

Structure and Carbon Stocks in Small-Scale Agroforestry Systems on Degraded Pasture in Southeastern Brazil: A Descriptive Case Study

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Short Report

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Abstract

Agroforestry systems (AFS) are a key strategy for restoring degraded pastures while sequestering atmospheric carbon. However, most studies focus on large-scale systems, with limited data on small, intensive plots. This descriptive case study quantifies the structure and carbon stocks of two small-scale AFS (597 m² each) established on degraded pasture in the Atlantic Forest-Cerrado transition zone of São Paulo State, Brazil. We inventoried all trees with DBH > 5 cm in a 3-year-old system (AFS-3) and a 6-year-old system (AFS-6). AFS-3 contained 54 trees (*Hevea brasiliensis* (Willd. ex A.Juss.) Müll.Arg., *Theobroma cacao* L., and *Corymbia citriodora* (Hook.) K.D.Hill & L.A.S.Johnson) and stored 17.8 t C (95% CI: 10.6–27.3 t C), while AFS-6 contained 55 trees (*H. brasiliensis* and *T. cacao*) and stored 22.1 t C (95% CI: 18.2–26.1 t C). The difference of 4.3 t C over 3 years represents an annual accumulation rate of 1.4 t C yr⁻¹. In AFS-6, *H. brasiliensis* contributed 63.5% of total carbon, while *C. cacao* dominated in AFS-3 (65.6%). Mean carbon per tree was 329 kg in AFS-3 and 402 kg in AFS-6. This study provides a valuable baseline for understanding the carbon sequestration potential and structural development of intensive, small-scale AFSs, while acknowledging the limitations of extrapolating from small plots.

1. Introduction

The restoration of degraded pastures, which cover millions of hectares in the tropics, is a critical strategy for climate change mitigation and biodiversity conservation. Converting these areas into a productive restoration with high carbon landscapes is a key mitigation pathway for climate and biodiversity (Strassburg et al 2020). Agroforestry systems (AFS) can rebuild ecosystem services, store carbon, and sustain livelihoods (Montagnini and Nair 2020). While the carbon storage potential of large-scale AFS is well-documented, there is a knowledge gap concerning small, intensively managed systems, which are common among smallholders and in educational settings. To avoid over-extrapolation from small plots, we report plot-level totals (t) and compare species composition, stem density/DBH, and total carbon between a 3-year (AFS-3) and an adjacent 6-year system (AFS-6), providing a baseline for similar restoration efforts.

Additionally, small-scale systems are increasingly important in educational contexts, where they serve as living laboratories for teaching sustainable agriculture, carbon accounting, and ecosystem restoration principles. Understanding the performance of these systems is crucial for informing policy and practice at the smallholder level.

2. Materials and Methods

2.1 Study Site

The study was conducted at ETEC Padre José Nunes Dias, a technical school in Monte Aprazível, São Paulo, Brazil (20°46'05.3"S, 49°41'59.7"W, ~ 450 m elevation). The climate is classified as Aw (tropical savanna) according to Köppen-Geiger, with a mean annual temperature of 23.5°C and annual

precipitation of approximately 1,400 mm. The soil is a Oxisol and the region lies in the Atlantic Forest-Cerrado transition zone.

The site was previously occupied by degraded pasture with negligible tree cover. This situation reflects a widespread challenge in Brazil, where over 160 million hectares of pasture exist, with more than half showing clear signs of degradation (EMBRAPA 2021). Conventional extensive livestock production on these degraded pastures contributes significantly to greenhouse gas emissions, with carbon footprints exceeding 20 kg CO₂ eq per kilogram of beef produced (Lourenço et al. 2023), underscoring the urgency for more sustainable production alternatives. Two agroforestry systems were established on adjacent plots of equal size (597 m² each). The first section was converted to an AFS in 2019 (AFS-6, 6 years old at time of measurement), and the second in 2022 (AFS-3, 3 years old).

2.2 System Design and Inventory

Both systems were designed with a high density of trees. AFS-3 was established 3 years prior to measurement (June 2022), comprising *Hevea brasiliensis* Willd. ex A.Juss.) Müll.Arg. (rubber), *Theobroma cacao* L. (cacao), and *Corymbia citriodora* (Hook.) K.D.Hill & L.A.S.Johnson (eucalyptus) and AFS-6 was established 6 years prior to measurement (June 2019), comprising *H. brasiliensis* and *T. cacao*. Both employed a "Box" planting design, with structural species (*H. brasiliensis* and *C. citriodora*) positioned around the perimeter as windbreaks, and cacao planted in the interior. Banana plants (*Musa spp.*) were used initially for shade but were not measured as they are herbaceous and fell below the minimum DBH threshold.

