



Influence of cacao management on tree diversity, carbon stocks and soil properties in the cabruca agroecosystem: a case study in land reform settlements in southern Bahia, Brazil

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Abstract Agroforestry systems (AFS) cultivated with cacao (*Theobroma cacao* L.) shaded by native or exotic trees offer advantages for biodiversity conservation, carbon storage, and soil and water conservation compared to other agroecosystems. However, management practices can influence the extent of an AFS's contribution to ecosystem services. In southern Bahia, Brazil, the AFS known as cacao-cabruca involves cultivating cacao under the shade of

remnant and regenerating trees from the Atlantic Forest biome. Research and extension projects focused on the agroecological transition were developed in two farming communities, aiming to increase cacao bean productivity through practices that enhance nutrient cycling, biological nitrogen fixation, and soil fertility. We conducted this study to assess the influence of the management system on tree species diversity, carbon stocks, and litter and soil properties in areas of cacao-cabruca AFS under conventional, traditional, and agroecological management in two land reform settlements in southern Bahia. Our results demonstrated that areas under agroecological management had greater species richness. However, there was no significant difference in carbon stocks in the soil, leaf litter, or cacao trees among the three management systems. Regarding carbon stocks in shade trees, agroecological and traditional management did not differ, but both were significantly higher than conventional management. Areas under agroecological management showed higher soil levels of Ca, Mg, and K than those under traditional management, and lower C:N and C:S ratios in the leaf litter than those under conventional management. These findings demonstrate the importance of extension projects for enhancing the ecosystem services associated with AFSs.

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Introduction

At the beginning of the twenty-first century, in addition to the supply of food, fiber, and fuel, human society has placed increasing demands on agroecosystem management to prevent environmental degradation and contribute to ecosystem services, particularly regarding biodiversity conservation and carbon capture and storage; (Rosati et al. 2021; Asitoakor et al. 2023). Cacao (*Theobroma cacao* L.) is cultivated in more than 60 tropical countries, covering approximately 11.54 million hectares (Fountain and Hutz-Adams 2022). Cacao agroecosystems support the livelihoods of more than six million smallholder farmers in the humid tropics (Olwig et al. 2023). Agroforestry Systems (AFSs) where cacao is grown under the shade of native trees are among the tropical agroecosystems with the greatest potential to reconcile socioeconomic development with the conservation of biodiversity, soil, and water, in addition to contributing to carbon sequestration and storage in the biomass of shade trees, cacao trees, leaf litter, and soil (Pérez-Neira et al. 2020; Bennett et al. 2021; Pantera et al. 2021). In southern Bahia, a traditional cacao-producing region in Brazil, this association is found in areas of the Atlantic Forest biome, considered a biodiversity hotspot (Faria et al. 2025). In this region, cacao trees are grown in an AFS known as cacao-cabruca. This system involves planting cacao trees within thinned forest areas, which entails removing part of the understory while maintaining trees in the mid- and upper canopy to provide the necessary shade (Piasentini and Saito 2014).

The cacao-cabruca AFS associated with native forest remnants forms a land use mosaic that maintains the forested landscape, promoting the partial conservation of biodiversity, gene flow, connectivity between fragments, and a reduction in vulnerability to climate change (Schroth et al. 2016; Heming et al. 2022). Its long-term maintenance is associated with agronomic and environmental advantages perceived by cacao farmers, such as lower implementation costs, soil protection against erosion, nutrient cycling, improved pollination, the self-regulation of insect populations, protection against wind, and reduced weed growth (Cassano et al. 2009; Nogueira et al. 2019). Furthermore, the cacao-cabruca system is associated with the use of tree species for human food and animal feed, medicinal purposes, timber, and

firewood by workers, family farmers, and land reform settlers (Sambuichi et al. 2012; Nogueira et al. 2019).

Regarding the carbon stored in the above-ground biomass of shade trees, cacao-cabruca AFS across the southern region of Bahia account for a stock of 43.5 Tg of C (Schroth et al. 2013). Furthermore, studies have shown that areas with more intensive management and lower shade tree density suffer reductions in stored C, diversity, structure, and species composition (Figueiredo et al. 2024; Faria et al. 2025). The intensification of management in pursuit of high productivity, through technologies such as mechanization, full-sun cultivation, forced pollination, modular fertilization, and irrigation, among others (Zugaib et al. 2020; Benevides and Conceição, 2025), poses a threat to the preservation and enhancement of the environmental assets associated with this AFS. In more intensive management systems, in addition to C loss from the partial removal of shade trees, another aspect to consider is the loss of C in the leaf litter and soil. This occurs because the partial removal of shade trees can lead to reduced biomass deposition in the litter and accelerated decomposition of soil organic matter, driven by higher near-ground temperatures (Da Costa et al. 2021; Heming et al. 2022). Maintaining C stocks in the soil and litter is crucial because most of the cacao-growing area in southern Bahia is dominated by soils of low to medium fertility, such as Red-Yellow Latosols, Yellow Latosols, and Dys-trophic Argisols (Virgens Filho et al. 2025a, b), which are poor in easily weatherable minerals and provide few nutrients to the plants. In these environments, the majority of nutrients, including C, is immobilized in the above-ground biomass and in the organic layer within the top few centimeters of the soil (Mello et al. 2019; Suárez et al. 2026).

Starting in the 1990s, with the epidemic of “witch’s broom” disease (caused by the fungus *Moniliophthora perniciosa*), coupled with falling international prices and declining, low-productivity harvests, the cacao-cabruca AFS became vulnerable to being replaced by other land uses such as pastures and coffee. At the same time, many rural properties were expropriated for land reform, most often due to their low productivity, leading to the establishment of land reform settlements composed of family farmers organized into cooperatives and associations. Most of these settlements are formed mainly by former rural workers, known in Brazil as “assentados”

(land reform settlers) (INCRA, 2018). Many of these settlers adopted organic and/or agroecological management in areas with significant remnants of cacao-cabruca AFSs on the expropriated properties. The economic viability of this type of management has been demonstrated by several authors, especially when associated with a premium payment, either for the organic quality of the beans or for the environmental services provided (Crowder and Reganold 2015; Esche et al. 2023). In light of this reality, research and extension projects by public educational institutions and non-governmental organizations, with an emphasis on agroecology and organic production, began to target these settlements (Nogueira et al. 2019). Such projects focused on maintaining natural cycles and processes over the intensive use of inputs, including the maintenance via natural regeneration (Sambuichi et al. 2012) and planting of leguminous and fruit trees, organo-mineral fertilization, association with mycorrhizae, control of herbivorous insect populations by natural enemies, and nutrient cycling, achieving satisfactory production (Sabatier et al. 2013; Altieri et al. 2024).

