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ECOLOGICAL AND ECONOMIC SUSTAINABILITY OF COCOA AGROFORESTS IN BRAZIL

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Tese apresentada ao Programa de Pós-Graduação em Ecologia e Conservação da Biodiversidade da Universidade Estadual de Santa Cruz, para a obtenção do Título de Doutor em Ecologia e Conservação da Biodiversidade

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Inclui referências e apêndices.

1. Biodiversidade – Conservação. 2. Florestas – Manejo. 3. Árvores sombreadoras. 4. Cacau – Produção. 5. Indicações geográficas.

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O cacau não é apenas fruto da terra.
É suor, é sangue, é luta de homens.
– Inspired by Jorge Amado, Cacau (1933)

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Life is full of surprises, and I am excited to see where the next adventure will take me. For now, I will enjoy good nights of sleep, weekends without thinking about my PhD, and time with the people I love most.

Cheers, Steffi

Summary

Global value chains for tropical agricultural commodities have long been associated with significant environmental and socio-economic challenges, particularly in some of the world's most biodiverse regions. Rising international demand has driven agricultural expansion and intensification, contributing to deforestation, biodiversity loss, and land degradation, while many small-scale producers remain exposed to low productivity, poverty, and structural inequalities. These intertwined challenges have intensified calls for sustainability transitions that reconcile agricultural production with environmental conservation and rural livelihoods. Agroforestry systems (AFS) have emerged as a promising nature-based solution in this context, as they integrate trees with crops within agricultural production systems and offer the potential to balance multiple sustainability goals. However, substantial variability exists within AFS as a land-use type, particularly in terms of shade-tree management, reflecting farmers' decisions regarding the retention and removal of shade trees, and constitutes a key dimension of farm-level management within AFS. Yet, empirical evidence remains limited on how such within-system management variation shapes ecological and economic outcomes. Moreover, the effectiveness of governance instruments in valorising AFS and incentivising their sustainable management remains insufficiently understood.

Against this background, this dissertation addresses these gaps through an in-depth analysis of cocoa agroforestry systems (CAFS), a globally important production system predominantly managed by small-scale farmers that offers a relevant context to examine sustainability trade-offs and synergies. Specifically, this dissertation aims to reveal how shade-tree management in CAFS shapes ecological and economic trade-offs and synergies, and to evaluate the potential of origin-based certification to promote their sustainable development. The research adopts a case-study approach in the CAFS landscapes of southern Bahia, Brazil, a region of high ecological importance in which highly shaded CAFS are widespread, support rural livelihoods, and face increasing pressures to intensify production.

Following a general introduction in Chapter I, Chapter II examines the ecological implications of shade-tree management in CAFS. Using ecological data collected across 18 farms, the chapter analyses how variation in shade-tree management, in terms of shade-tree density and cover, affects the presence of the golden-headed lion tamarin, an endangered primate species highly dependent on shaded CAFS, as well as the terrestrial medium- and large-sized mammal community. The results show that reduced shade-tree cover is associated with lower golden-headed lion tamarin occupancy and decreased mammal detections, highlighting the negative effects of shade-tree removal on biodiversity. These findings indicate that ~65% of shade cover, corresponding to min. 100 shade trees per hectare, is required to sustain biodiversity conservation in the CAFS of southern Bahia, suggesting that current legal threshold of 40 shade trees per hectare is insufficient.

Chapter III focuses on the economic performance of CAFS and assesses how variation in shade-tree density influences cocoa yields, production costs, revenues from non-cocoa agroforestry products,

and overall returns from CAFS. Drawing on household economic survey data from 313 cocoa-producing households combined with on-farm measurements of shade-tree density, the chapter demonstrates that while higher shade-tree densities may be associated with lower cocoa yields, reductions in cocoa production costs partly offset these losses, leaving net cocoa income largely unaffected. As a result, even substantial increases in shade-tree density entail limited economic trade-offs, supporting the maintenance of shade trees in CAFS as a means to better align farm-level economic performance with the long-term ecological resilience of these systems.

Chapter IV integrates ecological and economic dimensions to identify the conditions under which CAFS generate trade-offs or synergies between biodiversity conservation and farm profitability. By combining household-level economic survey data with farmers' self-reported observations of mammal presence, and applying a multinomial probit modelling approach, the analysis shows that high economic returns per hectare within CAFS can, under specific conditions, coexist with biodiversity conservation. While higher shade-tree density can mitigate ecological trade-offs, increasing shade-tree density alone does not guarantee ecological–economic synergies, indicating that shade-tree retention constitutes a necessary but insufficient condition. Instead, the results demonstrate that synergies are contingent on supportive social and institutional conditions, including measures that promote gender equality and improve farmers' access to information and resources relevant for farm-level decision-making.

Chapter V examines the role of the Sul da Bahia Geographical Indication (GI) for high-quality cocoa as a governance instrument for the sustainable development of CAFS. Using a mixed-methods approach that combines in-depth biodiversity assessments on 18 farms with detailed household-level economic data and semi-structured interviews with key GI stakeholders, this chapter evaluates whether participation in the GI scheme is associated with improved economic and ecological outcomes at the farm level. While the GI shows potential to strengthen cocoa quality recognition, product differentiation, traceability, and regional identity, no improvement in economic returns and lower environmental performance relative to non-certified farms are observed. Its current contribution to farm-level economic and ecological benefits remains constrained by limited market uptake, weak institutional capacity and a lack of binding ecological requirements.

In conclusion, this dissertation demonstrates that trade-offs between biodiversity conservation and farm profitability are not inevitable and that well-managed AFS can deliver ecological–economic synergies when embedded within supportive social, institutional, and value-chain contexts. These findings have direct implications for policy and governance, highlighting the need for incentive-based governance instruments that explicitly value the maintenance of mature shade trees within AFS and provide financial compensation that reflects the ecological services these systems already deliver. Finally, by providing robust empirical evidence on within-system variation in AFS performance, this research advances debates on sustainable agricultural transitions and highlights the value of integrating ecological and economic perspectives in the study of AFS.

Keywords: Agricultural intensification; Shade-tree management; Mammals; *Leontopithecus chrysomelas*; Biodiversity conservation; Economic performance; Smallholder livelihood; Trade-offs and synergies; Geographical Indications; Southern Bahia

Resumo

As cadeias de valor globais para commodities agrícolas tropicais têm sido associadas a desafios ambientais e socioeconômicos significativos, particularmente em regiões mais biodiversas do mundo. O aumento da demanda internacional de produtos tem impulsionado a expansão e a intensificação agrícola, contribuindo para o desmatamento, a perda de biodiversidade e a degradação dos solos, enquanto pequenos produtores permanecem expostos à baixa produtividade, à pobreza e a desigualdades estruturais. Esses desafios intensificaram os apelos por uma transição para a sustentabilidade conciliando produção agrícola, conservação ambiental e avida rural. Nesse contexto, os sistemas agroflorestais (SAFs) emergiram como uma promissora solução baseada na natureza, pois integram árvores e culturas agrícolas nos sistemas produtivos e oferecem potencial para equilibrar múltiplos objetivos de sustentabilidade. No entanto, existe uma variação substancial dentro dos SAFs em relação ao uso da terra, particularmente no que se refere ao manejo de árvores de sombra, refletindo as decisões dos agricultores quanto à retenção e ou remoção dessas árvores, e constituindo um aspecto central do manejo em nível de propriedade nos SAFs. Ainda assim, as evidências empíricas permanecem limitadas quanto à forma como essa variação de manejo (intra-sistema) influencia os parâmetros ecológicos e econômicos. Além disso, a efetividade dos instrumentos de governança para valorizar os SAFs e incentivar seu manejo sustentável ainda é pouco compreendida.

Diante desse contexto, esta tese aborda as lacunas por meio de uma análise aprofundada dos sistemas agroflorestais de cacau (SAFs de cacau), conhecidos localmente como *cabrucas*, um sistema produtivo de importância global predominantemente manejado por pequenos produtores e que oferece um contexto relevante para examinar *trade-offs* e sinergias em sustentabilidade. Especificamente, esta tese busca elucidar como o manejo de árvores de sombra nas *cabrucas* molda os *trade-offs* e sinergias ecológico-econômicas, bem como avaliar o potencial da certificação baseada na origem geográfica para promover seu desenvolvimento sustentável. A pesquisa adota uma abordagem de estudo de caso nas paisagens de *cabrucas* do sul da Bahia, Brasil, uma região de grande importância ecológica na qual os sistemas tradicionais de cultivo sombreados são amplamente difundidos, sustentam os meios de vida rurais e enfrentam pressões crescentes para a intensificação da produção de cacau.

Após uma introdução geral no Capítulo I, o Capítulo II examina as implicações ecológicas do manejo de árvores de sombra nas *cabrucas*. Utilizando dados ecológicos coletados em 18 propriedades, o capítulo analisa como a variação no manejo da sombra, em termos de densidade de árvores e cobertura de sombra, afeta a presença do mico-leão-de-cara-dourada, uma espécie de primata em perigo de extinção e altamente dependente de *cabrucas* sombreados, além da comunidade de mamíferos terrestres de médio e grande porte nessas áreas. Os resultados mostram que a redução da cobertura de árvores de sombra está associada a menores probabilidades de ocupação do mico-leão-de-cara-dourada e a uma diminuição nos registros de mamíferos, evidenciando os efeitos negativos da remoção de árvores de sombra sobre a biodiversidade. Esses achados indicam que ~65% de cobertura de sombra,

correspondente a no mínimo 100 árvores de sombra por hectare, é necessário para sustentar a conservação da biodiversidade das cabrucas do sul da Bahia, sugerindo que o atual limite legal de 40 árvores de sombra por hectare é insuficiente.

O Capítulo III concentra-se no desempenho econômico das *cabrucas* e avalia como a variação na densidade de árvores de sombra influencia os rendimentos da produção de cacau, os custos de produção, as receitas provenientes de produtos agroflorestais não relacionados ao cacau e os retornos totais das *cabrucas*. Com base em dados de pesquisas econômicas domiciliares coletados em 313 domicílios produtores de cacau, combinados com medições em campo da densidade de árvores de sombra, o capítulo demonstra que, embora maiores densidades de sombra possam estar associadas a menores produtividades de cacau, reduções nos custos de produção compensam parcialmente essas perdas, mantendo a renda líquida do cacau praticamente inalterada. Como resultado, mesmo aumentos substanciais na densidade de árvores de sombra implicam em *trade-offs* econômicos limitados, reforçando a manutenção das árvores de sombra nas *cabrucas* como uma estratégia para alinhar melhor o desempenho econômico das propriedades com a resiliência ecológica a longo prazo desses sistemas.

O Capítulo IV integra as dimensões ecológica e econômica para identificar as condições sob as quais as *cabrucas* geram *trade-offs* ou sinergias entre a conservação da biodiversidade e a rentabilidade das propriedades. Ao combinar dados econômicos dos moradores com observações relatadas pelos agricultores sobre a presença de mamíferos e aplicar um modelo probit multinomial, a análise demonstra que elevados retornos econômicos por hectare nas *cabrucas* podem, sob condições específicas, coexistir com a conservação da biodiversidade. Embora maiores densidades de árvores de sombra possam mitigar *trade-offs* ecológicos, o aumento da densidade de sombra por si só não garante sinergias ecológico-econômicas, indicando que a retenção de árvores de sombra constitui uma condição necessária, porém não suficiente. Em vez disso, os resultados mostram que as sinergias dependem de condições sociais e institucionais favoráveis, incluindo medidas que promovam a equidade de gênero e ampliem o acesso dos agricultores à informação e a recursos relevantes para a tomada de decisão em nível de propriedade.

O Capítulo V examina o papel da Indicação Geográfica (IG) Sul da Bahia para o cacau de alta qualidade como um instrumento de governança para o desenvolvimento sustentável das *cabrucas*. Utilizando uma abordagem de métodos mistos que combina avaliações aprofundadas da biodiversidade em 18 propriedades com dados econômicos domiciliares detalhados e entrevistas semiestruturadas com atores-chave da IG, o capítulo avalia se a participação no IG está associada a melhorias nos resultados econômicos e ecológicos em nível de propriedade. Embora a IG apresente potencial para fortalecer o reconhecimento da qualidade do cacau, a diferenciação de produtos, a rastreabilidade e a identidade regional, não se observam melhorias nos retornos econômicos e verifica-se um desempenho ambiental inferior em comparação com propriedades não certificadas. Sua contribuição atual para benefícios econômicos e ecológicos em nível de propriedade permanece limitada pela baixa adesão de mercado, pela fragilidade da capacidade institucional e pela ausência de requisitos ecológicos vinculantes.

Em conclusão, esta tese demonstra que os *trade-offs* entre a conservação da biodiversidade e a rentabilidade das propriedades não são inevitáveis e que SAFs bem manejados podem gerar sinergias ecológico-econômicas quando inseridos em contextos sociais, institucionais e de cadeias de valor favoráveis. Esses resultados têm implicações diretas para políticas públicas e governança, destacando a necessidade de instrumentos de governança baseados em incentivos que valorizem explicitamente a manutenção de árvores de sombra maduras nos SAFs e ofereçam compensações financeiras condizentes com os serviços ecológicos que esses sistemas já fornecem. Por fim, ao fornecer evidências empíricas robustas sobre a variação intra-sistema no desempenho dos SAFs, esta pesquisa contribui para o avanço dos debates sobre transições agrícolas sustentáveis e evidencia o valor de integrar perspectivas ecológicas e econômicas no estudo dos SAF.

Palavras-chave: Intensificação agrícola; Manejo de árvores de sombra; Mamíferos; *Leontopithecus chrysomelas*; Conservação da biodiversidade; Desempenho econômico; Meios de subsistência da agricultura familiar; Trade-offs e sinergias; Indicações Geográficas; Sul da Bahia

Résumé

Les chaînes de valeur mondiales des produits agricoles tropicaux sont depuis longtemps associées à des défis environnementaux et socioéconomiques majeurs, en particulier dans certaines des régions les plus riches en biodiversité au monde. La hausse de la demande internationale a favorisé l'expansion et l'intensification agricoles, contribuant à la déforestation, à la perte de biodiversité et à la dégradation des terres, tandis que de nombreux petits producteurs demeurent exposés à une faible productivité, à la pauvreté et à des inégalités structurelles. Ces défis imbriqués ont renforcé les appels en faveur de transitions vers la durabilité capables de concilier production agricole, conservation de l'environnement et moyens de subsistance ruraux. Dans ce contexte, les systèmes agroforestiers (SAF) ont émergé comme une solution fondée sur la nature prometteuse, dans la mesure où ils intègrent arbres et cultures au sein des systèmes de production agricole et offrent un potentiel pour équilibrer plusieurs objectifs de durabilité. Toutefois, une variabilité substantielle existe au sein des SAF en tant que catégorie d'usage des terres, en particulier en ce qui concerne la gestion des arbres d'ombrage. Cette variabilité reflète les décisions des agriculteurs relatives au maintien ou à l'élimination des arbres d'ombrage et constitue une dimension clé de la gestion à l'échelle de l'exploitation dans les SAF. Néanmoins, les preuves empiriques demeurent limitées quant à la manière dont cette variation de gestion intra-système influence les résultats écologiques et économiques. De plus, l'efficacité des instruments de gouvernance visant à valoriser les SAF et à inciter à leur gestion durable reste insuffisamment comprise.

Dans ce contexte, cette thèse aborde ces lacunes au moyen d'une analyse approfondie des systèmes agroforestiers de cacao (CAFS), un système de production d'importance mondiale majoritairement géré par des petits producteurs et offrant un cadre pertinent pour examiner les compromis et les synergies en matière de durabilité. Plus précisément, cette thèse vise à analyser comment la gestion des arbres d'ombrage dans les CAFS façonne les compromis et les synergies écologico-économiques, et à évaluer le potentiel de la certification fondée sur le lieu d'origine pour promouvoir leur développement durable. La recherche adopte une approche par étude de cas dans les paysages de CAFS du sud de Bahia, au Brésil, une région d'une grande importance écologique où les systèmes traditionnels à forte densité d'ombrage sont largement répandus, soutiennent les moyens de subsistance ruraux et sont confrontés à des pressions croissantes en faveur de l'intensification de la production cacaoyère.

Après une introduction générale au Chapitre I, le Chapitre II examine les implications écologiques de la gestion des arbres d'ombrage dans les CAFS. En s'appuyant sur des données écologiques collectées sur 18 exploitations, ce chapitre analyse comment la variation de la gestion de l'ombrage, en termes de densité et de couverture arborée, affecte la présence du tamarin-lion à tête dorée, une espèce de primate menacée fortement dépendante des CAFS ombragés, ainsi que la communauté de mammifères terrestres de taille moyenne et grande. Les résultats montrent qu'une réduction de la couverture d'arbres d'ombrage est associée à une diminution de l'occupation par le tamarin-lion à tête dorée et à une baisse des détections de mammifères, mettant en évidence les effets négatifs de l'élimination des arbres

d'ombrage sur la biodiversité. Ces résultats indiquent qu'une couverture d'arbres d'ombrage de ~65%, correspondant à un min. de 100 arbres d'ombrage par hectare, est nécessaire pour assurer la conservation de la biodiversité dans les paysages de SAF du sud de Bahia, ce qui suggère que les seuils juridiques actuels de 40 arbres d'ombrage par hectare sont insuffisants.

Le Chapitre III se concentre sur la performance économique des CAFS et évalue comment la variation de la densité d'arbres d'ombrage influence les rendements en cacao, les coûts de production, les revenus issus des produits agroforestiers non cacaoyers et les rendements globaux des CAFS. En mobilisant des données issues d'enquêtes économiques auprès de 313 ménages de producteurs de cacao, combinées à des mesures de terrain de la densité d'arbres d'ombrage, ce chapitre montre que, bien que des densités plus élevées d'arbres d'ombrage puissent être associées à des rendements en cacao plus faibles, les réductions des coûts de production compensent en partie ces pertes, laissant le revenu net du cacao largement inchangé. Par conséquent, même des augmentations substantielles de la densité d'arbres d'ombrage entraînent des compromis économiques limités, ce qui soutient le maintien des arbres d'ombrage dans les CAFS comme moyen de mieux aligner la performance économique des exploitations avec la résilience écologique à long terme de ces systèmes.

