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Managing shade trees, balancing trade-offs: Effects of shade-tree density on economic performance of Brazilian cocoa agroforests

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ABSTRACT

Cocoa agroforestry systems (CAFS) exhibit considerable variation in shade-tree management, defined by farmers' decisions to retain or remove shade trees. Yet, empirical evidence on the economic implications of shade-tree management remains limited, and few studies offer a multidimensional economic assessment. This study examines the effect of shade-tree density on the economic performance of CAFS in southern Bahia, Brazil. Using data from 313 cocoa-farming households, we combine household-level economic data with ecological field measurements from CAFS plots. We apply Ordinary Least Squares regressions and a coefficient stability approach to assess the effects of shade-tree density on cocoa yield, cocoa production costs, net cocoa income, revenues from other agroforestry crops, and overall returns from CAFS. Results indicate that higher shade-tree densities are associated with lower cocoa yields, but reductions in production costs partly offset these losses, limiting their effect on net cocoa income. Revenues from other crops also decline with increasing shade-tree density, providing insufficient economic benefits to improve overall returns. However, even substantial increases in shade-tree density involve only limited economic trade-offs. The losses are more pronounced in larger CAFS, whereas smaller CAFS appear better able to mitigate productivity losses and sustain returns under higher shade-tree densities. As shade trees provide substantial ecological benefits, policies should therefore prioritise financial incentives that reward farmers for maintaining shade trees in CAFS. These incentives are particularly relevant in the current policy context promoting cocoa production. Emphasizing conservation-oriented mechanisms would better align farm-level economic performance with long-term sustainability objectives in cocoa-producing regions.

1. Introduction

Shade trees play a central role in agroforestry systems (AFS), where they are integrated with agricultural crops to deliver multiple ecological and socio-economic benefits (Blaser et al., 2018; Dekegel et al., 2025; Muthuri et al., 2023; Nair et al., 2021). By supporting biodiversity conservation, delivering ecosystem services and contributing to climate change mitigation, shade trees position AFS among the most effective nature-based solutions for climate-smart, sustainable agricultural production in the tropics (Becker et al., 2025; Blaser et al., 2018; Muthuri et al., 2023; Wenzel et al., 2024; Wurz et al., 2022). Despite these diverse co-benefits, AFS are often perceived to underperform economically compared to monoculture systems, particularly in terms of short-term productivity and profitability (Blaser et al., 2018; Niether et al., 2020; Steffan-Dewenter et al., 2007). This perception has contributed to a global trend toward agricultural intensification in AFS, characterised by the systematic removal of shade trees to achieve higher crop yields and secure immediate income (Harvey et al., 2021; Steffan-Dewenter et al., 2007; Tscharntke et al., 2011). As a result, AFS across the tropics differ substantially, ranging from traditional systems that retain many native

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shade trees after forest thinning to simplified, intensively managed systems with few remaining native shade trees and low species diversity (Becker et al., 2025; Krumbiegel and Tillie, 2024; Schroth et al., 2015; Steffan-Dewenter et al., 2007).

These shifts in land-use and management are particularly pronounced in the cocoa sector, where production systems are characterised by persistent environmental and socio-economic sustainability challenges (Boeckx et al., 2020; Coral et al., 2024; Kalischek et al., 2023; Van den Broeck and Akaribo, 2024). In many regions, cocoa is still cultivated in cocoa agroforestry systems (CAFS), where native shade trees provide essential ecological functions that support long-term production, including disease prevalence, erosion prevention, and regulating microclimates (Blaser et al., 2018; Tscharntke et al., 2011). At the same time, shade trees generate significant socio-economic benefits by supplying timber, fruits, medicinal plants, and other non-timber forest products that diversify income sources and strengthen household food security (Armengot et al., 2016; Cerda et al., 2014). These multifunctional benefits make shade trees valuable assets in systems where smallholder livelihoods are highly vulnerable to market volatility and climate-related risks (Muthuri et al., 2023; Tscharntke et al., 2011). However, farmers also report drawbacks associated with shade trees, such as increased pest and disease pressure, physical damage to cocoa trees from falling branches, and competition for light, water and nutrients (Asitoakor et al., 2022; Blaser et al., 2018; Brown et al., 2025), all of which can reduce cocoa yields.

While cocoa sustainability has received increasing scholarly and policy attention in recent years (Cammelli et al., 2025), several research gaps remain. First, the existing literature has predominantly focused on the role of governance instruments, particularly sustainability standards (Aaron et al., 2024; Depoorter, 2025; Dröge et al., 2025a; Wätzold et al., 2025) and market channels. Research on farming systems in general and agroforestry specifically is more limited. The studies that focus on agroforestry treat it as a distinct land-use type, comparing it to monocultures (Abdulai et al., 2018; Bisseleua et al., 2009; De Beenhouwer et al., 2013; Ferreira et al., 2020; Mattalia et al., 2022; Niether et al., 2020). This dichotomous comparison overlooks the considerable variability within AFS, particularly in terms of shade-tree management, which can have important implications for economic and ecological outcomes. Second, existing research has concentrated on cocoa yield responses along shade-tree management gradients (Asare et al., 2019; Blaser et al., 2018; Clough et al., 2011; Figueiredo et al., 2026; Wade et al., 2010), with limited attention to other dimensions such as production costs and the value of non-cocoa agroforestry products. Although some studies have addressed income diversification (Armengot et al., 2016; Cerda et al., 2014; Notaro et al., 2020), few offer a comprehensive assessment of the overall economic potential of CAFS (Jezeer et al., 2017). Additionally, most of the existing studies focus on Africa (Asare et al., 2019; Bisseleua et al., 2009, 2013; Blaser et al., 2018; Wade et al., 2010), whereas evidence from Latin-America is limited to a handful of studies (Armengot et al., 2016; Cerda et al., 2014; Notaro et al., 2020; Waldron et al., 2012).

With this study, we address key research gaps by using CAFS in southern Bahia as a case study to examine the relationship between shade-tree density and economic performance. In southern Bahia, Brazil's principal cocoa-producing region, traditional, highly shaded and structurally complex CAFS remain prevalent, called *cabrucas* (Dekegel et al., 2025; Sambuichi et al., 2008; Schroth et al., 2015). These systems exhibit a much wider gradient in shade-tree density than the intensively managed, low- or unshaded systems that dominate production in West Africa or other tropical countries,[1] providing an ideal context for assessing how variation in shade-tree density influences economic outcomes. At the same time, cocoa farmers in southern Bahia face market and policy pressures to increase productivity (Ministério da Agricultura e Pecuária, 2024), underscoring the importance of understanding the economic trade-offs associated with shade-tree removal in a context where high-shade systems still predominate.

Using data from 313 cocoa-farming households across 12 municipalities in one of Brazil's main cocoa-producing regions, we combine detailed household-level economic data with ecological data collected through field measurements of shade-tree density in the CAFS plots associated with each surveyed household. We employ Ordinary Least Squares (OLS) regression models and a coefficient stability approach to assess the effects of shade-tree density on multiple economic dimensions, including cocoa yield, production costs, net cocoa income, income from other agroforestry crops, and overall economic returns to land. Doing so, this study offers new insights into how shade-tree density affects the overall economic viability of CAFS. First, our study focuses exclusively on variation within CAFS, assessing how economic outcomes vary across a gradient of shade-tree density. Second, we provide a comprehensive evaluation of economic outcomes that goes beyond cocoa yield to capture the multi-dimensional nature of economic performance in CAFS. Third, our study uniquely integrates detailed household survey data with field-based ecological measurements of shade-tree density across a large sample of cocoa farms. Unlike most other studies that rely on farmers' self-reported estimates, this approach is based on direct field measurements and provides a more accurate assessment of the effects of shade-tree density.

2. Conceptual framework and empirical evidence

To understand how shade-tree density[2] affects the economic performance of CAFS, we develop a conceptual framework (Fig. 1) grounded in existing literature. The framework outlines three primary pathways through which shade-tree density may influence the economic performance of CAFS at the farm level: i) cocoa yield, ii) cocoa production costs, and iii) gross revenue from non-cocoa crops within CAFS, including both income from sales and the value of self-consumed produce. Net income from cocoa is determined by the interaction between yield, price and production costs, while total returns from CAFS combine net cocoa income with gross revenues from non-cocoa crops.