Recent studies comparing conventional monoculture, organic AFS, and organic monoculture agroecosystems have shown that organic AFSs presented several advantages, such as better soil quality, lower energy consumption, reduced agrochemical residues, less water pollution, and reduced total costs, while highlighting increased biodiversity and ecosystem services (Rosati et al. 2021). Notably, across the world, traditional farmers purposefully promote increased species diversity in their agroecosystems for multiple objectives, such as controlling insect populations, increasing resilience to climate instability, and ensuring food security (Berthet et al. 2018; Altieri et al. 2024). This results in higher levels of biodiversity, making these systems more robust, stable, and resistant to disturbances than input-intensive, low-diversity agroecosystems (Armengot et al. 2016; Poggi et al. 2018), and better able to adapt to global climate change (Altieri et al. 2024). Currently, in agrarian settlements of southern Bahia, the profile of cacao farmers can be classified into three management types in areas of cacao-cabruca AFS: (i) farmers using an input-intensive management system aimed at maximizing cacao bean productivity, with partial removal of shade trees permitted by law, without major concerns for the production of forest products

or food security, also called conventional agriculture; (ii) farmers with low input use, who employ traditional management with an emphasis on natural regeneration, nutrient cycling, system stability, and resilience; and (iii) farmers who have adopted organic and agroecological production projects, using inputs permitted by organic agriculture and managing their systems to maintain and increase natural regeneration, nutrient cycling, biological N fixation, food security, and the production of forest products (Nogueira et al. 2019). We conducted this study to assess the influence of the management system on tree species diversity, carbon stocks, and litter and soil properties in areas of cacao-cabruca AFS under conventional, traditional, and agroecological management in two land reform settlements in southern Bahia.

Methods

Background and selection of study area

Between 2007 and 2014, several research and extension projects were conducted in southern Bahia aiming to maintain and improve production efficiency, add value, and sustain and expand the ecosystem services associated with the region's cacao production (Baiardi et al. 2025). These projects were led by the Cabruca Institute, a non-profit organization whose mission is to preserve and enhance the value of the cacao-cabruca production system, in partnership with the Universidade Estadual de Santa Cruz, the Instituto Federal Baiano—Campus Uruçuca, and other partners. The projects benefited approximately 500 family farmers, agrarian reform settlers, quilombola (Afro-Brazilian rural communities), and indigenous communities. In addition to experimental and exploratory research, activities included training technicians and farmers, producing and distributing cacao, fruit tree, forest, and legume seedlings, applying organo-mineral fertilization, renewing declining cacao plantations, and managing biomass to increase nutrient cycling and the biological fixation of atmospheric N (Mello et al. 2019). In 2014, to evaluate changes resulting from the agroecological management promoted by these projects, two communities were selected. They were chosen for being the first areas to benefit, as the involved institutions had initiated

activities there in 2006, eight years prior to the evaluation (Mello et al. 2014).

Area characterization

The data were collected in 2014 in the municipality of Arataca, southern Bahia, Brazil, within the Terra Vista ($15^{\circ}15'06.59''\text{S}$, $39^{\circ}26'38.87''\text{W}$; 151 m of altitude.) and Rio Aliança ($15^{\circ}15'52.35''\text{S}$, $39^{\circ}27'01.90''\text{W}$; 164 m of altitude) agrarian reform settlements (Fig. 1). These contiguous settlements are located in the area surrounding the Serra das Lontras National Park. The study region has become a hub for the production of organic cacao and other crops under agroecological management, and it contains significant remnants of the Atlantic Forest and areas of cacao-cabruca AFS. According to the

Köppen classification, the region's climate is defined as type Af, with high annual precipitation (averaging 2,000 mm) and an average temperature of 23°C (SEI 2023). The geology of the region consists of granulitic rocks formed in the middle or lower Precambrian (Souto et al. 1972), and the predominant soils in both communities are dystrophic Red-Yellow Argisols (Santos et al. 2025; Santana et al. 2002).

Selection of farmers and areas based on management

In agricultural lands previously expropriated under conventional management, farmers and their respective areas (land reform settlers) were selected based on their management practices, defined as conventional, traditional, and agroecological. These lands had a 22-year history of traditional cacao-cabruca

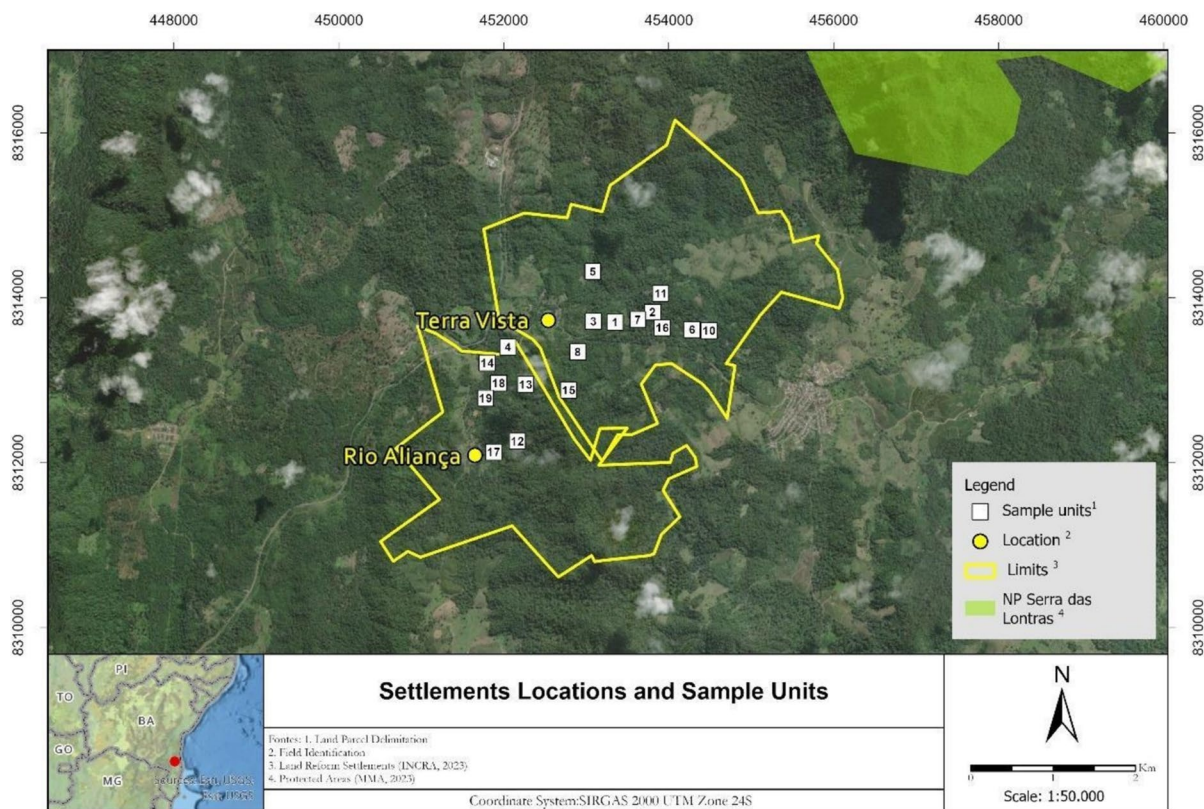


Fig. 1 Geographic location of the Terra Vista and Rio Aliança agrarian reform settlements in the municipality of Arataca, southern Bahia, Brazil, as well as the spatial distribution of the 19 sampled cacao-cabruca areas. The map, referenced to the SIRGAS 2000 UTM zone 24S coordinate system, identifies the sampling units numbered 1–5 as areas under conventional

