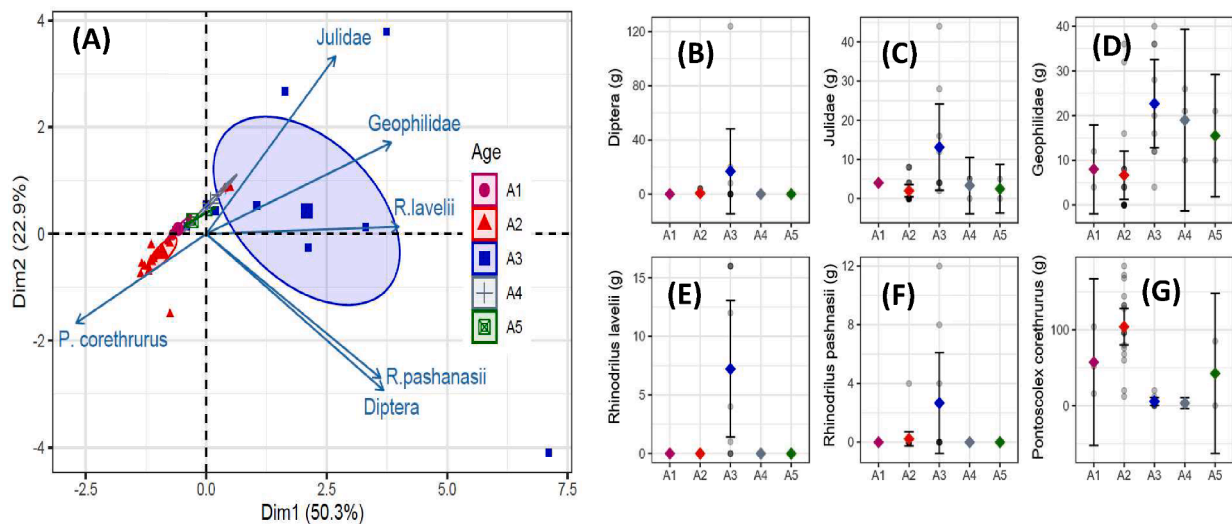


Fig. 5. Principal component analysis (A) and confidence intervals (CI: 95 %) of the soil macrofauna (B-G) in natural and agroforestry systems of Tornillo trees (*C. catenaeformis*) of A1- 7, A2- 17, A3- 37, A4- 140, and A5-180 years of age.