Le Chapitre IV intègre les dimensions écologiques et économiques afin d'identifier les conditions dans lesquelles les CAFS génèrent des compromis ou des synergies entre la conservation de la biodiversité et la rentabilité des exploitations. En combinant des données économiques à l'échelle des ménages avec des observations auto-déclarées par les agriculteurs concernant la présence de mammifères, et en appliquant un modèle probit multinomial, l'analyse montre que des rendements économiques élevés par hectare au sein des CAFS peuvent, sous certaines conditions, coexister avec la conservation de la biodiversité. Si une densité plus élevée d'arbres d'ombrage peut atténuer les compromis écologiques, l'augmentation de la densité d'ombrage à elle seule ne garantit pas des synergies écologico-économiques, indiquant que la rétention des arbres d'ombrage constitue une condition nécessaire mais non suffisante. Les résultats montrent plutôt que les synergies dépendent de conditions sociales et institutionnelles favorables, notamment des mesures favorisant l'égalité de genre et améliorant l'accès des agriculteurs à l'information et aux ressources pertinentes pour la prise de décision à l'échelle de l'exploitation.

Le Chapitre V examine le rôle de l'Indication Géographique (IG) Sul da Bahia pour le cacao de haute qualité en tant qu'instrument de gouvernance pour le développement durable des CAFS. À l'aide d'une approche de méthodes mixtes combinant des évaluations approfondies de la biodiversité sur 18 exploitations, des données économiques détaillées à l'échelle des ménages et des entretiens semi-directifs avec des acteurs clés de l'IG, ce chapitre évalue si la participation au dispositif d'IG est associée à de meilleurs résultats économiques et écologiques au niveau de l'exploitation. Bien que l'IG présente un potentiel pour renforcer la reconnaissance de la qualité du cacao, la différenciation des produits, la traçabilité et l'identité régionale, aucune amélioration des rendements économiques et une performance

environnementale inférieure par rapport aux exploitations non certifiées ne sont observées. Sa contribution actuelle aux bénéfices économiques et écologiques à l'échelle de l'exploitation demeure limitée par une faible adoption par le marché, une capacité institutionnelle insuffisante et l'absence d'exigences écologiques contraignantes.

En conclusion, cette thèse démontre que les compromis entre la conservation de la biodiversité et la rentabilité des exploitations ne sont pas inévitables et que des SAF bien gérés peuvent générer des synergies écologico-économiques lorsqu'ils sont intégrés dans des contextes sociaux, institutionnels et de chaînes de valeur favorables. Ces résultats ont des implications directes pour les politiques publiques et la gouvernance, en soulignant la nécessité d'instruments de gouvernance fondés sur des incitations qui valorisent explicitement le maintien d'arbres d'ombrage matures au sein des SAF et offrent une compensation financière reflétant les services écologiques que ces systèmes fournissent déjà. Enfin, en apportant des preuves empiriques solides sur la variation intra-système des performances des SAF, cette recherche contribue à faire progresser les débats sur les transitions agricoles durables et met en évidence l'intérêt d'une intégration des perspectives écologiques et économiques dans l'étude des SAF.

Mots-clés: Intensification agricole; Gestion des arbres d'ombrage; Mammifères; *Leontopithecus chrysomelas*; Conservation de la biodiversité; Performance économique; Moyens de subsistance des petits producteurs; Compromis et synergies; Indications géographiques; Sud de la Bahia

List of main abbreviations and acronyms

ACSB	Associação Cacau Sul Bahia
AFS	Agroforestry systems
ATET	Average Treatment Effect on the Treated
BaLTCI	Bahian Lion Tamarin Conservation Initiative
BRL	Brazilian Real
CAAE	Certificado de Apresentação de Apreciação Ética
CAFS	Cocoa agroforestry systems
CEP	Comitê de Ética em Pesquisa
CIC	Centro de Inovação do Cacau
CRC	Centre for Research and Conservation
DBH	Diameter at breast height
FAO	Food and Agriculture Organization of the United Nations
GI	Geographical Indication
GHLT	Golden-headed lion tamarin
GLMM	Generalised Linear Mixed Model
IBGE	Instituto Brasileiro de Geografia e Estatística
ICMBio	Instituto Chico Mendes de Conservação da Biodiversidade
ICCO	International Cocoa Organization
IP	Indicação de Procedência
IVI	Importance Value Index
NGO	Non-governmental organisation
OLS	Ordinary Least Squares
PDO	Protected Designation of Origin
PSM	Propensity Score Matching
UESC	Universidade Estadual de Santa Cruz
USD	United States Dollar
VSS	Voluntary Sustainability Standards

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Chapter I

General introduction

1.1. Global context

Global value chains for tropical commodity crops have been increasingly associated with negative environmental and social outcomes in some of the world's most vulnerable ecosystems (Lenzen et al., 2012; Meyfroidt et al., 2014; Pendrill et al., 2022). Rising global demand for commodities such as cocoa, coffee and palm oil has led to the expansion and intensification of tropical agricultural production, which is a major contributor to biodiversity loss, deforestation, climate change, and land degradation (Grass et al., 2020; Laurance et al., 2014; Meyfroidt et al., 2014). Meanwhile, production of these crops is concentrated in low- and middle-income countries, where millions of small-scale farmers depend on them for their livelihoods. Yet, these commodity sectors are characterized by low productivity, price volatility, and structural inequalities within global value chains (FAO, 2017). Consequently, many smallholders remain trapped in persistent poverty despite their central role in global agricultural production (Waarts et al., 2021).

These environmental and socio-economic challenges underscore the urgent need to transition tropical commodity production systems toward sustainability (Webb et al., 2020). Such transition requires balancing multiple goals, yet progress towards one goal frequently comes at the expense of another, revealing the inherent trade-offs that define agricultural sustainability transitions. For instance, yield-oriented intensification can enhance short-term productivity and income but may undermine ecosystem integrity and long-term resilience (Fischer et al., 2024). Building sustainable food systems therefore entails strategies that minimise trade-offs and promote synergies between economic, social, and environmental outcomes. Two main pathways for achieving this transition have been proposed. Sustainable intensification focuses on increasing productivity and resource-use efficiency while reducing environmental impacts through technological and management innovations, whereas agroecology promotes more systemic transitions toward diversified, biodiversity-based, and socially just farming systems (Fischer et al., 2024). Despite their different emphases, both approaches highlight the importance of adopting sustainable farming practices as a means to increase productivity while reducing environmental impacts and enhancing ecosystem resilience. However, farmers' decisions and motivation to adopt these practices are strongly influenced by the governance and market structure of the value chains they participate in (Grabs et al., 2024; Krumbiegel and Tillie, 2024; Liverpool-Tasie et al., 2020; Piñeiro et al., 2020; Tennhardt et al., 2023). Lasting progress thus not only depends on farm-level adoption of sustainable practices but also on inclusive value-chain governance that enables, rewards, and up-scales such sustainability practices.

Agroforestry systems (AFS) have emerged as a promising nature-based solution for promoting sustainable food system transitions in tropical small-scale farming contexts (Blaser et al., 2018; Broeckhoven et al., 2025; Clough et al., 2011; Wurz et al., 2022). By deliberately integrating or retaining trees with crops and/or livestock (Nair et al., 2021), AFS offer multiple ecological and socio-economic benefits. Ecologically, they contribute to climate change mitigation and adaptation through carbon sequestration and microclimate regulation (Becker et al., 2025; Blaser et al., 2018; Wätzold et al., 2026). Although AFS cannot fully replace native forests, they support biodiversity conservation by providing secondary habitat for native fauna and serving as ecological corridors that facilitate species dispersal between forest fragments (Bennett et al., 2022; Blaser et al., 2018; Dekegel et al., 2025; Ferreira et al., 2023). Socio-economically, AFS strengthen household resilience by diversifying income sources through the production of associated crops, timber, medicinal plants, and other non-timber forest products, and reducing farmers' dependence on a single crop, thereby improving household food security (Armengot et al., 2016; Cerda et al., 2014).

AFS are therefore increasingly promoted in tropical agricultural landscapes as a strategy to balance productivity goals with environmental sustainability and to enhance farmers' adaptive capacity to climate and market shocks (Becker et al., 2025; Blaser et al., 2018; Broeckhoven et al., 2025; Muthuri et al., 2023; Schroth et al., 2016b; Vaast and Somarriba, 2014). AFS, however, differ widely in their land-use history, configuration, and management intensity due to different trajectories of establishment (Ruf and Schroth, 2004). In forest-to-AFS transitions, a selectively thinned natural forest is underplanted with tree crops beneath retained old forest trees, protecting crops from climatic hazards and pests while conserving part of the original forest structure and biodiversity. In some regions, such forest-derived AFS are still standing (Schroth et al., 2015) while in others, however, they have undergone progressive simplification, evolving into mixed-tree plantations where tree cops are cultivated alongside fruit, timber or leguminous trees to retain minimal tree cover. In contrast, degraded-land or monoculture-to-AFS transitions establish tree crops after forest clearing or on degraded fallows, with shade trees gradually introduced to restore soil fertility and microclimatic regulation (Blaser et al., 2018, 2017; Niether et al., 2020). These systems can enhance ecological functions compared to full-sun monocultures but initially lack the structural complexity and biodiversity of forest-derived agroforests (Ruf and Schroth, 2004). These differences in establishment pathways have led to substantial variability *within* AFS as a land-use type, ranging from highly shaded, species-rich, and structurally complex systems to simplified, low-shade configurations with few native or planted trees and limited diversity.

While shade trees in AFS provide important benefits, they may also reduce crop yields through resource competition (Blaser et al., 2018), cause physical damage to tree crops from falling branches, and are perceived by farmers as creating microclimates that favour pests and diseases (Armengot et al., 2016; Brown et al., 2025). AFS therefore involve inherent trade-offs between ecological and economic outcomes, which are further shaped by farmers' perceptions and management decisions. In practice, management decisions in AFS are most directly expressed in shade-tree management, particularly through the decision to retain or remove shade trees, which alters shade-tree density and associated shade-tree cover. Effectively managing the trade-offs associated to shade trees therefore requires a better understanding of how shade-tree management, in terms of shade-tree density and cover, affects ecological and economic outcomes within AFS. Such knowledge is essential for identifying optimal shade-tree management strategies in AFS that minimises trade-offs and maximises synergies, yet empirical evidence is still limited. Moreover, our understanding remains limited regarding how institutional and governance mechanisms, such as sustainability or origin-based certification, can valorise AFS and incentivise their sustainable management. Addressing these gaps is central to realising the full sustainability potential of AFS and designing policies that reconcile production and conservation objectives in tropical agriculture.

1.2. The cocoa sector and its sustainability challenges

Cocoa production provides a particularly relevant context to investigate these trade-offs because of its global economic importance and its strong link with agroforestry. Cocoa (*Theobroma cacao L.*) is one of the world's leading tropical commodities, with more than 4.4 million tonnes traded globally each year (ICCO, 2025). Its cultivation is almost entirely confined to tropical regions within 20° latitude of the equator, with West Africa, Latin America, and Southeast Asia as the principal production zones. Cocoa is of major economic importance for several countries, particularly Côte d'Ivoire and Ghana, which together account for over 60% of global output, while Indonesia, Ecuador, Brazil, and Cameroon also rank among the top producers (FAO, 2025). The crop supports the livelihoods of an estimated 40-50 million people worldwide, including about five million farming households, the vast majority of whom are small-scale farmers in low-income countries (Voora et al., 2019). However, significant sustainability concerns have been raised regarding the environmental and socio-economic impacts of cocoa production systems (Boeckx et al., 2020; Kalischek et al., 2023; Renier et al., 2023; Van den Broeck and Akaribo, 2024). A large proportion of those farmers are poor and do not earn a living income (Boeckx et al., 2020; Waarts et al., 2021). Productivity in the sector remains low due to ageing cocoa trees, declining soil fertility, lack of input and labour investment, which constrain farmers' ability to rehabilitate plantations or diversify income sources (Kongor et al., 2018; Waarts et al., 2021). At the same time, farm-gate prices for cocoa are volatile, exposing producers to market shocks and income instability (FAO, 2017). These combined factors trap many cocoa-producing households in cycles of poverty and underinvestment. Labour-related challenges compound these structural constraints, including the presence of children working on the farms (Van den Broeck and Akaribo, 2024) and precarious working conditions (Meemken et al., 2019). Meanwhile, the global cocoa value chain is increasingly consolidated downstream, dominated by three major trading and grinding corporations controlling about 60% of global cocoa flows and five confectionery manufacturers dominating chocolate production and retail. This concentration makes cocoa one of the most consolidated agricultural commodity sectors worldwide, reinforcing structural asymmetries in value capture and leaving farmers with limited bargaining power and low returns (Carodenuto and Buluran, 2021; Grabs et al., 2024).

In addition to its socio-economic challenges, cocoa production is also closely linked to environmental degradation in tropical regions. Cocoa has been a major driver of deforestation, particularly in West Africa (Kalischek et al., 2023), where it has contributed both directly, through the conversion of forested land to cocoa farms, and indirectly, by displacing food crops and other land uses into remaining forest areas (Renier et al., 2025). Beyond deforestation, the intensification of cocoa cultivation within existing AFS has further reduced their ecological value. In many regions, shaded cocoa agroforests have been progressively transformed into low-shaded or full-sun monocultures through shade tree removal, a trend initially driven by expectations of higher yields and the need to secure short-term income (Steffan-Dewenter et al., 2007; Tscharntke et al., 2011a). This transition towards simplified production systems has led to marked declines in biodiversity and ecosystem service provision (Bennett et al., 2022; Cassano et al., 2014; De Beenhouwer et al., 2013; Dekegel et al., 2025; Jarrett et al., 2021), ultimately undermining the ecological resilience of cocoa landscapes.

Given these interconnected challenges, there is an urgent need to identify practices that reconcile productivity, income, and environmental objectives. A growing array of public, private, and hybrid sustainability initiatives now seeks to address these issues. Among these, Voluntary Sustainability Standards (VSS) have proliferated as non-state, market-based governance mechanisms. Cocoa is the leading certified crop under such standards, with at least 22% of the global production area certified (Meemken et al., 2021). VSS set economic, environmental, and social requirements that producers must meet in exchange for benefits such as price premiums, market access, or training (Marx & Wouters, 2015). They include multi-stakeholder third-party schemes such as the Rainforest Alliance and corporate in-house programs like Mondelēz International's Cocoa Life. While some encourage farmers to maintain or plant shade trees, they rarely define strict thresholds. For instance, the Rainforest Alliance recommends an optimal 15% natural vegetation cover, though its application unit (individual vs. group) remains ambiguous (Wätzold et al., 2025). While all aim to foster sustainable production and improve farmer livelihoods, differences in governance and implementation generate variable outcomes for smallholders (Bemelmans et al., 2025). In parallel, public regulation is advancing, most notably the EU Regulation on Deforestation-Free Products, which mandates traceability and proof of non-deforestation sourcing for high-risk commodities such as cocoa (Berning and Sotirov, 2023). These initiatives mark a shift from voluntary to legally binding forms of sustainability governance, aiming to enhance corporate accountability and traceability throughout global supply chains. In addition to these mechanisms, origin-based certification, such as Geographical Indications (GIs), is emerging as a complementary territorial strategy for sustainable development, linking product quality to its geographical and cultural origin (FAO, 2025).

Despite growing scholarly and policy attention to cocoa sustainability, research on the functioning and performance of cocoa farming systems, particularly agroforestry, remains limited. The majority of studies assess the consequences of land-use transitions by comparing AFS to other land-use systems or farming systems (Abdulai et al., 2018; Bisseleua et al., 2009; Broeckhoven et al., 2025; De Beenhouwer et al., 2013; Ferreira et al., 2020; Grass et al., 2020; Jezeer et al., 2017; Mattalia et al., 2022; Niether et al., 2020; Wenzel et al., 2024; Wurz et al., 2022). While this between-system approach has been essential for demonstrating the relative ecological and economic benefits of agroforestry, it overlooks the large within-system variation that characterizes AFS. This within-system variability has important implications for both ecological and economic outcomes but remains poorly understood. As a result, the mechanisms through which shade-tree management affects biodiversity, productivity, and livelihoods, and the potential to reconcile these outcomes, remain insufficiently investigated.

1.3. Case study

This dissertation addresses the limited understanding of how shade-tree management influences ecological and economic outcomes in cocoa agroforestry systems (CAFS), and how governance instruments such as origin-based certification can valorise these systems. To do so, it adopts an in-depth case study of cocoa agroforestry landscapes in southern Bahia, Brazil, a region where traditional high-shade systems remain widespread, biodiversity value is globally significant, and policy pressures to intensify production are increasing.

1.3.1. Motivation of the case study

Brazil offers an excellent case to examine how agroforestry and governance innovations intersect within the cocoa sector. Over the past two decades, Brazil's cocoa production has increased by 74.2% (FAOSTAT, 2025), reflecting a steady recovery and renewed investment following the sector's prolonged crisis in the 1990s (Pereira et al., 1996). The country consistently ranks among the world's top ten cocoa-producing countries and currently stands as the fifth largest producer globally and the second in Latin America (FAOSTAT, 2025). In 2024, production reached ~297,000 tonnes, harvested from ~617,000 hectares with an estimated production value of R$15.3 billion (IBGE, 2024; Figure 1.1). These figures confirm Brazil's strong position within the global cocoa value chain and highlight its growing importance as a major and expanding producer. Unlike the cocoa sectors in major West African producing countries (Staritz et al., 2023), Brazil's cocoa sector operates under a largely liberalised market regime, with farmgate prices determined by private transactions that closely follow international cocoa prices rather than state-controlled pricing mechanisms. Cocoa production is primarily destined for the domestic market, making it the only major producing country that remains a net importer, with an estimated annual demand of ~300,000 tonnes (Hütz-Adams et al. 2022). This combination of a liberalised market and a strong domestic demand reinforces Brazil's potential, as a producer-country, for domestic value capture along the cocoa–chocolate chain (Hütz-Adams et al., 2022).

Recognising the strategic economic importance of the cocoa sector, the Brazilian federal government launched the Inova Cacau 2030 Plan to position the country as a global reference for sustainable cocoa production (Ministério da Agricultura e Pecuária, 2023). The plan aims to increase national output to 400,000 tonnes by 2030 and to enhance the efficiency of production units by improving productivity, cocoa quality, and cost-effectiveness while simultaneously generating socio-economic benefits for producers. A central pillar of the strategy is the promotion of cocoa cultivation in AFS, thereby integrating production growth with environmental conservation and the sustainable use of natural resources. The plan further prioritises cocoa quality and traceability, aiming for 10% of marketed cocoa to be sold at premium prices and 70% to be fully traceable by 2030, thereby strengthening value creation through quality improvement and market differentiation (MAPA & CEPLAC, 2023).

Expanding cocoa production is therefore of strategic importance for Brazil's rural development. However, achieving this growth sustainably requires a better understanding of how productivity improvements can be reconciled with environmental sustainability in CAFS and highlights the need to identify pathways through which value can be added by recognising product differentiation.