management, 6–14 under agroecological management, and 15–19 under traditional management, allowing visualization of the proximity between the management systems and their insertion in a landscape marked by remnants of the Atlantic Forest and the vicinity of the Serra das Lontras National Park

AFS management. The areas designated for agroecological management had been under this system for eight years, following the start of projects focused on agroecological transition in areas previously under traditional management. In contrast, the areas under conventional management had been cultivated in this way for ten to twelve years, based on rural credit projects implemented by INCRA (National Institute for Colonization and Agrarian Reform). In each farmer's plot, a 1.0 ha area with low slope was selected, characterized by Red-Yellow Argisol, classified according to the Brazilian soil classification system (Santos et al. 2025) through excavations and micro-trench analyses of $0.8 \times 0.8 \times 0.8$ m. The criteria used to select the type of management employed by the farmer were the farmer's self-declaration and on-site verification by extension agents from the Cabruca Institute. For conventional management, verification involved confirming the constant removal of shade trees, phytosanitary pruning, and bark management, along with the use of liming, chemical fertilizers, and the application of synthetic insecticides, herbicides, and fungicides. For traditional management, the criteria were that farmers did not prune or remove shade trees, did not use synthetic fertilizers, performed liming sporadically, did not use herbicides or fungicides, and made sporadic use of formicides. For agroecological management, the main criterion was the farmer's adherence to the guidelines of technicians and researchers—or their own initiative—regarding recommended cultural practices, such as pruning shade trees, maintaining and planting nitrogen-fixing leguminous species (Canosa et al. 2012), using biological

sprays, organic and organo-mineral fertilization, biomass management, green manure, and composting cocoa husks. Nineteen areas were selected because they fully met the criteria of one of the management approaches; nine areas belonged to farmers practicing agroecological management, five to traditional management, and five to conventional management.

Floristic inventory of tree species and carbon stock estimates

In the 19 1.0-ha plots, all shade trees with a diameter at breast height (DBH) ≥ 10 cm—measured at 130 cm above the ground—as well as their commercial height (CH) and total height (H) were measured. This was done using a standard diameter tape and a 200m-capacity laser hypsometer, respectively. From the collected data, the total vegetation biomass (TB) was estimated using allometric equations. For native trees in southern Bahia (Tiepolo et al. 2002), rubber trees (*Hevea brasiliensis*), peach palm (*Bactris gasipaes*), and *Cecropia* spp., the equations were based on DBH. For cacao (*Theobroma cacao*) (Fernandes 2018) and banana (*Musa paradisiaca*) (Noordwijk et al. 2002), they were based on the diameter at 30 cm above ground level (D_{30}) (Table 1). To calculate the total carbon stock, the TB for shade trees was multiplied by 0.5, following the methodology proposed by the Intergovernmental Panel on Climate Change and used by several authors (IPCC 2014; Somarriba et al. 2021; Schroth et al. 2013). For cacao trees, the carbon stock was calculated by multiplying the TB value by 0.46 (Fernandes 2018).

Table 1 Allometric equations used to estimate the total aboveground biomass (TB) of the trees that make up the cocoa-cabruca AFS in the studied settlements, discriminating species groups and equation sources

Species	Equation (Author)
Native trees Atlantic Forest Southeast of Bahia	$TB = 21.297 - 6.953 \cdot (DBH) + 0.74 \cdot (DBH)^2$ Tiepolo et al. (2002)
Cacao (<i>Theobroma cacao</i>)	$TB = 10^{(-1.625 + 2.63 \cdot \text{LOG}(D_{30}))}$ Andrade et al. (2008)
Native palm trees	$TB = 6.6666 + (12.826) \cdot (DBH)^{0.5} \text{Ln}(DBH)$ Pearson et al. (2005)
<i>Cecropia</i> sp.	$TB = 2.764 + 0.2588 \cdot (DBH)^{2.0515}$ Pearson et al. (2005)
<i>Bactris gasipaes</i>	$TB = 0.97 + 0.078BA - 0.00094$ Pearson et al. (2005)
<i>Musa paradisiaca</i>	$TB = 0.030 \times D_{30} H^{2.13}$ Van Noordwijk et al. (2002)
<i>Hevea brasiliensis</i>	$TB = 3.84 + 0.528 \cdot BA + 0.001 \cdot BA^2$ Schroth et al. (2013)

Each equation is associated with a specific group (native Atlantic Forest trees, rubber tree, palm trees, *Cecropia* spp., banana, and cacao), using the diameter at breast height (DBH) or the diameter at 30 cm from the ground (D_{30}) as the explanatory variable. This allows transforming field dendrometric measurements into estimates of dry biomass per individual or per hectare, forming the basis for calculating carbon stocks in shade vegetation and cacao trees

Chemical composition and litter carbon stock

During September 2014, litter was collected in the 19 areas where the phytosociological survey was conducted. Within each 1.0 ha plot, 12 random samples were collected using a 0.25×0.25 m quadrat. To determine dry mass, samples were placed in paper bags and dried in a forced-air oven at 65 °C until a constant weight was achieved. The amount of litter collected in the quadrat ($\text{g}/0.0625 \text{ m}^2$) was used to estimate the total accumulated mass, expressed as Mg C ha^{-1} . The litter was then ground in a Wiley mill, passed through a 1.0 mm (20-mesh) sieve, and stored in glass vials for subsequent chemical analysis. Plant tissue was subjected to wet digestion for the determination of N, P, S, K, Ca, Mg, and organic carbon. N was determined by the Kjeldahl method via titration. K was measured using a flame photometer, while P and S were measured using a visible spectrophotometer. Ca and Mg were measured using an atomic absorption spectrophotometer. Organic carbon was determined by the Walkley–Black method (Miyazawa, 1999).