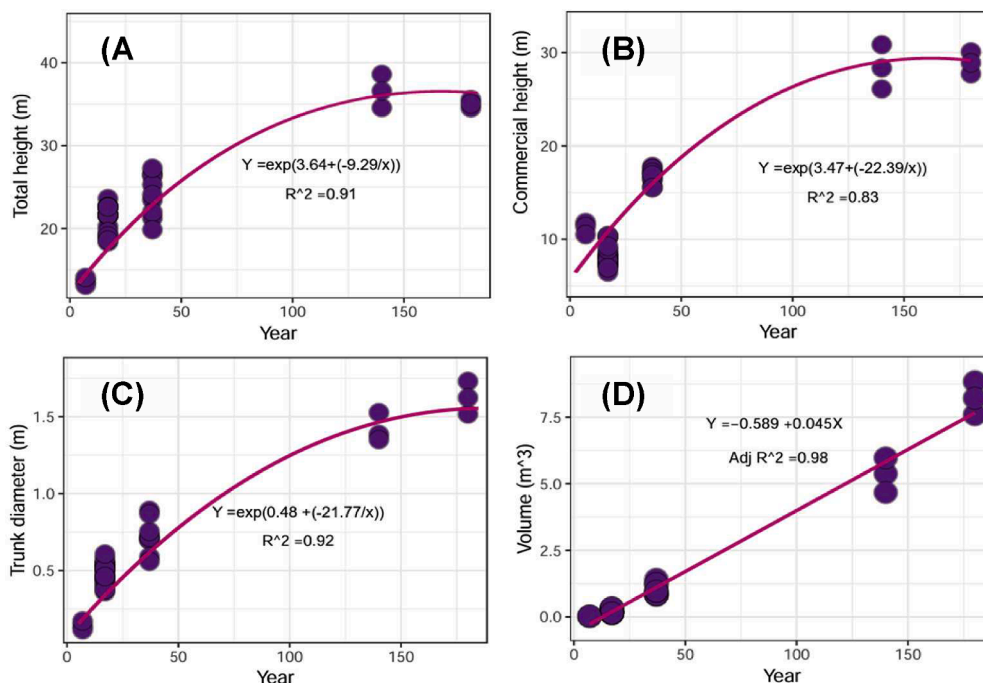


Fig. 6. Regression analysis of total height (A), commercial height (B), trunk diameter at breast height (DBH) (C), and wood volume (D) of Tornillo trees (*C. catenaeformis*) at different ages in natural and agroforestry systems.

from 150 years onwards. Despite this, the total height can reach 36.2 m in 180 years. Regarding commercial height (Fig. 6B), there is evidence of an average increase of 16 cm/year, with higher values of 76 cm/year up to 15 years. As the tree ages, these values progressively decrease, reaching an increase of <2 cm/year from 165 years onwards. However, the total height can reach 28.4 m within a span of 180 years. In Fig. 6C, the regression reveals an average increase in trunk diameter of 0.081 cm/year. During the first 10 years, this increase is more pronounced, reaching 3 cm/year; however, this growth is <1 cm/year from 70 years onwards. Nevertheless, it is observed that the total diameter can reach 1.5 m over a period of 180 years. As for volume (Fig. 6D), average increases of 0.05 m³/year are identified, with the potential to reach up to 7.5 m³ in 180 years. These findings provide a detailed understanding of how the age of Tornillo trees influences their morphological

development over time.

3.5. Soil and dendrometry of the Tornillo tree in agroforestry systems

In Fig. 7, Pearson correlation matrices ($p < 0.05$) are presented to examine the relationships of N, P, K and CEC with the dendrometry of Tornillo trees in agroforestry systems established for 17 and 37 years (Fig. 7A and 7B). For the 17-year-old agroforestry system (Fig. 7A), strong correlations are observed between total height and N ($r = 0.72$ and $r = 0.65$) and moderate correlation with CEC ($r = 0.53$); also within dendrometry, strong correlations are found between DBH and commercial height with volume ($r = 0.89$ and $r = 0.75$) and moderate correlations between total height and commercial height ($r = 0.48$). On the other hand, for the 37-year-old agroforestry system (Fig. 7B), very