Within this framework, cocoa prices are treated as an exogenous factor, as they are largely determined by global market conditions and are not directly influenced by farm-level shade-tree density. Price fluctuations therefore affect the level of net cocoa income and total returns from CAFS but do not constitute a pathway through which shade-tree density influences economic performance. Nonetheless, farmgate prices may vary across farmers due to differences in marketing channels,

[1] In Ghana and Côte d'Ivoire, the world's main cocoa-producing countries (FAOSTAT, 2023), over 80% of cocoa production is implemented on farms with less than 20% shade (Becker et al., 2025) and fewer than 9% of farmers maintain at least 15 shade trees per hectare on their cocoa plots. Similarly, in Indonesia, forests were often cleared to directly plant cocoa, rather than integrating it underneath the native forest cover (Ruf and Schroth, 2004), with a recent study reporting mean shade-tree densities of only 32 trees per hectare and an average shade cover of 45% (Dröge et al., 2025a).

[2] Shade-tree density is an easily and objectively measurable attribute of agroforestry systems that is also used in regulatory frameworks, such as the Bahia state decree for cocoa agroforestry (State Decree No. 15180/2014, Seção IV, Art. 19), making it directly relevant for evidence-based policy design. Direct measurement of shade cover was not feasible due to time constraints associated with large-scale field data collection.

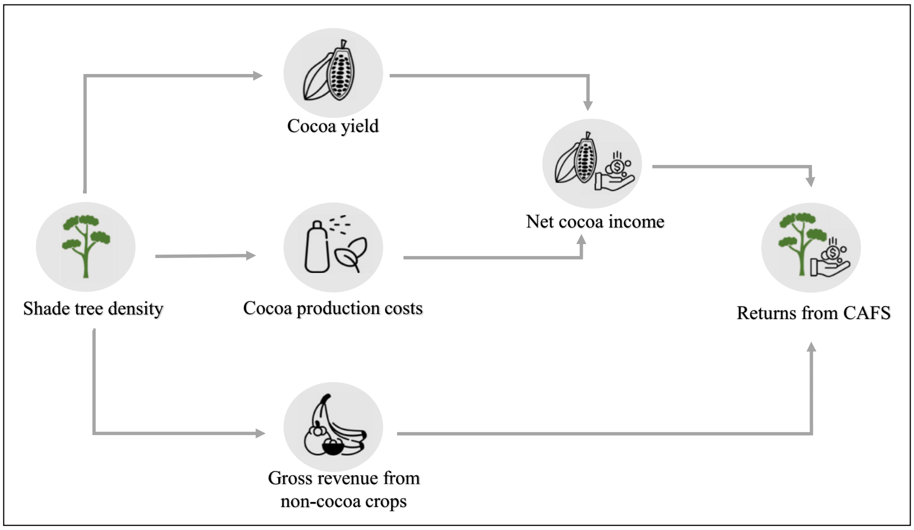

Fig. 1. Conceptual framework illustrating the pathways through which shade-tree density may affect the economic performance of CAFS, defined by five economic outcome variables.

participation in certification schemes, or access to price premiums (Meemken, 2020; Middendorp et al., 2020; Sellare et al., 2020). However, in our research area, such economic valorization schemes are very limited, explaining why we do not consider this as an impact pathway.

The first impact pathway through which shade-tree density influences CAFS returns is through cocoa yield. Comparisons between full-sun monocultures and shaded AFS indicate higher average yields in monocultures. For instance, a global and multi-dimensional meta-analysis by Niether et al. (2020) showed that cocoa yields in AFS were approximately 26% lower than in full-sun systems, while Armengot et al. (2016) reported that monocultures achieved yields that were, on average, 41% higher. Within AFS, yield responses to shade-tree density are more nuanced. Several studies have identified optimal thresholds for shade-tree density, suggesting that cocoa yields[3] are maximised under low-to-intermediate shade levels, with productivity declining beyond these levels. In Ghana, Asare et al. (2019) found that cocoa yields doubled when shade cover increased to approximately 30%, whereas in Cameroon, Bisseleua et al. (2009) observed that yields peaked between 28% and 47% shade cover, declining beyond 60%. Similarly, Blaser et al. (2018) found that cocoa yields in CAFS of Ghana are generally uncompromised up to 30–50% shade cover, with more substantial reductions at higher levels. In Ecuador, Waldron et al. (2012) also identified a tipping point for maximum yield at around 144 shade trees per hectare, corresponding to approximately 40% shade cover. In contrast, other studies have documented more negative yield responses to shade in CAFS. For instance, in Ghana, Wade et al. (2010) reported a non-linear decline in yield with increasing shade, while in Indonesia (Clough et al., 2011), Ghana (Blaser et al., 2017) and Cameroon (Bisseleua et al., 2013) yields declined linearly as shade cover increased. While these studies primarily assess the effects of shade cover, it is important to note that shade cover and shade-tree density are related but not interchangeable variables. Shade-tree density is a strong determinant of shade-tree cover (Blaser et al., 2018; Dekegel et al., 2025), but shade levels also depend on other factors such as shade-tree diameter and canopy height (Blaser et al., 2018; Blaser-Hart et al., 2021). Nevertheless, shade-tree density remains a key structural component influencing shade levels and, consequently, yield responses. Based on this empirical evidence, we expect an inverted U-shaped relationship between shade-tree density and cocoa yield, with yields peaking at low to intermediate shade-tree density levels.

The second impact pathway through which shade-tree density influences CAFS returns is through production costs, which are primarily driven by external input use and labour requirements. Shade-tree reduction in CAFS is commonly associated with increased use of agrochemical inputs and the adoption of hybrid varieties, both of which are expected to raise production costs (Obiri et al., 2007). Labour constitutes another major cost component, particularly for larger and more intensively managed farms that rely on hired labour, whereas smallholder systems often rely on household labour (Jezeer et al., 2017). The empirical evidence for CAFS is mixed.[4] While Bisseleua et al. (2013) found a negative linear relationship between shade levels and production costs, Armengot et al. (2016) reported that AFS required, on average, 16% more labour per hectare than full-sun monocultures, mainly due to labour-intensive practices such as shade-tree pruning and the harvesting of associated crops. However, labour demands for core cocoa-related tasks, including harvesting, pruning of cocoa trees, weeding, fertiliser application, and post-harvest processing, were found to be similar or even lower in AFS than in monocultures. Similarly, Esche et al. (2023) highlighted that the additional labour costs for shade tree pruning are often substantial. Based on this evidence, higher shade-tree density in CAFS is expected to increase labour demands, particularly for shade-tree pruning, but these may be offset by reduced input use and reliance on household labour. Consequently, we expect total production costs to decline with increasing shade-tree density.

The third impact pathway through which shade-tree density influences CAFS returns is through economic returns from intercrops and shade trees. Studies have documented the economic benefits of crop diversification in AFS, while others emphasise its role in enhancing household food security. For instance, Armengot et al. (2016) found that

[3] Comparable patterns have been observed in coffee agroforestry systems, where a trade-off between yield and shade-tree management has also been reported. A global meta-analysis by Mokondoko et al. (2022) found shade-tree density and cover were more important drivers of coffee yield than climatic or biotic factors. In particular, systems with 35–50% shade cover and 100–250 trees ha^{-1} maintained relatively high yields, whereas those exceeding 50% shade cover and 250 trees ha^{-1} experienced pronounced yield declines.

[4] Studies on coffee agroforestry systems present mixed results as well. Alves et al. (2016) comparing shaded and full-sun coffee systems in the Brazilian Amazon, reported substantially lower production costs in shaded systems, primarily due to reduced labour requirements. Conversely, Jezeer et al. (2017) found no significant difference between shaded and full-sun systems, or within shaded systems in both cocoa and coffee production.

revenues from by-crops can economically offset lower cocoa yields in AFS, with the return on labour being twice as high as in monocultures. Similarly, Brown et al. (2025) reported that shade-tree derived products comprised a large share, and in some cases the majority, of cocoa farmers' total income in Nigeria. In contrast, other studies indicate that additional crops within AFS often only generate modest cash income that rarely offsets low cocoa yields, but can contribute significantly to household food security through self-consumption (Cerda et al., 2014; Notaro et al., 2020). Cocoa generally commands higher market prices than its by-crops grown in AFS, which are mainly sold locally or consumed on-farm, as commercialisation is limited due to major challenges in marketing and transporting diversified produce from AFS (Cerda et al., 2014; Jacobi et al., 2017). Nevertheless, crop diversification in AFS remains a particularly important strategy for farmers relying on cash crops with highly volatile prices, such as cocoa (Tschora and Cherubini, 2020). Based on this evidence, we expect gross revenues from non-cocoa crops within CAFS, comprising both income from sales and the value of self-consumption, to increase with shade-tree density (Fig. 1).