Chemical properties, density, and soil carbon stock

A Dutch auger was used to collect disturbed samples from depths of 0–20 cm and 20–40 cm. Within the 1.0 ha sampling units, each composite sample consisted of 50 simple sub-samples. These same units were used for the dendrometric survey and botanical identification. Total organic carbon (TOC) was determined using the Walkley–Black method, which was chosen because it measures only oxidizable C (Braz et al. 2014). The chemical properties of the soil, pH, CEC, CEC at pH 7.0, exchangeable calcium, magnesium and potassium, and available phosphorus were determined according to analytical methods described in EMBRAPA (2011). Soil bulk density (Ds) was determined from 10 undisturbed samples taken from each 1.0 ha plot at each depth (0–20 cm and 20–40 cm) using the volumetric ring method. Ds was calculated with the formula: $D_s = M_s/V$, where M_s is the mass after oven-drying at 110 °C and V is the volume.

Statistical analysis

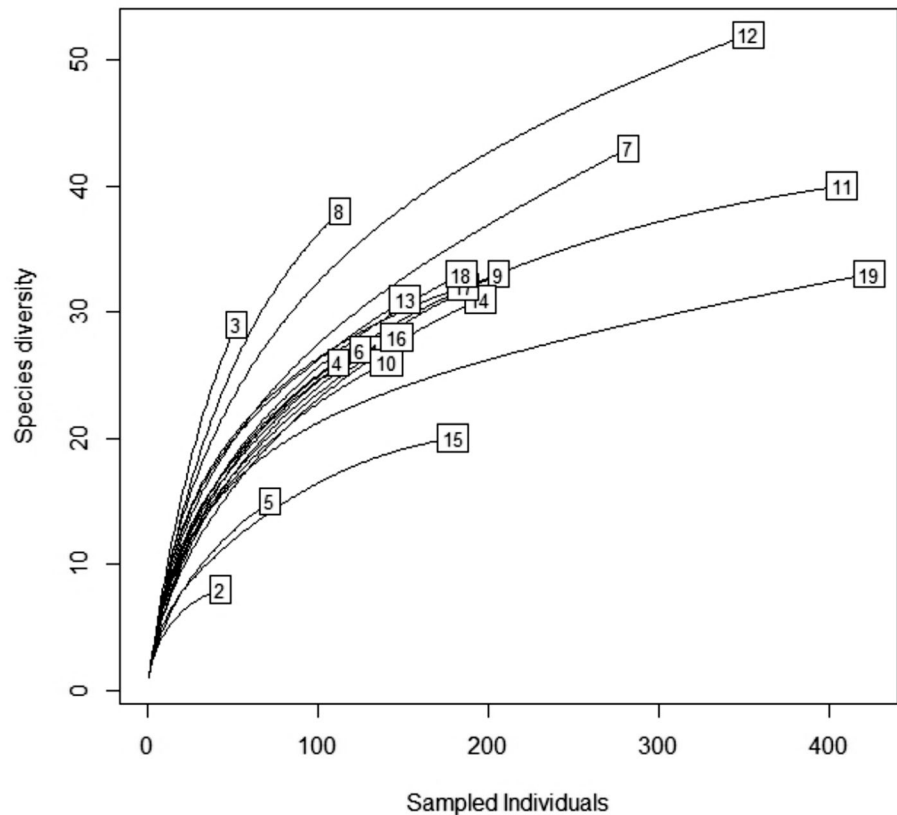
We collected data on C content in soil, litter, and vegetation; soil chemical properties; litter chemical composition; and vegetation biomass (shade trees and cacao). We also gathered floristic diversity estimates, including the Shannon–Wiener index (H'), the Pielou's evenness index (Pielou 1975) evenness coefficient (J') (Gotelli and Colwell 2001), and diameter measurements (IN, DBH, H, CH, and BA) for all 19 areas. From these data, we calculated the average for each management type and compared all variables using Tukey's test at a 5% significance level ($p < 0.05$). Additionally, we generated a species rarefaction curve for the 19 areas, species accumulation curves for each management type, and frequency density histograms by management type and ecological group. Ecological groups were defined according to Budowski (1965) classification as: pioneer, early secondary, late secondary, climax, and exotic/undetermined species. Each species identified in the field was classified into its ecological group following Carvalho (2008). All analyses were performed in the R statistical software (version 4.3.3) with the following packages: TukeyHSD, vegan, BiodiversityR, ggplot2, rayshader, dplyr, raster, and Rcmdr (R Core Team 2024).

Results

Floristic inventory of tree species and carbon stock estimates

In the 19 areas studied, regardless of management type, 3,507 individual trees belonging to 110 species and 32 botanical families were recorded (Supplementary material). The agroecological management system contained 95 species (87 native, 91.57%; 8 exotic, 8.43%); the conventional system had 66 species (56 native, 90.32%; 6 exotic, 9.68%); and the traditional system had 51 species (47 native, 92.16%; 4 exotic, 7.84%). The species rarefaction curve showed greater species richness for sampling units 3, 7, 8, 11, 12, 13, and 18 compared to units with the same number of individuals (Fig. 2), comprising one area under conventional management (3), five under agroecological management (7, 8, 11, 12, and 13), and one under traditional management (18). The species accumulation

Fig. 2 Rarefaction curve of tree species obtained from the 3,507 individuals recorded in the 19 cacao-cabruca areas, regardless of the management system. The curve shows the relationship between the cumulative number of sampled individuals and the expected species richness, highlighting that some sampling units (3, 7, 8, 11, 12, 13, and 18) exhibit greater richness than others with a similar number of individuals, indicating floristic heterogeneity between areas. Arataca, Bahia, Brazil



curve indicated that agroecological management had the highest species richness, with values higher than those of conventional and traditional management from points 1 to 5 (Fig. 3). The mean richness for all possible combinations of 5 locations (point 5) was 83.43 for agroecological management, 59 for traditional management, and 57 for conventional management (Fig. 3). The highest mean species richness was observed in the agroecological management system (34.33), which was statistically different from the conventional system (23.4) but not from the traditional system (29.2) (Table 2). Regarding the Shannon index, areas under agroecological management had the highest mean (2.87), followed by areas under traditional (2.63) and conventional (2.31) management; however, there was no significant statistical difference among them. The highest mean values for Pielou's evenness index were also obtained in the agroecological system (0.81) and were similar to the conventional (0.78) and traditional (0.78) systems, with no statistical differences among them (Table 2). The results showed that the management system

influenced DBH, H, IN, and C stock of shade tree biomass (Table 3), but no significant differences were found between management systems for BA. In addition to exhibiting higher species richness, areas under agroecological management also showed a higher relative frequency for all ecological groups within the 10–30 cm DBH range (Fig. 4). For climax species, the percentage in this range was 89.09%, followed by pioneer (71.79%), early-secondary (63.91%), late-secondary (53.33%), and exotic (44.65%) species. Areas under traditional management followed the same sequence: 76.60% for climax, pioneer (64.53%), early-secondary (58.16%), late-secondary (42.76%), and exotic (11.03%) species. Conversely, areas under conventional management had a higher percentage of pioneer species (38.46%) in this range, followed by early-secondary (36%), exotic (32.94%), climax (13.64%), and late-secondary (11.48%) species (Fig. 4). For all ecological groups except exotics, areas under conventional management had a higher percentage of individuals in the larger DBH classes (from 30–50 cm to > 110 cm). For exotic species in