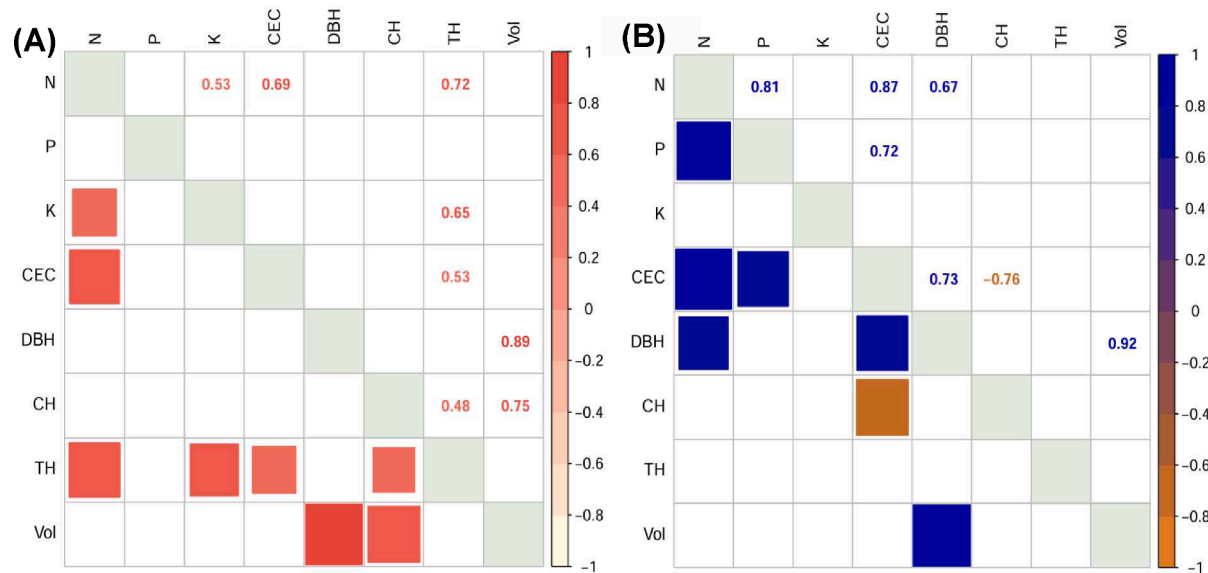


Fig. 7. Pearson correlation coefficient ($p < 0.05$). Agroforestry system of 17 years (A) and 37 years (B) of Tornillo trees (*C. cateniformis*). DBH- diameter at breast height, CH- commercial height, TH- total height, Vol- wood volume, N- nitrogen, P- phosphorus, K- potassium, CEC- cation exchange capacity.

strong and strong correlations of DBH with N and CEC are observed ($r = 0.87$ and $r = 0.73$) and a strong negative correlation of commercial height with CEC ($r = -0.73$); likewise, among dendrometric variables, there are very strong correlations of DBH with volume ($r = 0.92$).

4. Discussion

4.1. Tornillo tree in protected areas

Protected areas, such as "Cordillera Azul" and "Kashimbo" in the Peruvian Amazon, play a fundamental role in preserving the biodiversity of flora and fauna, characterized by minimal human-induced alteration. The longevity of Tornillo trees, surpassing 100 years, is directly attributed to the existence of these protected areas and the harmonious interaction with local communities, who act as guardians of biodiversity in the region. Despite being constantly deforested, invaded, and burned, protected areas remain the best way to preserve biodiversity in the Amazon (Paiva et al., 2020), with four times lower odds of being destroyed compared to unprotected areas. Their care should be a global priority, as they provide benefits to biodiversity and climate (Gonçalves-Souza et al., 2021).

4.2. Soil and macrofauna in different management systems

The physical and chemical properties of the soil, along with its macrofauna in natural and agroforestry systems with Tornillo trees, are similar, as per the PCA (Fig. 3A and 3B). These results stem from the appropriate association of the Tornillo tree with *Centrosema*, as this legume generates abundant biomass in less time, consequently contributing organic matter to the soil. It enhances and maintains the presence of biological indicators such as earthworms *P. corethrurus*, *R. pashanasii*, and *R. lavellei*, and other arthropods, while also contributing to the nutrient cycle. In this regard, Murga-Orrillo et al. (2023a) determined that soil macrofauna like earthworms, including *P. corethrurus* in interaction with *Vigna unguiculata*, improve the availability of N P and K in the soil. Particularly in agroforestry systems with Tornillo trees, *Centrosema* establishes rapidly, is used as forage, reduces compaction, and enriches the soil with N and K in the short term (Alegre et al. 2017). This legume is employed as ground cover associated with fruit trees in orchards, in groves, and other permanent crops (Wang et al. 2022). In silvopasture, *Centrosema* enhances the physical and chemical

properties of the soil and increases livestock weight compared to traditional systems (Arevalo et al. 1998). Thus, *Centrosema* serves as an alternative in soil conservation, maintaining soil macrofauna under similar conditions to natural systems (Morales-Márquez et al. 2022).

4.3. Soil and macrofauna at different management ages

It's challenging to determine whether soil properties change due to the age of Tornillo trees, especially when the study plots are distant from each other (Fig. 1A); thus, differences in soil properties (Fig. 4) are assumed to be intrinsic, based on their origin within the diversity of soils in the Peruvian Amazon. Amazonian soils are heterogeneous, typically acidic due to high concentrations of Al^{+3} (Souza et al. 2018).