In sum, the overall economic performance of CAFS is shaped by the combined effects of shade-tree density on cocoa yields, production costs, and revenues from crop diversification, with optimal outcomes depending on a balance that sustains cocoa productivity, minimises costs, and maximises diversification benefits. These pathways can generate both trade-offs and co-benefits, highlighting the importance of a comprehensive economic assessment.

3. Data and methods

3.1. Study area

The study was conducted in the cocoa region of southern Bahia, in north-eastern Brazil. Brazil is the world's fifth-largest cocoa producer and has recorded a 74% increase in domestic production over the past two decades (FAOSTAT, 2023). Most of Brazil's cocoa production is destined for domestic markets, with only a small share (∼2%) exported (WITS, 2023). Cocoa prices in Brazil are not regulated by the government but are determined by market conditions and closely linked to international cocoa prices. Southern Bahia is the country's principal cocoa-producing region, accounting for 46% of national production (IBGE, 2023) and hosting 74% of all cocoa-producing properties in Brazil (Chiapetti et al., 2020). The cocoa sector plays a vital economic and social role, supporting the livelihoods of ∼69,000 farm-households, most of whom cultivate less than 12 ha of cocoa (Chiapetti et al., 2020).

Cocoa is the dominant source of household income in the region. The vast majority of farmers sell their cocoa to local warehouses, which function as the primary buyers in the value chain. A smaller share sells to middlemen, particularly in more remote areas, where they purchase cocoa directly on farms and provide transport. Only a minority of farmers sells directly to milling companies, which generally offer higher farmgate prices (Chiapetti et al., 2020). Participation in producer organizations is relatively common in southern Bahia, although farmers are far more frequently affiliated with local farmers' associations than with cooperatives (Chiapetti et al., 2020). Land and labour arrangements vary in the sector, with both privately owned farms and sharecropping occurring. A minority of cocoa farmers reside in *assentamentos* (i.e. agrarian reform settlements) and acquired their land through public agrarian reform policies. These properties are often large, and land tenure documents are not always formalised (Chiapetti et al., 2020). All of these farm types are represented in our study sample.

Cocoa cultivation in southern Bahia is traditionally practised in shaded AFS known as *cabrucas*, which are unique to the Atlantic Forest biome of this region and represent 78% of cocoa farms (Chiapetti et al., 2020). Traditional cabrucas are established by removing the native forest understory and planting cacao trees beneath the canopy of predominantly native tree species, followed by selective shade-tree thinning and, in some cases, the replacement of native shade trees with exotic species (Schroth et al., 2015). Most cabrucas in the region are mature systems with a long history of continuous cocoa cultivation. Although cabrucas have replaced areas originally occupied by primary Atlantic Forest (Alger and Caldas, 1994), they remain structurally complex and ecologically valuable systems. On average, cabrucas contain 197 shade trees per hectare (ranging from 70 to 480), with around 63% of tree species being native (Schroth et al., 2015), and shade cover typically ranging from ∼45% to 90% (De Almeida-Rocha et al., 2020; Dekegel et al., 2025). This AFS contrasts sharply with the simplified, low-shade cocoa production systems that dominate in other major cocoa-producing countries in West Africa, where shade cover and shade-tree density commonly remain below 20% and 15 trees per hectare, respectively (Becker et al., 2025; Krumbiegel and Tillie, 2024).

Embedded within the Atlantic Forest, one of the world's most threatened biodiversity hotspots (Myers et al., 2000), *cabrucas* provide critical habitat and corridors for native and endangered species (Cassano et al., 2009; Dekegel et al., 2025; Ferreira et al., 2025; Oliveira et al., 2010). Despite their ecological, cultural and historical value, *cabrucas* are increasingly threatened by agricultural intensification. The federal government has set a target to double cocoa production to 400,000 tons by 2030 (Ministério da Agricultura e Pecuária, 2024), a goal legally supported by a state decree allowing landowners to reduce shade-tree density in cabrucas to a minimum of 40 native trees per hectare (State Decree No. 15180/2014, Seção IV, Art. 19). This threshold falls well below the levels typically observed in traditional systems (Schroth et al., 2015) and therefore risks undermining their ecological and biodiversity conservation value. At the same time, persistent socio-economic constraints, including limited technical assistance, constrained access to credit and low household incomes (Chiapetti et al., 2020), further incentivize farmers to remove shade trees in pursuit of higher yields and short-term income.

3.2. Sampling and data collection

The farm-household survey was conducted between February and March 2024 among 313 cocoa farmers in southern Bahia (Fig. 2). A two-stage random sampling strategy was used to ensure geographic representativeness and capture the diversity in CAFS across the region. In the first stage, twelve municipalities were purposely selected based on their relative importance in the regional cocoa supply chain (Chiapetti et al., 2020). A comprehensive sampling frame of cocoa farmers within these municipalities was compiled using data from the most recent and extensive regional cocoa farmers' census (Chiapetti et al., 2020), complemented by records from farmers' cooperatives, associations, and communities and agrarian reform settlements. In the second stage, between 15 and 36 cocoa farmers were randomly selected within each municipality, with the number proportional to the distribution of cocoa-producing households across municipalities (Chiapetti et al., 2020).

Data collection was conducted through face-to-face interviews by a well-trained team of local enumerators, accompanied in the field by the first two authors. The interviews targeted the household member primarily responsible for the daily decision-making on the farm's cocoa production. We used a quantitative structured questionnaire, with modules on farm-household characteristics, cocoa production and commercialisation, general cocoa farm management activities, agricultural practices, and income sources from non-cocoa crops and other (non-)agricultural activities.

Following each household interview, a field visit was conducted to the nearest CAFS plot[5] relative to the household to assess shade-tree density. Within each CAFS, one vegetation plot of 25x20m (500m^2) was randomly established, positioned at least 100 m from the plot edge. All woody tree species with a diameter at breast height (DBH) of ≥10.0

[5] Only 3% of the sampled farmers have more than one CAFS plot.

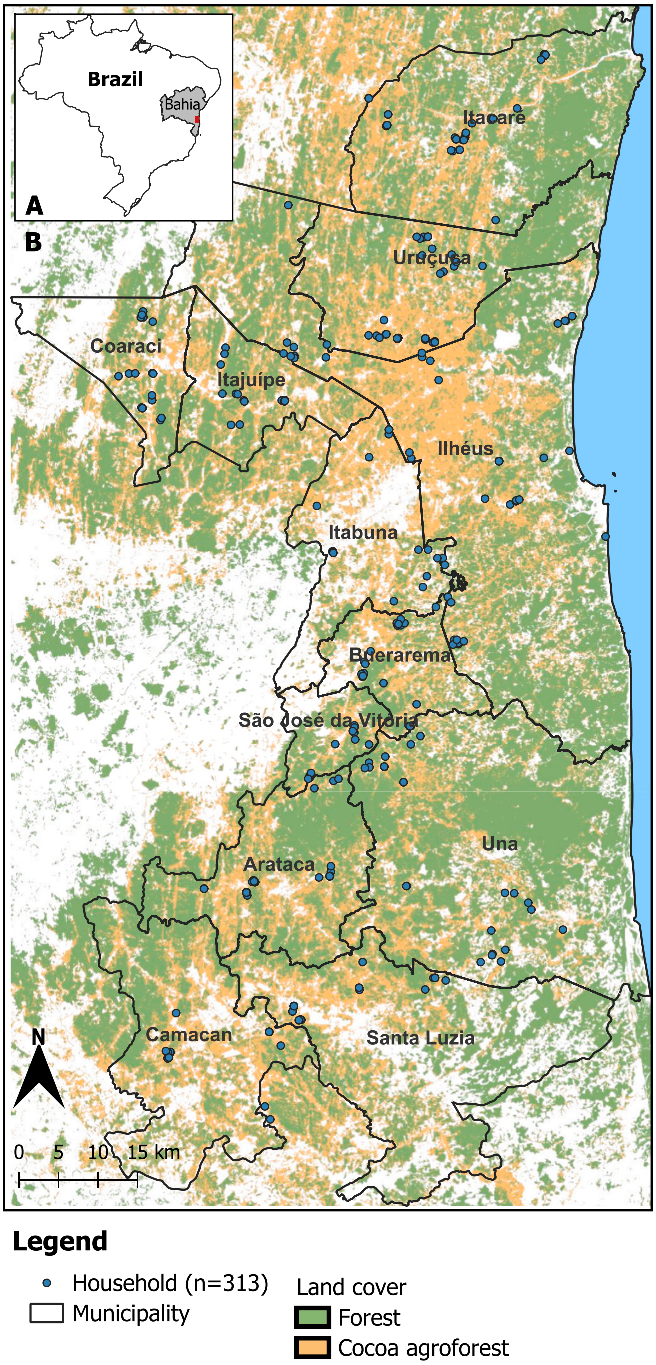

Fig. 2. Map of the sampled households in southern Bahia, Brazil. (A) Location of the research area (red) in the state of Bahia (grey) in Brazil. (B) Distribution of the 313 households across 12 municipalities in southern Bahia. Land cover data obtained from MapBiomas (MapBiomas Cacau, 2019). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

cm, including both native and exotic species, were identified and classified as shade trees within the plot. Additionally, GPS coordinates were recorded at the household and plot level, allowing for integration of survey data with available GIS data on land cover and topography.

