Carbon Dynamics Across Soil and Vegetation Land Management in the Caatinga Biome

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Abstract:

We investigated how various soil and vegetation management methods influence carbon (C) stocks in areas within the Caatinga biome. We sampled a total of 28 sites across seven municipalities and three states in Northeast Brazil, stratifying three vegetation types: preserved Caatinga, agroecological farming areas, and conventional agriculture. In 20 × 20 m plots, we quantified carbon in the following pools: aboveground and belowground biomass, litter, deadwood, and soil (0–30 cm), measuring both bulk density and the coarse fraction. Carbon content was determined using a CHNS elemental analyzer. We integrated remote sensing data (SAVI and fCover using high spatial resolution images at 3 m) to characterize photosynthetic activity and canopy cover. Average total C stocks were approximately 64.8 Mg ha^{-1} in preserved Caatinga, 35.1 Mg ha^{-1} in transitional areas, and 26.4 Mg ha^{-1} under conventional agriculture, with soil accounting for 61% in preserved areas and over 90% in managed systems, due to the collapse of woody biomass, roots, litter, and necromass. Cambisols and Oxisols had the highest stocks, whereas Luvisols, Planosols, and Entisols were more limiting. SAVI and fCover reflected the structural gradient (preserved > transitional > conventional) and seasonality (higher during the rainy season), supporting the link between canopy structure, photosynthetic activity, and carbon accumulation. We conclude that protecting native remnants is irreplaceable for maintaining carbon stocks and ecosystem services and that agroecological systems increase soil cover, help restore canopy structure, and reduce carbon losses compared to conventional management. We recommend implementing conservation policies in conjunction with the expansion of agroforestry systems, accompanied by continuous monitoring via remote sensing, as a pragmatic pathway for climate mitigation and low-carbon agriculture in the Brazilian semiarid region.

Keywords: Semiarid, agroecology, regenerative agriculture,

Introduction:

The Caatinga biome, the largest seasonally dry tropical forest in South America, is characterized by high hydroclimatic variability, marked seasonality, and a long history of land-use change. These factors strongly modulate carbon (C) dynamics in both soil and biomass (SILVA et al., 2017). At the global scale, there is a growing consensus that semiarid ecosystems play a disproportionately large role in the interannual variability and long-term trends of the terrestrial CO_2 sink, responding acutely to precipitation and temperature anomalies (AHLSTRÖM et al., 2015; POULTER et al., 2014). This context makes the Caatinga a critical case for investigating how soil and vegetation management influence C stocks and fluxes under chronic water limitation.

In the region, the conversion of forest/brush vegetation into pasturelands and conventional monocropping systems is associated with declines in soil organic carbon (SOC), degradation of physical-chemical attributes, and reduced microbial activity effects that may extend across multiple soil depths (FERREIRA et al., 2016; SILVA et al., 2024). At the same time, functional metrics such as soil respiration and photosynthetic rate tend to be lower in degraded pastures compared to preserved Caatinga areas, reflecting lower productivity and greater soil thermal exposure (LIMA et al., 2020). Intensive grazing, in turn, can further deplete soil C stocks in Caatinga areas, exacerbating the loss of soil quality (SCHULZ et al., 2016).

Climatic forcing adds another layer of complexity: at instrumented sites in the Caatinga, net CO_2 exchange varies seasonally, with reduced uptake and, in some cases, net emissions during the dry season, reflecting the strong control of water on ecosystem photosynthesis and respiration (MENDES et al., 2020). This behavior aligns with global evidence that semiarid ecosystems are the most sensitive to precipitation fluctuations in the terrestrial sink (AHLSTRÖM et al., 2015). In summary, chronic water stress tends to dampen productivity and reduce net C gain in semiarid landscapes.

As a counterpoint, transitions to agroforestry or agroecological systems have shown potential to increase SOC and improve biological and structural soil properties when compared to conventional monoculture land uses (FERREIRA et al., 2016; MEDEIROS et al., 2017). However, in dry environments, SOC recovery is slow, limited by saturation thresholds and long response times often spanning one to two decades. Therefore, early gains following land-use conversion are more likely to be observed in biomass than in soil (POST & KWON, 2000; SIX et al., 2002; MOINET et al., 2023).

This temporal asymmetry between carbon pools demands caution when assessing short-term climate benefits.

At the landscape scale, the lack of consistent time series on land use and cover has long hindered comparisons across management regimes. Recent annual collections, such as those from the MapBiomas Project, provide a standardized baseline for stratified sampling and spatial contextualization of carbon studies in the Caatinga, thereby improving reproducibility and comparability across areas and time periods (MAPBIOMAS PROJECT, 2025).

Given this context, two central knowledge gaps remain: (i) (i) the need for multi-compartment carbon measurements (soil, above- and belowground biomass, litter, and deadwood) under real-world management conditions in the Caatinga; and (ii) the urgency of integrated interpretations linking vegetation structure, soil functioning, and climatic context to inform low-carbon policies, ecological restoration, and agroecological transitions.

Thus, the objective of this study was to quantify and compare carbon stocks in soil and biomass across a management gradient that preserved Caatinga, agroforestry/agroecological transition systems, and monoculture agriculture within the Brazilian semiarid region. We also discuss implications for climate mitigation and regenerative landscape management.

MATERIAL AND METHODS

2.1. Study Area

The study was carried out in seven municipalities in Northeastern Brazil, all located within the Caatinga biome (semiarid climate): Vitória da Conquista, Condeúba, and Poções (in the southwestern region of the state of Bahia); Triunfo and Afogados da Ingazeira (in the Pajeú region, state of Pernambuco); Caruaru (in the Agreste region of Pernambuco); and Queimadas (in the eastern Cariri region of the state of Paraíba).