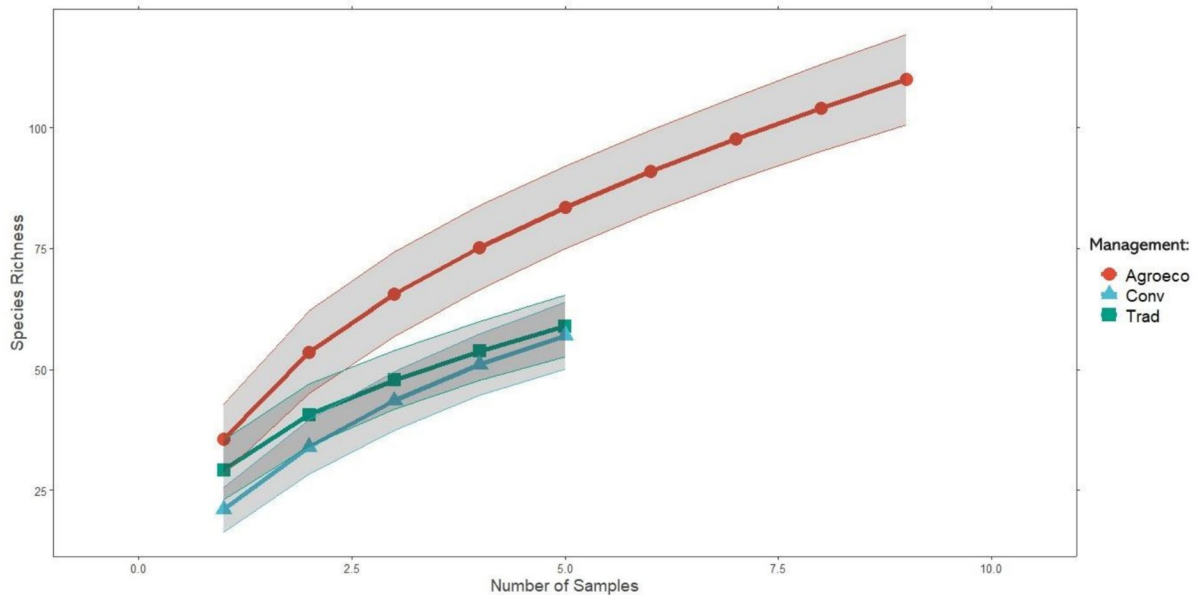


Fig. 3 Tree species accumulation curves in 19 sampled cacao-cabruca areas classified according to three management systems: agroecological (Agroeco), conventional (Conv) and traditional (Trad). Arataca, Bahia, Brazil

Table 2 Species richness, Shannon–Wiener index (H'), Pielou's evenness index (J') and coefficient of variation (CV) for shade trees in 19 sampled cacao-cabruca areas classified according to three management systems: conventional (Conv), agroecological (Agroeco) and traditional (Trad). Arataca, Bahia, Brazil

	N	Richness	H'	J'
Conv	5	23.40b	2.31a	0.78a
Agroeco	9	34.33a	2.87a	0.81a
Trad	5	29.20ab	2.63a	0.78a
CV (%)	–	21.02	5.23	1.17

Means followed by the same letter in the columns do not differ from each other according to the Tukey test at 5% significance. CV (coefficient of variation)

the 30–50 cm and 50–70 cm ranges, areas under traditional management had a higher percentage of individuals, while in the > 110 cm range, agroecological areas had the highest percentage. For climax species, areas under agroecological management had no individuals in the 70–90 cm and 90–110 cm DBH ranges. Similarly, areas under traditional management had no pioneer species in the 70–90 cm DBH range. Areas under conventional management showed a higher percentage for the climax (50.0%) and late-secondary (26.23%) ecological groups in the 30–50 cm DBH

range, compared to early-secondary and exotic groups in the 10–30 cm range.

The areas under traditional management had a mean C stock of 205.48 MgC ha⁻¹ (Table 3), which did not differ statistically from the areas under agroecological management (192.28 MgC ha⁻¹). In contrast, areas under conventional management were statistically different from the others, with only 67.35 MgC ha⁻¹. Mean values for DBH and CH in the conventional management system were significantly higher than those in the agroecological and traditional systems, which did not differ from one another. Conversely, the NI showed the opposite trend, with the highest mean values observed in the traditional and agroecological management systems, respectively; these two did not differ significantly from each other. The mean NI value in the traditional management system was approximately three times higher than that in the conventional management system.

For the cacao trees, no statistically significant differences were found between management systems for BA, D_{30} , and NI, other than the C stock in the biomass (Table 4). Areas under conventional management had the highest average diameters at 30 cm from the soil (D_{30}), followed by those under agroecological

Table 3 Means of basal area (BA, m² ha⁻¹), diameter at breast height (DBH, cm), total height (H, m), commercial height (CH, m), number of individuals per hectare (NI) and C stock in biomass (Mg ha⁻¹) of shade trees in 19 sampled cacao-cabruca

areas classified according to three management systems: conventional (Conv), agroecological (Agroeco) and traditional (Trad). Arataca, Bahia, Brazil

Species		N	BA	DBH	H	CH	NI	C
Total	Conv	5	13.01a	44.30a	16.18a	4.90a	83b	67.35b
	Agroeco	9	12.44a	27.52b	14.50a	2.40b	223a	192.28a
	Trad	5	15.30a	26.56b	15.57a	2.32b	247a	205.48a
	CV (%)		10.31	6.55	8.90	16.74	6.91	14.53%
Native	Conv	5	9.72a	44.16a	16.76a	4.50a	51b	40.32b
	Agroeco	9	8.01a	25.96b	14.64a	1.90b	173ab	150.49a
	Trad	5	10.07a	23.03b	14.68a	2.30b	196a	160.64a
	CV (%)		14.56	12.32	5.69	11.54	7.66	8.87%
Exotics	Conv	5	3.29a	36.19a	13.68b	4.80a	32a	27.12a
	Agroeco	9	4.43a	33.56a	14.50ab	3.70a	50a	41.92a
	Trad	5	5.23a	40.74a	17.67a	2.10b	51a	46.58a
	CV (%)		20.54	12.22	7.98	23.00	11.31	8.30

Means followed by the same letter in the columns do not differ from each other according to the Tukey test at 5% significance. CV (coefficient of variation)

management. In terms of the number of individuals (NI), the agroecological areas showed a higher plant density. As a result, these areas also had the highest average basal area at 12.7 m² ha⁻¹. Although the individual differences were not statistically significant, the results show that the greater plant density per ha, in the agroecological areas, combined with a slightly smaller average diameter (D_{30}) than in conventional areas, were the decisive factors. This combination resulted in the agroecological areas having an average C stock in the cacao plant biomass of 8.43 Mg C ha⁻¹, compared to 7.13 and 6.63 Mg C ha⁻¹ in the conventional and traditional management areas, respectively (Table 4).