3.3. Economic outcome variables

To assess the economic performance, we use five outcome indicators, each expressed per hectare of CAFS area: i) cocoa yield; ii) cocoa production costs; iii) net cocoa income; iv) gross revenue of non-cocoa crops cultivated within CAFS and v) returns from CAFS. The CAFS area was recorded using the farmer's preferred unit of measurement (hectares, acres, or tarefas[6]) and subsequently standardised to hectares. All values pertain to the 12 months preceding the survey (i.e. corresponding to the 2023 production year). To reduce the influence of outlying observations, outcome variables were trimmed at the top and bottom 1% values (Bemelmans et al., 2025).

First, cocoa yield is defined as the total quantity of dried cocoa beans harvested from the CAFS area expressed in kilograms per hectare. Farmers were asked to report their total cocoa harvest in units of kilogram, arrobas,[7] or number of cocoa bags, with standardised bag weights recorded. Cocoa losses are limited as farmers sell both high- and low-quality beans, albeit at different prices.

Second, cocoa production costs are calculated as the total monetary expenditures allocated to cocoa production, expressed in BRL per hectare of CAFS area. These include expenditures on external inputs (pesticides, fertiliser and lime), hired labour (salary of both permanent and temporary workers), and other production-related expenses (cocoa bags, cocoa seeds and seedlings, transportation and agricultural implements, whether rented or purchased, including associated fuel costs). Farmers were asked to report the share of labour and input expenditures dedicated specifically to cocoa production. Fees associated with certification programs or membership in cooperatives or farmers' associations were not collected and are therefore not included in the production cost estimates. Capital depreciation costs are negligible and therefore excluded from calculations.

Third, net cocoa income is calculated as the difference between gross revenue from cocoa sales and cocoa production costs, expressed in BRL per hectare of CAFS area. Gross revenue from cocoa sales was estimated by using the self-reported estimation from the farmer directly, or by multiplying the reported cocoa yield by the average farmgate price that the farmer received over the past 12 months. To account for cases in which farmers were unable to commercialize their entire harvest, this estimate was adjusted by the percentage of cocoa the farmer reported being able to sell. Gross revenue also included net revenues from the sale of cocoa derivatives such as chocolate, nibs, and cocoa honey.

Fourth, gross revenue from non-cocoa crops in CAFS is measured as the total revenue derived from fruits produced by native and exotic shade trees and all intercrops (annual and perennial) cultivated within the CAFS, expressed in BRL per hectare of CAFS area. Farmers were asked to specify the non-cocoa products harvested from both tree species and intercrops present in their CAFS, the quantities harvested, and whether each product was sold or consumed domestically. Farmers either reported the farmgate price per unit or the total revenue received per crop. We valued all products, including those retained for household consumption, using the self-reported farmgate prices or revenues provided by the farmers. Production costs for non-cocoa crops were negligible, as farmers reported that purchased inputs are not applied specifically to these crops and that they require minimal labour beyond occasional harvesting.

Fifth, returns from CAFS is defined as the sum of net cocoa income and gross revenue of non-cocoa crops cultivated in CAFS, expressed in BRL per hectare of CAFS area.

3.4. Econometric approach

3.4.1. Ordinary least squares regression

To estimate the relationship between shade-tree density (STD) and the economic outcome variables at the household level, we employ Ordinary Least Squares (OLS) regression models with robust standard

[6] Tarefa is a non-metric unit equivalent to 0.4356 ha in Bahia (Gagliano et al., 2018).

[7] One arroba in Brazil is equal to 15 kg (Lima, 1982).

errors to account for potential heteroscedasticity. We define the following regression model:

$$Y_i = \beta_0 + \beta_1 STD_i + \sum_{i=0}^{k} \beta_i X_{ni} + \varepsilon_i$$

where Y_i represents the five economic outcome variables for household i as described above. Our main explanatory variable of interest is STD_i measured at the CAFS plot of household i.[8] The term X_{ni} represents a set of control variables, and ε_i is the error term.

To control for possible selection bias from observed heterogeneity, we include a set of household- and plot-level control variables in our analysis. At the household level, we control for the household head's education level, gender and age and whether the household is part of an agrarian reform settlement. At the plot level, we control for the CAFS area, the use of hybrid or clonal cocoa varieties, and the elevation of the CAFS plot to capture variation in the agroecological suitability of land for cocoa cultivation. Additionally, we control for the distance from the household to the nearest paved road to capture differences in access to infrastructure and transaction costs for accessing input and output markets. The distance and altitude variables were derived by overlaying GPS data of household and CAFS plots, respectively, collected through the household survey with GIS data, including a Digital Elevation Model (DEM). We verified for multicollinearity and found an average variance inflation factor (VIF) of 1.16, with no variable having a larger VIF than 10, indicating that there are no problems of multicollinearity.

3.4.2. *Coefficient stability approach*

The effect of STD on economic performance might be biased, due to omitted variable bias arising from unobserved factors that simultaneously influence shade-tree density and the economic outcomes. Such factors include farmers' management objectives, risk preferences, access to resources, and historical land-use decisions. To assess the robustness of our estimates to such endogeneity concerns, we conduct a recently developed coefficient stability approach[9] (Diegert et al., 2025), which calibrates sensitivity parameters by comparing the magnitude of selection on observed variables with the magnitude of selection on unobserved variables. In contrast to other coefficient stability methods, such as Oster (2019), it allows correlation between omitted variables and included controls, thus allowing for endogenous controls and offering a more flexible framework for evaluating coefficient stability.

4. Results

4.1. *Descriptive statistics*

Table 1 shows the descriptive statistics of the sampled cocoa farming households. The average age of household heads is 55.7 years, with female-headed households comprising a minority, accounting for 22% of the sample. On average, household heads have completed 9–10 years of formal education, corresponding to primary education, and reported having 19–20 years of experience in cocoa production. Households consist on average of three members, including two individuals within the working-age population who are physically capable of engaging in labour activities. Sharecroppers represent 6% of the sample, while 42% of the households are located within agrarian reform settlements. Households are generally situated at relatively low elevations, averaging 137 m above sea level and are located in proximity to their CAFS, at an average distance of 610 m. However, farms are often situated at considerable distances from key infrastructure, averaging 4 km from the nearest paved road and 9 km from the nearest city.

Table 1
Descriptive statistics of sample cocoa farmers (n = 313) in southern Bahia, Brazil.

Variable	Mean	Std. Dev	Min	Max
Producer characteristics				
Female HH head (%)	21.73		0	100
Age HH head (yrs)	55.70	13.94	23.00	90.00
Education HH head (yrs)	9.26	4.45	0.00	18.00
Experience HH head (yrs)	19.04	12.32	1.00	67.00
HH size	3.03	1.60	1.00	10.00
Dependency ratio[1]	0.73	0.27	0.00	1.00
HH head is sharecropper (%)	5.75		0.00	100.00
HH head is part of agrarian reform settlement (%)	41.53		0.00	100.00
Farm characteristics				
HH head has income from other crops in CAFS (%)	46.65		0.00	100.00
HH head has income from other crops outside CAFS (%)	18.21		0.00	100.00
HH head has income from livestock (%)	24.92		0.00	100.00
HH head has income from off-farm employment[2] (%)	29.07		0.00	100.00
HH head has non-labour income source[3] (%)	66.13		0.00	100.00
Altitude HH (m)	136.71	70.68	8.00	399.00
Slope HH (%)	10.47	6.19	0.00	32.45
Distance HH-CAFS (km)	0.61	1.70	0.00	26.28
Distance HH-road (km)	3.98	3.96	0.00	15.97
Distance HH-city (km)	9.11	5.94	0.00	29.15
Cocoa production				
Cocoa price[4] (USD kg^{-1})	3.16	0.63	0.47	5.34
Middlemen channel[5] (%)	83.39	37.28	0.00	100.00
Third-party certification[6] (%)	2.56	15.81	0.00	100.00
CAFS size (ha)	16.61	37.88	1.00	376.00
Shade-tree density (trees ha^{-1})	192.83	79.69	40.00	600.00
Native shade tree (%)	64.05	24.28	0.00	100.00
Young cocoa trees (%)	11.32	15.57	0.00	90.00
Presence of cocoa hybrids/clones (%)	73.48		0.00	100.00
Cocoa fermentation (%)	77.32		0.00	100.00
Cocoa drying (%)	98.08		0.00	100.00
Cocoa full-sun (%)	6.07		0.00	100.00
Full-Time Equivalent family labour devoted to cocoa	0.73	0.41	0.00	2.74
Full-Time Equivalent hired labour devoted to cocoa	0.75	2.38	0.00	17.00
External inputs devoted to cocoa (%)	56.87		0.00	100.00
Altitude CAFS (m)	147.71	76.51	17.00	402.00
Slope CAFS (%)	15.48	10.08	1.31	45.79
Distance CAFS-forest (km)	0.10	0.13	0.00	1.00