A detailed list of study sites, including geographic coordinates, type of agriculture practiced, and soil classification, is presented in Table 1.

Tabela 1 . Coordenadas, tipo de cultivo, municípios e classe de solo de solo das áreas amostradas no Estudo.

plot	**Lat**	**Long**	**Land use**	**Municipality**	**Soils class (IBGE, 2023)**	**Average precipitation (mm/ano)**	**Elevation (m)**
1	-14.42114	-40.32946	Transição Agroecológica	Poções (BA)	Cambissolo	983	760
2	-14.41942	-40.33082	Agricultura convencional	Poções (BA)	Cambissolo	983	760
3	-14.834798	-41.156780	Transição Agroecológica	Vitória da Conquista (BA)	Latossolo Vermelho Amarelo	717	923
4	-14.837235	-41.157216	Caatinga preservada	Vitória da Conquista (BA)	Latossolo Vermelho Amarelo	717	923
5	-14.764793	-41.952480	Caatinga Preservada	Condeúba (BA)	Latossolo Amarelo	637	634
10	-14.762310	-41.952480	Agricultura convencional	Condeúba (BA)	Latossolo Amarelo	637	634
11	-14.866447	-42.133709	Agricultura tradicional	Condeúba (BA)	Latossolo	637	634
12	-14.869379	-42.139404	Caatinga Preservada	Condeúba (BA)	Latossolo	637	634
13	-8.070917	-35.840611	Agricultura convencional	Caruaru (PE)	Neossolo Litólico	534	554
14	-8.070911	-35.843510	Transição Agroecológica	Caruaru (PE)	Neossolo Litólico	534	554
15	-7.905000	-35.974000	Agricultura convencional	Vertentes (PE)	**Luvissolo Crômico (TC)**	423	412
16	-7.910000	-35.995000	Transição Agroecológica	Vertentes (PE)	**Neossolo Litólico (RL)**	423	412
17	-8.149000	-36.374000	Transição Agroecológica	Brejo da Madre de Deus (PE)	Luvissolo Crômico (TC).	377	614
18	-8.130000	-36.370000	Caatinga Preservada	Brejo da Madre de Deus (PE)	Neossolo Litólico (RL)	377	614

19	-8.283000	-35.974000	Agricultura convencional	Caruaru (PE)	Neossolo Litólico (RL)	534	554
20	-8.295000	-35.965000	Transição Agroecológica	Caruaru (PE)	Neossolo Litólico (RL)	534	554
21	-7.832000	-38.10045	Caatinga Preservada	Triunfo (PE)	Cambissolo Háplico (CX)	553	1004
22	-7.840000	-38.110000	Transição Agroecológica	Triunfo (PE)	Cambissolo Háplico (CX).	553	1004
23	-7.813000	-38.15000	Agricultura convencional	Santa Cruz da Baixa Verde (PE)	Cambissolo Háplico (CX).	578	852
24	-7.820000	-38.16000	Transição Agroecológica	Santa Cruz da Baixa Verde (PE)	Cambissolo Háplico (CX).	578	852
25	-7.753000	-37.631010	Agricultura convencional	Afogados da Ingazeira (PE)	Luvissolo Crômico (TC).	430	525
26	-7.760000	-37.640450	Transição Agroecológica	Afogados da Ingazeira (PE)	Planossolo Háplico (SX).	430	525
27	-7.365000	-35.903123	Agricultura convencional	Queimadas (PB)	Luvissolo Crômico (TC).	488	450
28	-7.380000	-35.91500	Transição Agroecológica	Queimadas (PB)	Neossolo Regolítico (RR).	488	450

2.2. Land Use Stratification and Site Selection

Stratified sampling in this study included three management classes along a gradient of anthropogenic intervention:

(i) Preserved Caatinga; (ii) Agroforestry/Agroecological Transition; and (iii) conventional Agriculture (monocropping/pasture with soil preparation using agricultural machinery and low residue return).

Within each site (defined here by municipality), priority was given to properties containing at least two classes, and ideally, a preserved Caatinga remnant within the same landscape.

The inclusion criteria for the areas were contiguous plots ≥ 2 ha, a slope < 15%, no recent fires (< 12 months), a documented management history of≥ 3 years, and the same lithology for the compared areas when outside the same property (≤ 5 km apart). Land use and land cover were verified by combining annual time series from the MapBiomas initiative (Collection 10) with field reconnaissance by the research team (MAPBIOMAS, 2024).

2.3. Sampling Design and Units

At each site, we aimed to install three permanent plots of 20 × 20 m (400 m²), ositioned using restricted randomization (≥ 30 m from roads, edges, or atypical areas). Plots were georeferenced and marked with stakes at the corners.

Within each 20 × 20 m plot, sub-units were defined by compartment:

- Four 1 × 1 m subplots (at corners) for sampling herbaceous layer and litter;
- Two 2 × 2 m subplots (at midpoints of opposite edges) for sampling regeneration and coarse woody debris (CWD);
- Full woody biomass was quantified by field census within the 20 × 20 m area for trees and shrubs. It is important to mention that live wood was estimated using allometric equations, which are described in the following section.

2.4. Phytosociology and Woody Biomass

All included woody individuals were measured for CAP (1,30 m) and, when necessary, CNB (0,30 m), with botanical identification at the species level whenever possible. Inclusion criteria: CAP ≥ 6 cm and/or CNB ≥ 9 cm. DAP was calculated as DAP = CAP/π; multi-stem individuals were converted to equivalent DAP (Sampaio & Silva, 2005).

Aboveground biomass (kg) was estimated using regional allometric equations based on DAP/CAP for seasonally dry formations. Standing dead individuals were quantified separately. Belowground biomass was estimated using the root-to-shoot ratio (R:S) documented for tropical dry forests, with sensitivity analysis described in the Methodological Supplement (CHAVE et al., 2014; IPCC, 2006).