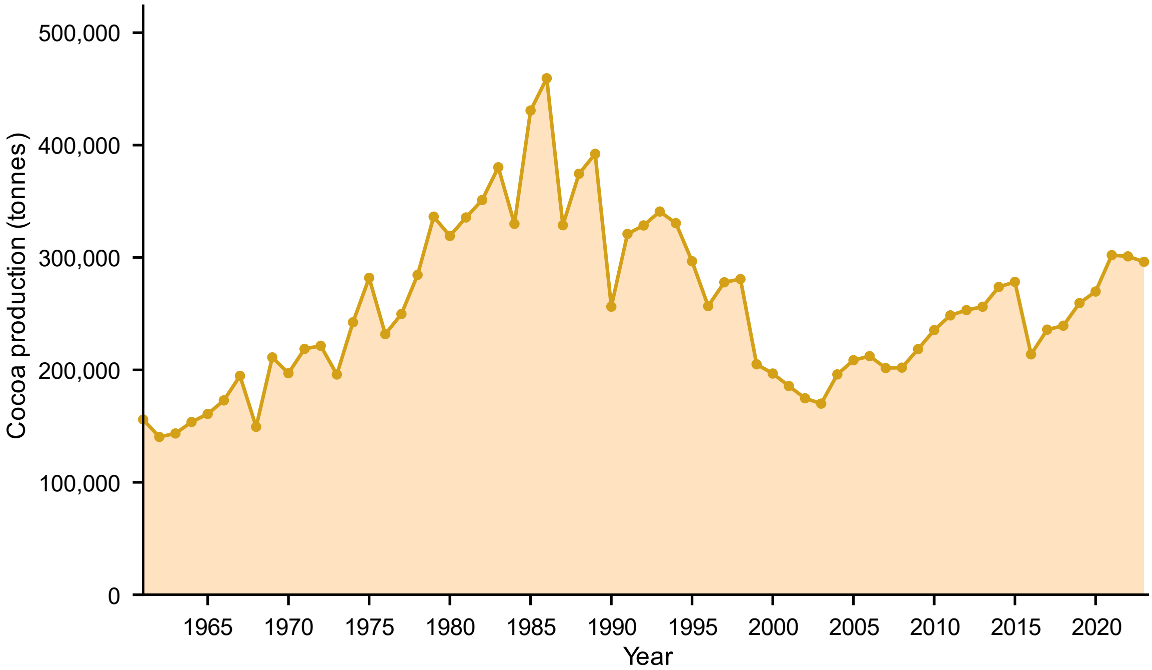

Figure 1.1 Cocoa production in Brazil in terms of volume produced between 1961 and 2023. Data from FAOSTAT (2025).

1.3.2. Background

Within this national context, southern Bahia constitutes a particularly relevant region for examining the ecological and economic sustainability of CAFS. As one of the country's major cocoa-producing states, southern Bahia accounts for 46% of national cocoa production, covering ~428,000 hectares under cultivation and producing an annual output of 137,028 tonnes (IBGE, 2024)[1]. Cocoa cultivation plays an important socio-economic role in the region, supporting an estimated ~69,000 farming households and contributing significantly to employment and rural income generation (Chiapetti et al., 2020). The crop is deeply embedded in the regions' cultural heritage and historical development, representing the oldest and most established cocoa-producing area in Brazil (Sambuichi et al., 2012).

Historically, southern Bahia was Brazil's leading cocoa-producing region, accounting for over 90% of the country's cocoa output for much of the twentieth century (IBGE, 2023). During this period, Brazil ranked as the world's second-largest cocoa producer (Alger and Caldas, 1994). However, the sector suffered a severe decline in the late 1980s and mid-1990s following the outbreak of the witches' broom disease (*Moniliophthora perniciosa*), a fungal pathogen that severely reduced yields across southern Bahia (Pereira et al., 1996). The crisis was compounded by recurrent droughts and declining international cocoa prices driven by the rapid expansion of cocoa cultivation in West Africa, particularly in Ghana and Côte d'Ivoire (Alger and Caldas, 1994). As a result, national cocoa production declined from 458,000 tonnes in 1986 to 170,000 tonnes in 2003 (FAO, 2023). This crisis triggered widespread rural impoverishment in the region, leading to farm abandonment, the illegal logging of high-value native shade trees in traditional CAFS and the conversion of traditional CAFS into pasture (Alger and Caldas, 1994). Although cocoa production has steadily increased over the past two decades (FAOSTAT, 2025), farmers continue to face significant socioeconomic challenges. Low productivity remains a major constraint for farmer livelihoods, with regional yields averaging 319 kg ha^{-1} year^{-1} (IBGE, 2024), substantially below those in Côte d'Ivoire and Ghana (500-570 kg ha^{-1}; FAOSTAT, 2025). Most farmers sell their cocoa through local warehouses or middlemen, channels that typically offer lower farmgate prices than direct sales to milling companies. Support through producer organisations remains relatively uncommon, with farmers more frequently affiliated with local associations and only a minority participating in cooperatives (Chiapetti et al., 2020). Limited access to credit and technical assistance further constrains farmers' capacity to invest in productivity improvements (Chiapetti et al., 2020). These factors contribute to persistently low economic returns, with household incomes often below the legal minimum wage (Chiapetti et al., 2020), which in turn incentivise shade-tree removal in pursuit of short-term income gains. Since shade-tree management ultimately reflects farmers' production

[1] For comparison, the state of Pará, the largest cocoa-producing state in Brazil, counts ~18,000 cocoa-producing households and ~163,000 hectares under cultivation, yielding a similar annual output of 137, 455 tonnes (IBGE, 2024). This contrast highlights the greater socio-economic relevance of cocoa production in Bahia and its broader role in sustaining rural employment and livelihoods.

decisions, understanding its implications for productivity and farmers' income is key to guiding sustainable intensification efforts.

Cocoa in southern Bahia is traditionally cultivated under the *cabruca* system (Figure 1.2), a forest-derived AFS in which cocoa trees are planted beneath a selectively thinned canopy of predominantly native trees, some of which are later regenerated or planted (Schroth et al., 2015). Although they have replaced parts of the primary Atlantic Forest (Alger and Caldas, 1994), these systems, which still represent 78% of cocoa farms in southern Bahia (Chiapetti et al., 2020), remain structurally complex and ecologically valuable systems. On average, *cabrucas* contain 197 shade trees per hectare (ranging from 70 to 480 trees per hectare), with around 63% of tree species being native (Schroth et al., 2015). The structural characteristics of *cabrucas* sharply contrast with CAFS in Brazil's other major cocoa-producing region and other major producing countries. In Pará, expansion has occurred more recently and particularly on degraded pastures or fallows through the deliberate planting of shade and companion trees as part of land restoration programs (Schroth et al., 2016a). In West Africa, CAFS have largely transitioned into simplified mixed-tree plantations, with over 80% of cocoa cultivated on low-shaded farms with less than 20% shade cover (Becker et al., 2025), and fewer than 9% of farmers maintaining more than 15 shade trees per hectare (Krumbiegel and Tillie, 2024). Similarly, in Indonesia, most cocoa farms were established through forest clearing (Ruf and Schroth, 2004), resulting in simplified AFS with mean shade-tree densities of only 32 trees per hectare (Dröge et al., 2025a). In this global context, Bahia's *cabrucas* stand out as one of the few remaining large-scale, high-shade cocoa production landscapes, offering a unique opportunity to analyse ecological and economic outcomes along gradients in shade-tree density.

Importantly, *cabrucas* are formally recognised and protected under Bahia's environmental legislation. State Decree No. 15180/2014 legally defines *cabruca* systems as AFS containing at least 20 native trees per hectare (Art. 15). At the same time, the decree allows for shade-tree thinning within *cabrucas* down to a minimum of 40 native trees per hectare (Art. 19), although this threshold remains well below that of traditional systems and risks undermining their ecological value (Schroth et al., 2015). Moreover, systems with fewer than 40 native trees per hectare, though still legally recognised as *cabruca*, are ineligible for environmental incentives such as payments for ecosystem services under the state decree. This legal framework positions Bahia among the few cocoa-producing regions globally where traditional agroforestry is explicitly defined and regulated, reflecting its recognised ecological and cultural value.

Situated within the Atlantic Forest, one of the world's most threatened biodiversity hotspots (Myers et al., 2000), *cabrucas* play a critical role in maintaining biodiversity by providing secondary habitat and functional connectivity between remaining forest fragments (Cassano et al., 2009; Oliveira et al., 2010; Schroth et al., 2011). They support a wide array of forest-dependent taxa, including birds, bats, and mammals (Figure 1.2), thereby contributing to the persistence of native and threatened species in this highly fragmented landscape (Almeida-Rocha et al., 2020; Cabral et al., 2021; Cassano et al., 2014; Faria et al., 2007; Ferreira et al., 2025). Among these, the golden-headed lion tamarin (*Leontopithecus chrysomelas*; GHLT; Figure 1.2), an endangered primate endemic to southern Bahia, is highly dependent on *cabrucas* for its persistence (Oliveira et al., 2010, 2011). Shade trees within *cabrucas* provide essential trophic and structural resources for this species, including fruits, nectar, and tree cavities used as sleeping sites (Oliveira et al., 2010), underscoring the role of shade-tree management in sustaining biodiversity within CAFS.

In addition to their ecological and socio-economic relevance, *cabruca* systems have recently gained institutional recognition through the establishment of the *Sul da Bahia* Geographical Indication (GI) in 2018. Officially registered as an Indicação de Procedência (IP, Indication of Provenance), the GI was developed through a collective initiative led by local producers, cooperatives, and technical institutions under the coordination of the Associação Cacau Sul Bahia (ACSB) (Ferreira, 2017a). The *Sul da Bahia* GI aims to promote sustainable regional development by linking high-quality cocoa production with the preservation of traditional shaded CAFS. Certification is granted to cocoa that meets defined quality standards (Figure 1.3) and is cultivated within the delimited geographical area under these AFS. Beyond protecting regional reputation and product authenticity, the scheme seeks to enhance market differentiation, local value addition, and collective territorial identity (Ferreira, 2017b). The initiative also includes the Chocolate *Sul da Bahia* brand, which features the GHLT as a flagship symbol of the intrinsic link between traditional cocoa cultivation and biodiversity conservation (Figure 1.3). The *Sul da Bahia* GI thus provides a compelling case for investigating how origin-based certification can serve as a governance instrument of sustainable development, integrating environmental stewardship, rural development, cultural heritage, and local value creation in traditional AFS.

Figure 1.2 Cabrucas in southern Bahia play a critical role in maintaining biodiversity. (Top left) Traditional shaded cocoa agroforestry system (*cabruca*), characterised by cocoa cultivated under a native tree canopy. (Top right) Golden-headed lion tamarin (*Leontopithecus chrysomelas*), an endangered and endemic primate species highly dependent of *cabrucas*. (Bottom left) Red-rumped agouti (*Dasyprocta leporina*), a key seed disperser in Atlantic Forest biome. (Bottom right) Margay (*Leopardus wiedii*), a small felid classified as *Vulnerable* on the IUCN Red List.

Figure 1.3 Cocoa and chocolate certified under the Sul da Bahia Geographical Indication (GI) scheme. (Left) Cocoa bags certified under the Sul da Bahia GI scheme. (Right) the Chocolate Sul da Bahia, which features the golden-headed lion tamarin as a flagship symbol for the conservation of the cocoa agroforests of southern Bahia.

1.3.3. Broader project setting

This dissertation is undertaken as a cotutelle between UCLouvain (Belgium) and the Universidade Estadual de Santa Cruz (UESC, Brazil), ensuring both academic supervision and local institutional integration within the region where the research is conducted. This dissertation is also carried out within the framework of Project BioBrasil, a long-term conservation and research project coordinated by the Antwerp ZOO Centre for Research and Conservation (CRC), Belgium, with core funding through the Ministry for Economy, Science and Innovation of the Flemish Government (EWI, Belgium). Established in 2002, Project BioBrasil conducts fundamental and applied research on GHLTs and their habitat in southern Bahia to inform science-based conservation strategies for this endangered primate. Over the past two decades, the project has expanded from ecological monitoring in fragmented and degraded forests to an integrative socio-ecological approach that engages local communities and small-scale farmers in conservation-oriented land management. Because much of the GHLT's remaining habitat overlaps with CAFS, Project BioBrasil recognises the pivotal role of sustainable agricultural practices in maintaining biodiversity and promoting landscape connectivity. This interdisciplinary framework provides the scientific and institutional foundation for the present dissertation.

The Bahian Lion Tamarin Conservation Initiative (BaLTCI) complements this research by planning and operationalising conservation strategies across a scope area within the GHLT's range in southern Bahia. Building on years of fundamental research and combining this with local expertise, knowledge and institutional committment, BaLTCI unites conservation scientists from universities and research initiatives (e.g., Project BioBrasil and Project Cabruca), local institutions (e.g., Bicho do Mato Instituto de Pesquisa), landowners, civil society and government agencies (e.g., Instituto Chico Mendes de Conservação da Biodiversidade) to jointly develop and implement a coordinated strategic plan. Its mission is to maintain remaining natural vegetation and restore functional habitat connectivity through forest restoration, sustainable land-use planning, and the promotion of biodiversity-friendly cocoa agroforestry. Coordinated jointly by the Antwerp Zoo Centre for Research and Conservation and the Bicho-do-Mato Instituto de Pesquisa, the initiative provides a collaborative platform for translating scientific findings into effective conservation action, involving all stakeholders. This institutional linkage ensures that the results of this PhD study can directly inform ongoing conservation planning and contribute to integrated biodiversity and rural development strategies in the region.

1.4. Research gaps and objectives

The overall research objective of this dissertation is to reveal how shade-tree management in cocoa agroforestry systems shapes ecological and economic trade-offs and synergies, and to evaluate the potential of the *Sul da Bahia* Geographical Indication to promote their sustainable development in southern Bahia, Brazil.

To achieve this objective, four general research questions are addressed:

I. How does shade-tree management affect the presence of the golden-headed lion tamarin and terrestrial medium- and large-sized mammals in CAFS?
II. How does variation in shade-tree density affect the economic performance of CAFS?
III. Under which conditions do CAFS deliver ecological-economic trade-offs and synergies?
IV. Does the *Sul da Bahia* GI promote economic and ecological sustainability of CAFS?

In this study, we use the term shade-tree management to refer specifically to farmers' decisions regarding the retention, removal, and thinning of shade trees within CAFS. While shade-tree management can encompass a broader set of practices, including pruning regimes and tree species selection, shade-tree density and associated shade-tree cover represent the primary and most consequential management dimensions in our study region.

The following sections describe the research gaps, objectives, and methods of each chapter, highlighting how this dissertation contributes to understanding the interactions between ecological sustainability and economic viability in CAFS.

1.4.1. Shade tree management and mammal conservation

The ecological implications of shade-tree management within AFS, and cocoa AFS in particular, remain insufficiently understood. Meta-analyses consistently show that AFS sustain higher biodiversity than monocultures (De Beenhouwer et al., 2013; Niether et al., 2020; Wynter et al., 2024), yet empirical evidence on how variation in shade-tree management, in terms of shade-tree density or cover, within these systems affects biodiversity is still limited. Most existing studies focus on birds (e.g. Bennett et al., 2022; Blaser et al., 2018; Jarrett et al., 2021; Pappo et al., 2025) and arthropods (e.g. Bisseleua et al., 2009, 2013; Clough et al., 2011; Pappo et al., 2025; Steffan-Dewenter et al., 2007), showing that reduced shade-tree cover or diversity generally lowers species richness and functional diversity. For birds, shade cover reduction results in the loss of specialised and insectivorous species, while generalist and open-habitat species increase in relative abundance (Bennett et al., 2022; Jarrett et al., 2021). For arthropods, declining shade-tree diversity and cover are associated with lower abundance and diversity of predatory and pollinating species, as well as reduced natural pest control (Bisseleua et al., 2009, 2013;

Steffan-Dewenter et al., 2007). Large mammals, despite their essential roles in ecosystem functioning and sensitivity to habitat modification (Ferreira et al., 2025), have received little attention in this context. In southern Bahia, where cocoa AFS are legally permitted to be thinned to a minimum of 40 native trees per hectare (State Decree No. 15180/2014), the implications of such shade-tree management for biodiversity remain poorly quantified. In particular, no studies have examined how shade-tree management affects the presence of the endangered golden-headed lion tamarin or identified the thresholds required to sustain its presence, which is crucial for evidence-based management and policy decisions.

To address these gaps, Chapter II evaluates how shade-tree management affects the presence of the golden-headed lion tamarin and the medium- and large-sized terrestrial mammal community in CAFS of southern Bahia. I combine vegetation assessments, playback surveys to detect GHLT, and camera trapping to record terrestrial mammals across 18 CAFS spanning a gradient of shade-tree density. I analyse the relationship between shade-tree management and GHLT occupancy and mammal detection rates using occupancy modelling and generalised linear mixed models (GLMM), respectively. This chapter provides insights into whether the current state-mandated threshold of 40 native shade trees per hectare is sufficient to sustain GHLT and whether shade tree management recommendations for this species may also provide co-benefits for the terrestrial medium- and large mammal community in CAFS.

1.4.2. Shade-tree management and economic performance

Evidence on the economic implications of shade-tree management within CAFS remains scarce. Most existing studies have been conducted in West Africa, with only a few focusing on Latin America (Armengot et al., 2016; Cerda et al., 2014; Notaro et al., 2020; Waldron et al., 2012), despite regional differences in ecological conditions and socio-economic context that may shape economic trade-offs differently. Current evidence has largely focused on yield responses to shade-tree management (Asare et al., 2019; Blaser et al., 2018; Clough et al., 2011; Wade et al., 2010), while other dimensions, such as production costs and the revenues from non-cocoa products, have received limited attention (Armengot et al., 2016; Cerda et al., 2014; Jezeer et al., 2017; Notaro et al., 2020). Findings on cocoa yield responses are mixed and highly context-specific. Some studies report that low-to-intermediate shade levels (~30–50% canopy cover or 140–150 shade trees per hectare) can sustain or even enhance yields compared to low-shade conditions (Asare et al., 2019; Bisseleua et al., 2009; Blaser et al., 2018; Waldron et al., 2012), whereas others demonstrate a steady decline in yields with increasing shade cover (Clough et al., 2011; Wade et al., 2010). Few studies have assessed the implications of shade-tree management for production costs and net income, offering a fragmented and incomplete view of the profitability of CAFS. For instance, Bisseleua et al. (2013) found that reduced shade cover increases input dependence and costs, while Armengot et al. (2016) and Esche et al. (2023) observed that AFS often entail higher labour requirements due to shade-tree management and harvesting of associated crops. The economic contribution of crop diversification within CAFS also remains insufficiently quantified. Although non-cocoa crops and shade-tree products can buffer income instability and improve food security (Armengot et al., 2016; Brown et al., 2025; Cerda et al., 2014), their commercialisation is often limited by logistical and market barriers (Cerda et al., 2014; Jacobi et al., 2017). Moreover, the extent to which revenues from non-cocoa crops offset lower cocoa yields or enhance overall CAFS returns under different shade conditions remains unclear. Overall, the literature provides an incomplete understanding of the economic performance of CAFS and the mechanisms through which shade-tree density influences key economic indicators, including yields, production costs, non-cocoa revenues and overall returns from CAFS. Addressing this knowledge gap is essential to identifying shade-tree management strategies that optimise the overall economic performance of CAFS.