[1] Household ratio of working-age adults to HH size.
[2] Income from any type of job in the non-farm sector (both wage and self-employment) as hired labour on other farms.
[3] Income from other non-labour sources, such as pension, remittances, renting out land and/or houses.
[4] The average annual exchange rate in 2023 was 1 USD = 4.994 BRL (World Bank, 2025).
[5] Farmers market at least part of their cocoa output through middlemen rather than exclusively through direct sales to milling companies or bean-to-bar buyers.
[6] Other certification schemes, including UTZ/Rainforest Alliance, Organic (EU, IBD, USDA), and Demeter.

While cocoa is the principal crop cultivated within CAFS, many farmers diversify their income sources through complementary on- and off-farm activities. Nearly half of all households (47%) report generating income from the cultivation of crops other than cocoa within their CAFS, highlighting the multifunctionality of these systems. Non-cocoa crops harvested within CAFS include both intercrops and fruit harvested from native and exotic shade trees. Importantly, the fruit that contributes to farmers' income is derived almost exclusively from exotic shade-tree species such as jackfruit (*A. heterophyllus*) and cupuaçu (*T.*

[8] We also tested for non-linear relationships between STD and each economic outcome variable, but the quadratic terms were never statistically significant.
[9] We tried an instrumental variable approach as well, but could not identify instruments that simultaneously satisfy the relevance and exogeneity criteria.

subincanum). The most commonly harvested intercrops are bananas and plantains (*Musa* sp.). These products are either sold in local markets or consumed within the household, thereby contributing both to cash income and household food security. Other income sources are also common, with 18% earning income from crop production outside CAFS, 25% from livestock rearing, 29% from off-farm employment and 66% from non-labour income sources, such as pensions, social assistance, or remittances.

Regarding cocoa production specifically, farmers received an average farmgate price of 15.75 R$ kg^{-1} in 2023, closely aligning with the international farmgate benchmark of 3.35 USD kg^{-1} (ICCO, 2023). The majority of the farmers (%) market their cocoa through middlemen, not selling directly to milling companies or specialty bean-to-bar buyers. Only 3% of the farmers of our sample hold a third-party certification (UTZ-Rainforest Alliance, organic or Demeter), reflecting the limited role of certification schemes in the domestic cocoa value chain in Brazil. CAFS have an average area of 17 ha, but with large differences across farms. They are situated at elevation levels (148 m) comparable to those of the households and characterised by moderately steep terrain, with an average slope of 15%. Most cocoa plantations are mature, reflecting low rates of recent replanting of cocoa trees. Over one-third of farmers (37%) reported having no young cocoa trees on their plots, and nearly three-quarters (72%) had 10% or fewer. Only a small minority (5%) had more than half of their CAFS plot planted with young trees, suggesting that cocoa stands in the region are ageing and that farm-level renovation efforts remain limited. A substantial proportion of farmers (74%) cultivate improved cocoa varieties. Regarding post-harvesting practices, 73% of farmers ferment their cocoa beans and nearly all dry the beans prior to sale. The cultivation of cocoa in full-sun systems alongside CAFS is rare, observed in only 6% of the sample. The use of external agricultural inputs is relatively common, with 57% of the farmers reporting the application of pesticides, fertilisers and/or lime. The labour dedicated to cocoa production is 0.73 full-time equivalent (FTE) family workers, complemented by 0.75 FTE of hired labour.

Table 2
Descriptive statistics of economic outcome variables of the sample of cocoa farmers (n = 313) across 12 municipalities in southern Bahia, Brazil.

Economic variables	Mean	Std. Dev.	Min	Max
Cocoa yield (kg ha^{-1})	217.57	177.31	2.53	964.29
Gross revenue of cocoa (R$ ha^{-1})	3459.68	3081.69	50.56	17,894.74
Cocoa production costs (R$ ha^{-1})	1126.84	1721.63	0.00	9620.00
Net cocoa income (R$ ha^{-1})	2552.14	3073.16	−4620.00	15,699.00
Gross revenue from other crops than cocoa (R$ ha^{-1})	295.92	736.86	0.00	4410.00
Returns from CAFS (R$ ha^{-1})	2858.57	3271.51	−4620.00	16,809.29
Share of household income derived from CAFS[1] (%)	52.60	43.30	0.00	100.00

Note: Outcome variables trimmed at 1% extreme values. The average annual exchange rate in 2023 was 1 USD = 4.994 BRL (World Bank, 2025). CAFS means cocoa agroforestry system.

[1] Share of household income derived from CAFS is calculated as total returns from CAFS divided by total household income. Total returns from CAFS represent the total net income generated by CAFS and are calculated by multiplying the returns from CAFS by the total CAFS area managed by the household (expressed in BRL). Total household income represents the total net income of the household over the past 12 months (expressed in BRL) and includes total returns from CAFS, as well as the total net revenues from livestock rearing, crop production outside the CAFS, off-farm employment and non-labour income sources.

Table 2 presents descriptive statistics of the five economic outcome indicators. Cocoa farmers in our sample achieve an average cocoa yield of 218 kg of dry beans per ha. This falls below the average yield estimates reported by the Brazilian national government for Bahia[10] (326.00 kg ha^{-1}; IBGE, 2023) and by the FAO for Brazil (483.30 kg ha^{-1}; FAOSTAT, 2023), which include a wide range of production systems, including higher-yielding monoculture cocoa systems. At the same time, it exceeds the average yield of 177.00 kg ha^{-1} year^{-1} reported by Chiapetti et al. (2020) for CAFS in a subset of municipalities of southern Bahia between 2015 and 2019, which is consistent with productivity growth in the sector in more recent years (IBGE, 2024). Gross revenue from cocoa production averaged 3460 R$ ha^{-1}, while production costs are on average 1127 R$ ha^{-1}. A notable observation is that 7% of the farmers reported no monetary costs associated with cocoa production, reflecting production systems that rely exclusively on family labour and make little or no use of purchased inputs. The resulting mean net cocoa income is 2552 R$ ha^{-1}, with 9% of the farmers experiencing negative income. Revenues from other crops than cocoa cultivated within CAFS are substantially lower, averaging 296 R$ ha^{-1} for the whole sample. Among the subset of farmers cultivating additional crops, the average income from these crops reaches 634 R$ ha^{-1}. Overall, returns from CAFS are on average 2859 R$ ha^{-1}, but with a large standard deviation, demonstrating substantial variation across the sample. Nevertheless, households derive more than half (52.6%) of their total income from CAFS, underscoring the substantial contribution of CAFS to rural livelihoods.

Fig. 3 demonstrates the considerable variation in shade-tree density across the 313 CAFS, ranging from 40 to 600 trees ha^{-1} with on average 193 trees ha^{-1} and 64% native species (Table 1). The values are consistent with those reported by Schroth et al. (2015) for the region. Spearman correlation test indicates a significant positive correlation between shade-tree density and share of native shade tree species ($\rho = 0.19$, $p < 0.001$; Fig. 3), indicating that as shade-tree density increases, CAFS are more dominated by native shade-trees compared to planted non-native species.

Fig. 4 visualizes the correlation between shade-tree density and the five economic outcome variables. Across all five economic outcome variables, we observe a negative correlation with significant effects for four of the five economic indicators (only net cocoa income is insignificant).

4.2. Regression results

Table 3 presents the results from the OLS regressions. We find that an increase of 100 shade trees per hectare is associated with a reduction in cocoa yield of 22 kg ha^{-1} and a decrease in cocoa production costs of R$168.5 ha^{-1}. Although net cocoa income also declines with increasing shade-tree density, this effect is not significant. We observe a significant decline in income from other non-cocoa crops cultivated within CAFS, with an increase of 100 shade trees per hectare associated to a R$90.8 ha^{-1} decline in gross revenue from other crops. The overall returns from CAFS is also negatively affected by higher shade-tree density, with an increase of 100 shade trees per hectare associated with a decrease of R$309.3 ha^{-1} in total returns.