The agroforestry system at 37 years exhibited greater macrofauna with *R. lavellei*, *R. pashanasii*, Diptera, and Julidae compared to soils from natural or agroforestry systems with 140 and 180 years or with trees aged 7 and 17 years, respectively (Fig. 5A, 5B, 5C and 5F). These findings suggest that the longer association time of the Tornillo tree with *Centrosema* favors macrofauna, surpassing soil macrofauna in natural environments. Considering that the soil has a higher sand content, greater AD and lower CEC compared to other plots (Fig. S1A). Soil management techniques that promote and enhance soil macrofauna activity include cover crops, agroforestry, and other ecologically compatible agricultural systems (Lal 1988). Similar results were found by Kamau et al. (2017) and Vasconcellos et al. (2013) when they determined that soil macrofauna increases with the duration of associated cultivation.

4.4. Dendrometry of the Tornillo tree

Understanding the behavior of dendrometric variables of the Tornillo tree will allow for effective management of this forest resource, from the perspective of timber harvesting to conservation, within sustainable forest and agroforestry environments. Estimates determine that growth stagnations of the tree occur in total height at 150 years (Fig. 6A); in commercial height at 165 years (Fig. 6B), and in trunk DBH at 70 years (Fig. 6C); the only variable with constant increase was wood volume (Fig. 6D); in this case, it is inferred that the increase occurs over DBH, possibly until the commercial height adopts a uniform cylindrical shape. Dendrometric variables of total and commercial height (Fig. 6A and 6B) will allow determining the health and age of trees without age

records; on the other hand, trunk diameter and volume (Fig. 6C and 6D) can be used for sustainable logging planning. In ecological and biodiversity terms, dendrometric variables can be used to determine relationships with associated flora and fauna, for long-term forest and agroforestry management, conservation, and informed decision-making.

4.5. Soil and dendrometry of the Tornillo tree in agroforestry systems

Soil fertility plays a fundamental role in the development of Tornillo trees. In the 17-year-old agroforestry system, strong correlations are observed between total tree height and soil N and K content (Fig. 7A). Conversely, in the 37-year-old agroforestry system, very strong and strong correlations are observed between DBH and soil N and CEC content, respectively (Fig. 7B). These results suggest possible higher demands for N, K and CEC content in the soil for Tornillo development and growth, and the availability of these nutrients is closely related to pH, organic matter, texture (Table 1 and Fig. 3A and 4), soil macrofauna (Table 3, Fig. 3B and 5), which are in constant interaction with *Centrosema*, primarily fixing N and making other nutrients available to the soil in the agroforestry system. N is an essential macronutrient for plant functioning and growth (Wang et al. 2023). In *Caesalpinia spinosa* in agroforestry systems, there was a larger crown diameter and tree height associated with *Medicago sativa*, which showed higher soil N content compared to other agroforestry systems not associated with legumes (Murga-Orrillo et al. 2023b).

5. Conclusions

Agroforestry systems of *Cedrelinga catenaeformis* associated with *Centrosema macrocarpum* maintain soil properties and macrofauna similarly to natural systems. However, the soil in the older agroforestry system showed higher activity of *Rhinodrilus lavellei*, *Rhinodrilus pashanasi*, Dipteran orders, and Julidae compared to soils with shorter establishment times in agroforestry systems and natural systems.

Estimations of dendrometric variables of *Cedrelinga catenaeformis* indicate growth stagnation in total height, commercial height, and trunk DBH starting at 150, 165, and 70 years of age, respectively. These estimations will allow for better management of agroforestry and natural systems with *Cedrelinga catenaeformis*.

In the 17- and 37-year-old agroforestry systems, very strong and strong positive correlations were found between total tree height and DBH with soil N and CEC content.

CRediT authorship contribution statement

Hipolito Murga-Orrillo: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Beto Pashanasi Amasifuén:** Validation, Resources, Methodology. **Luis A. Arévalo López:** Visualization, Validation, Project administration, Methodology. **Melis Chujutalli Inuma:** Project administration, Methodology, Data curation. **Carlos Abanto-Rodríguez:** Writing – original draft, Visualization, Formal analysis.