I address these shortcomings in Chapter III of this dissertation. Using data from 313 cocoa-farming households, I combine household-level economic data with field measurements of shade-tree density from CAFS plots. I apply Ordinary Least Squares regressions and a coefficient stability approach to assess the effects of shade-tree density on cocoa yield, production costs, net cocoa income, revenues from other agroforestry crops, and overall returns from CAFS. The findings in this chapter contribute to providing a comprehensive, farm-level economic assessment of CAFS and informing policies on economic incentives to align farm-level economic performance with long-term sustainability objectives.

1.4.3. Ecological and economic trade-offs and synergies

Although existing evidence shows that shade-tree management influences both ecological and economic outcomes in CAFS, the conditions under which these outcomes align or compete remain poorly understood. Most existing studies address only a single sustainability dimension, focusing either on ecological (Bennett et al., 2022; Cassano et al., 2014; Ferreira et al., 2023, 2025) or economic outcomes (Asare et al., 2019; Jezeer et al., 2018), rather than integrating both dimensions within a joint analytical framework. As a result, empirical evidence that jointly quantifies farm-level ecological-economic trade-offs and synergies across a shade-tree management gradient remains scarce.

Interdisciplinary research that combines ecological and economic perspectives exists across different crops, including coffee (Broeckhoven et al., 2025; Grandez-Alberca et al., 2025; Mokondoko et al., 2022; Walsh et al., 2025; Wright et al., 2024), vanilla (Wurz et al., 2022), oil palm (Grass et al., 2020; Teuscher et al., 2015; Wenzel et al., 2024), rubber (Grass et al., 2020), as well as cocoa (Bisseleua et al., 2009, 2013; Blaser et al., 2018; Clough et al., 2011; Steffan-Dewenter et al., 2007). However, these studies remain limited in scope and the sustainability indicators employed. They often focus primarily on yield as the sole economic outcome (Blaser et al., 2018; Broeckhoven et al., 2025; Wurz et al., 2022) with few accounting for production costs or additional revenues from associated crops, both of which are key components for assessing the overall economic returns of CAFS and are likely to vary with shade-tree density (Bisseleua et al., 2009, 2013; Jezeer et al., 2018). On the ecological side, research has primarily relied on indicator taxa such as trees, invertebrates, and birds (Blaser et al., 2018; Bisseleua et al., 2013; Waldron et al., 2012), while large mammals have rarely been considered in such interdisciplinary analyses. Consequently, whether CAFS specifically can remain both economically viable and environmentally sustainable remains unclear and limited interdisciplinary research provides mixed results (Bisseleua et al., 2009, 2013; Blaser et al., 2018; Clough et al., 2011; Steffan-Dewenter et al., 2007).

Moreover, current studies provide limited insight into how ecological-economic trade-offs and synergies are influenced by other important factors, such as farmers' perceptions of shade trees as well as farm and household characteristics. Understanding these interactions is essential to identifying pathways through which synergies may emerge beyond shade-tree management alone.

To this end, Chapter IV investigates the conditions under which CAFS generate ecological–economic trade-offs and synergies. The analysis combines detailed household survey data, including farmers' observations of mammal presence, with ecological field measurements to assess medium- and large-sized mammals as an ecological indicator and overall returns from CAFS as the economic indicator. Thresholds for both indicators were defined to classify farms into four outcome categories representing different combinations of ecological and economic performance. I apply a multinomial probit model to examine how shade-tree density, as well as farm- and farmer-level characteristics, influence farms' positioning within each outcome category. By doing so, this chapter provides novel empirical evidence from Latin America and offers insights into whether shade-tree management serves as the principal driver of ecological-economic synergies between biodiversity conservation and farm profitability in cocoa agroforestry landscapes.

1.4.4. *Sul da Bahia* GI and sustainable development of CAFS

Despite the growing number of studies on sustainability certification as a governance instrument for sustainable development, research has remained largely centred on VSS such as Fairtrade, Rainforest Alliance, and organic certification. A substantial body of literature has assessed the effectiveness of these in improving socio-economic outcomes; however, their impacts remain highly variable and context-dependent (DeFries et al., 2017; Dietz et al., 2022; Meemken, 2020). While several studies report positive effects on farm productivity, producer prices, and income (Chiputwa et al., 2015; Vanderhaegen et al., 2018), others find no significant impacts (Boonaert et al., 2024; Gather and Wollni, 2022). Most evaluations of VSS lack an integrated perspective that jointly considers environmental and socio-economic dimensions. The limited interdisciplinary evidence available for cocoa suggests that sustainability standards tend to improve economic outcomes but fall short of delivering environmental benefits (Thompson et al., 2022; Wätzold et al., 2025). Yet, most sustainability standards remain designed for global markets, with limited adaptation to local ecological and socio-economic contexts.

In this context, GI have emerged as an alternative governance instruments that link a product's quality, reputation, or other distinctive characteristics to its geographical origin (FAO, 2025), offering a more locally grounded pathway toward sustainable rural development. In recent years, GIs have gained prominence as territorial approaches that link product quality to environmental and cultural heritage (Bowen, 2011). Unlike sustainability standards that standardise production practices, GIs valorise region-specific characteristics, reinforcing the interdependence between territorial identity, resource management, and market value (Vanderhaegen et al., 2018).

Despite their growing prominence, existing studies tend to discuss the conceptual potential of GIs to promote sustainability and rural development (Egelyng et al., 2017; Marie-Vivien et al., 2014; Portes et al., 2021), while empirical assessments of their realised economic and environmental benefits in tropical agricultural is limited and fragmented. Most studies focus on economic outcomes, particularly price premiums and market access, whereas the environmental dimension of GIs remains critically underexplored, even in well-established European cases (Belletti et al., 2015; Falasco et al., 2024). Research from emerging economies further indicates that while GIs can improve market recognition and enhance producer income, these benefits are often constrained by weak institutional frameworks, governance challenges, and limited market alignment (Cardoso et al., 2022; Neilson et al., 2018). Moreover, few studies assess environmental outcomes, and those that do report minimal or negative effects, questioning the environmental contribution of GIs (Carvalho and Vieira, 2022; Ingram et al., 2020). These limitations underscore a broader research gap, namely the absence of integrated, evidence-based analyses that jointly assess economic and environmental outcomes of GIs and identify the institutional conditions enabling sustainability synergies. This gap is particularly evident in the cocoa sector, where origin-based certification remains at an early stage of development. Although several Latin American countries have recently introduced cocoa GIs, systematic evaluations of their socio-economic and environmental performance are still lacking. Consequently, whether and how GIs can contribute to sustainable development in cocoa-producing regions, particularly through the valorisation of shaded AFS, remains an open empirical question.

To address this gap, Chapter V investigates the potential of the *Sul da Bahia* GI to enhance the environmental and economic sustainability of CAFS at the farm level. The study integrates qualitative evidence from stakeholder interviews with quantitative data from household surveys and farm-level biodiversity assessments. First, an institutional analysis examines the GI's governance structure and certification framework as well as the evolution of certified cocoa production and farmers' perceptions of assocoiated benefits and challenges. Second, household-level data are used to compare economic outcomes between certified and non-certified farms, considering multiple indicators ranging from cocoa yield to overall returns from CAFS. Third, ecological indicators derived from a subsample of farms assess whether participation in the GI scheme is associated with differences in ecological outcomes. This chapter offers one of the first field-based empirical assessments of a cocoa GI's potential to jointly strengthen market differentiation, enhance farm profitability, and promote biodiversity conservation within CAFS.

Figure 1.4 provides an overview of the dissertation structure by first illustrating the different data sources and how they are used across chapters in relation to the associated research questions, and subsequently indicating the methodological approaches applied in each chapter. Before moving on to the empirical chapters, the following section presents an overview of the different types of data collected and used in this dissertation, followed by a brief outline of the dissertation.

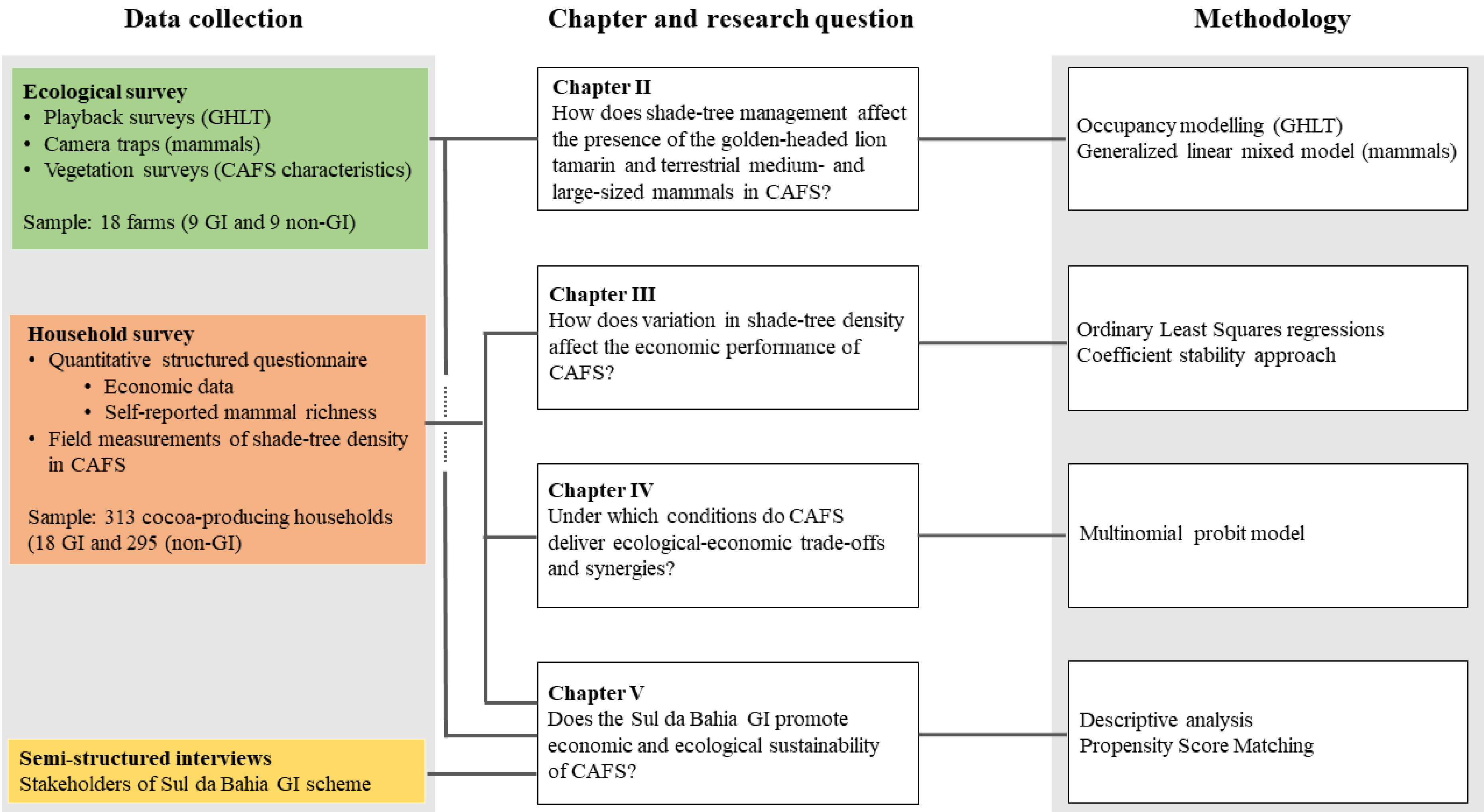

Figure 1.4 Overview of the dissertation structure, illustrating how the data sources used in each chapter relate to the corresponding research question and the methodological approach applied.

1.5. Data

Primary and secondary data for this study were collected in multiple phases between October 2021 and April 2024. The data collection process started with a two-week exploratory visit in October 2021 to familiarise with the study area, meet BioBrasil project members, complete administrative procedures for enrolment at the UESC, and engage with stakeholders of the *Sul da Bahia* GI scheme. Administrative delays related to the joint PhD agreement, visa application, and research permits postponed the start of fieldwork until July 2022.

A preparatory field mission was conducted between July and September 2022 to construct the sampling frame for the household survey and to design the biodiversity surveys. During this phase, a comprehensive sampling frame for the household survey was constructed through meetings with GI representatives and local institutions, integrating multiple data sources, including the most recent regional cocoa census (Chiapetti et al., 2020), the database of registered producers under the *Sul da Bahia* GI, and membership lists from cooperatives, producer associations, communities, and agrarian reform settlements. These data provided coverage of both certified and non-certified cocoa producers in the region. In parallel, the biodiversity survey design involved the systematic selection of 18 traditional CAFS within the six municipalities representing the core distribution area of the GHLT and the BaLTCI scope. These CAFS were purposely selected along a gradient of shade-tree density (60-310 trees ha^{-1}, DBH >10 cm) to represent low- to highly shaded agroforestry systems and capture biodiversity responses along a shade-tree management gradient. Sampling methods were tested and refined in collaboration with experts from UESC.

The biodiversity assessment was conducted between January and October 2023 across the 18 pre-selected CAFS. I led the data collection campaign, supported by one field assistant from Project BioBrasil. In each farm, I implemented three complementary survey methods: (i) playback surveys to register the presence of the GHLT, (ii) camera trap surveys to detect medium- and large-sized terrestrial mammals, and (iii) vegetation surveys. Because these methods rely on repeated visits and extended sampling periods to increase detection probability, the biodiversity assessment survey was necessarily time-intensive. Fieldwork was organised so that each farm was visited once a week, with the full assessment of one farm completed within 6 weeks. The first ten farms were surveyed from January to April 2023, followed by the remaining eight farms from July to September 2023. Environmental data collection was completed by October 2023.

Building on the sampling frame developed during the preparatory field mission, an extensive household survey was conducted between January and March 2024 across 12 municipalities in southern Bahia. I led the data collection effort, supported by a team of six local enumerators and one field supervisor. I organised and conducted enumerator training sessions and a pilot survey to test the implementation of the questionnaire. Particular emphasis was placed on ensuring a consistent understanding of survey questions, standardising response coding, and harmonising the interpretation of farmers' answers. A two-stage sampling design was employed to ensure geographic representativeness and capture the diversity of CAFS across the region. In the first stage, twelve municipalities were purposively selected based on their importance within the regional cocoa supply chain (Chiapetti et al., 2020) and the presence of farms participating in the *Sul da Bahia* GI scheme. In the second stage, enumerators randomly selected between 15 and 36 farmers per municipality, proportionate to the regional distribution of cocoa producers, with oversampling of GI-certified farmers. Target sample sizes were informed by ex-ante power calculations (Dong & Maynard, 2013).

The respondent was the household member responsible for day-to-day management decisions related to cocoa production. In total, 314 cocoa-producing households were surveyed (18 certified and 296 non-certified). The structured questionnaire was administered using tablets and the online data collection platform KoboToolbox, which enabled real-time data entry and automated quality control, minimising potential digitisation errors. The survey covered household demographics, cocoa production and marketing, management practices, certification, input use, and income sources from cocoa, other crops, and non-agricultural activities. Farmers were also asked to report mammal species observed within their CAFS.

To obtain accurate, plot-level measurements of shade-tree density for each surveyed household, enumerators visited the CAFS associated with the respondent following each interview. Within each CAFS, shade-tree density was measured in one randomly established 25x20m (500m²) vegetation plot located at least 100m from the plot boundary. All shade trees with a diameter at breast height (DBH) ≥ 10 cm were inventoried, and GPS coordinates were recorded at both the household and plot locations. These field-based measurements provided a more reliable estimate of shade-tree density than farmer self-reported values, which is essential given the central role of shade-tree density in this research. The on-farm visits also enabled systematic ground-truthing of survey responses through direct field observation.

From the survey data, a final dataset combined household-level economic data with field measurements on shade-tree density of the corresponding CAFS of the household. One household was excluded from Chapter III analyses because its production system was identified as a cocoa–rubber plantation lacking native shade trees, thus not qualifying as *cabruca* under Bahia's legal requirement of at least 20 native shade trees per hectare (State Decree No. 15180/2014, Seção IV, Art. 15). Another household was excluded from Chapter IV due to missing biodiversity data. An overview of the sampling strategy with sampled households is presented in Table 1.1, and a map of the research area is in Figure 1.4.

In addition to the household survey, qualitative data were collected through semi-structured key informant interviews conducted in person during the various field missions. The interviews targeted a range of stakeholders, including cocoa producers, presidents of farmer associations and cooperatives, and the executive director of the *Sul da Bahia* GI scheme. Questions for farmers and cooperative representatives focused on their experiences with and perceptions of GI certification, including perceived benefits, challenges, and market opportunities. The interview with the GI executive director addressed the institutional and certification framework, covering certification requirements and costs, cocoa marketing and processing procedures, the structure of the regional supply chain, and collaboration with cooperatives and public institutions. I also obtained access to the official *Sul da Bahia* GI database, which includes records of all farmers who participated at least once since 2019, as well as annual data on certified cocoa volumes (2019–2024) and GI-branded chocolate sales (2021–2024).

All research activities complied with relevant institutional and national ethical guidelines. Fieldwork used non-invasive methods, including unbaited, motion-activated camera traps, and involved no direct contact with animals. The study was conducted under authorisation from the National Institute for Biodiversity Conservation (ICMBio, license no. 47178-12) and approved by the Ethics Committee for Research with Human Beings (CEP) of the State University of Santa Cruz (Opinion no. 6.729.579 / CAAE: 73531423.3.0000.5526) as well as the Institute for Humanities and Social Sciences (IACCHOS) at UCLouvain. Before starting the interview, we explained the nature and objectives of the research, asking the informants for permission to record the information. Before being interviewed, we also presented the informants with a Free and Informed Consent Form, according to the norms established by Resolution n° 196 of the National Health Council of 10/10 1996. Participation was voluntary.

Table 1.1 Overview of cocoa farms sampled for the household survey and the biodiversity assessment across 12 municipalities in southern Bahia, Brazil. Certification refers to participation in the *Sul da Bahia* Geographical Indication scheme.