Belowground biomass was estimated using the root:shoot ratio (R:S) for tropical dry forests, with sensitivity analysis detailed in the Supplementary Methods (CHAVE et al., 2014; IPCC, 2006).

2.5. Non-Woody Compartments: Herbaceous Layer, Litter, and Necromass

Sampling of non-woody compartments followed the protocol described by HARMON; SEXTON, (1996), in which the herbaceous layer was harvested by close cutting in the four 1 × 1 m subplots and weighed in the field (portable scale), with aliquots sent for determination of moisture and C content.

Litter was fully collected in the same subplots, removing visible mineral soil. Necromass (deadwood on the ground) was inventoried within the 20 × 20 m plot by measuring the diameter and length of logs/branches; when material extended beyond the boundary, only the internal fraction was considered. Calibration subsamples were sent to the laboratory for moisture and carbon content.

2.6. Soil Sampling and Bulk Density

In each plot, soil samples at 0–20 cm from the topsoil were used to create a composite soil sample. The sampling was carried out using a Dutch auger, pooling five subsamples (four corners and the center). From the formed core, representative aliquots were taken for the 0–10 cm and 10–20 cm depths.

To estimate soil bulk density (Ds), an undisturbed sample auger (Castelo type with a stop) was used to obtain samples from the 0–10 cm, 10–20 cm, and 20–30 cm layers at a point adjacent to the plot. Surface stoniness and the coarse fraction (> 2 mm, volumetric) were recorded for stock corrections. Samples received a unique ID (State–Municipality–Property–Class–Plot) and a standardized chain of custody.

2.7. Laboratory Procedures

2.7.1. Biomass – Moisture and Carbon Content

Samples were oven-dried at 65–70 °C to constant mass and ground (Willey-type mill). Carbon content (% dry weight) was determined by dry combustion using a CHNS elemental analyzer, with daily calibration using acetanilide and accuracy checks using certified reference materials (DUMAS, 1831; NELSON & SOMMERS, 1996; ASTM D5373-16). Results are reported on a dry weight basis.

2.7.2. Soil – Preparation, Spectroradiometry, and SOC

Soil carbon was quantified via dry combustion using a CHNS elemental analyzer. To isolate soil organic carbon (SOC) in potentially calcareous soils, acid fumigation with HCl vapors (12–24 h) was applied before analysis, followed by drying and encapsulation in airtight capsules. Duplicate non-acidified samples were also analyzed to detect carbonates (KOMADA et al., 2008; ISO 10694, 1995). Quality control included blanks, duplicates (10%), and intermediate standards every 10 samples (NELSON & SOMMERS, 1996).

2.7.3. Bulk Density and Rock Fragment Correction

Bulk density was calculated as the dry mass divided by the ring volume. Stocks were corrected by the coarse fraction (> 2 mm, volumetric). Samples with coarse fraction > 20% received specific solid volume corrections as described by Menezes et al. (2022).

2.8. CARBON STOCK CALCULATION

2.8.1. soil (0–20 cm)

For estimating soil carbon stock in the 0–20 cm layer, the calculation described by Ellert & Bettany (1995) was adopted:

$$\text{Csoil (Mg ha}^{-1}) = \text{C\%} \times \text{Ds (g cm}^{-3}) \times \text{Z (cm)} \times (1 - \text{CF}) \times 0.1$$

where C% is the soil carbon concentration (%), Ds is soil bulk density, Z = 20 cm, and CF is the volumetric fraction > 2 mm; the factor 0.1 converts g cm^{-2} to Mg ha^{-1}.

2.8.2. biomass (aboveground, belowground, herbaceous, litter, necromass)

To estimate carbon stocks in aboveground biomass, the equation described by IPCC (2006) was used:

$$\text{C (Mg ha}^{-1}) = \text{Dry biomass (Mg ha}^{-1}) \times \text{fC}$$

where fC is the C content (fraction) determined by CHNS (dry basis). Woody biomass was derived from allometries, including herbaceous/litter/necromass by extrapolating from subplots to the hectare. Belowground biomass was estimated using the R:S ratio, where destructive sampling was not possible (IPCC, 2006; CHAVE et al., 2014).

2.9. Seasonality and field calendar

To reduce intra-annual variation, sampling was carried out at the end of the rainy season (biomass peak) in each region. Accumulated rainfall (30/90 days) and preceding dry days were recorded. A sentinel subset (≥ 1 plot per class/municipality) was re-sampled at the beginning of the dry season to assess the stability of estimates.

2.10. Spectral analysis by remote sensing (Planet, 3 m):

SAVI and fCover PlanetScope imagery (surface reflectance, 3 m) was employed to characterize the spectral behavior and photosynthetic activity of the sites.

Pre-processing: UDM2 mask (cloud/shadow) and selection of cloud-free images within windows centered on field dates (±15 days); seasonal composites (median) of the RED and NIR bands ensured phenological comparability (PLANET TEAM, 2017). SAVI (Soil-Adjusted Vegetation Index) was calculated with $L = 0.5$ to reduce the soil background effect in sparse canopies, as is the case for vegetation distribution in semiarid regions (HUETE, 1988):

$$SAVI = ((NIR - RED)) / ((NIR + RED + L)) \times (1 + L)$$

Mean SAVI per plot (20 × 20 m) was extracted and used as a metric of photosynthetic activity. A historical data series of the 24 months before field sampling was adopted as the analysis period.

Fractional cover (fCover, 0–1) was derived by linear mixture based on SAVI, whose methodology is described by Baret et al. (2010), and expressed by the equation:

$$fCover = clip((SAVI - SAVIsoil) / (SAVIveg - SAVIsoil)) \times 0.1$$

Where SAVIsoil and SAVIveg were obtained, respectively, as P5 in exposed soil patches and P95 in dense vegetation in the neighborhood (SHIMABUKURO; SMITH, 1991; BARET et al., 2010).