Declaration of competing interest

Hipolito Murga-Orrillo reports administrative support, equipment, drugs, or supplies, and travel were provided by National Autonomous University of Alto Amazonas. Hipolito Murga-Orrillo reports a relationship with National Autonomous University of Alto Amazonas that includes: employment. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.tfp.2024.100577.

References

- Alegre, J., Lao, C., Silva, C., Schrevens, E., 2017. Recovering degraded lands in the Peruvian Amazon by cover crops and sustainable agroforestry systems. *Peruvian J. Agron.* 1 (1), 1–7. <https://doi.org/10.21704/pja.v1i1.1005>.
- Anderson, J.M., Ingram, J.S., 1994. *Tropical soil biology and fertility: a handbook of methods*. Soil. Sci. 157 (4), 265.
- Arévalo, L.A., Alegre, J.C., Bandy, D.E., Szott, L.T., 1998. The effect of the cattle grazing on soil physical and chemical properties in a silvopastoral system in the Peruvian Amazon. *Agrofor. Syst.* 40, 109–124. <https://doi.org/10.1023/A:1006075114659>.
- Barahona, J.C., Robalino, D.R., Cabezas, E., Castañeda, E.S., 2021. Determination of Physical and Mechanical Properties of Three-layer Boards of Teak (*Tectona grandis*), Seike (*Cedrelinga catenaeformis*) and Mascarey (*Hieronima alchorneoides*), Company PISMADE SA, Riobamba Canton, Chimborazo Province. ESPOCH Congresses: Ecuad. J. STEAM 1111–1119. <https://doi.org/10.18502/epoch.v1i4.9502>.
- Cannell, M.G.R., 1984. Woody biomass of forest stands. *For. Ecol. Manag.* 8 (3–4), 299–312. [https://doi.org/10.1016/0378-1127\(84\)90062-8](https://doi.org/10.1016/0378-1127(84)90062-8).
- Cusi, J.C., Moravec, J., Lehr, E., Gvozdík, V., 2017. A new species of semiarboreal toad of the *Rhinella festae* group (Anura, Bufonidae) from the Cordillera Azul National Park. *Peru. ZooKeys* 21 (673). <https://doi.org/10.3897/zookeys.673.13050>.
- Gonçalves-Souza, D., Vilela, B., Phalan, B., Dobrovolski, R., 2021. The role of protected areas in maintaining natural vegetation in Brazil. *Sci. Adv.* 7 (38), eabh2932. <https://doi.org/10.1126/sciadv.abh2932>.
- Gongalsky, K.B., 2021. Soil macrofauna: study problems and perspectives. *Soil Biol. Biochem.* 159, 108281. <https://doi.org/10.1016/j.soilbio.2021.108281>.
- Hunter, A.H., 1986. *Suggested Soil and Plant Analytical Techniques for Tropical Soils Research Programme Laboratories*. Agroservices International.
- Jolliffe, I.T., 1972. Discarding Variables in a Principal Component Analysis. I: artificial Data. *J. R. Stat. Soc. Ser. C Appl. Stat.* 21 (2), 160–173. <https://doi.org/10.2307/2346488>.
- Kamau, S., Barrios, E., Karanja, N.K., Ayuke, F.O., Lehmann, J., 2017. Soil macrofauna abundance under dominant tree species increases along a soil degradation gradient. *Soil Biol. Biochem.* 112, 35–46. <https://doi.org/10.1016/j.soilbio.2017.04.016>.