	Household survey			Biodiversity assessment survey		
Municipality	Non-certified	Certified	Total	Non-certified	Certified	Total
Arataca	26	1	27	0	1	1
Buerarema	21	3	24	1	1	2
Camacan	17	1	18	0	0	0
Coaraci	20	0	20	0	0	0
Ilhéus	30	6	36	1	5	6
Itabuna	18	2	20	1	2	3
Itacare	35	1	36	0	0	0
Itajuipe	24	2	26	0	0	0
Santa Luzia	25	0	25	2	0	2
São José da Vitória	15	0	15	0	0	0
Una	31	0	31	4	0	0
Uruçuca	33	2	35	0	0	0
Total	**295**	**18**	**313**	**9**	**9**	**18**

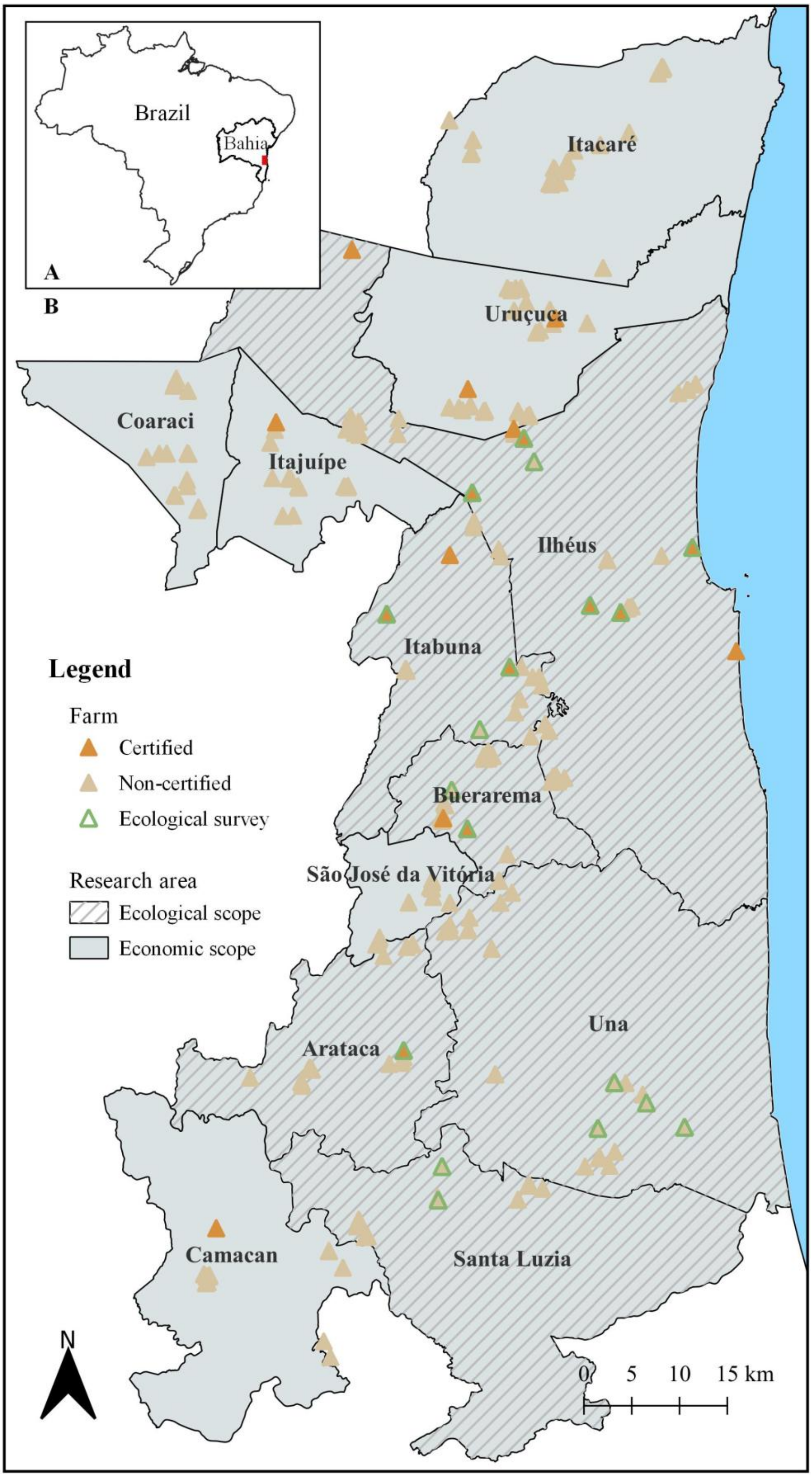

Figure 1.4 Map of the sampled households in Southern Bahia, Brazil. (A) Location of the state of Bahia (grey) and the research area (red) in Brazil. (B) Distribution of the certified (n=18) and non-certified (n=295) households across 12 municipalities in southern Bahia.

1.6. Dissertation outline

Chapter I introduces the global context and conceptual framing, outlines the research gaps on shade-tree management and governance in cocoa agroforestry, and presents the case study and institutional setting. **Chapter II** examines how variation in shade-tree management influences the presence of the GHLT and the medium- and large-sized terrestrial mammal community in CAFS. **Chapter III** assesses the economic implications of shade-tree density for CAFS, considering yields, production costs, non-cocoa revenues, and overall CAFS returns. **Chapter IV** integrates ecological and economic indicators to identify the conditions under which trade-offs and synergies across farms, and examines how shade-tree density and household and farm-characteristics influences these outcomes. **Chapter V** investigates the potential of the *Sul da Bahia* GI to promote the environmental and economic sustainability of CAFS, considering governance design, farmer participation, and farm-level performance. **Chapter VI** synthesises the main findings, outlines limitations and recommendations for future research and discusses implications for policy and practice.

Chapter II

How many shade trees are enough? Identifying the threshold for golden-headed lion tamarin presence in cocoa agroforests of Southern Bahia, Brazil[2]

2.1. Introduction

As global demand for agricultural commodities continues to rise, biodiversity and ecosystem services are rapidly declining due to forest conversion for agriculture and the intensification of agricultural systems (De Beenhouwer et al., 2013; Lenzen et al., 2012; Pendrill et al., 2022). Among these commodities, cocoa (*Theobroma cacao*) has raised significant sustainability concerns due to the environmental and socio-economic impacts associated with its production systems (Boeckx et al., 2020; Kalischek et al., 2023; Renier et al., 2023; Van den Broeck and Akaribo, 2024). Cocoa agroforestry systems (CAFS), where cocoa is cultivated under a canopy of native shade trees retained after forest thinning, have been advocated as a sustainable solution for supporting biodiversity conservation alongside cocoa production while providing decent livelihoods for farmers (Blaser et al., 2018; Niether et al., 2020; Steffan-Dewenter et al., 2007). However, farmers in many cacao-growing regions throughout the tropics increasingly shift towards unshaded or low-shaded cocoa cultivation, driven by expectations of higher yields and the need to secure short-term income (Steffan-Dewenter et al., 2007; Tscharntke et al., 2011a).

While the ecological benefits of agroforestry are well-documented, most studies have primarily focused on comparing biodiversity outcomes to other land-use systems or farming systems, treating agroforestry as a distinct land-use type (Cassano et al., 2012; De Beenhouwer et al., 2013; Etana et al., 2021; Ferreira et al., 2020; Niether et al., 2020). This approach overlooks the substantial variability within CAFS, which can range from intensively managed agroforestry systems with few shade trees and limited species diversity to highly shaded and diversified systems (Schroth et al., 2015). Although some research has addressed the effects of management intensification within CAFS on biodiversity, studies in South America remain scarce (Aaron et al., 2024; Cabral et al., 2021; Cassano et al., 2014; Ferreira

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Author contributions: Steffi Dekegel: Writing – original draft, Funding acquisition, Formal analysis, Conceptualization. Goedele Van den Broeck: Writing – review & editing, Supervision, Funding acquisition, Conceptualization. Leonardo Oliveira: Writing – review & editing, Supervision, Funding acquisition, Conceptualization. Kristel De Vleeschouwer: Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

et al., 2025; Waldron et al., 2012), despite evidence indicating that biodiversity responses to intensification are highly region-specific and that biodiversity declines are among the highest on this continent (De Beenhouwer et al., 2013).

Brazil is the world's seventh-largest cocoa producer and has experienced a 57% increase in domestic cocoa production in the past two decades (FAOSTAT, 2025). The country's major cocoa-producing region, southern Bahia, accounts for 47% of the country's total production (IBGE, 2023) and provides livelihoods for approximately 69,000 households (Chiapetti et al., 2020; Rocha Sousa Filho et al., 2024). Traditionally, cocoa cultivation in this region occurs within shaded agroforestry systems locally known as *cabrucas*, which remain widespread and account for 78% of cocoa-producing properties (Chiapetti et al., 2020). *Cabrucas* are structurally complex and highly diversified systems, with an average of 197 shade trees per hectare (ranging from 70 to 480) and approximately 63% native tree species (Schroth et al., 2015). As a result, *cabrucas* provide habitat for native and endangered species of the Atlantic Forest biome (Cassano et al., 2009; Faria et al., 2007; Schroth et al., 2011), one of the world's most threatened biodiversity hotspots (Myers et al., 2000). Despite their ecological significance, *cabrucas* are under increasing pressure from intensification. Brazil's ambition to double its cocoa production to 400,000 tons by 2030 (Ministério da Agricultura e Pecuária, 2023) could have substantial environmental implications for the sustainability of its traditional agroforestry systems. This goal is legally supported by a state decree established in 2014, allowing landowners to reduce the number of shade trees in *cabrucas* to a minimum of 40 native trees per hectare (State Decree No. 15180/2014, Seção IV, Art. 19, Bahia; hereafter referred to as "*shade tree management decree*"), a threshold well below the densities typically observed in traditional *cabrucas* (Schroth et al., 2015). While the intention is to boost production, this ambition aided by the *shade tree management decree*, risks simplifying the structural complexity of these traditional agroforests, potentially diminishing their biodiversity conservation value.

Recent studies highlight the role of southern Bahia's CAFS in supporting diverse mammal communities as well as other forest biodiversity, including endemic and threatened species, while also enhancing landscape connectivity in a highly fragmented landscape (Almeida-Rocha et al., 2020; Cabral et al., 2021; Cassano et al., 2014; Faria et al., 2007; Ferreira et al., 2025). The ability of *cabrucas* to sustain mammal populations is strongly influenced by the landscape context, particularly the extent of surrounding forest cover (Ferreira et al., 2020; 2025). Yet, *cabrucas* can support a significant portion of the mammal fauna even in landscapes with reduced forest cover, provided they remain the dominant land-use type in the landscape (Ferreira et al., 2020). While the role of landscape context is well-documented (Faria et al., 2007; Ferreira et al., 2020, 2025; Raboy et al., 2010; Teixeira et al., 2024), the effects of intensified shade-tree management on mammal communities, particularly for species of conservation concern, remain insufficiently understood, as highlighted by previous studies (Almeida-Rocha et al., 2020; Ferreira et al., 2025). Given the trend of intensified shade-tree removal not only in CAFS of southern Bahia but throughout the tropics, understanding how such management practices, alongside resource availability and anthropogenic disturbances, affect mammal communities is crucial for developing effective conservation strategies.

The golden-headed lion tamarin (*Leontopithecus chrysomelas*), an endangered primate endemic to the Atlantic Forest, is an emblematic species of the *cabrucas* of southern Bahia and particularly relies on these shaded agroforestry systems for its persistence in the fragmented landscape (Oliveira et al., 2010, 2011). *Cabrucas* provide essential trophic and structural resources for *L. chrysomelas*, with shade trees in particular offering key food sources (such as fruits, flowers, nectar, gums), and providing sleeping sites, primarily tree holes (Oliveira et al., 2010). In *cabrucas*, *L. chrysomelas* also depend on bromeliads, which are concentrated on shade trees and serve as foraging sites for animal prey (Rylands, 1989; Oliveira et al., 2011), and exotic jackfruit trees (*Artocarpus heterophylus*) when other key resources are scarce (Oliveira et al., 2011). Among native shade tree species, those belonging to the Sapotaceae and Myrtaceae families are especially important, being the most frequently used for both feeding and sleeping (Oliveira et al., 2010). Although *cabrucas* contain fewer individual trees used by *L. chrysomelas* compared to forests, the frequency of use per tree is higher in *cabrucas* (Oliveira et al. 2010), suggesting that individual trees play an important role in supporting the species' resource use (Oliveira et al. 2011). Moreover, large-diameter shade trees are associated with a higher probability of the species' occurrence, likely due to their suitability as sleeping sites (Almeida-Rocha et al., 2020). Additionally, shade trees enhance canopy connectivity, offering travel routes that facilitate movement across the fragmented landscape (Cassano et al., 2014). Over the last 30 years, *L. chrysomelas*' geographic range has contracted by 42% and its population size has declined by 60% due to extensive deforestation (Teixeira et al., 2024), with approximately 60% of the species' remaining habitat comprised of CAFS (Zeigler et al., 2010). Despite *L. chrysomelas*' reliance on shade trees in *cabrucas*, the effects of shade-tree management on its occurrence remain unstudied, leaving it unclear whether the current *shade tree management decree*'s threshold is adequate to sustain its populations.

This study addresses these research gaps by evaluating how shade-tree management intensification influences our focal species, the golden-headed lion tamarin, and the terrestrial medium- and large mammal community within cocoa agroforestry systems in Southern Bahia, Brazil. Specifically, it examines whether the current state-mandated intensification threshold of 40 native shade trees per hectare is sufficient to sustain *L. chrysomelas* and whether shade tree management recommendations for this species may also provide co-benefits for the terrestrial medium- and large mammal community in *cabrucas*. To this end, data on shade tree management intensity (i.e., shade tree density and cover), vegetation structural complexity (e.g., height of shade trees and canopy connectivity), and the availability of key trophic resources for *L. chrysomelas* (e.g., presence of bromeliads and key tree species) were collected across 18 *cabrucas* in southern Bahia, Brazil. Using playback surveys and camera traps, *L. chrysomelas'* presence and terrestrial medium- and large-sized mammal detections were assessed, respectively. We expect that intensified shade-tree management, characterised by reduced tree density, will be associated with lower levels of shade cover, and predict that both *L. chrysomelas* occupancy and mammal detections will decrease under such management in CAFS.

This research on the effects of shade-tree management intensification on biodiversity has the potential to inform evidence-based policy adjustments to the *shade tree management decree,* guiding the establishment of shade-tree density thresholds that better support biodiversity conservation in cocoa agroforestry systems. In particular, it aims to enhance understanding of the tipping point at which shade tree management intensification negatively affects species of conservation concern, such as *L. chrysomelas*. Our insights help to promote sustainable agroforestry practices in the southern Bahia's cocoa landscape, as well as for other cocoa-producing landscapes facing similar intensification pressures.

2.2. Data and Methods

2.2.1. Research area

We conducted our research in the south-eastern cocoa region of Bahia, in north-eastern Brazil (Figure 2.1A). The region is characterised by a mean annual temperature and rainfall of 24°C and 2,500 mm, respectively, with no distinct seasonality (Mori et al., 1983). A total of 18 *cabrucas* were surveyed, all located across six major cocoa-producing municipalities (Figure 2.1B), which constitute the eastern part of the golden-headed lion tamarin's distribution range (Teixeira et al., 2024). According to the most recent and comprehensive assessment of *L. chrysomelas* distribution (Teixeira et al., 2024), the eastern region is characterised by a higher species occurrence and harbours its most viable populations (Zeigler et al., 2010). This area consists of a relatively continuous complex of coastal evergreen tropical rainforest, along with an increasingly fragmented landscape of *cabrucas*, pasture, other agricultural crops, and urban areas (Zeigler et al., 2010). In contrast, the western part of the species' range has undergone extensive anthropogenic modification through agriculture and livestock (Zeigler et al., 2010), resulting in lower *L. chrysomelas* occurrence (Teixeira et al., 2024) and near total absence of cocoa plantations and is therefore out of scope for our research area.

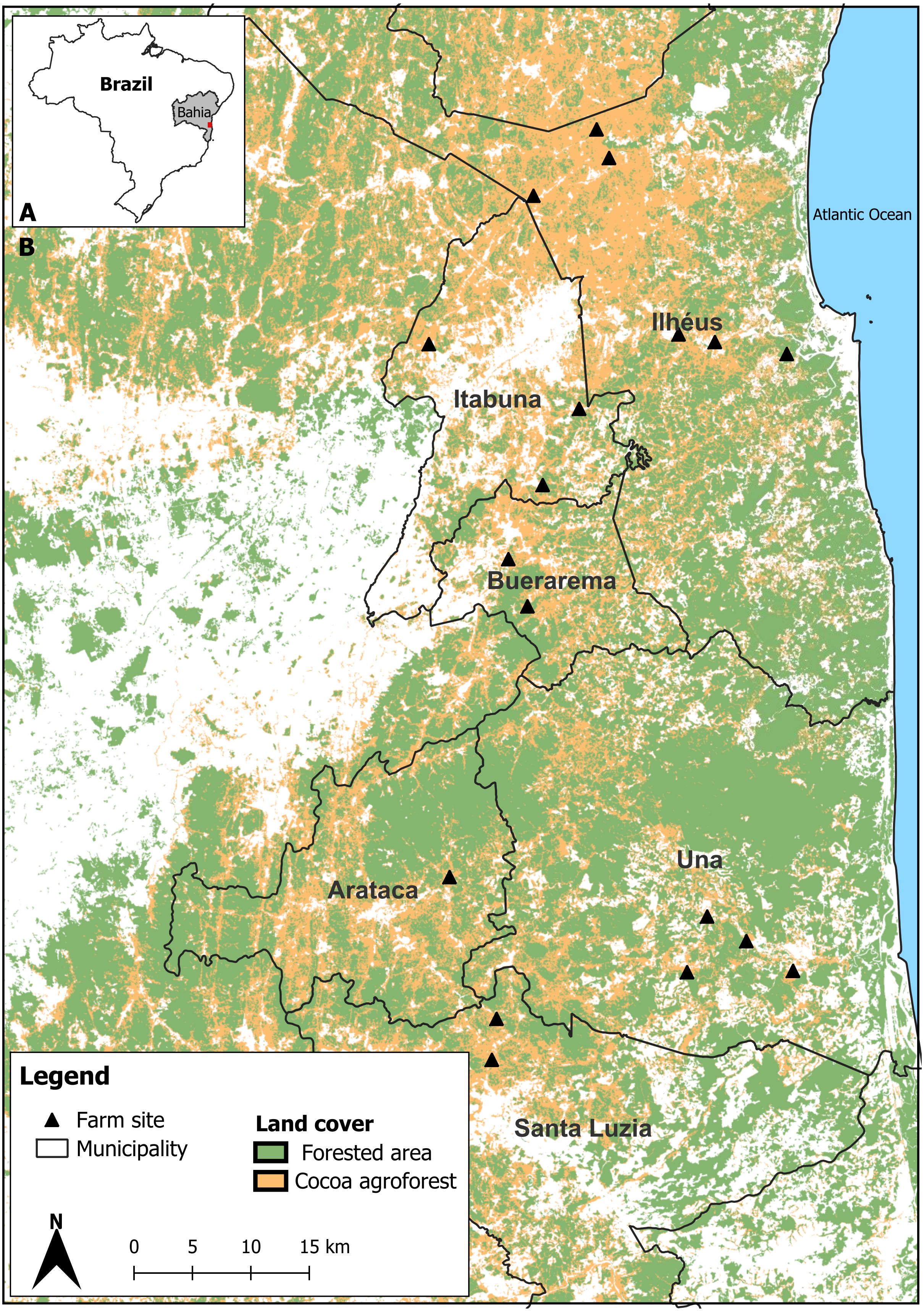

Figure 2.1 (A) Location of the state of Bahia (grey) and the research area (red) in Brazil. (B) Distribution of the 18 farm sites across six municipalities in southern Bahia. Land cover data obtained from MapBiomas Cacau (MapBiomas Cacau, 2019).