We apply a coefficient stability approach to assess the robustness of the estimated effect of shade-tree density to potential omitted variable bias. The estimated breakdown points range from 26% to 34% across the economic outcome variables of cocoa yield, cocoa production costs, gross revenues of non-cocoa crops and net returns from CAFS (Table S1, in Appendix). This implies that the negative effects of shade-tree density remain significant as long as the selection on unobservable is at least 26% to 34% as large as the selection on observables, suggesting that our main findings are relatively robust.

Beyond shade-tree density, several other characteristics are

[10] Statistics from the Instituto Brasileiro de Geografia e Estatística (IBGE) aggregate data across all cocoa-producing municipalities in Bahia, although most cocoa-producing municipalities in the state are located in southern Bahia.

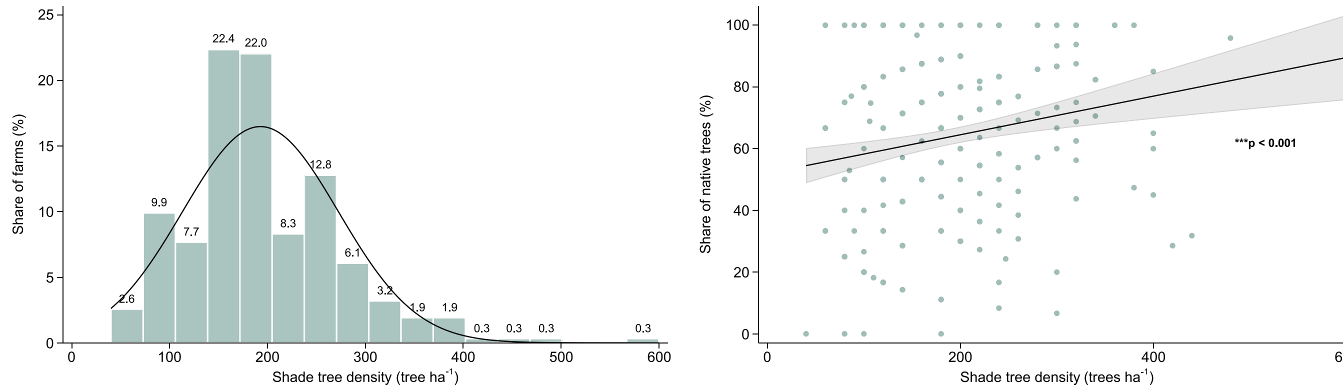

Fig. 3. Shade-tree characteristics in 313 cocoa agroforestry systems (CAFS) in southern Bahia. Left: distribution of shade-tree density (trees ha^{-1}) across farms, ranging from 40 to 600 trees ha^{-1}. Right: relationship between shade-tree density and the share of native shade-tree species, showing a significant positive correlation (Spearman's $\rho = 0.19$, $p < 0.001$). Relationship is robust to trimming shade-tree density at the upper 1% of the distribution (i.e. excluding observations with >420 trees ha^{-1}).

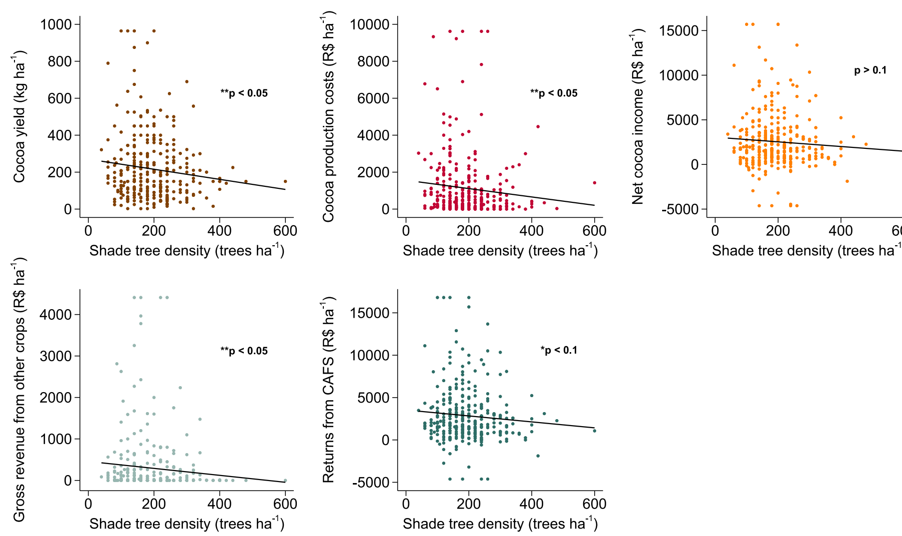

Fig. 4. Scatterplots illustrating the relationship between shade-tree density and economic performance indicators from cocoa agroforestry systems (CAFS) in southern Bahia, Brazil. Each panel presents one economic indicator (i.e. cocoa yield, cocoa production costs, net cocoa income, gross revenue from other crops than cocoa, or returns from CAFS) plotted against shade-tree density (tree ha^{-1}). Fitted lines represent bivariate ordinary least squares (OLS) regressions. Outcome variables trimmed at 1% extreme values. Results are robust to trimming shade-tree density at the upper 1% of the distribution (i.e. excluding observations with >420 trees ha^{-1}). *$p < 0.10$, **$p < 0.05$, ***$p < 0.01$.

significantly associated with the economic outcome variables (Table 3). Female-headed households produce lower cocoa yields and earn less net cocoa income and returns from CAFS, indicating gender inequalities in economic performance of CAFS. Education of the household head is positively associated with cocoa production costs and with gross revenue from non-cocoa crops cultivated within CAFS, suggesting that producers with higher education levels are more likely to adopt input- and labour-intensive practices and engage in diversified production strategies. Residing in an agrarian reform settlement is associated with lower cocoa yields and reduced production costs, yet also with lower net cocoa income and total returns from CAFS, indicating overall lower economic returns for households located in settlements. Regarding cocoa production characteristics, CAFS size is negatively associated with cocoa yield, production costs, gross revenues from other crops, and total returns from CAFS, except for net cocoa income, indicating that larger CAFS are associated with lower economic performance. The use of cocoa hybrid varieties is associated with higher cocoa yields and increased production costs. No significant associations were found for variables reflecting farm characteristics.

As the effect of shade-tree density might differ across CAFS size, we include an interaction model between shade-tree density and CAFS size in an additional model (Table 4). The main effect for shade-tree density remains negative but becomes insignificant for all outcome variables, except for gross revenues from other crops. In contrast, the main effect of CAFS size becomes positive for these four indicators. However, the interaction term is significantly negative, except for gross revenues from other crops. This means that higher shade-tree density is associated with more pronounced yield losses, greater reductions in production costs, larger net income declines, and steeper decreases in total returns on larger CAFS, but not on smaller CAFS. Gross revenues from other crops decline with higher shade-tree density, but this effect is independent of CAFS size.

5. Discussion

5.1. Effects of shade-tree density on the economic performance of CAFS

We find that higher shade-tree density is negatively associated with four of the five economic indicators (cocoa yield, cocoa production costs, income from non-cocoa crops, and overall returns from CAFS), but

Table 3
Results of OLS regression estimates on economic performance indicators of cocoa agroforestry systems in southern Bahia, Brazil.