Litter chemical composition and carbon stock

The management systems significantly influenced the N and S levels, as well as the C:N and C:S ratios in the litter (Table 5). In contrast, no significant differences were found between the management systems for C and P levels, the C:P ratio, and the carbon stock in the litter biomass. The highest mean N level in the litter was observed in the traditional management system, which differed from the conventional system. This was followed by the agroecological system, which did not differ significantly from either the traditional or conventional systems. Regarding S, the

highest mean levels were found in the agroecological and traditional systems. The mean S level in the agroecological system was significantly higher than in the conventional system, while the traditional system did not differ from the other two. The lowest C:N ratios were found in the areas under traditional and agroecological management, which differed statistically from the conventional management areas. Similarly, the C:S ratio in the agroecological areas was lower and statistically different from the conventional and traditional areas; however, no statistical difference was observed between the conventional and traditional areas, nor between the traditional and agroecological areas.

Soil chemical properties, density, and carbon stock

Significant differences were observed between management systems for Ds, with the highest and lowest mean values corresponding to the traditional and conventional systems, respectively (Table 6). Neither TOC, CEC (pH 7.0), nor carbon stock differed significantly across the three management systems analyzed. Significant differences between management systems were also observed for pH, CEC, and for P, K, Ca, and Mg levels. For soil chemical properties, the highest mean values of pH, CEC, K, and Ca were found under agroecological management.

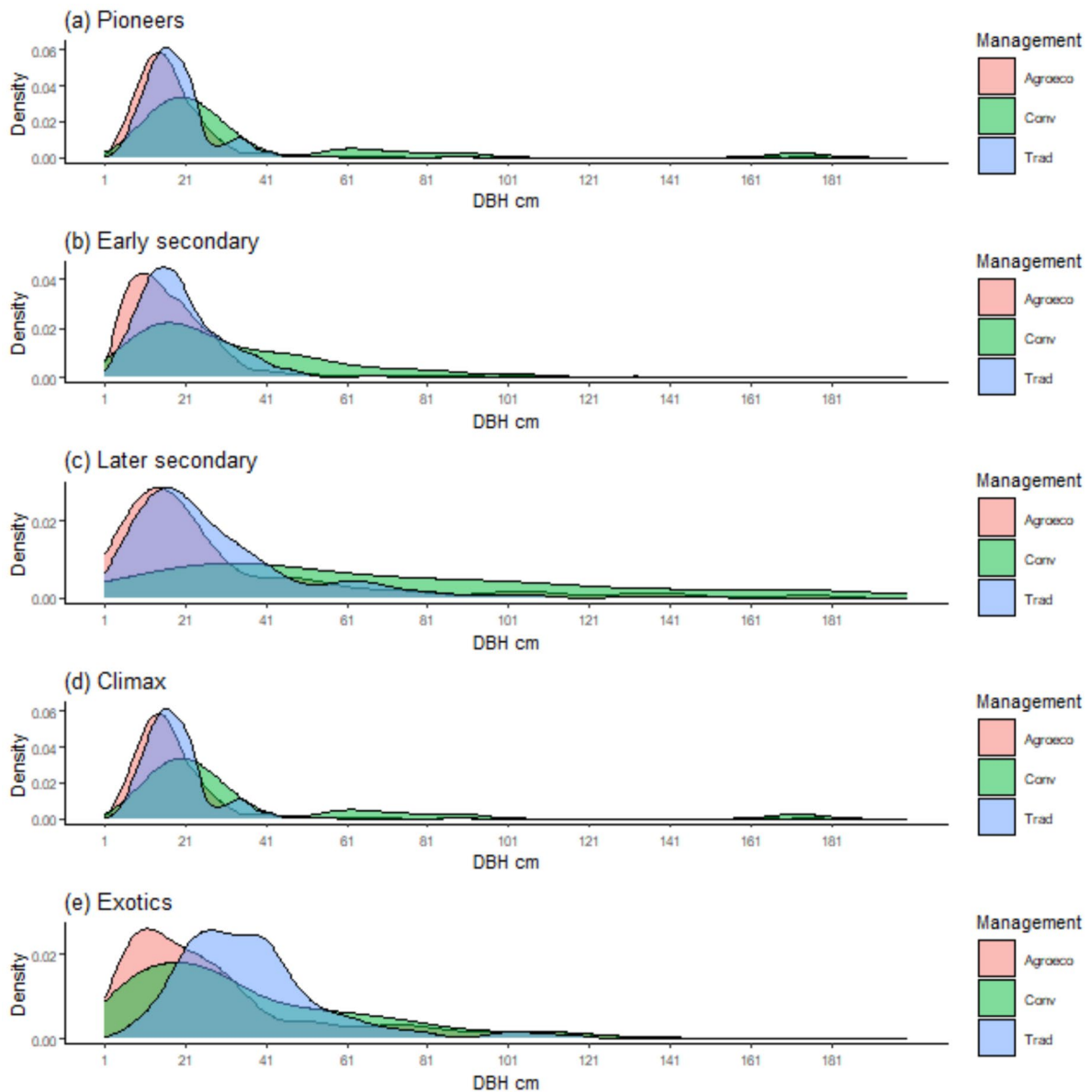


Fig. 4 Histograms of individual density frequency by diameter at breast height (DBH) classes for different ecological groups of species (pioneer, early secondary, late secondary, climax, and exotic) in 19 sampled cacao-cabruca areas classi-

fied according to three management systems: agroecological (Agroeco), conventional (Conv) and traditional (Trad). Arat-aca, Bahia, Brazil

These did not differ significantly from conventional management, but both were significantly higher than traditional management. For soil phosphorus levels alone, conventional management resulted in significantly higher values than agroecological and traditional management, which did not differ from

each other. Finally, while mean Mg levels under agroecological management were significantly higher than under conventional management, traditional management did not differ significantly from either.