2.2.2. Sampling

Between June and September 2022, we systematically selected 18 traditional CAFS (i.e. *cabrucas*) along a gradient of shade-tree density, ensuring the inclusion of sites ranging from intensively managed to highly shaded agroforestry systems (60 to 310 shade trees ha^{-1}, with a diameter at breast height (DBH) >10 cm). This approach ensured that the study design effectively met its objective of quantifying changes in biodiversity along a shade-tree management gradient. Sampling sites were at least 2.5 km apart. Environmental data collection was conducted from January to October 2023. All sampling was performed by the first author with the help of an experienced field assistant.

2.2.3. Golden-headed lion tamarin survey

Playback surveys were conducted to detect the presence of *L. chrysomelas* in each CAFS. This sampling method, which involves broadcasting the long call vocalisation of *L. chrysomelas* along a point-transect to elicit intraspecific responses and stimulate countercalls (Kierulff and Rylands, 2003), is particularly effective for detecting territorial primates that rely on long-distance vocalisations to signal the presence of other individuals or groups in their territory, such as *L. chrysomelas*. Its effectiveness has been demonstrated in several field studies targeting *L. chrysomelas* (Almeida-Rocha et al., 2020; Pinto and Rylands, 1997; Raboy et al., 2010; Teixeira et al., 2024) as well as other primate species (Gestich et al., 2017; Hilário et al., 2022).

To ensure standardised sampling, a 200 x 200 m grid was overlaid on satellite imagery of the CAFS using QGIS *3.22.5* (QGIS Development Team, 2022). Playback points were established at each grid intersection, with points spaced 200 m apart, as recommended by previous studies to prevent overlap within the species' auditory range (~100 m) and to reduce the likelihood of detecting the same group more than once on the same day (Kierulff and Rylands, 2003). The number of playback points surveyed per farm ranged from 3 to 10, proportional to farm size, following the sampling design of de Almeida et al. (2022). Up to 10 points were surveyed during a single morning (06:00–11:00 h), the maximum achievable during the peak activity period *of L. chrysomelas* in agroforests (Almeida-Rocha et al., 2020). Surveyed areas included a 100 m buffer from the agroforest edge. In the field, the location of each playback point was pinpointed using a handheld GPS (Model Garmin GPSMAP 66S).

At each playback point, one recorded long-call from an adult male and female was broadcast in each cardinal direction using a JBL Charge 5 speaker (frequency response: 60 Hz–20 kHz), followed by a 4-minute waiting period for responses from *L. chrysomelas*. This procedure was repeated three times at each point before moving to the next point along the transect. The total time spent at each playback point was 15 minutes. When *L. chrysomelas* groups were detected, either through vocal responses or direct observation, their geographic location was recorded, the time of detection, and, when possible, the number of individuals and their group composition (adults, juveniles, and infants) to ensure that the same group was not counted more than once on the same survey day.

The number of visits (three) to CAFS was determined *a priori* based on the detection history of *L. chrysomelas* from previous studies using the same sampling method (Almeida-Rocha et al., 2020; Teixeira et al., 2024). To prevent habituation, playback surveys were conducted over three non-consecutive days, with at least one week between visits to the same CAFS. When *L. chrysomelas* was not detected after the third visit, the species was considered absent in the CAFS. A thermo-hygrometer was used to record mean air temperature and humidity during each visit to model the influence of survey-specific covariates on species detectability. Playback surveys were avoided during rainy or windy weather conditions.

2.2.4. Terrestrial medium- and large-sized mammal survey

Camera traps were used to assess the presence of the terrestrial medium- and large-sized mammals (defined as those larger than >500 g) in the CAFS. This widely recognised, non-invasive method is effective for surveying mammal communities and simultaneously recording multiple species with minimal disturbance (Bruce et al., 2018; Etana et al., 2021; Lhoest et al., 2020; Wearn and Glover-Kapfer, 2017). Camera traps (Browning Spec Ops Elite HP5) were placed on each grid intersection point 400m apart, based on similar studies on terrestrial large mammals in agroforestry systems. The number of camera traps per farm ranged from 1 to 5, proportional to farm size, following the sampling design of de Almeida et al. (2022). At each predefined point, one camera was attached at a random location to a tree trunk, 20-50cm above ground level. No bait was used to prevent differences in detection probability among mammal species. Cameras were operational for 24h a day and set to take a minimum of 5 consecutive rapid-fire pictures per trigger, with a 1-second delay between consecutive triggers. They were checked every 8–20 days to replace SD cards and maintain camera functionality. Cameras remained in the field for a one-month period, depending on uncontrollable conditions, including malfunctions. When possible, malfunctioning cameras were replaced and kept operating longer to compensate for any losses in sampling effort. Independent detection events were defined as consecutive pictures of the same species taken > 60 minutes apart (Bruce et al., 2018; Tobler et al., 2008) across all cameras within the same farm to reduce the likelihood of counting the same individual multiple times at different camera traps within the same farm. The sampling effort for each camera trap was quantified in camera trap days, defined as the total number of days the camera was operational. To account for differences in sampling effort, the mammal detection rate for each camera was then standardised as the number of independent detections per 100 effective camera trap days.

2.2.5. Vegetation survey

Vegetation surveys were conducted in each CAFS to assess a set of local vegetation variables related to and influenced by shade tree management practices. Plots of 500m² (20mx25m) were established at each CAFS at 400m intervals, following the sampling design of Almeida-Rocha et al.

(2020). In each plot, cocoa trees were counted as well as native and non-native shade trees with a diameter at breast height (DBH) of ≥ 10.0 cm) to determine shade tree density within each plot. The percentage of shade cover within each plot was estimated using a hand-held concave spherical densiometer (Forestry Suppliers, Inc., Jackson, MS, USA). Shade measurements were taken along the centreline of the plot, at every 10m along the 20m axis. Shade-tree density and shade cover are indicators of shade tree management intensification within agroforestry systems (Blaser et al., 2018), i.e. lower tree density or shade cover reflects higher levels of shade-tree management intensification in the CAFS. The DBH of shade trees and their height were recorded using a hypsometer (Forestry Pro, Nikon Co., Ltd., Tokyo, Japan). Shade trees were identified *in situ* at the lowest possible taxonomic level by experienced local field assistants. Shade tree species used by *L. chrysomelas* for food and sleeping sites were identified based on previous studies (Catenacci et al., 2016, 2009; Oliveira et al., 2010, 2011; Raboy and Dietz, 2004; Couto et al., 2019; Table A1, Appendix A). Jackfruit trees were also included as a separate variable due to their particular importance in the diet of *L. chrysomelas* in CAFS (Oliveira et al., 2011). Other main habitat requirements for *L. chrysomelas* were identified: i) presence of bromeliads on shade trees; ii) canopy connectivity, defined by the number of crown connections with adjacent shade trees; and iii) number of banana trees.

Landscape characteristics were accounted for by including data on elevation, surrounding forest cover, and the distance to the closest urban area and road accessible for car transportation, extracted in QGIS software. For elevation, the Digital Elevation Model (USGS, 2015) were used. The percentage of surrounding forest cover within a 2 km radius buffer from the CAFS centroid was used, based on previous studies in the region that identified this threshold as the most relevant for landscape analysis of medium- and large-sized mammals (Faria et al., 2023; Ferreira et al., 2020). Forest cover data were obtained from MapBiomas Cacau and urban area data from the broader MapBiomas Project (MapBiomas, accessed on 1 October 2024, via: https://brasil.mapbiomas.org/en/mapbiomas-cacau/)– both part of a collaborative initiative involving interdisciplinary teams from universities, NGOs, and technology companies. The underlying classification methodology has been validated in peer-reviewed literature (Souza et al., 2020). While a known challenge in MapBiomas Cacau is distinguishing degraded forests or agroforestry systems from native forests, this is unlikely to significantly affect the reliability of our analysis, as these habitat types are used by *L. chrysomelas*. Farmers were interviewed about their pesticide use (R$ ha^{-1}) within their CAFS in 2023 as part of a socioeconomic survey conducted in 2024.

2.2.6. Data analyses

Vegetation variables were first calculated at the plot level, and median values were subsequently computed for each variable to obtain farm-level estimates for each CAFS. Shade tree diversity was quantified using Hill-Simpson's diversity index, which was selected above Hill-Shannon's due to its robustness to sample size (Roswell et al., 2021). The contribution of key tree species to the shade tree community composition on CAFS was weighted using the Importance Value Index according to (Curtis and McIntosh, 1951). IVI integrates relative values of frequency, density, and dominance (through basal area). Tree species with the highest IVI are considered more dominant (Tesfay et al., 2022). IVI of key tree species for *L. chrysomelas* and IVI of jackfruit were calculated as a single value for each CAFS.

Variables were selected a priori to reflect key ecological processes and different aspects of shade management intensification relevant to our main hypothesis, with demonstrated or hypothesized importance for either *L. chrysomelas* or terrestrial medium- and large-sized mammals, based on previous studies. Multicollinearity among predictor variables was assessed using Spearman correlations ($|r| < 0.6$; Figure A1 in Appendix) and Variance Inflation Factors (VIF < 4.0) using the *car* package. For each pair of highly correlated variables ($r \geq .6$), we excluded one, prioritising the retention of variables that enabled us to test our main hypotheses. As a result, we removed banana density, IVI of key tree species for *L. chrysomelas*, native shade tree density, and canopy height. We excluded the following variables due to high multicollinearity as indicated by Variance Inflation Factors (VIF > 4): non-native shade tree density, shade tree species richness, DBH of shade trees and elevation. Additionally, distance to roads and cocoa density were excluded due to high multicollinearity (VIF > 4), to prioritise the retention of canopy connectivity for *L. chrysomelas*.

Due to differences in survey method and resulting data structure, we applied complementary analytical approaches. The focal species of this study, *L. chrysomelas*, was surveyed using playback surveys, generating detection–non-detection data suitable for single-season occupancy modelling that accounts for imperfect detection (Mackenzie et al., 2002). In contrast, data on terrestrial medium- and large-sized mammals were obtained from unbaited camera traps deployed continuously for a one-month period in each farm. Given the limited sampling duration, we calculated detection rates standardised by camera trap effort and modelled these using a Generalised Linear Mixed Model (GLMM). All statistical analyses were done in R version 4.3.1 (R Core Team, 2023).

2.2.6.1. Occupancy modelling

Single-season occupancy modelling (Mackenzie et al., 2002) was used to investigate the influence of shade tree management on *L. chrysomelas* occupancy (ψ) in *cabrucas*, while accounting for imperfect detection (p). A detection history matrix was constructed for each playback point (sampling unit i), with species detections (1) and non-detections (0) across three survey occasions (sampling occasion j). Detection probability (p) was modelled as a function of survey-specific covariates (i.e. temperature, humidity, time of visit) along with sampling effort and neighbouring forest cover. Occupancy (ψ) was modelled using variables related to CAFS management and vegetation characteristics (i.e. shade-tree density and diversity, shade cover, basal area and pesticide use), key habitat variables for *L. chrysomelas* (i.e. canopy connectivity, vertical stratification, IVI of jackfruit trees and the presence of bromeliads), as well as landscape characteristics (i.e. distance to urban area). To account for the nested sampling design and spatial non-independence between playback points (i.e. the sampling unit) within the same farm, a random effect of farm was included in the occupancy model (Kellner et al., 2023). As *L. chrysomelas* can move between playback points and across farm boundaries, potentially exiting or entering sampling units during the survey period, the assumption of population closure was not met. Consequently, as proposed by Mackenzie et al. (2006), occupancy should be interpreted as the proportion of the area being used by the species, rather than true occupancy.

Model building followed a stepwise approach. First, a null model with constant detection and occupancy probabilities was constructed. Detection probability was then modelled, with the best-supported detection model subsequently used to model occupancy (Table A2, Appendix A). Considering that survey effort may influence the detectability of primates, we included sampling effort as a covariate to model detection probability. Since the model including the sampling effort covariate had less support than the null model and showed no significant effect, this covariate was not retained in the subsequent occupancy model (Table A2, Appendix A), following the approach of. To reduce the risk of overfitting and ensure robust parameter estimation, we limited candidate models to a maximum of two covariates. Models were fitted using the function ‘occu’ from the *Unmarked* package. Model ranking and selection were based on the smallest Akaike information criterion corrected for small samples (AICc). AICc allows identifying the model that explains the most variation with the fewest variables: the model with the lowest AICc best explains the data (Burnham and Anderson, 2002). *L. chrysomelas* occupancy was predicted using the best-supported model, and covariate effects were extracted. The fit of the global model (i.e. including all covariates) was assessed by estimating the overdispersion parameter (*c-hat*) through 1,000 bootstrap simulations, using the *AICcmodavg* package.

2.2.6.2. Generalised Linear Mixed Model

The influence of shade tree management on medium- and large-sized mammal detections was analysed using a GLMM with a Negative Binomial distribution to account for the count-based structure of the data and overdispersion. The total number of independent mammal detections was used as the response variable. Similar for occupancy modelling, a random effect of farm was included in the model to account for the nested sampling design and spatial non-independence between camera trap points (i.e. the sampling unit) within the same farm. We also accounted for differences in camera trap sampling effort by including a log-offset for camera trap effort (i.e., number of camera trap days) in the model. Explanatory variables included CAFS management and vegetation characteristics (i.e. shade tree cover, shade tree density and diversity, basal area, pesticide use, cocoa density and IVI of jackfruit trees) as well as landscape characteristics (neighbouring forest cover, distance to road and urban areas) relevant for terrestrial medium- and large-sized mammals. Candidate models were generated using the *MuMIn* package, and the most parsimonious model was selected based on the smallest ΔAICc value. Mammal detections were predicted using the best-supported model and covariate effects were extracted.

2.3. Results

2.3.1. Management and vegetation characteristics of cocoa agroforestry systems

Shade tree density and shade levels demonstrated considerable variation across the 18 CAFS, ranging from 60 to 310 (±59.42) shade trees ha^{-1} and 46.18% to 88.33% (±11.06) shade cover, respectively (Table A3, Appendix A). Spearman correlation test on plot-level measurements indicated a significant positive correlation between shade tree density and shade cover ($\rho = 0.34$, $p < 0.05$; Figure A2, Appendix A) and a significant negative correlation between shade tree density and DBH ($\rho = -0.45$, $p < 0.001$). A total of 64 shade tree species from 30 families were recorded, of which 39 were identified as key tree species for *L. chrysomelas* (Table A1, Appendix A). The IVI of those key resource tree species, and particularly of jackfruit trees, ranged between 39.07– 269.62% and 0–80.53%, respectively (Table S1, Appendix A). Cocoa tree density ranged between 465- 990 trees ha^{-1} (±156.94).

2.3.2. Golden-headed lion tamarin occupancy

A total of 21 detections of *L. chrysomelas* were recorded across 17 playback points in 11 CAFS. The maximum number of groups detected on a single farm during the same sampling occasion was two. We recorded solitary individuals and groups with up to 10 individuals. Additionally, groups of *Callithrix kuhlii* were regularly observed, often forming mixed-species groups with *L. chrysomelas*. The playbacks also elicited responses from Black-headed titi *(Callicebus melanochir*).

The estimated detection probability (*p*) was 0.20 (95% CI: 0.08; 0.42). Based on the lowest AICc value and highest Akaike weights, the model including the percentage of forest cover around CAFS improved the detection probability of *L. chrysomelas* in CAFS (Table A2, Appendix A). The estimated occupancy probability (Ψ) was 0.29 (95% CI: 0.12; 0.55). The best supported occupancy model (ΔAICc = 0.00; Table A3, Appendix A) showed that the probability of occupancy of *L. chrysomelas* increased significantly with higher shade cover percentage ($\beta = 0.15 \pm 0.24$; $p < 0.01$; Table 2.1; Figure 2.2), with *L. chrysomelas* remaining absent below 65% shade cover and occupancy reaching its maximum at approximately 75%. This indicates that the threshold required for *L. chrysomelas'* persistence is 65% shade cover, corresponding to approximately 100 native shade trees per hectare in our sampled CAFS (Figure A2, Appendix A**).** The best supported occupancy model also indicated a significant positive effect of the importance value index (IVI) of jackfruit, indicating an increase in *L. chrysomelas* occupancy with higher dominance of jackfruit trees ($\beta = 0.15 \pm 0.24$; $p < 0.01$; Table 2.1). However, the species' occupancy probability was already high (~0.95) in cocoa agroforestry systems where jackfruit was either absent or not the dominant shade tree species (Figure A3, Appendix A). The goodness-of-fit test of the global model indicated no evidence of overdispersion ($\chi^2 = 4.83$; P = 0.26; *c-hat* = 0.95).

Table 2.1 Covariates used to model occupancy (ψ) and detection (p) probability, along with parameter estimates from the best-supported model (ΔAIC = 0.00), for *L. chrysomelas* in 18 cocoa agroforestry systems in southern Bahia, Brazil.