	Cocoa yield	Cocoa production costs	Net cocoa income	Gross revenue ofother crops	Returns from CAFS
Shade-tree density	−0.220**	−1.685*	−2.133	−0.908**	−3.093*
	(0.103)	(1.003)	(1.784)	(0.363)	(1.846)
Female HH head	−48.144**	−65.459	−1008.260***	−71.693	−1059.626***
	(20.786)	(231.354)	(328.849)	(111.389)	(342.247)
Age HH head	0.684	7.590	1.229	0.894	2.443
	(0.727)	(7.288)	(12.756)	(3.828)	(13.123)
Education HH head	0.820	66.271***	9.974	19.512*	28.092
	(2.439)	(23.830)	(43.842)	(9.929)	(45.170)
Settlement (dummy)	−61.638***	−772.364***	−600.094	−11.133	−622.092
	(19.097)	(211.012)	(368.960)	(84.846)	(392.365)
Distance HH-road	3.787	14.083	19.835	−6.724	15.574
	(3.113)	(30.464)	(51.269)	(11.327)	(53.334)
CAFS size	−0.675**	−4.017**	−8.618*	−2.168***	−10.668**
	(0.261)	(1.855)	(4.381)	(0.693)	(4.623)
Elevation CAFS	0.160	−1.139	3.029	−0.500	2.574
	(0.156)	(1.374)	(2.845)	(0.486)	(2.965)
Cocoa hybrids (dummy)	46.618**	379.488**	426.168	92.503	523.072
	(20.053)	(168.663)	(348.143)	(93.401)	(361.929)
Constant	188.584***	650.607	2574.534**	329.451	2898.147**
	(64.920)	(698.923)	(1223.925)	(268.804)	(1272.186)
Number of observations	313	313	313	313	313
R^2	0.12	0.11	0.06	0.03	0.06

Note: Coefficient estimates for the economic outcome variables are shown with robust standard errors between parentheses. Outcome variables trimmed at 1% values. Results are robust to trimming shade-tree density at the upper 1% of the distribution (i.e. excluding observations with >420 trees ha^{-1}).
* $p < 0.10$.
** $p < 0.05$.
*** $p < 0.01$.

Table 4
Summary of OLS regression estimates on economic performance indicators from cocoa agroforestry systems, including the interaction between shade-tree density and CAFS size.

	Cocoa yield	Cocoa production costs	Net cocoa income	Gross revenue of other crops	Returns from CAFS
Shade-tree density	−0.082	−0.638	−0.210	−0.857**	−1.121
	(0.104)	(1.019)	(1.881)	(0.399)	(1.936)
Shade-tree density x CAFS size	−0.011***	−0.086***	−0.158***	−0.004	−0.162***
	(0.003)	(0.028)	(0.047)	(0.008)	(0.047)
CAFS size	0.776*	6.974*	11.573*	−1.640	10.041
	(0.423)	(4.172)	(6.646)	(1.055)	(6.786)
Constant	168.345***	497.282	2292.864*	322.086	2609.253**
	(64.661)	(698.939)	(1222.567)	(267.598)	(1271.572)
Number of observations	313	313	313	313	313
R^2	0.13	0.12	0.07	0.04	0.07

Note: Coefficient estimates for the economic outcome variables are shown with robust standard errors in parentheses. Outcome variables trimmed at 1% extreme values. Full estimation results, including coefficients of control variables, are provided in Table S2 in Appendix.
* $p < 0.10$.
** $p < 0.05$.
*** $p < 0.01$.

the magnitude of the effects matters for the interpretation of the results and their policy implications. On average, an increase of 100 shade trees per hectare is associated with a reduction of 22 kg of dry beans per hectare per year in cocoa yield. At the prevailing average farmgate price of 16 R$ per kg in 2023, this corresponds to a decline in gross cocoa revenues of 347 R$ per hectare per year. The same increase in shade-tree density is associated with a reduction in cocoa production costs of 169 R$ per hectare per year, which mitigates part of the revenue loss. Although net cocoa income also declines with increasing shade-tree density, this relationship is not statistically significant, suggesting that cost savings partly balance yield declines. However, higher shade-tree density is significantly associated with a reduction of 91 R$ per hectare per year in gross revenues from non-cocoa crops cultivated within CAFS, and a decline in overall returns from CAFS of 309 R$ per hectare per year. Given that the average CAFS returns are 2859 R$ per hectare per year, this corresponds to a relative loss of 11%. This indicates that a substantial increase of 100 shade trees per hectare has limited economic trade-offs and does not even come with a penalty for net cocoa income.

Our analysis reflects cross-sectional data of the 2023 production year, prior to the sharp cocoa price increases observed in 2024. While a reduction in cocoa prices (e.g. 20%) would reduce net cocoa income and total CAFS returns per hectare for all farmers, such price shocks are unlikely to systematically bias the estimated associations between shade-tree density and economic outcomes. Cocoa prices are largely determined by global markets and do not vary systematically with shade-tree density within the study region. These associations between shade-tree density and economic outcomes therefore primarily arise through changes in cocoa yields and cocoa production costs rather than through variation in output prices. Potential heterogeneity in farmgate prices may arise from differences in marketing channels, certification, or access to price premiums, but these are very limited in our research area. Yet, large and persistent price changes may alter farmers' opportunity costs of maintaining high shade-tree densities, potentially incentivizing shade-tree removal.

Our findings are in line with some studies but contrast others. First, we confirm that higher shade-tree density is associated with significantly lower cocoa yields, but this effect is linear. This contrasts with our expectation of an inverted U-shaped relationship, in which cocoa yields would peak at low to intermediate shade-tree density levels before declining at higher densities. Our results align with evidence from Cameroon reporting consistent yield declines as shade-tree density increases (Bisseleua et al., 2013). Importantly, the minimum level of shade-tree density in our sample is 40 trees per hectare, which in southern Bahia corresponds to shade levels above ~35% (Dekegel et al., 2025). As a result, our data might not capture the lower shade levels under which non-linear relationships have been reported (Asare et al., 2019; Bisseleua et al., 2009; Blaser et al., 2018; Waldron et al., 2012).

Second, we show a significant negative association between shade-tree density and cocoa production costs. This finding aligns with evidence from West Africa that higher shade levels are associated with a lower dependence on external inputs and lower labour requirements (Bisseleua et al., 2013). Such reductions in input and labour costs may partially offset the yield losses associated with higher shade-tree densities, thereby limiting their overall effect on net cocoa income.

Third, contrary to our expectation, higher shade-tree density was also negatively associated with gross revenues from non-cocoa crops within CAFS. This pattern likely reflects the specific species composition of CAFS in southern Bahia, where higher shade-tree densities are dominated by native forest species that provide important ecological functions but few marketable products. In contrast, systems with lower shade-tree densities tend to introduce a greater proportion of exotic fruit trees and intercrops, such as bananas which benefit from increased light availability (Israeli et al., 1995), that generate income. This aligns with local management practices in CAFS of southern Bahia, where farmers often thin native shade trees or replace them with exotic species to enhance productivity. The additional economic benefits of agroforestry thus depend on the presence of commercially valuable shade tree species within CAFS. In other cocoa-producing regions where shade trees consist largely of productive fruit or timber species, higher shade-tree densities may increase, or at least not reduce, non-cocoa revenues. However, in cocoa systems such as those in southern Bahia, where native forest tree species dominate, higher shade-tree densities do not necessarily translate into higher economic returns from non-cocoa crops. Our finding contrasts with studies reporting that by-crops can partially or fully offset lower cocoa yields in AFS (Armengot et al., 2016; Brown et al., 2025; Niether et al., 2020), but is consistent with evidence indicating that non-cocoa crops in CAFS often generate only modest cash income (Cerda et al., 2014; Notaro et al., 2020). Consequently, these results indicate that current diversification practices within the CAFS of southern Bahia do not sufficiently compensate for lower cocoa yields, limiting its contribution to the overall farm-level economic performance of CAFS.

While our results point to trade-offs in the economic performance of CAFS associated with shade-tree density, we find that these effects differ across farm sizes. Interaction effects indicate that higher shade-tree density is associated with more pronounced yield losses, greater reductions in production costs, larger net income declines, and steeper decreases in total returns on larger CAFS, but not on smaller CAFS. This is consistent with the inverse farm size-productivity relationship (Ali and Deininger, 2015), whereby smaller farms often achieve higher land productivity through more efficient family labour use and lower household supervision costs, while larger farms often operate under more extensive production strategies with lower land productivity. In our context of shade-tree management, larger CAFS appear more vulnerable to the productivity constraints imposed by higher shade-tree densities, likely reflecting management practices that are less adapted to higher shade-tree densities due to their greater reliance on hired labour and lower household supervision intensity. Although production costs decline more strongly on larger CAFS as shade-tree density increases, these cost savings do not compensate for the associated yield losses, ultimately leading to larger net productivity declines for larger farms under high shade-tree densities. In contrast, gross revenues from other crops declined with increasing shade density regardless of CAFS size, reflecting the dominance of non-commercial native tree species in shaded CAFS rather than scale effects.

Overall, these findings suggest that shaded AFS remain a viable land-use strategy for small-scale farmers in terms of land productivity, whereas larger farms face stronger per-hectare economic trade-offs under higher shade-tree densities. Our findings underscore the critical role of smaller family farms in strategies to promote sustainable cocoa production and rural development. At the same time, the context-specificity of our results should be acknowledged, as the average farm size in our sample (17 ha) is substantially larger than cocoa farm sizes in Africa and Asia. Moreover, lower land productivity on larger CAFS may not necessarily translate into lower farm-level returns, as larger farms may rely on scale effects or additional income sources beyond cocoa production that compensate for lower per-hectare returns from CAFS.