- Karsten, R.J., Meilby, H., Larsen, J.B., 2014. Regeneration and management of lesser known timber species in the Peruvian Amazon following disturbance by logging. *For. Ecol. Manag.* 327, 76–85. <https://doi.org/10.1016/j.foreco.2014.04.035>.
- Korning, J., Balslev, H., 1994. Growth and Mortality of Trees in Amazonian Tropical Rain Forest in Ecuador. *J. Veg. Sci.* 5 (1), 77–86. <https://doi.org/10.2307/3235641>.
- Lal, R., 1988. Effects of macrofauna on soil properties in tropical ecosystems. *Agric. Ecosyst. Environ.* 24 (1–3), 101–116. [https://doi.org/10.1016/0167-8809\(88\)90059-X](https://doi.org/10.1016/0167-8809(88)90059-X).
- Marsden, C., Martin-Chave, A., Cortet, J., Hedde, M., Capowicz, Y., 2020. How agroforestry systems influence soil fauna and their functions—a review. *Plant Soil.* 453, 29–44. <https://doi.org/10.1007/s1104-019-04322-4>.
- MINAM, 2017. Bosque y Pérdida De Bosque. <http://geobosques.minam.gob.pe/geobosque/ue/perdida.php> (accessed on January 15, 2024).
- MINAM, 2014. Guía Para Muestreo de Suelos. <https://www.gob.pe/institucion/minam/informes-publicaciones/2702-guia-para-muestreo-de-suelos>. (accessed on February 21, 2023).
- Miranda, J.J., Corral, L., Blackman, A., Asner, G., Lima, E., 2016. Effects of protected areas on forest cover change and local communities: evidence from the Peruvian Amazon. *World Dev.* 78, 288–307. <https://doi.org/10.1016/j.worlddev.2015.10.026>.
- Morales-Márquez, J.A., Jiménez-Ballesta, R., Hernández-Hernández, R.M., Sánchez, G.K., Lozano, Z., Castro, I., 2022. Effect of Maize Conservation Crops Associated with Two Vegetal Covers on the Edaphic Macrofauna in a Well-Drained Savanna of Venezuela. *Land. (Basel)* 11 (4), 464. <https://doi.org/10.3390/land11040464>.
- Murga-Orrillo, H., Abanto-Rodríguez, C., Fernandes Silva Dionisio, L., Chu-Koo, F.W., Schwartz, G., Nuñez Bustamante, E., ..., Bardales-Lozano, R.M., 2023b. Tara (*Caesalpinia spinosa*) in Natural and Agroforestry Systems under an Altitudinal Gradient in the Peruvian Andes: responses to Soil and Climate Variation. *Agron* 13 (2), 282. <https://doi.org/10.3390/agronomy13020282>.
- Murga-Orrillo, H., Chuquimez Gonzales, J.K., Pashanasi Amasifuén, B., Arévalo López, L.A., 2023a. *Vigna unguiculata*: a Productive Option in the Face of Climate Change? *Front. Agron.* 5, 1284173. <https://doi.org/10.3389/fagro.2023.1284173>.
- Nogueira, E.M., Yanai, A.M., de Vasconcelos, S.S., de Alencastro Graca, P.M.L., Fearnside, P.M., 2018. Carbon stocks and losses to deforestation in protected areas in Brazilian Amazonia. *Reg. Environ. Change* 18, 261–270. <https://doi.org/10.1007/s10113-017-1198-1>.
- Olsen, S.R., Cole, C.V., Watanabe, F.S., Dean, L.A., 1954. *Estimation of Available Phosphorus in Soils By Extraction With Sodium Bicarbonate*. Government Printing Office, Washington, D.C: U.S.