In June 2025, all trees with diameter at breast height (DBH) ≥ 5 cm were measured at 1.30 m above ground. For trees with buttresses, swellings, or forks, DBH was measured immediately above the irregularity, following international forestry guidelines. Species identity was verified in the field.

2.3 Biomass and Carbon Estimation

Aboveground biomass (AGB) was estimated using species-specific allometric equations (see Online Resource S1 for details). For *H. brasiliensis* and *C. citriodora*, we used the pantropical equation for moist forests from Chave et al. (2014), which requires DBH and wood density (ρ) as inputs. For *T. cacao*, we applied the cacao-specific equation from Somarriba et al. (2013). Wood density values were sourced from the Global Wood Density Database (Zanne et al. 2009). Aboveground carbon (C) content was estimated by multiplying AGB by a carbon fraction of 0.47, following IPCC (2006) guidelines. Carbon dioxide equivalent (CO₂e) was then calculated by multiplying the carbon stock by 3.667. We report all results in terms of carbon (t C), but CO₂-equivalent (CO₂e) values can be obtained by multiplying C by 44/12 (3.667). Plot-level CO₂e estimates are provided in Online Resource 1 (Table S2).

2.4 Data Analysis

Descriptive statistics (mean, standard deviation, minimum, maximum) were calculated for DBH and carbon stocks for each species within each system. To quantify uncertainty, 95% confidence intervals (CI) for the total carbon stocks were generated using a non-parametric bootstrap method with 10,000

iterations. A sensitivity analysis was performed to assess the influence of the largest tree (a *C. citriodora* with 83 cm DBH) on the total carbon stock of AFS-3.

All analyses were performed in Python 3.11 (Python Software Foundation 2023).

3. Results

3.1 System Structure

The structural characteristics of the two systems are summarized in Fig. 1. In AFS-3, structural diversity was higher due to the presence of *C. citriodora*, which also included the individual with the largest diameter at breast height (DBH = 83.0 cm). In AFS-6, *H. brasiliensis* dominated the stand structure, with a larger mean DBH compared to AFS-3.

A summary of tree DBH by species and system is provided in Table S1 in the Online Resource, and the full DBH distributions are illustrated in Figure S3.

3.2 Carbon Stocks

The total aboveground carbon stock in AFS-3 was 17.8 t (95% CI: 10.6, 27.3 t). In AFS-6, the total stock was 22.1 t (95% CI: 18.2, 26.1 t), indicating a net accumulation of 12.5 t C over three years (Table 1, Fig. 1). Expressed as CO₂-equivalents, these plot-level aboveground stocks correspond to approximately 65 and 81 t CO₂e for AFS-3 and AFS-6, respectively (Online Resource 1, Table S2). In AFS-3, *C. citriodora* was the largest contributor to the carbon stock (65.6%), largely due to a few large individuals (Fig. 1b). In AFS-6, *H. brasiliensis* was the dominant species, accounting for 63.5% of the total carbon (Fig. 1b). The DBH distribution (Fig. 1c) shows that AFS-6 has a more uniform structure with larger *H. brasiliensis* individuals, while AFS-3 exhibits greater structural diversity due to the presence of *C. citriodora* .

Table 1
Total aboveground carbon stocks by species and system.

System	Species	Carbon Stock (t)	95% CI (t)	Contribution (%)
AFS-3	<i>Hevea brasiliensis</i>	4.1	-	23.1%
	<i>Theobroma cacao</i>	2.0	-	11.3%
	<i>Corymbia citriodora</i>	11.7	-	65.6%
	Total	17.8	[10.6, 27.3]	100%
AFS-6	<i>Hevea brasiliensis</i>	14.0	-	63.5%
	<i>Theobroma cacao</i>	8.1	-	36.5%
	Total	22.1	[18.2, 26.1]	100%

3.3 Sensitivity Analysis

Sensitivity analysis revealed that carbon accumulation in AFS-3 is driven by a few large trees. The largest individual, a *Corymbia citriodora* with 83 cm diameter at breast height (DBH), stored 3.8 t C, representing 21.2% of the system's total stock. The five largest trees collectively accounted for 45.8% of AFS-3's total carbon. Notably, even after removing the largest tree, the remaining 53 trees retained 14.0 t C, demonstrating substantial carbon storage capacity across the system. In contrast, AFS-6 showed more equitable carbon distribution, with the largest tree representing only 5.0% of total stock and a median tree carbon content of 0.38 t C compared to 0.07 t C in AFS-3. These patterns suggest that AFS-6's more uniform structure provides more stable carbon accumulation, while AFS-3's younger age results in greater size heterogeneity.