Field–satellite integration via mean SAVI and fCover per plot was performed by correlating these data with C stocks (soil and biomass) and with structural metrics (density and basal area), evaluating the coupling between active cover and carbon accumulation (POULTER et al., 2014). All orbital data processing was performed in Python.

2.11. Statistical analysis

Variables were inspected for outliers (robust methods), normality (Shapiro–Wilk), and homoscedasticity (Levene).

Within-municipality comparisons: ANOVA among classes, with appropriate post-tests. Integrated analysis (seven municipalities): linear mixed model:

Response ~ Management + fCover/SAVI + (1 | State/Municipality/Property) with 95% CIs, effect sizes, and adjustment for multiple comparisons.

Field–satellite associations were assessed using Pearson/Spearman correlations between SAVI/fCover and C stocks by compartment. PCA/RDA was then used to integrate C compartments, vegetation structure, and spectral metrics.

RESULTS AND DISCUSSION:

Figure 1 presents total carbon stocks (soil + live biomass + deadwood + litter) across different vegetation physiognomies: preserved areas, ecological transition areas, and conventional agriculture. The observed pattern shows higher carbon stocks in Caatinga areas, followed by agroecological cropping areas, with the lowest stocks in conventional agriculture. This pattern is consistent with other studies that evaluated carbon dynamics at a regional scale across different physiognomies in the Caatinga biome (MENEZES et al., 2021).

On average, Caatinga areas store ≈64.79 Mg C ha^{-1}, whereas ecological transition areas store 35.08 Mg C ha^{-1} approximately 48% less carbon than the dry forest. Conventional agricultural areas stored 26.36 Mg C ha^{-1}, representing approximately 70% less carbon than forested areas (Caatinga) and approximately 25% less than agroecological cropping systems.

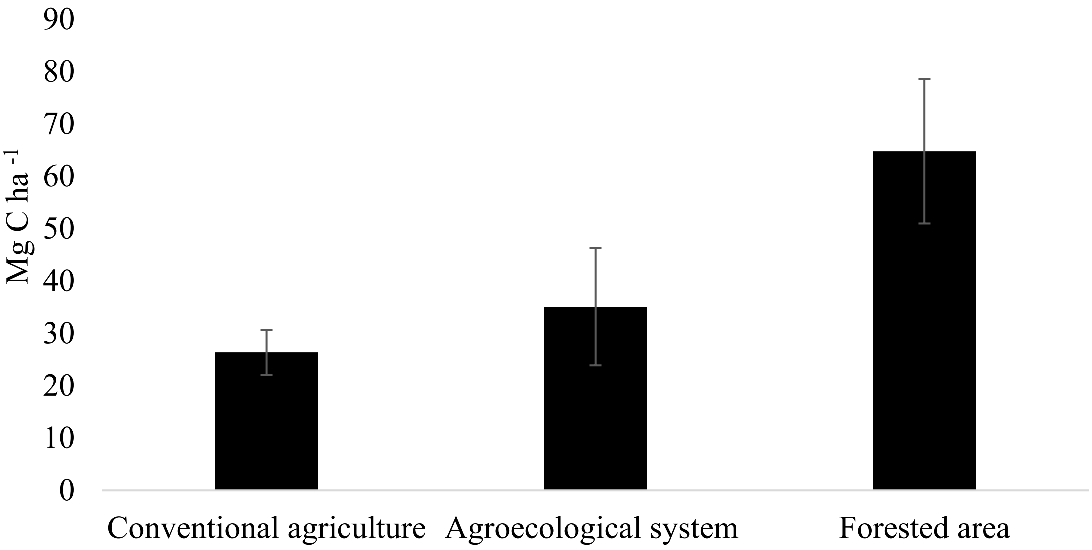

Figure 1 Total carbon stocks (Mg ha^{-1}) in different vegetation physiognomies: preserved area, ecological transition areas, and conventional agriculture across 28 sites in the Caatinga Biome.

Among the mechanisms responsible for explaining the differences in carbon stocks among the land uses, the following stand out: (i) removal of the woody layer during the conversion of forests into cultivated areas, leading to a consequent collapse of necromass and litter stocks, which reduces the annual input of organic matter to the soil; (ii) greater physical disturbance (clearing, harrowing, animal trampling) that exposes soil organic matter to rapid mineralization, consequently reducing carbon stocks; and (iii) agricultural areas are also used for livestock grazing (cattle, goats, and sheep) at moderate to high stocking rate, which causes over the years significant reductions in soil organic carbon (SOC) within the top 5 cm is the most sensitive soil layer disturbed, however effects at greater depths tend to be smaller in the short term (SCHULZ Et al.,2016). Other factor that market the conventional agriculture in the semiarid of Brazil, is if the área was not allowed grazing to the animals, the biomass crop residual are harvested to be used conserved as sillage and hay production to be use for the animals in the dry season. The soil is kept bare until the next agricultural cycle, with minimal presence of vegetation cover. These processes explain why productive systems converge toward lower levels of total carbon.

The values observed for Caatinga areas in this study are slightly lower than those reported by Menezes et al. (2021), which can be explained by the presence of grazing in all areas. However, they are higher than those reported by Pereira Junior et al. (2016), who found an average of 21.64 Mg C ha^{-1}.

The intermediate performance of agroecological cultivation indicates partial recovery of total carbon stocks, consistent with the increase in structural complexity (reintroduction of woody cover, accumulation of litter and deadwood) and higher residue input, which favors carbon stabilization in the soil. Evidence from open vegetation formations in Brazil shows that systems with greater vertical structure retain more carbon and are less vulnerable to disturbances than simplified arrangements dominated by herbaceous vegetation (MAIA et al., 2006).