Covariates	Estimate	SE	Z	P-value
ψ(Intercept)	4.97	0.48	10.39	<0.001
ψ(Shade cover)	7.52	0.01	1338.03	< 0.01
ψ(IVI Jackfruit)	2.04	0.38	5.39	< 0.01
p(Intercept)	-2.48	0.23	-10.72	<0.001
p(Forest cover)	0.15	0.24	0.61	0.54

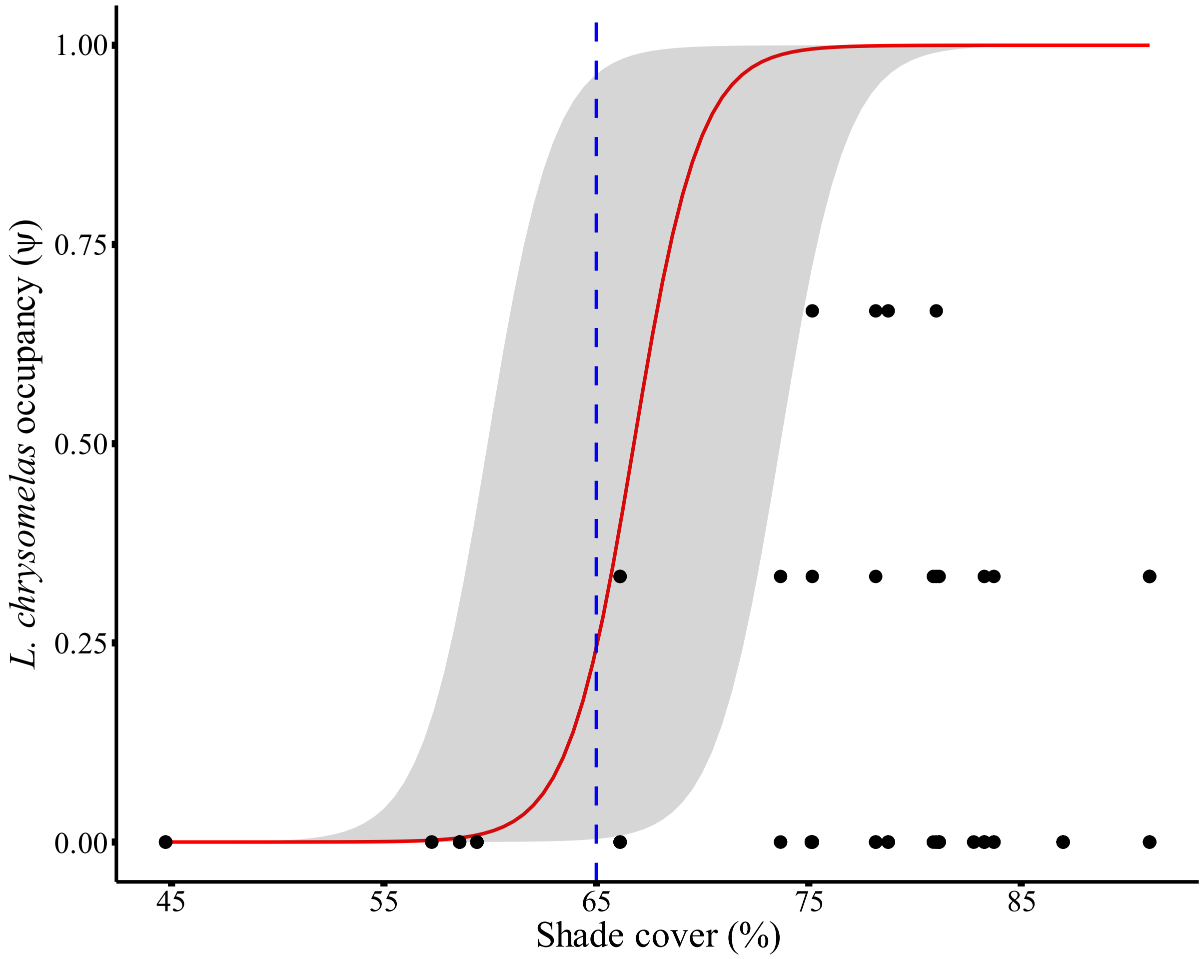

Figure 2.2 Predicted occupancy (Ψ) of *L. chrysomelas* within cocoa agroforestry systems as a function of shade cover (%). The prediction was based on the model from Table 1. The red line and the colour-coded area represent the estimates and the 95% confidence intervals, respectively.

2.3.3. Terrestrial medium- and large-sized mammal detections

Throughout the study period, a total sampling effort of 1811 operational camera-trap days was achieved across 18 CAFS, with a mean of 37.72 ± 5.06 days per camera trap. A total of 14 medium-and large-sized terrestrial mammals were recorded, belonging to six orders and 13 families (Table 2.2). Three arboreal mammal species (*L. chrysomelas*, *Callithrix kuhlii* and *Coendou insidious*) were recorded that were not the target of this camera trap survey. Besides for *L. chrysomelas*, which is classified as 'Endangered' on the IUCN Red List, *C. kuhlii* is also classified as 'Vulnerable' and considered a species of conservation concern. The most frequently detected medium-and large-sized terrestrial mammal species were crab-eating fox (*Cerdocyon thous*) and nine-banded armadillo (*Dasypus novemcinctus*). The Amazonian brocket (*Passalites nemorivagus*) was identified in three distinct CAFS. This species, previously thought to be restricted to the Amazon region, was also recently documented in the Una Biological Reserve (Oliveira et al., 2020) in southern Bahia.

Based on the best-supported model (ΔAICc = 0.00; Table A4, Appendix A), mammal detections significantly increased with increasing shade cover ($\beta = 0.32 \pm 0.10$; $p < 0.01$; Table 2.3; Figure 2.3). However, a decrease in total basal area of shade trees was significantly associated with decreasing mammal detections ($\beta = -0.44 \pm 0.12$; $p < 0.001$; Table 2.3). The fit of the best-supported model was assessed by checking for overdispersion (Figure A4, Appendix A), with a Pearson overdispersion value of 1.12, indicating no overdispersion (Zuur et al., 2009). Additionally, Nagelkerke's R-squared value of 0.34 indicated a moderate model fit (Nagelkerke, 1991). Among models with ΔAICc < 2, additional models incorporating distance to road, shade tree diversity, and pesticide use were evaluated. However, these variables were not statistically significant ($p > 0.1$), suggesting the inclusion of these variables did not contribute to the model fit.

The best-supported model for total mammal detections was subsequently applied to both mammal species sensitive and insensitive to forest conversion into cocoa agroforests, as classified by Ferreira et al. (2025). The results suggest that for insensitive species, mammal detections significantly decreased with increasing basal area of shade trees ($\beta = -0.55 \pm 0.16$; $p < 0.001$; Table A5, Appendix A). In contrast, for sensitive species, mammal detections significantly increased with increasing shade cover ($\beta = 0.37 \pm 0.15$; $p < 0.05$; Table A5, Appendix A), while mammal detections decreased with increasing basal area ($\beta = -0.40 \pm 0.13$; $p < 0.01$; Table A5, Appendix A).

Table 2.2 Medium- and large-sized mammals recorded during the camera trap survey at 18 cocoa agroforestry systems in southern Bahia, Brazil. The number of records (i.e. independent detection events per 100 trap days) is given for each species across all sites. Species are classified as either sensitive (X) or insensitive (-) to forest conversion into CAFS based on the classification of Ferreira et al. (2025).

Taxon	Common name	Sensitive	IUCN status	N° records
Artiodactyla				
CERVIDAE		X		79
Mazama rufa (Illiger, 1815)	Red brocket deer		LC	
Passalites nemorivagus (Cuvier, 1817)	Amazonian Brown Brocket		LC	
TAYASSUIDAE				
Pecari tajacu (Linnaeus, 1758)	Collared peccary	X	LC	57
Carnivora				
CANIDAE				
Cerdocyon thous (Linnaeus, 1766)	Crab-eating fox	-	LC	286
MUSTELIDAE				
Eira barbara (Linnaeus, 1758)	Tayra	X	LC	48
Nasua nasua (Linnaeus, 1766)	South American coati	X	LC	14
FELIDAE				
Leopardus wiedii (Schinz, 1821)	Southern margay	-	NT	30
PROCYONIDAE				
Procyon cancrivorus (G. Cuvier, 1798)	Crab-eating raccoon	-	LC	67
Cingulata				
CHLAMYPHORIDAE				
Euphractus sexcinctus (Linnaeus, 1758)	Six-banded armadillo		LC	5
DASYPODIDAE				
Dasypus novemcinctus (Linnaeus, 1758)	Nine-banded armadillo	-	LC	102
Didelphimorphia				
DIDELPHIDAE				
Didelphis aurita (Wied-Neuwied, 1826)	Black-eared opossum	X	LC	37
Pilosa				
MYRMECOPHAGIDAE				
Tamandua tetradactyla (Linnaeus, 1758)	Southern tamandua	X	LC	33
Primates				
CALLITRICHIDAE				
Callithrix kuhlii (Coimbra-Filho, 1985)	Wied's marmoset		VU	4
Leontopithecus chrysomelas (Kuhl, 1820)	Golden-headed lion tamarin		EN	1
Rodentia				
CUNICULIDAE				
Cuniculus paca (Linnaeus, 1766)	Spotted paca	-	LC	74
DASYPROCTIDAE				
Dasyprocta leporina (Linnaeus, 1758)	Red-rumped agouti	X	LC	14
ERETHIZONTIDAE				
Coendou insidiosus (Lichtenstein, 1818)	Bahia porcupine		LC	2

International Union for Conservation of Nature (IUCN) status: critically endangered (CR), endangered (EN), vulnerable (VU), near threatened (NT), least concern (LC).

Table 2.3 Estimates of parameters predicting total mammal detections as a function of shade cover (%) and total basal area of shade trees (m^2 ha-1) analysed using a Generalised Linear Mixed Model (family = Negative Binomial).

Response variable	Covariates	Estimate	SE	Z	P-value
Total mammal detections	Intercept	-0.89	0.10	-8.64	< 0.001
	Shade cover	0.33	0.10	3.11	< 0.01
	Total basal area	-0.43	0.12	-3.59	< 0.001

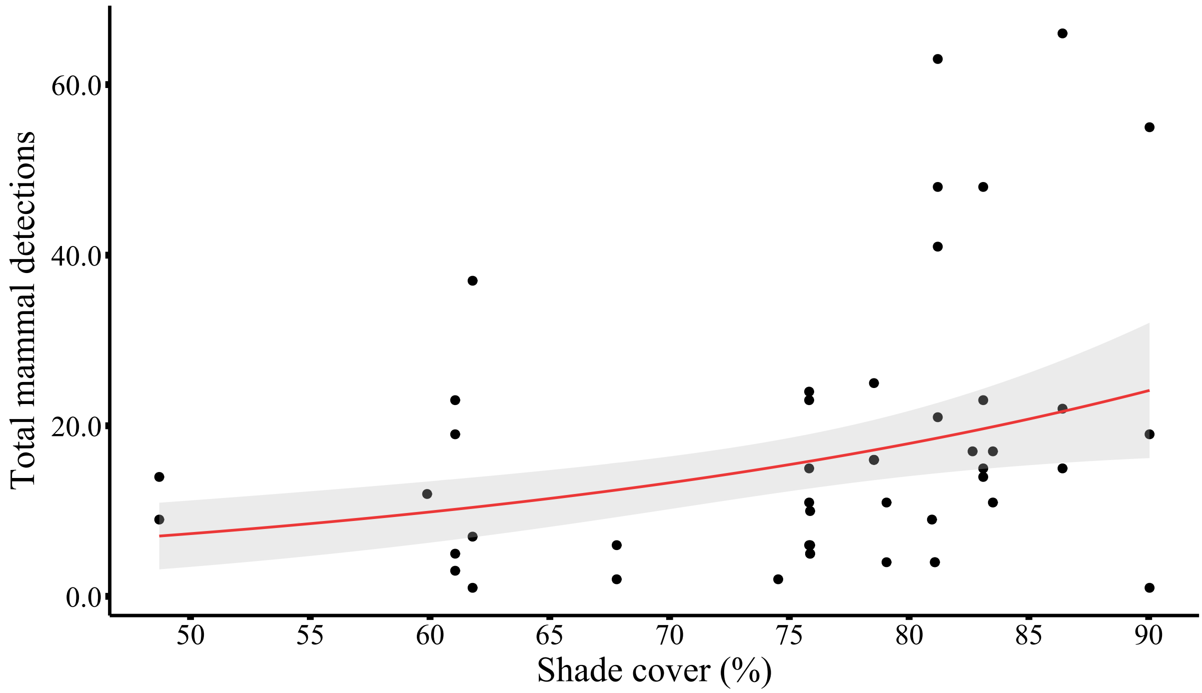

Figure 2.3 Predicted mammal detection rates (i.e. number of independent detections per 100 effective camera trap days) as a function of shade cover (%) in 18 cocoa agroforestry systems in southern Bahia, Brazil. The prediction was based on the model from Table 3. The red line and the colour-coded area represent the estimates and the 95% confidence intervals, respectively.

2.4. Discussion

2.4.1. Linking shade tree density to shade cover and the *shade tree management decree*

The significant positive correlation between shade tree density and shade cover suggests that reductions in shade tree density influence shade cover levels, underscoring the important role of shade tree density in shaping the canopy structure in CAFS. While shade cover can be provided by either many small trees or fewer large trees (Blaser et al., 2018), our results indicate a significant negative correlation between shade tree density and DBH of shade trees, suggesting that higher shade cover in CAFS is associated with a higher density of smaller trees. While shade cover can be provided by either a high density of small shade trees or a lower density of large, mature shade trees (Blaser et al., 2018), our results indicate a significant negative correlation between shade tree density and DBH, suggesting that higher shade cover in CAFS is associated with a higher density of smaller trees. The correlation between shade tree density and shade cover also allows us to convert the threshold set by the *shade tree management decree*, specified as shade tree density, into shade cover. Under the decree, farmers are allowed to thin their CAFS to 40 native shade trees per hectare, which is equivalent to less than 35% shade cover based on plot-level measurements. This threshold is much lower than the shade tree density and shade cover observed in our sampled CAFS, which raises concerns about the structural simplification that could result from the *shade tree management decree*.

2.4.2. Golden-headed lion tamarin response to shade-tree management and vegetation variables

Shade cover was the most important determinant of *L. chrysomelas* occupancy in CAFS. *Cabrucas* with higher shade cover were significantly more likely to contain *L. chrysomelas*, with *L. chrysomelas* remaining absent below 65% shade cover and occupancy reaching its maximum at approximately 75%. This suggests that a minimum threshold of 65% shade cover is required for the species' persistence in agroforestry systems, corresponding to an estimated 100 native shade trees per hectare in our sampled CAFS. This is much higher than the 35% of shade cover as promoted by the *shade tree management decree*. While the decree aims to enhance cocoa production, its low shade-tree threshold raises concerns that intensifying shade-tree management may render agroforestry systems unsuitable for *L. chrysomelas* conservation, as highlighted by previous research of Almeida-Rocha et al. (2020).

Although Almeida-Rocha et al. (2020) emphasised the importance of large-diameter shade trees–likely due to their role in providing preferred sleeping sites–our findings indicate that shade cover is a more important predictor of *L. chrysomelas* occupancy in *cabrucas* than DBH or basal area of shade trees. *L. chrysomelas* may be more likely to rely on *cabrucas* primarily for foraging and as movement corridors between isolated forest patches, where increased shade cover offers greater ecological benefits. In particular, increased shade cover likely mitigates predation risk, which is especially important in *cabrucas*, where *L. chrysomelas* is more exposed to predation due to reduced canopy connectivity and increased use of upper canopy strata compared to relatively undisturbed forests (Oliveira and Dietz, 2011). Although *L. chrysomelas* typically prefer lower canopy levels in forests, they tend to use the higher canopy strata more frequently in *cabrucas* (De Almeida Rocha et al., 2015), further increasing their vulnerability in less shaded *cabrucas*, which may be directly affected by intensified shade-tree management practices.

In contrast, a study in the coffee agroforestry landscape of Ethiopia– the only one to our knowledge comparing primate occurrences across agroforestry systems of varying management intensities–found no significant differences in primate detections between intensively managed and traditional coffee systems with low levels of management intensity (Etana et al., 2021). However, 99% of detections involved olive baboons (*Papio anubis*), a primarily terrestrial and generalist species. This difference may suggest that terrestrial generalist primates may be more resilient to intensifying shade-tree management compared to primarily arboreal species like *L. chrysomelas*. Arboreal primates, which are highly dependent on canopy connectivity and habitat complexity for movement and foraging, may therefore benefit more from structurally complex, shaded agroforestry systems (Cassano et al., 2014; Estrada et al., 2012). While responses to shade-tree management likely vary among primate taxa, promoting shade-tree management practices that maintain higher shade-tree cover may be especially important for conserving canopy-dependent species like *L. chrysomelas* within agroforestry landscapes.

Furthermore, we found a significant positive association between the IVI of jackfruit trees and *L. chrysomelas* occupancy, suggesting that *cabrucas* with a higher prevalence of jackfruit trees were more likely to contain *L. chrysomelas*. However, this contrasts with the findings of Almeida et al. (2020), who reported a negative relationship between jackfruit dominance and *L. chrysomelas* occupancy in *cabrucas*. This discrepancy may reflect differences in both local CAFS characteristics and broader landscape context. In our study, jackfruit trees were more dominant (higher IVI values), yet *L. chrysomelas* showed a high probability of occupancy even in *cabrucas* where jackfruit was absent or not the dominant shade tree species. This suggests that while the presence of jackfruit trees enhances occupancy of *L. chrysomelas*, it likely serves as a supplementary food source rather than a limiting factor for species' occupancy. This aligns with previous research highlighting the importance of jackfruit as a food resource for *L. chrysomelas* (Oliveira et al., 2010, 2011), particularly during seasons of native fruit scarcity (Costa et al., 2022). Additionally, Almeida et al. (2020) included sites outside the core distribution range of *L. chrysomelas* (Teixeira et al., 2024), where anthropogenic disturbances are more pronounced, forest fragments are more isolated by pasture, and *L. chrysomelas* populations are more vulnerable to local extinction (Raboy et al., 2010; Teixeira et al., 2024; Zeigler et al., 2010). In such degraded landscapes, local habitat features–such as jackfruit dominance–may play a more unfavourable role in determining *L. chrysomelas* occupancy, particularly in areas with reduced native food resources.

2.4.3. Mammal responses to shade-tree management and vegetation variables

Our findings confirm that *cabrucas* harbour diverse assemblages of medium and large terrestrial mammals, reinforcing their conservation value within human-modified landscapes. This aligns with previous studies from the region (Cassano et al., 2014, 2012; Ferreira et al., 2020, 2025), which demonstrate the role of *cabrucas* in supporting mammal populations, even in landscapes dominated by shaded cocoa cultivation and reduced forest cover (Ferreira et al., 2020). However, our results provide a more nuanced perspective, identifying that shade cover is a key driver of terrestrial mammal detections within *cabrucas*, particularly for species sensitive to forest conversion. Specifically, total mammal detections, as well as detections for sensitive mammal species, declined significantly in *cabrucas* with reduced shade cover. This finding underscores the dual importance of preserving *cabrucas* as a land-use system and implementing effective shade-tree management practices that maintain adequate shade cover. Such practices not only benefit species of conservation concern, such as the *L. chrysomelas*, but also the terrestrial mammal community.