4. Discussion

This study provides a quantitative assessment of two young, intensive AFSs, revealing significant carbon storage potential even in small plots. The accumulation of 17.8 t C and 22.1 t C in 3 and 6 years, respectively, on just 597 m² of formerly degraded pasture is remarkable. The annual accumulation rate of approximately 1.4 t C yr⁻¹ is significant and highlights the rapid biomass development in the early years of system establishment. This rate translates to approximately 5.1 t CO₂e yr⁻¹, which aligns well with the range reported for well-managed tropical AFS (0.5–2 tonnes CO₂/hectare/year; Jung e Vendrametto 2025). The observed accumulation demonstrates that even small-scale, intensive systems can achieve carbon sequestration rates comparable to larger agroforestry operations

Our results align with findings from other cacao-based agroforestry systems in the tropics (e.g., Suárez et al. 2025; Palma et al. 2023). The high carbon stock in AFS-6, dominated by *H. brasiliensis*, highlights the critical role of large, long-lived trees in maximizing long-term carbon sequestration.

The structural shift from a *C. citriodora* dominated system (AFS-3) to a *H. brasiliensis* dominated one (AFS-6) reflects a typical agroforestry management strategy: fast-growing pioneer species are gradually replaced by the primary crop or timber species as the system matures. This structural development reflects the progressive establishment of complex vegetation strata characteristic of mature AFS. Research demonstrates that such systems create stable microclimates, enhance moisture retention, and intensify nutrient cycling (Lopes et al. 2024), factors that strengthen system resilience and productivity over time. This dynamic management optimizes both ecological and economic outcomes, in line with established agroforestry principles (Montagnini and Nair 2004).

These findings have important implications for climate change mitigation strategies. The rapid carbon accumulation rates observed (1.4 t C yr⁻¹) suggest that small-scale, intensive AFS can contribute meaningfully to carbon sequestration at the farm level. When scaled across multiple smallholder properties, such systems could provide significant co-benefits including improved livelihoods, enhanced biodiversity, and landscape restoration. Furthermore, the success of these systems demonstrates the potential for nature-based solutions to climate change that simultaneously address food security and livelihood concerns in tropical regions

It is important to acknowledge the limitations of this study. The small plot size and lack of spatial replication mean that these results cannot be directly extrapolated to a per hectare basis for regional carbon accounting. The results should be interpreted as a descriptive case study rather than a representative sample of agroforestry systems in the region. We quantified only aboveground biomass; belowground biomass and soil organic carbon were not measured, meaning total ecosystem carbon is underestimated. The values reported here likely represent an upper bound scenario due to the intensive management and "Box" design, which may create edge effects that enhance growth.

Despite these limitations, the study provides valuable data for several audiences. For practitioners, it demonstrates that small, intensive plots can store meaningful quantities of carbon, even on degraded land. For educators, it illustrates the application of allometric equations and carbon accounting in a real-world context. For researchers, it contributes baseline data on species performance and carbon accumulation in an underrepresented system type (small-scale, intensive AFS in the Atlantic Forest-Cerrado transition).

Future studies should expand the spatial extent, include replicate plots, and incorporate belowground and soil carbon measurements to provide a more complete picture of carbon dynamics in these systems.

Beyond carbon sequestration, the agroforestry approach offers additional benefits. Silvopastoral systems incorporating tree species improve forage productivity and digestibility (Silva et al. 2023), providing co-benefits for livestock production. Furthermore, the diversification inherent in AFS reduces dependence on external inputs and improves socioeconomic stability for smallholder farmers (Oliveira et al. 2023), making these systems particularly valuable in contexts of climate variability and market uncertainty.

5. Conclusion

This descriptive case study provides direct measurements of the structure and aboveground carbon stocks of two young, intensive agroforestry systems. The findings confirm that even small-scale systems can accumulate significant carbon stocks in a short period, contributing to the restoration of degraded landscapes. Future work should focus on long-term monitoring of these plots and expanding the study to include replicated plots of larger sizes to validate these findings at a broader scale. Future work should incorporate long-term monitoring and replicated, larger plots to validate these findings at broader spatial scales and to track how carbon dynamics evolve as systems mature. Additionally, future research should explore the potential of these systems for carbon credit generation (Awazi et al. 2025), which could provide additional financial incentives for smallholders to adopt and maintain AFS, thereby enhancing both environmental and socioeconomic outcomes.