Finally, regional literature emphasizes that soil carbon recovery is slow: after deforestation, levels comparable to those in dense Caatinga may take decades to reestablish, reinforcing the importance of productive restoration trajectories (e.g., agroforestry systems) to increase total ecosystem carbon in managed areas over the short and medium term.

Table 2 shows that the reduction in total ecosystem carbon (soil + live biomass + deadwood + litter) results from the combined losses across multiple compartments.

Table 2. Carbon stocks by compartment in the phytophysiognomies of preserved areas, ecological transition areas, and conventional agriculture areas.

	Forested area	Agroecological system	Conventional agriculture
		(Mg ha^{-1})	
Soil	39,7	32,7	25,4
Woody biomass	14,27	0,87	0,02
Herbaceous biomass	0,79	0,44	0,50
Belowground biomass	7,18	1,02	0,46
Deadwood	1,67	0,05	0,00
Litter	1,18	0,06	0,04

In the preserved area, carbon is distributed as follows: soil 39.7 Mg ha^{-1} (61.3%), woody biomass 14.27 (22.0%), belowground biomass 7.18 (11.1%), deadwood 1.67 (2.6%), litter 1.18 (1.8%), and herbaceous biomass 0.79 (1.2%). This hierarchy aligns with regional estimates for dense Caatinga, in which soil accounts for ~72% of ecosystem carbon, followed by aboveground biomass (~16%), belowground (~7%), and detrital fractions (deadwood + litter) (~4%) (MENEZES et al., 2021).

In agroecological transition and conventional agriculture systems, there is a greater dependence on soil carbon within the total stock, with this compartment concentrating >90% of total carbon (32.7/35.08 and 25.4/26.36 Mg ha^{-1}, respectively) not because SOC increases, but because of the collapse of biotic (woody and belowground biomass) and detrital compartments (litter and deadwood). This pattern mirrors regional results: converting dense Caatinga to pastures/croplands entails >50% losses of ecosystem carbon, with reductions of similar magnitude in both soil and vegetation stocks (MEDEIROS et al., 2020).

Soil organic carbon stocks (0–30 cm) decrease from 39.7 to 32.7 and 25.4 Mg C ha^{-1} along the gradient of preserved Caatinga to agroecological cultivation to conventional agriculture, corresponding to reductions of 17.6% (preserved to agroecological) and 36.0% (preserved to conventional), as well as 22.3% between agroecological and conventional systems. The literature attributes this decline chiefly to lower residue inputs (litter and fine roots), greater physical soil disturbance (tillage, machinery traffic), and, where present, grazing. Notably, stocks in agroecological areas approach those observed in preserved areas, suggesting that agroecological management is an effective strategy for maintaining soil carbon and should be considered in transition pathways toward low-carbon agriculture systems (MAIA, 2006).

Biomass

Woody biomass showed a marked decline, decreasing from 14.27 Mg ha^{-1} in preserved areas to 0.87 Mg ha^{-1} in agroecological systems, and reaching negligible values in conventional systems, indicating the near-total removal of canopy and consequent loss of structural complexity affecting the biomass distribution in the compartments of the ecosystem. Regional studies confirm this pattern: in stratified samplings across the Caatinga biome, aboveground biomass in dense Caatinga areas is several times higher than in open systems, pastures, or croplands (MENEZES et al., 2021; PEREIRA JÚNIOR et al., 2016). The removal of woody vegetation not only reduces photosynthetic capacity and carbon cycling but also compromises the soil's physical protection against erosive processes and degrades the quality of the edaphic microclimate (LIMA et al., 2025; SANTANA et al., 2019).

This set of alterations creates a more hostile environment for biodiversity, affecting both larger fauna and microbial communities responsible for key processes governing soil fertility and resilience (ALBUQUERQUE et al., 2015; TIESSEN, SALCEDO & SAMPAIO, 1998).

Root biomass decreased from 7.18 to 1.02 to 0.46 Mg ha^{-1}, following the simplification of the woody biomass stratum. This pattern is consistent with regional evidence: in stratified samples of the Caatinga, root (and belowground C) stocks are higher in dense Caatinga than in open formations and decline further in pastures and cultivated areas, with statistically significant differences between native vegetation and agricultural uses (MENEZES et al., 2021; SCHULZ et al., 2016). In addition, the literature shows that the reduction of the woody component leads to lower root input and a smaller root-to-shoot ratio, which helps explain the observed decline in root biomass along the land-use gradient (MOKANY, RAISON & PROKUSHKIN, 2006; ALBUQUERQUE et al., 2015; PEREIRA JÚNIOR et al., 2016).

The herbaceous fraction showed relatively low values across all evaluated uses (0.79; 0.44; 0.50 Mg ha^{-1}). The fact that the preserved area recorded the highest stock is not unusual, in some soils, MENEZES et al. (2021) observed higher herbaceous biomass in dense Caatinga compared to pastures or open areas, particularly in Leptosols and Planosols. This variation is associated with floristic composition, which inckluded seedlings and fine shrubs species phenology, and the sampling period (PEREIRA JÚNIOR et al., 2016; ALBUQUERQUE et al., 2015).

Furthermore, reports from local farmers indicate that all studied areas are subjected to grazing by goats, sheep, and cattle, which, when over continuous grazing, causes a drastic reduction in herbaceous cover. This process affects both grasses and dicotyledons and may result not only in lower aboveground biomass but also in depletion of the seed bank, compromising natural regeneration and the ecological resilience of the systems (SCHULZ et al., 2016; TIESSEN, SALCEDO & SAMPAIO, 1998).