Table 4 Mean basal area (BA, m² ha⁻¹), diameter at 30 cm above ground level (D₃₀, cm), number of individuals per hectare (NI) and C stock (Mg ha⁻¹) of cocoa trees in 19 sampled cacao-cabruca areas classified according to three management systems: conventional (Conv), agroecological (Agroeco) and traditional (Trad). Arataca, Bahia, Brazil

	N	BA	D ₃₀	NI	C
Conv	5	12.33a	13.23a	932a	7.13a
Agroeco	9	12.7a	12.27a	1107a	8.43a
Trad	5	9.79a	11.89a	830a	6.63a
CV (%)		18.73	13.45	25.60	13.40

Means followed by the same letter in the columns do not differ from each other according to the Tukey test at 5% significance. CV (coefficient of variation)

Discussion

The results of this study showed that farmers' management practices affect C stocks, tree diversity, and the quality of soil and leaf litter. Regarding C, the values obtained in this study were higher than those reported by Schroth et al. (2013) for conventionally

and traditionally managed cabruças, respectively. These values were also very close to the mean values reported by Fernandes (2018) and Faria et al. (2025) for areas under agroecological and traditional management, while values for conventionally managed areas in the present study were lower. The higher C values in tree biomass in both the present study and that of Fernandes (2018) may be attributed to the natural soil fertility—medium to high in both study regions—compared to the areas in Schroth et al. (2013), which were predominantly of low soil fertility (Virgens Filho et al. 2025a, b). The variation found between areas with the same management type was also high across all studies, reflecting the influence of individual farmer practices, even among farmers adopting the same management system or located in the same region (Guimarães et al. 2017; Figueiredo et al. 2024; Hernández-Nóñez et al. 2025; Suárez et al. 2026). Traditional farmers emphasize maintaining trees in their agroecosystems to increase soil fertility through nutrient cycling, enhance resilience to extreme climate events like droughts and floods,

Table 5 Means of carbon (C), nitrogen (N), phosphorus (P) and sulfur (S) contents, C:N, C:P and C:S ratios, and C stock in litter of 19 sampled cacao-cabruca areas classified according

to three management systems: conventional (Conv), agroecological (Agroeco) and traditional (Trad). Arataca, Bahia, Brazil

	N	C (mg.kg ⁻¹)	N	P	S	C:N	C:P	C:S	C stock (Mg ha ⁻¹)
Conv	5	44.15a	1.39b	0.11a	0.14b	32.08a	425.3a	304.2a	3.89a
Agroeco	9	40.42a	1.56ab	0.09a	0.17a	26.20b	443.9a	243.2b	3.87a
Trad	5	42.90a	1.86a	0.09a	0.16ab	23.35b	456.7a	271.3ab	4.27a
CV (%)		43.23	4.13	0.41	0.14	56.40	45.20	25.60	26.40

Means followed by the same letter in the columns do not differ from each other according to the Tukey test at 5% significance. CV (coefficient of variation)

Table 6 Means of water pH, cation exchange capacity (CEC, cmolc dm⁻³), phosphorus (P, mg dm⁻³), potassium (K, mg dm⁻³), calcium (Ca, cmolc dm⁻³) and magnesium (Mg, cmolc dm⁻³), soil bulk density (Ds, kg dm⁻³), total organic carbon (TOC, g dm⁻³) and carbon stock (Mg ha⁻¹) in the soil between

0 and 40 cm depth, in 19 sampled cacao-cabruca areas classified according to three management systems: conventional (Conv), agroecological (Agroeco) and traditional (Trad). Arataca, Bahia, Brazil

	N	pH	CEC	P	K	Ca	Mg	Ds	TOC	carbon stock
Conv	5	5.85a	5.39a	5.63a	59.85a	3.76a	1.33ab	1.1b	11.52a	46.1 a
Agroeco	9	5.86a	6.38a	2.2b	50.31a	4.52a	1.93a	1.21ab	11.62a	46.5a
Trad	5	4.71b	3.63b	2.45b	23.00b	1.98b	1.00b	1.31a	10.54a	42.2a
CV (%)		2.84	18.36	24.02	29.56	14.54	4.05%	3.85%	4.89%	—

Means followed by the same letter in the columns do not differ from each other according to the Tukey test at 5% significance. CV (coefficient of variation)

and reduce dependence on external inputs by valuing local resources and traditional knowledge (Sabatier et al. 2013; Altieri et al. 2015, 2024). In contrast, producers who adopt conventional practices prioritize cacao productivity through the application of various inputs in agroecosystems with little or no shade (Zugaib et al. 2020; Porto 2024; Benevides and Conceição, 2025). Despite this individual influence, the higher biomass and consequently higher C stocks in traditionally and agroecologically managed areas may be linked to the producer's focus and mindset regarding management objectives (Nogueira et al. 2019; Figueiredo et al. 2024).

In cacao-cabruca AFS, several authors note that farmers maintain trees to facilitate nutrient cycling, control weeds, and conserve soil organic matter during the early stages of cultivation (Asitoakor et al. 2022; Esche et al. 2023), as well as to preserve native legume species and other species by selecting seedlings via natural regeneration (Sambuichi et al. 2012; Waqar et al. 2025) and selectively maintain shade-producing species following system disturbances (Sambuichi et al. 2012; Lobão et al. 2022). However, most of these traditional farmers generally lack access to credit, technical assistance, and inputs, both globally and specifically in southern Bahia (Chiapetti et al. 2020). In this study, areas under agroecological management, which benefited from extension projects, showed no statistically significant differences compared to areas under traditional management regarding carbon stocks, diversity indices, and shade tree species richness. These areas exhibited a diametric structure with a higher number of individuals with a smaller DBH, particularly for climax and early secondary species. Areas under agroecological management also showed greater species diversity and a higher number of exotic species—including those recommended to increase food and economic security, such as *Euterpe oleracea* and *Persea americana*—compared to areas under traditional and conventional management. This suggests that initiatives promoting the planting and maintenance of nitrogen-fixing and climax species may have contributed to these results. Previous work has also found that floristic composition can be influenced by the actions of public and private institutions through forestry development programs. In the cacao-cabruca AFS, a higher

prevalence of young *Paubrasilia echinata* individuals was also linked to a development program implemented by local and international institutions (Sambuichi et al. 2012). Another key finding was that although areas under agroecological and traditional management had a greater number of individuals than conventionally managed areas, the mean total basal area did not differ among the three management types. This was due to the larger DBH found in conventional areas, which may be influenced by reduced competition for light from lower tree density, resulting in greater radial growth.