Declarations

Author Contributions: JGCJ.: designed the study, collected the data and writing original draft. G.G.R.: methodology, performed the analysis, validation the data and wrote the final paper. Both authors reviewed the manuscript.

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Figures

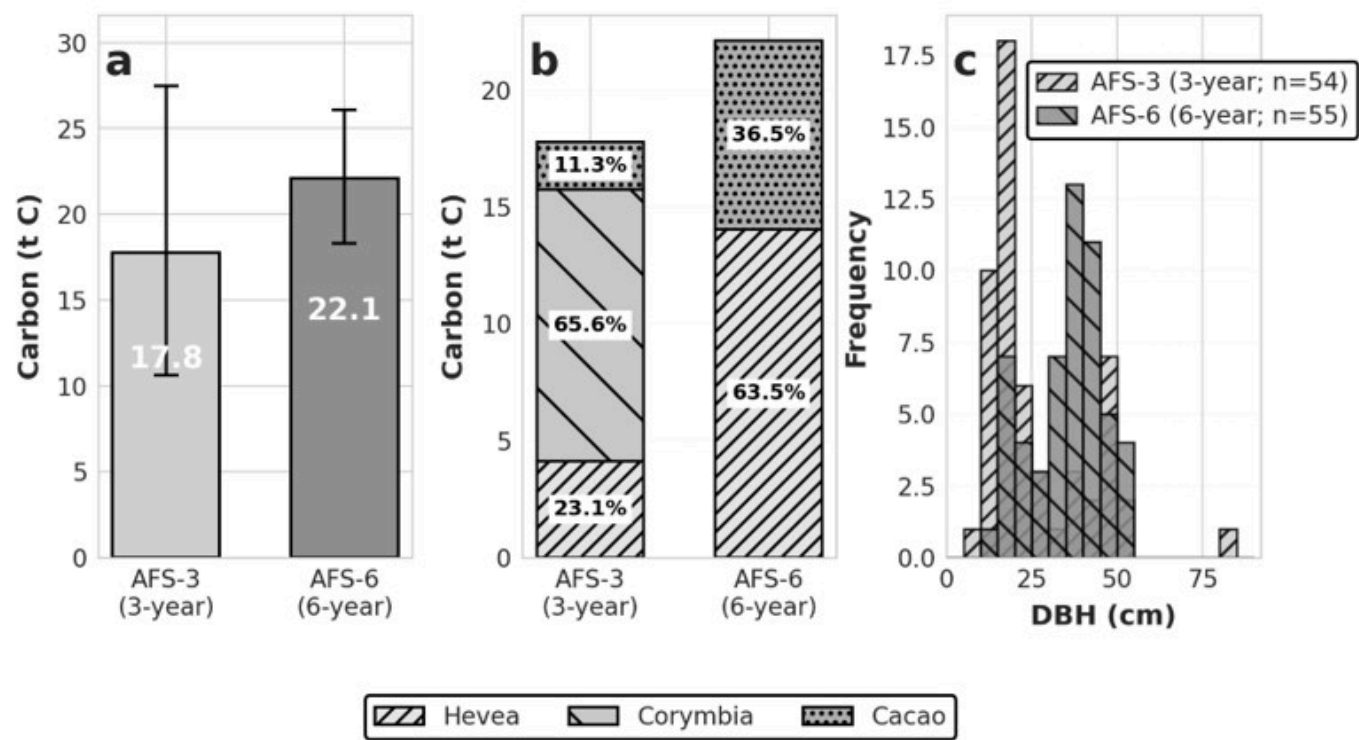


Figure 1

Aboveground carbon and stand structure in two small-scale agroforestry systems on degraded pasture in southeastern Brazil. (a) Total aboveground carbon stock (t C) per plot for the 3-year system (AFS-3) and the 6-year system (AFS-6); bars show means from the complete census and whiskers indicate 95% bootstrap intervals. (b) Contribution of each species to total carbon (stacked bars; *Hevea brasiliensis*, *Corymbia citriodora* and *Theobroma cacao* distinguished by gray tones/hatching) with percentage share printed inside/near segments. (c) DBH frequency distributions (cm) for all trees in each system (AFS-3: n

= 54; AFS-6: $n = 55$), shown with distinct hatching/grays to aid P&B printing. One extreme outlier in AFS-3 (DBH ≈ 80 cm) is displayed in panel (c) but excluded from panel (a) confidence interval computation to avoid leverage. Carbon stocks were calculated from DBH using species-specific allometry and converted to carbon with CF = 0.47.