Deadwood virtually disappears outside the preserved area (1.67 → 0.05 → 0 Mg ha^{-1}), and litter is absent in managed systems (1.18 → 0 → 0 Mg ha^{-1}). These components are crucial for protecting the soil from raindrop impact and erosion, moderating the microclimate (surface humidity and temperature), and feeding soil carbon stocks through particulate organic matter inputs; their removal accelerates mineralization and reduces C occlusion within aggregates, weakening the physical mechanisms of carbon stabilization (MENEZES et al., 2021; LAL, 2004; SIX, ELLIOTT & PAUSTIAN, 2000; COTRUFO et al., 2013). Stratified surveys in the Caatinga reveal that woody necromass and litter are compartments found in native formations (dense/open) and are virtually absent in areas converted to croplands or pastures, reflecting the structural simplification of the system (Menezes et al., 2021).

The contrast among the three physiognomies in Table 2 revealed that the most significant carbon losses arise from two main processes: (i) the immediate removal of woody vegetation and structural detritus, which reduces canopy complexity and eliminates key compartments such as deadwood and litter, and (ii) the gradual degradation of soil carbon stocks caused by reduced fine root and litter inputs, combined with increased decomposition and decreased physical protection of organic matter (Lal, 2004; Cotrufo et al., 2013; Schulz et al., 2016).

In this context, agroecological cropping systems emerge as a more sustainable alternative compared to conventional agriculture. Although they do not fully restore the carbon stocks of native vegetation, these systems partially reconstitute canopy cover, favor fine-root development, increase soil cover, and maintain litter and necromass inputs, resulting in intermediate carbon values that are closer to preserved Caatinga than to conventional systems (MENEZES et al., 2021; PEREIRA JÚNIOR et al., 2016). Thus, by sustaining carbon cycling and reducing soil vulnerability to erosion and fertility loss, agroecology represents a viable transition pathway toward low-carbon agriculture in Brazil's semiarid region, reconciling productivity with environmental conservation (MEDEIROS, CESÁRIO & MAIA, 2023).

Soils

Figure 2 shows that Cambisols and Oxisols recorded the highest mean carbon stocks among the soil classes studied. In Oxisols, this can be attributed to the role of mineralogy in carbon stabilization, where associations between organic carbon and mineral surfaces facilitate retention and protection against decomposition (XU et al., 2024). In turn, the high stoniness of Cambisols in drylands of Brazil limits the use for agricultural purposes. This condition prevents land use changes, which may favor the maintenance of organic stocks, even though these soils are not naturally the most fertile.

Conversely, Luvisols, typically characterized by higher base saturation and fertility potential, may exhibit lower carbon stocks under more intensive use and management due to increased oxidation and loss of organic matter (SATDICHANH et al., 2023). The observed order of C stocks, therefore, does not necessarily reflect greater fertility, but rather a combination of mineral stabilization properties and management/disturbance history.

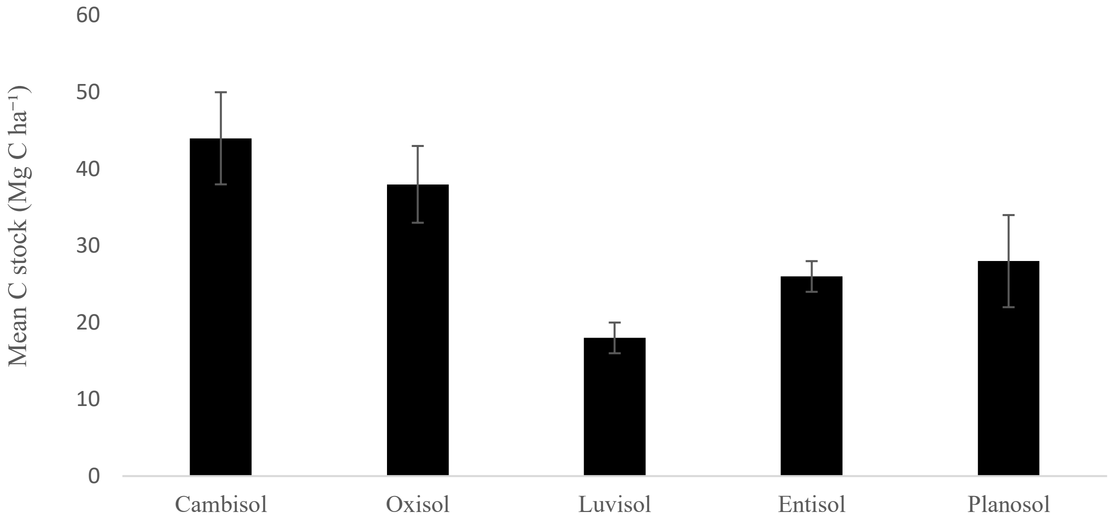

Figure 2. Carbon stocks by soil classes across vegetation physiognomies: preserved area, ecological transition areas, and conventional agriculture in 28 sites within the Caatinga Biome, based on PlanetScope data (3-meter spatial resolution).

Planosols and Entisols were the least fertile in the evaluated areas. In Planosols, the presence of a plinthic B horizon implies poor drainage, low permeability, and greater densification/compaction, restricting root growth and nutrient cycling (SiBCS; Embrapa; technical chapters for the Semiarid 2025).

Entisols, being poorly developed (often shallow and with low nutrient reserves), tend to require more amendments and fertilization. When quartzarenic, they also have very low water retention in semiarid areas (Embrapa Information Agency on Entisols; Quartzarenic Entisols). Planosols and Entisols were the least fertile soils observed in the study areas; as a rule, these soils present serious physical–chemical constraintsthe former due to drainage and compaction issues, and the latter due to being shallow and weakly developed.

Seasonal patterns of photosynthetic activity (Figure 4) and implications for ecosystem carbon

Figure 4 shows the spectral behavior for photosynthetic activity and vegetation vigor, adjusting for soil background using the SAVI index from PlanetScope (3 m) data over a 2020–2024 time series for the three physiognomies (Caatinga, agroecological cultivation, and conventional cultivation). Mean values were: conventional agriculture 0.24, agroecological transition 0.28, and preserved Caatinga 0.32.