- Paiva, P.F.P.R., de Lourdes Pinheiro Ruivo, M., da Silva Júnior, O.M., Monteiro Ferreira, B., 2020. Deforestation in protect areas in the Amazon: a threat to biodiversity. *Biodivers. Conserv.* 29, 19–38. <https://doi.org/10.1007/s10531-019-01867-9>.
- Putzel, L., Peters, C.M., Romo, M., 2011. Post-logging regeneration and recruitment of shihuahuaco (*Dipteryx spp.*) in Peruvian Amazonia: implications for management. *For. Ecol. Manag.* 261 (6), 1099–1105. <https://doi.org/10.1016/j.foreco.2010.12.036>.
- R Core Team., 2021. R: a language and environment for statistical computing. v. 4.1.0 (Version 4.1.0). <https://www.r-project.org/>.
- Robiglio, V., Reyes, M., 2016. Restoration through formalization? Assessing the potential of Peru's Agroforestry Concessions scheme to contribute to restoration in agricultural frontiers in the Amazon region. *World Dev. Perspect.* 3, 42–46. <https://doi.org/10.1016/j.wdp.2016.11.013>.
- Rodríguez, L., Suárez, J.C., Rodríguez, W., Artunduaga, K.J., Lavelle, P., 2021. Agroforestry systems impact soil macroaggregation and enhance carbon storage in Colombian deforested Amazonia. *Geoderma* 384, 114810. <https://doi.org/10.1016/j.geoderma.2020.114810>.
- Rojas Briceño, N.B., Cotrina Sánchez, D.A., Barboza Castillo, E., Barrena Gurbillón, M.Á., Sarmiento, F.O., Sotomayor, D.A., ..., Salas López, R., 2020. Current and future distribution of five timber forest species in Amazonas, Northeast Peru: contributions towards a restoration strategy. *Diversity. (Basel)* 12 (8), 305. <https://doi.org/10.3390/d12080305>.
- Rorato, A.C., Picoli, M.C., Verstegen, J.A., Camara, G., Silva Bezerra, F.G., Escada, M.I.S., 2021. Environmental threats over Amazonian indigenous lands. *Land*, 10 (3), 267. <https://doi.org/10.3390/land10030267>.
- Schumacher, F.X., Hall, F.S., 1933. Logarithmic expression of timber-tree volume. *J. Agric. Res.* 47 (9), 719–734.
- SERFOR. 2015. Reglamento para la gestión de las plantaciones forestales y los sistemas agroforestales. <https://siar.regionpiura.gob.pe/documentos/normativa/2340.pdf> (accessed on January 20, 2024).
- Silva-Souza, K.J., Souza, A.F., 2020. Woody plant subregions of the Amazon forest. *J. Ecol.* 108 (6), 2321–2335. <https://doi.org/10.1111/1365-2745.13406>.
- Sofo, A., Mininni, A.N., Ricciuti, P., 2020. Soil macrofauna: a key factor for increasing soil fertility and promoting sustainable soil use in fruit orchard agrosystems. *Agron* 10 (4), 456. <https://doi.org/10.3390/agronomy10040456>.
- Souza, E.S.D., Fernandes, A.R., De Souza Braz, A.M., Oliveira, F.J.D., Alleoni, L.R.F., Campos, M.C.C., 2018. Physical, chemical, and mineralogical attributes of a representative group of soils from the eastern Amazon region in Brazil. *Soil*, 4 (3), 195–212. <https://doi.org/10.5194/soil-4-195-2018>.
- Vasconcellos, R.L., Segat, J.C., Bonfim, J.A., Baretta, D., Cardoso, E.J., 2013. Soil macrofauna as an indicator of soil quality in an undisturbed riparian forest and recovering sites of different ages. *Eur. J. Soil Biol.* 58, 105–112. <https://doi.org/10.1016/j.ejsobi.2013.07.001>.
- Visscher, A.M., Chavez, E., Caicedo, C., Tinoco, L., Pulleman, M., 2024. Biological soil health indicators are sensitive to shade tree management in a young cacao (*Theobroma cacao L.*) production system. *Geoderma Reg* e00772. <https://doi.org/10.1016/j.geodrs.2024.e00772>.
- Walkley, A., Black, I.A., 1934. An examination of the detjareff method for determining soil organic matter and a proposed modification to the chronic acid titration method. *Soil. Sci.* 37, 29–38. <https://doi.org/10.1097/00010694-193401000-00003>.
- Wang, Q., Li, Y., Hanlon, E.A., Klassen, W., Olczyk, T., Ezenwa, I.V., 2022. Cover Crop Benefits For South Florida commercial Vegetable producers. UF-IFAS Extension. University of Florida, pp. SL–242. <https://doi.org/10.32473/edis-ss461-2006>.
- Wang, R., Wang, Y., Zhang, Z., Pan, H., Lan, L., Huang, R., ..., Peng, Y., 2023. Effects of Exponential N Application on Soil Exchangeable Base Cations and the Growth and Nutrient Contents of Clonal Chinese Fir Seedlings. *Plants* 12 (4), 851. <https://doi.org/10.3390/plants12040851>.