The higher proportion of individuals in smaller diameter classes for all ecological groups in areas under agroecological management, and the greater number of trees per hectare with diameter distributions closer to those of tropical forests, may have provided a more favorable habitat for the monodominant growth of climax and secondary species (Lima and Leão, 2013; Sambuichi et al. 2012). This, combined with recommendations to maintain and promote the planting of these species through extension work, likely led to the observed trend when compared to areas under traditional management. Areas under conventional management, on the other hand, have fewer individuals in smaller diameter classes and diameter distributions more similar to planted forests (Lima and Leão, 2013). This may have been influenced by the maintenance of individuals with taller canopies to increase light availability and by the constant removal of individuals with smaller DBH (Sambuichi et al. 2012; Lobão et al. 2022). According to several authors, this practice is necessary to increase light intensity, achieve a higher photosynthetic rate, and improve productivity (Heming et al. 2022). However, the excessive removal of shade trees can negatively affect factors beyond biodiversity and C stock losses, such as increased flooding (Olwig et al. 2023), lower water availability (Heming et al. 2022), greater wind impact (Virgens Filho et al. 2025b), and lower nutrient availability (Olwig et al. 2023). Some authors note that family farmers with limited access to inputs perceive that the lower interception of photosynthetically active radiation is offset by other advantages, resulting in greater productivity in cacao agroforestry systems (AFSC) compared to full-sun systems (Figueiredo

et al. 2024), mainly due to the enhanced nutrient cycling and lower nutrient depletion provided by shade trees (Rosati et al. 2021; Esche et al. 2023; Asitoakor et al. 2023). In the present study, despite the greater shade tree biomass in the agroecological and traditional management systems—which could suggest higher C stocks in the soil and litter due to greater deposition and lower soil temperatures (Brandão et al. 2022; Heming et al. 2022)—no difference was found among the three management types for total C in the litter and soil. However, in the traditional and agroecological systems, lower C:N and C:S ratios were found in the litter compared to that under conventional management. This may have contributed to a higher rate of biomass decomposition and mineralization (Zaia et al. 2012; Mello et al. 2019), thus compensating for the higher soil temperatures in conventionally managed areas and the lower deposition. This effect is likely intensified by the use of organic matter for fertilization in agroecological management and by the greater biomass deposition due to increased forest cover (Zaia et al. 2012; Brandão et al. 2022; Heming et al. 2022). This finding is also corroborated by recent studies that compared managed and abandoned agroforestry cultivation areas of cacao-cabruca with secondary forests, which demonstrated that abandoned agroforestry cultivation areas of cacao-cabruca were more similar to secondary forests in terms of total litter deposition and biomass stocks (Brandão et al. 2022).

This study also demonstrated that the agroecological management system does not differ from the conventional system in terms of nearly all chemical soil properties, and both are statistically different from areas under traditional management. Previous studies in areas with Argisols and Cambisols in southern Bahia revealed that soil organic carbon levels increased after five years of agroecological management in Cambisols, while remaining unchanged in Argisols. However, consistent with the present study, the agroecological management system led to increases in pH, CEC, and exchangeable bases in both soil classes (Mello et al. 2019). These same authors demonstrated that clonal cacao cultivars under agroecological management achieved average yields exceeding regional benchmarks for some cultivars (Mello

et al. 2019; Macêdo et al. 2021; Porto 2024). In this context, maintaining the cacao-cabruca AFS and expanding its potential for C capture are crucial for mitigating GHG emissions, conserving biodiversity both in situ and across the landscape, and enhancing soil fertility. Maintaining and increasing current diversity and complexity can also contribute to the greater resilience of this agroecosystem to climate change, primarily through its ability to maintain natural cycles and processes, such as nutrient cycling and biological N fixation, reducing dependence on inputs and self-regulating insect and plant pathogen populations (Sabatier et al. 2013; Schroth et al. 2016; Pantera et al. 2021; Heming et al. 2022). Therefore, initiatives such as extension projects linked to payment for environmental services, commercialization with premiums for organic quality, and the promotion of native and exotic plants for human and animal nutrition (including non-timber forest products from the cacao-cabruca AFS) are key strategies for conserving biodiversity and mitigating the effects of climate change.

This case study in two agrarian reform settlements in southern Bahia, Brazil, shows that, in this specific context of cacao-cabruca AFS, areas under conventional management exhibit lower diversity of shade trees and lower carbon stocks compared to areas under traditional and agroecological management. At the same time, agroecological areas supported by extension activities and transition projects tended to combine greater species richness—especially of climax, early secondary, and useful exotic species—with carbon stocks in shade trees similar to those of traditional management, in addition to soils with higher pH, effective CEC, and K, Ca, and Mg contents, and litter with lower C:N and C:S ratios than in conventional management, suggesting more efficient nutrient cycling without carbon loss in the soil and cacao biomass. However, because it is based on a limited number of areas (19 plots of 1 ha) in only two settlements, this study does not allow these patterns to be generalized to all cacao-cabruca AFS in southern Bahia or other regions, since edaphic, historical, and farmer practice differences can strongly influence vegetation structure, soil fertility, and carbon stocks. Furthermore, the use of allometric equations and indirect methods

for determining carbon and chemical attributes restricts the ability to infer causal relationships and may introduce uncertainties in the estimated absolute values. Therefore, the results should be interpreted as local evidence that, under conditions similar to those of this study, the agroecological management of cacao-cabruca AFS can reconcile the conservation of tree diversity, maintenance of carbon stocks, and improvement of soil fertility aspects compared to conventional management, highlighting the potential of technical assistance policies, rural extension, payment for environmental services, and organic certification to support agroecological transition trajectories in rural settlements. Studies encompassing a larger number of areas, in different edaphoclimatic contexts, and employing longitudinal and/or experimental approaches are necessary to test the robustness of these patterns and expand their external validity.

Conclusions

Based on the results of this study, we conclude that conventional managed areas in agrarian reform communities experience losses in shade-tree diversity and C stocks when compared with traditional and agroecological managed areas. In contrast, agroecological managed areas, supported by extension projects, increase species richness (especially climax, early secondary, and useful exotic species), maintain C stocks equivalent to those under traditional management, and outperform it in key soil fertility properties (pH, effective CEC, and exchangeable bases K, Ca, Mg), while also presenting litter with lower C:N and C:S ratios, indicative of more efficient nutrient cycling than in the conventional management. These results show that agroecological management of cacao-cabruca AFS reconciles the conservation of tree diversity, the maintenance of carbon stocks, and the improvement of soil fertility, reinforcing the importance of technical assistance, rural extension, payment for environmental services, and organic certification policies to scale up this transition in partnership with local communities.

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Data availability Data will be made available on reasonable request.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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