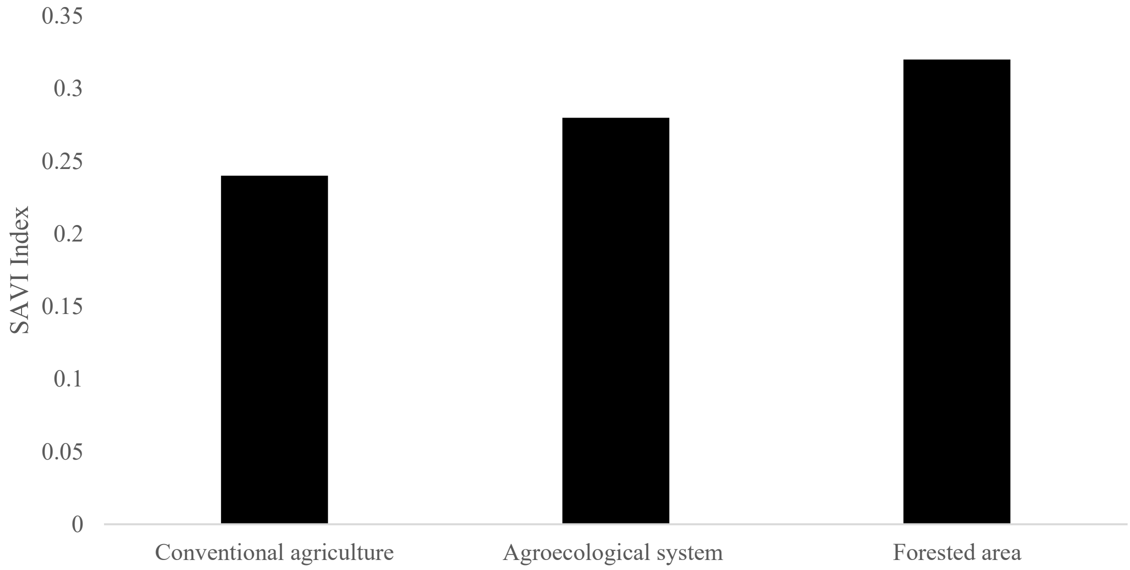

Figure 3 – Mean SAVI (Soil-Adjusted Vegetation Index) values from 2020 to 2024 across vegetation physiognomies: preserved area, ecological transition areas, and conventional agriculture in 28 sites within the Caatinga Biome, based on PlanetScope data (3-meter spatial resolution).

The increase in SAVI from the dry to the rainy season (ΔSAVI) reflects the phenological responsiveness of each physiognomy: +0.10 in preserved Caatinga (≈+37%), +0.06 in the transition (≈+24%), and +0.07 in agriculture (≈+35%). In Caatinga areas, the greater SAVI amplitude between dry and wet periods indicates a stronger productive pulse and higher leaf area during the humid season expected effects in systems with more developed woody biomass and belowground roots (~16% and ~7% of ecosystem C, respectively), capable of accessing deep water and sustaining canopy flushing (BAUDENA et al., 2004).

In conventional agricultural systems, the SAVI index starts from lower values in the dry season and remains lower during the rainy period, consistent with structural simplification of the canopy, greater soil exposure, and reduced litter and deadwood input factors that diminish annual inputs to SOC and carbon accumulation in vegetation (VERBURG et al., 2012). Schulz et al. (2016), assessing livestock effects on semiarid landscapes, concluded that under intense grazing, there is a rapid and strong decline in green cover and an increase in soil compaction, with significant reductions in carbon within the top 5 cm of soil and in vegetation spectrally expressed as lower and more fragmented SAVI values.

The intermediate performance of the agroecological transition (0.25 → 0.31 in SAVI) indicates that these systems fall within a range of structural recomposition of the woody stratum, characterized by the return of necromass and increased leaf-litter cover on the soil. This increases the fractional cover (fCover) and canopy continuity, buffering direct water impact on the soil and favoring microorganisms by reducing soil exposure to sunlight and other extreme microclimatic events (MATEO-MARÍN et al., 2022).

Although not reaching the levels of preserved Caatinga, agroecological crops exhibit higher photosynthetic activity and detrital fluxes than conventional cultivation areas a condition associated with larger carbon stocks and reduced soil carbon depletion under less intensive management (MEDEIROS, CESÁRIO & MAIA, 2023). In Brazilian open formations, greater vertical complexity and aboveground biomass sustain higher spectral indices and lower vulnerability to disturbances, consistent with increased SAVI in areas undergoing productive restoration (OLIVEIRA et al., 2019).

To some extent, the spectral signatures in Figures 3 and 4 mirror the carbon stocks: where SAVI is higher (indicating greater cover and vigor), higher vegetation carbon stocks and soil inputs are observed; where SAVI is lower (discontinuous canopy, exposed soil), the system tends to have smaller stocks and greater susceptibility to losses by mineralization and erosion (MENEZES et al., 2021; SCHULZ et al., 2016; LAL, 2004; COTRUFO et al., 2013).

Thus, agroecological cropping systems are more sustainable than traditional ones because: (i) they reduce soil exposure and erosion, (ii) they maintain the detrital cycle (litter/woody debris) that feeds and stabilizes SOM, and (iii) they bring system functionality closer to that observed in native vegetation (MEDEIROS, CESÁRIO & MAIA, 2023; COTRUFO et al., 2013).