5.2. Potential trade-offs or co-benefits with ecological outcomes

Our findings indicate that while shade-tree removal in CAFS in southern Bahia provides economic benefits for farmers, the magnitude of these benefits is relatively small. When placed in the broader sustainability context, these modest economic gains appear limited compared to the well-documented ecological costs of shade-tree removal. Previous studies in southern Bahia estimate that shade-tree removal in CAFS leads to a 24% decline in carbon stocks (Schroth et al., 2016) and negatively affects mammal communities (Dekegel et al., 2025; Ferreira et al., 2025), including the endangered and endemic golden-headed lion tamarin (*Leontopithecus chrysomelas*), a species whose persistence in the fragmented Atlantic Forest depends on shaded CAFS (Dekegel et al., 2025; Oliveira et al., 2011). Based on empirical evidence from southern Bahia, a minimum threshold of 100 shade trees per hectare, equivalent to 65% shade cover, has been identified as necessary for the persistence of this primate species in CAFS (Dekegel et al., 2025). This shade-tree threshold is substantially higher than the 40 trees per hectare currently permitted under Bahia's shade-tree management decree, underscoring the risks of policy incentives that prioritise short-term productivity under agricultural intensification over biodiversity conservation.

Similar trade-offs have been reported in other cocoa-producing regions across multiple taxa, including bats, birds and invertebrates. In Cameroon, shaded cocoa farms supported up to five times more forest bird specialists than unshaded farms (Jarrett et al., 2021), while invertebrate richness and abundance declined with decreasing shade in both Cameroon (Bisseleua et al., 2009, 2013) and Indonesia (Steffan-Dewenter et al., 2007). A global meta-analysis across cocoa and coffee AFS found that converting shaded AFS into monocultures reduced species richness by 46% and ecosystem service provision by 27% (De Beenhouwer et al., 2013). Similarly, increasing shade-tree cover has been shown to enhance carbon sequestration in CAFS, reinforcing the role of shaded systems in climate change mitigation (Becker et al., 2025; Blaser et al., 2018; Niether et al., 2020). Nevertheless, Blaser et al. (2018) has shown that “win-win” outcomes can occur in low- to intermediate-shade AFS, where maintaining 30% to 50% shade-tree cover, corresponding to approximately 25–75 shade trees per hectare, does not comprise production while still contributing to biodiversity conservation, and climate adaptation and mitigation (Blaser et al., 2018). Overall, this evidence demonstrates that shade-tree removal consistently undermines biodiversity conservation and ecosystem functioning, underscoring the important role of shade-tree management in balancing ecological and economic dimensions of sustainability in cocoa landscapes worldwide.

While our results demonstrate that economic trade-offs from higher shade-tree density are more pronounced in larger CAFS, Ricciardi et al. (2021) extend this pattern to both economic and ecological dimensions, showing that smaller farms tend to achieve both higher yields and greater biodiversity at farm and landscape scales compared to larger farms. This suggests that AFS on small properties can have a disproportionately large influence at the landscape level, particularly in regions where they collectively manage a substantial share of the production area. Small-scale farmers therefore occupy a central role in reconciling sustainable cocoa production and biodiversity conservation, reinforcing the need for targeted policies that strengthen their long-term capacity to maintain shaded AFS.

5.3. Limitations and future research

While our study provides valuable insights into the effect of shade-tree density on the economic performance of CAFS, some limitations should be noted. Our focus on traditional CAFS, which cannot legally be thinned below a minimum of 40 native shade trees per hectare, limits the inclusion CAFS with lower shade-tree densities. A broader shade-tree management gradient, especially at the lowest end, would further strengthen our understanding of economic implications of shade-tree density and may explain why we do not observe the hypothesized concave quadratic relationship between shade-tree density and cocoa yield. It remains possible that an optimal yield response occurs at lower shade densities not represented in our data. However, in the context of identifying trade-offs between ecological and economic sustainability, such low-shade systems are of limited relevance, as they are unlikely to sustain ecologically viable levels of biodiversity. Second, the study relies on cross-sectional data, which constrains our ability to draw causal inferences about the effects or dynamics of shade-tree management on economic performance. Third, while we focus on shade-tree density as the principal proxy for shade-tree management, our approach does not consider the full complexity of AFS, including shade-tree cover, height, and species composition, which are also known to influence cocoa yields (Blaser et al., 2018; Blaser-Hart et al., 2021). Yet, our focus on shade-tree density is justified because it is consistent with the use of shade-tree density as threshold in Bahia's state management decree, making it directly relevant for evidence-based policy design.

Finally, our study is primarily economic in scope and does not integrate additional ecological (e.g., biodiversity, ecosystem services) or social outcomes that are provided by AFS. As a result, our findings do not capture the full set of trade-offs and synergies associated with CAFS, which could be addressed by future research.

6. Summary and policy implications

This study assesses the economic performance of CAFS in southern Bahia, Brazil, where cocoa farmers have retained densely shaded CAFS dominated by native shade-tree species. We find that higher shade-tree densities are associated with modest economic trade-offs, which are more pronounced in larger CAFS, whereas smaller CAFS appear better able to mitigate productivity losses. These findings highlight substantial heterogeneity in the economic implications of shade-tree management and indicate that farm size plays a critical role in shaping the land productivity of maintaining shaded systems.

Although our analysis focuses on economic outcomes, these modest trade-offs must be weighed against the substantial ecological benefits of maintaining shade-trees in AFS, which can offset the relatively small reductions in farm-level economic performance and should therefore be central to policy design. However, under prevailing policy pressures to increase cocoa productivity, and in the absence of convincing economic mechanisms that compensate farmers for maintaining shaded AFS, shade-tree removal is likely to persist despite the considerable ecological value of these systems.

Translating these ecological benefits into effective incentives requires financial mechanisms that explicitly reward farmers for maintaining existing shade trees. Existing policy instruments, however, largely fall short in incentivizing the conservation of shaded CAFS. In Bahia, payments for environmental services (PES) are formally provided for in environmental legislation, yet remain inactive in practice. Although State Decree No. 15180/2014 (Art. 15) defines eligibility criteria for PES, excluding AFS with fewer than 40 native trees per hectare, the operational implementation framework remains largely absent, resulting in no effective implementation to date. Beyond PES, carbon credit programs have increasingly been promoted as a means of valuing the climate services provided by AFS. However, they predominantly remain skewed toward initiatives that incentivize carbon stock creation, through tree planting, and rarely reward the protection of existing AFS against shade-tree removal (Pappo et al., 2025). While tree planting initiatives generate rapid and easily measurable gains in carbon sequestration, preventing the conversion of AFS into simplified, low-shade systems represents a more effective strategy. Avoiding carbon losses from shade-tree removal delivers climate and biodiversity benefits that far exceed the potential gains from tree-planting initiatives (Pappo et al., 2025). Similarly, voluntary sustainability standards (VSS) represent another important governance tool to promote more sustainable cocoa production. However, most standards primarily encourage farmers to plant shade trees with no specific mandate for shade-tree management requirements. Rainforest Alliance (RA), one of the most widely adopted schemes, previously required a minimum of 70 shade trees per hectare, including at least 12 native species, a shade cover of at least 40%, and a minimum of two crown strata (Rainforest Alliance, 2005, 2009). More recent certification criteria lowered this requirement to maintaining at least 15% natural vegetation cover (Rainforest Alliance, 2017). Combined with weak enforcement, these low thresholds substantially limit the effectiveness of VSS in supporting biodiversity conservation and the maintenance of structurally complex shaded AFS (Dröge et al., 2025a, 2025b; Wätzold et al., 2025).

A conservation-first approach is therefore needed, in which incentive-based governance instruments explicitly value the maintenance of mature shade trees and provide financial compensation that reflect the ecological services these systems already deliver. This underscores the need for financial incentives embedded within a mitigation and conservation strategy that prioritizes the protection of existing shaded CAFS over the creation of new tree cover (Cammelli et al., 2025; Pappo et al., 2025).

CRediT authorship contribution statement

Steffi Dekegel: Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Diego Laviolette:** Writing – review & editing, Investigation, Formal analysis. **Kristel De Vleeschouwer:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Leonardo Oliveira:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Jorge Chiapetti:** Writing – review & editing, Investigation. **Alessandro Santos Da Conceição:** Writing – review & editing, Investigation. **Goedele Van den Broeck:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing 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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolecon.2026.108980.

Data availability

The database and the scripts used to conduct the data processing and statistical analyses are included as Supplementary Material.

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