Phytosociology

The frequency of tree individuals in the sampled physiognomies is presented in Table 3. A transparent structural gradient is evident among the three physiognomies. In preserved areas, the diameter distribution follows the reverse-J pattern typical of forests with continuous recruitment: 74.8% of individuals are concentrated in the 6.0–12.9 cm classes (254 + 186), followed by the 13.0–16.9 cm (16.7%) and 17.0–20.9 cm (6.0%) classes, with a small fraction in the upper class (>20.9 cm; 2.6%).

This demographic signature indicates high replacement of young individuals and the maintenance of biomass stocks over time (PEREIRA JÚNIOR et al., 2016; ALCOFORADO-FILHO, SAMPAIO & RODAL, 2003).

Table 3 Frequency of tree individuals sampled by diameter at breast height (DBH) class across vegetation physiognomies: preserved area, ecological transition areas, and conventional agriculture in 28 sites within the Caatinga Biome.

	Preserved area		Agroecological transition		Conventional agriculture	
DBH classes ($D_{30\ cm}$)	Frequency absolute	Relative frequency (%)	absolute frequency	Relative relative (%)	absolute frequency	Relative frequency (%)
6,0-8,9	254	43,20	90	42,25	0	0,00
9,0-12,9	186	31,63	60	28,17	0	0,00
13,0-16,9	98	16,67	32	15,02	0	0,00
17,0-20,9	35	5,95	18	8,45	1	25,00
< 20,9	15	2,55	13	6,10	3	75,00
Total	588	100	213	100	4	100

In the agroecological transition, the overall shape of the diameter distribution remains, but with a lower total density (213 vs. 588) and a slight relative increase in the larger classes (8.5% in the 17–20.9 cm class and 6.1% in the upper class). This suggests two concurrent processes: (i) loss of thin individuals due to past management (thinning, grazing, soil preparation), and (ii) retention or introduction of larger trees (either legacy trees or planted individuals) that provide structural inertia shade, perches, and litter production capable of buffering microclimatic extremes and favoring understory recovery (Santana et al., 2019; Pereira Júnior et al., 2016). Functionally, this partial recomposition of the diameter spectrum is consistent with the spectral (SAVI) results and with intermediate carbon stocks observed in less intensive systems (Medeiros, Cesário & Maia, 2023).

In contrast, under conventional agriculture, there is a collapse of the age pyramid, with only four tree individuals reported across 28 sitesall absent from the 6.0–16.9 cm classes and concentrated in the larger classes (25% in 17–20.9 cm and 75% in the upper class), a pattern typical of isolated remnants ("legacy trees") following canopy clearance.

The suppression of fine and medium classes indicates recruitment failure, reduced litter and fine-root input, and increased soil exposure to compaction, erosion, and accelerated C mineralization, as documented for areas under intensive tillage and/or grazing in the Caatinga (Schulz et al., 2016; Menezes et al., 2021).

From an ecological and management perspective, areas with structures encompassing a broad diameter spectrum (preserved and, to some extent, transition) tend to have higher and more stable C stocks in both vegetation and soil, due to the continuous flow of detritus and C occlusion within aggregates (COTRUFO et al., 2013). The truncated structure observed in conventional agriculture reduces these mechanisms and accelerates carbon losses (Lal, 2004).

Nevertheless, agroecological cropping areas despite having lower total density preserve the shape of the diameter distribution and retain a fraction of larger trees, which improves canopy cover and reduces soil exposure and erosion risk. This condition maintains microclimate stability and provides habitat for regeneration, resulting in carbon stocks that approach those of forested systems and significantly surpass those of conventional croplands (MEDEIROS, CESÁRIO, & MAIA, 2023; MENEZES et al., 2021).

Furthermore, agroforestry systems show a trend of recovery in the 6–12.9 cm classes, which can be interpreted as a sensitive indicator of renewed recruitment. Useful operational goals include: increasing the annual proportion of these classes, reducing the gap relative to the 13–16.9 cm class, and retaining legacy trees as structural nuclei and seed sources (Santana et al., 2019).

The preservation of the full diameter spectrum in native Caatinga with an abundance of thin individuals and, albeit fewer, large-diameter trees underpin higher carbon stocks in biomass, necromass, and soil. As land use truncates this distribution (transition → agriculture), ecosystem structure, function, and carbon are simultaneously lost (MENEZES et al., 2021), entirely consistent with the SAVI and carbon gradients shown in the previous figures and tables.

CONCLUSIONS:

The protection of Caatinga remnants is irreplaceable for maintaining high and stable carbon stocks, with ≈64.8 Mg C ha^{-1} distributed among soil, woody biomass, roots, litter, and necromass. These fragments function as “ecosystem service powerhouses,” regulating microclimate, reducing erosion, and sustaining a continuous input of organic matter to the soil. The loss of this structureas observed in conventional agriculture (≈26.4 Mg C ha^{-1}) implies canopy collapse, disruption of the detrital cycle, concentration of carbon solely in the soil, and greater vulnerability to degradation.

As a practical pathway for mitigation and adaptation in the semiarid region, agroecological systems stand out by partially restoring woody structure, increasing soil cover, and reactivating detrital fluxes, achieving intermediate stocks (≈35.1 Mg C ha^{-1}) and functionally approaching native vegetation. SAVI and fCover evidence confirm this structural and photosynthetic recovery. Therefore, we recommend: (i) legal protection and active management of forest remnants as nuclei of carbon stability.

In cultivated areas, we suggest guided expansion of agroforestry and agroecological arrangements that retain legacy trees, incorporate woody species, maintain permanent soil cover, and manage grazing intensity, prioritizing Cambisols and Oxisols while mitigating the limitations of Luvisols, Planosols, and Entisols.

Finally, continuous monitoring of these areas is necessary; remote sensing has proven to be a powerful supporting tool to guide productive restoration targets. Altogether, conserving what remains and transforming what is used represent the most effective strategies for a low-carbon transition in the Caatinga.

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