These findings align with those of Ferreira et al. (2025), who reported that higher shade-tree density positively influenced mammal assemblage structure, benefiting both species that are insensitive and sensitive to forest conversion into CAFS. Moreover, Ferreira et al. (2020) observed that intensified cocoa agroforests - where cocoa is cultivated predominantly under exotic tree species - contained less diversified mammal assemblages than *cabrucas* with a predominance of native trees and forests, even in highly forested landscapes. This further emphasises the necessity of maintaining a diversified, dense native shade-tree canopy in agroforestry systems to support mammal populations and enhance community composition.

Similar trends have been observed in coffee agroforestry systems across the tropics. A meta-analysis by Manson et al. (2024) found that mammal presence is significantly higher in agroforestry systems with higher shade cover (Manson et al., 2024). For instance, Etana et al. (2021) found that traditional coffee agroforestry systems in Ethiopia supported higher overall species richness, diversity, and detection of mammals compared to intensively managed coffee plantations, where intensive tree thinning and undergrowth removal likely reduced the potential natural plant regeneration (Hundera et al., 2013), ultimately diminishing mammal diversity.

In addition to shade cover, the total basal area of shade trees was also a significant driver of medium and large terrestrial mammal abundances. However, unlike shade cover, mammal detections were negatively associated with the total basal area of shade trees. Shade-tree cover in agroforests can be provided through either a high density of small shade trees or a low density of large, mature shade trees (Blaser et al., 2018). Our findings suggest that mammals were more frequently detected in agroforestry systems with high shade-tree cover provided by greater density of smaller shade trees, likely reflecting agroforests in early stages of forest regeneration (DeWalt et al., 2003) and less intensively managed systems. The tree diameter profile of *cabrucas* varies depending on the shade species used and the intensity of management practices, such as tree thinning and understory weeding (Sambuichi and Haridasan, 2007). In intensively managed systems, these practices limit natural regeneration of most shade-tree species (Hundera et al., 2013), likely reducing habitat complexity and resource availability for mammals, especially in agroforests with fewer shade trees.

Together, these findings highlight the importance of preserving traditional agroforestry systems that maintain adequate shade cover, supported by a sufficient density of native shade trees. However, since shade cover in agroforests is also determined by the DBH of shade trees, a potential trade-off may exist that could influence habitat use across taxa. For instance, *L. chrysomelas* may benefit from higher shade cover provided by larger, mature trees, which offer preferred sleeping sites, whereas terrestrial mammals may favour agroforests with higher shade cover provided by a higher density of smaller shade trees. Ultimately, limiting the intensification of shade management is key to preserving the biodiversity conservation value of cocoa agroforests.

2.4.4. Study limitations and further research

While our study provides valuable insights into the role of shade-tree management in *cabrucas*, some considerations should be noted. Although our sample size is smaller than some studies (Cassano et al., 2014; Ferreira et al., 2025), it is comparable to others assessing biodiversity responses to management intensity in CAFS (Almeida-Rocha et al., 2020; Blaser et al., 2018; Cabral et al., 2021; Steffan-Dewenter et al., 2007), and was sufficiently large to detect significant differences in biodiversity across the shade-tree management gradient. Our focus on traditional CAFS, which cannot legally be thinned below a minimum of 40 native shade trees per hectare, limited the inclusion of more intensively managed CAFS. A broader shade tree management gradient, especially at the lowest end, would further strengthen our understanding of biodiversity responses to varying shade tree management intensities.

The occupancy survey for *L. chrysomelas* was conducted during a single season, limiting our ability to account for potential seasonal variation in detection and habitat use. Moreover, as occupancy does not capture population dynamics, our study does not provide insights into abundance, survival, or reproductive success. Future studies should therefore aim to include multi-season population monitoring and demographic assessments to inform long-term conservation strategies for this endangered primate species.

Given that the study focused on detecting the presence of *L. chrysomelas* and determining shade tree management thresholds, a species-specific survey approach (i.e., playback surveys) and statistical analysis (i.e., occupancy modelling) were required, which constrained the camera trap deployment period for terrestrial mammals. While our findings provide valuable insights into mammal responses to shade-tree management, future research should extend camera-trap deployment periods, incorporate arboreal camera traps to adopt a community-level approach to assess mammal species richness, diversity, composition, and functional guild responses. Such efforts would contribute to refining shade tree management recommendations to benefit the broader mammal community.

Finally, while our study highlights the ecological benefits of maintaining a dense native shade-tree canopy, integrating the environmental benefits and ecosystem services associated with shade-tree density alongside socio-economic dimensions would provide a more comprehensive perspective on the overall sustainability of CAFS.

2.5. Management implications for conservation and conclusions

Our study highlights the importance of adequate shade-tree management practices in cocoa agroforestry systems for supporting biodiversity conservation, particularly for the golden-headed lion tamarin. We demonstrate that the current intensification threshold of 40 native shade trees per hectare – equivalent to less than 35% shade cover – set by the Bahian *shade tree management decree*, is insufficient for supporting *L. chrysomelas* conservation in *cabrucas*. Instead, we identify that a minimum threshold of 100 native shade trees per hectare, corresponding to 65% shade cover, is required for *L. chrysomelas* persistence, which would also directly benefit the terrestrial large mammal community. While the decree aims to increase cocoa production, this relatively low threshold raises significant concerns that intensive shade-tree management may render agroforestry systems unsuitable for the conservation of this endangered primate species, highlighting a potential trade-off between agricultural intensification and biodiversity conservation within agroforestry landscapes.

Studies focusing on biodiversity–productivity trade-offs suggest that a win–win scenario can be achieved with 30% to 50% shade-tree cover in cocoa agroforestry systems (Blaser et al., 2018; Clough et al., 2011; Steffan-Dewenter et al., 2007). However, our findings indicate that a minimum of 65% shade cover–equivalent to at least 100 native shade trees per hectare–is necessary to meet the ecological requirements of *L. chrysomelas*. This threshold raises concerns about potential trade-offs for cocoa farmers, as several studies report declining cocoa yields when shade cover exceeds 50–60% (Bisseleua et al., 2009; Blaser et al., 2018; Clough et al., 2011; Wade et al., 2010). Nevertheless, some studies suggest that higher shade levels may support biodiversity without necessarily compromising yields. For example, Waldron et al. (2012) identified 100 shade trees per hectare as a threshold for maintaining farm biodiversity, while also increasing cocoa yields by up to 50% in Ecuadorian cocoa agroforestry systems. Similarly, Ferreira et al. (2023) recommend a 65% shade cover threshold to support bat diversity in African cocoa agroforests, which aligns with our findings for *L. chrysomelas*, although the study did not assess the impact of this threshold on cocoa yield. These findings underscore the importance of region-specific shade-tree management strategies that consider both the ecological requirements of local fauna (De Beenhouwer et al., 2013) and the agronomic contexts of different cocoa-growing regions.

Increased shade-tree cover has been shown to benefit a variety of taxonomic groups, including birds (Bennett et al., 2022; Blaser et al., 2018; Jarrett et al., 2021), bats (Ferreira et al., 2023), and invertebrates (Bisseleua et al., 2009, 2013; Steffan-Dewenter et al., 2007) in both cocoa and coffee agroforestry systems. However, it is also essential to recognise the limitations of agroforests in conserving forest-specialist and threatened species. Numerous studies consistently show that these species are often more abundant and diverse in native forest fragments, particularly those under protection (Bennett et al., 2022; Ferreira et al., 2020; Rodrigues et al., 2018). While agroforestry systems provide valuable habitat for a variety of species, they cannot fully replace the ecological functions and habitat quality of native forests. This highlights the need for integrated conservation strategies that promote sustainable shade-tree management practices in agroforests with the protection of native forests in human-dominated landscapes, while also accounting for the livelihoods of smallholder farmers and the necessity of crop production.

In this context, further research is needed to explore the interactions between shade-tree density, cocoa yields, and biodiversity conservation. While shade trees offer numerous ecological benefits, including carbon sequestration, soil fertility, and buffering climatic extremes (Blaser et al., 2018; Niether et al., 2020; Tscharntke et al., 2011a), competition for land, resources and light can reduce cocoa yields (Abdulai et al., 2018; Blaser et al., 2018). Future studies should assess the environmental and economic trade-offs and synergies under different shade tree management practices. Such research is critical for developing agroforestry systems that simultaneously support biodiversity conservation and the livelihoods of smallholder farmers. Ultimately, the future of cocoa agroforestry systems lies in finding a balance between agricultural productivity and biodiversity conservation, which will guide policy decisions aimed at optimising both environmental and economic outcomes.

Chapter III

Managing shade trees, balancing trade-offs: Effects of shade-tree density on economic performance of cocoa agroforests[3]

3.1. 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., 2011b). As a result, AFS across the tropics differ substantially, ranging from traditional systems that retain many native 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.,

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[3] Under review. Authors: Dekegel, S., Laviolette, D. De Vleeschouwer, K., Oliveira, L., Chiapetti, J., Santos Da Conceição, A., Van Den Broeck, G.

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

2011b). 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., 2011a). 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 (Krumbiegel and Tillie, 2024; Middendorp et al., 2020; Moluh Njoya et al., 2025; Sellare et al., 2020). 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 to shade-tree management intensification (Asare et al., 2019; Blaser et al., 2018; Clough et al., 2011; 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[4], 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.

3.2. Conceptual framework and empirical evidence

To understand how shade-tree density[5] affects the economic performance of CAFS, we develop a conceptual framework (Figure 3.1) 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

[4] 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 (Krumbiegel and Tillie, 2024). 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).

[5] 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 hectare (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.

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, 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.

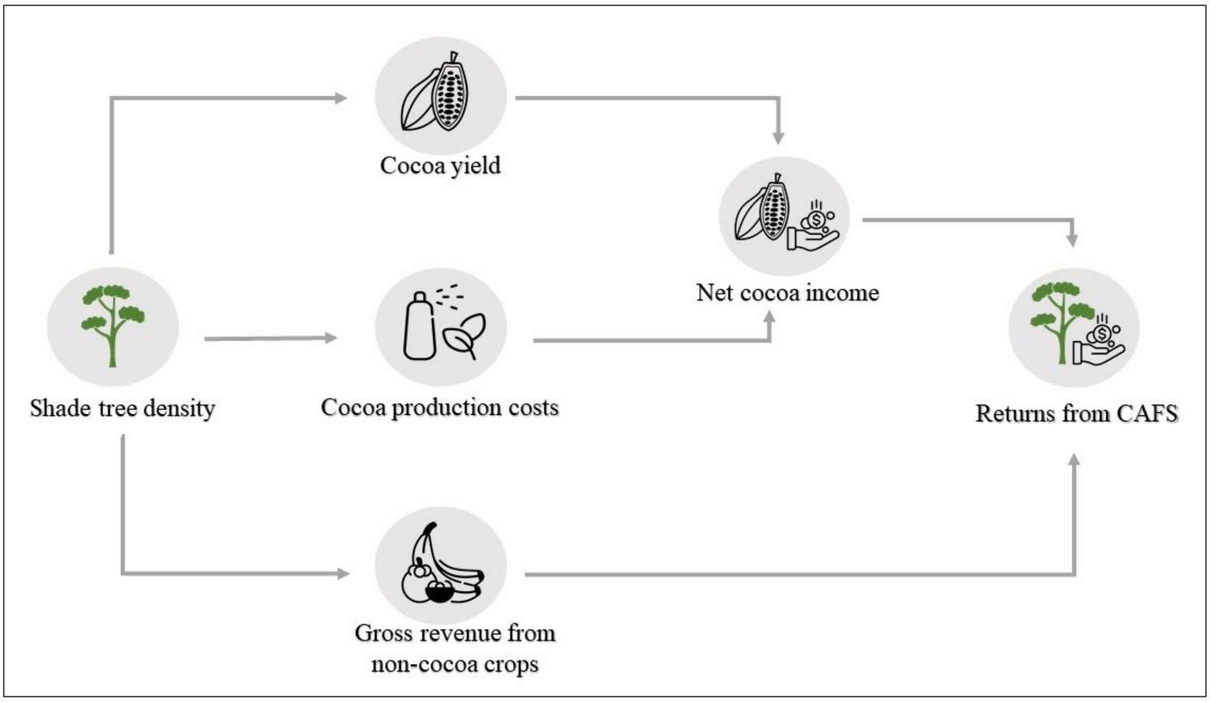

Figure 3.1 Conceptual framework illustrating the pathways through which shade-tree density may affect the economic performance of CAFS, defined by five economic outcome variables.

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[6] 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[7]. 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

[6] 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 that 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.

[7] 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.

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 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 (Figure 3.1).

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.

3.3. Data and Methods

3.3.1. 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 (Chiapetti et al., 2020), most of whom cultivate less than 12 hectares 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.

3.3.2. Sampling and data collection

The farm-household survey was conducted between February and March 2024 among 313 cocoa farmers in southern Bahia (Figure 3.2). 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[8] relative to the household to assess shade-tree density. Within each CAFS, one vegetation plot of 25x20m (500m²) was randomly established, positioned at least 100m from the plot edge. All woody tree species with a diameter at breast height (DBH) of ≥ 10.0 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.

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

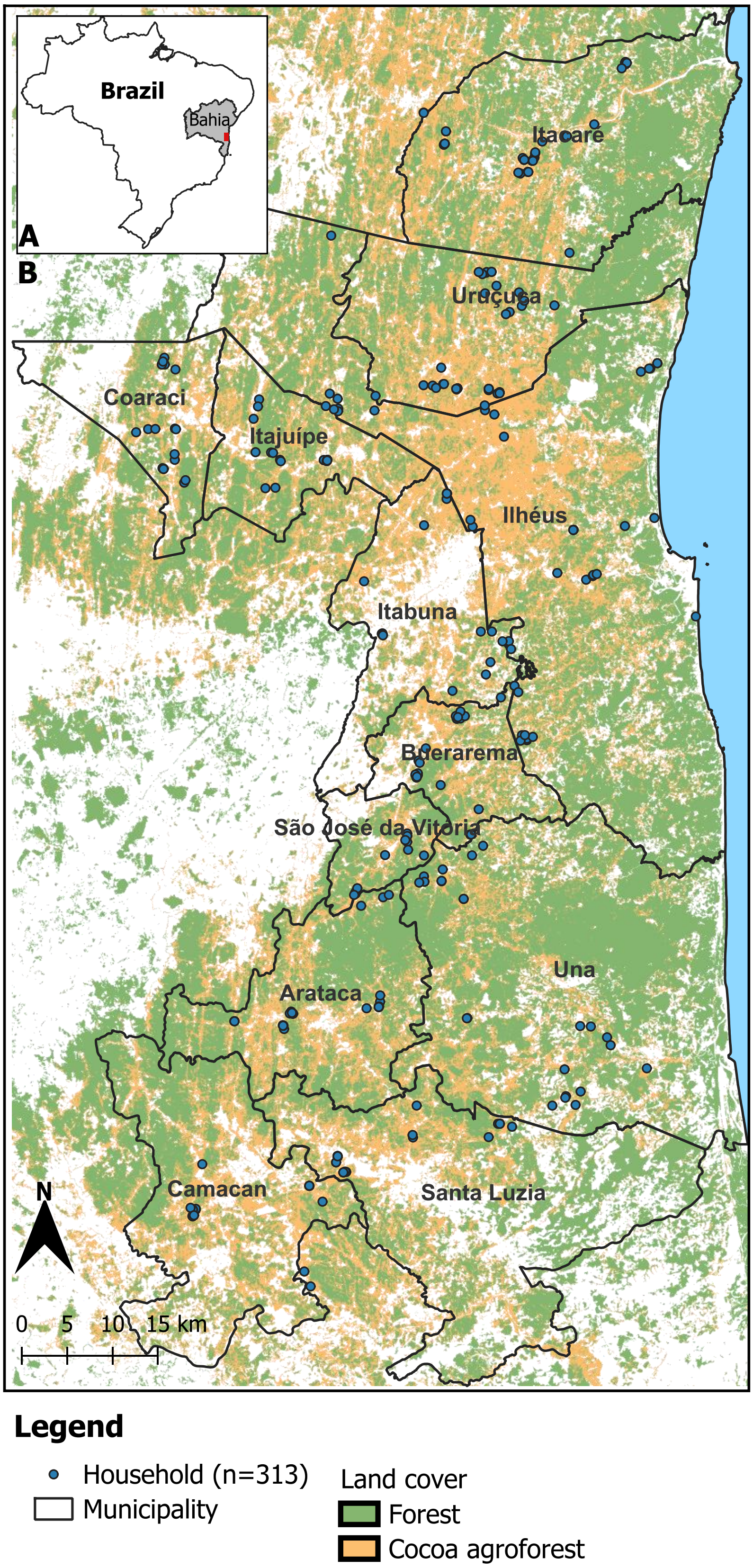

Figure 3.2 Map of the sampled households in Southern Bahia, Brazil. (A) Location of the research area (red) in the state of Bahia (grey) in Brazil. (B) Distribution of the 313 households across 12 municipalities in southern Bahia. Land cover data obtained from MapBiomas (MapBiomas Cacau, 2019).

3.3.3. 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[9]) 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[10], 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

[9] Tarefa is a non-metric unit equivalent to 0.4356 ha in Bahia (Gagliano et al., 2018).
[10] One arroba in Brazil is equal to 15 kg (Lima, 1982).

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.

3.3.4. Econometric approach

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

$$Y_i = \beta_0 + \beta_1 STD_{\mathrm{i}} + \sum_{i=0}^{k} \beta_{\mathrm{i}} X_{\mathrm{ni}} + \varepsilon_i$$

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*[11]. 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[12]. 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

[11] We also tested for non-linear relationships between STD and each economic outcome variable, but the quadratic terms were never statistically significant.

[12] We also estimated OLS regression models that included additional control variables (including market access and institutional factors) and found that the estimated effects of shade-tree density on the economic outcome variables remained robust in terms of magnitude, direction, and statistical significance (Table B2, in Appendix B).

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.

3.3.4.2. 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[13] (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.

3.4. Results

3.4.1. Descriptive statistics

Table 3.1 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 137m above sea level and are located in proximity to their CAFS, at an average distance of 610m. However, farms are often situated at considerable distances from key infrastructure, averaging 4km from the nearest paved road and 9km from the nearest city.

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

[13] We tried an instrumental variable approach as well, but could not identify instruments that simultaneously satisfy the relevance and exogeneity criteria.

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.* 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 sell 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 17ha, but with large differences across farms. They are situated at elevation levels (148m) 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 3.2 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[14] (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

[14] 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.

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 3,460 R$ ha^{-1}, while production costs are on average 1,127 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 2,552 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 2,859 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.

Table 3.1 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

Table 3.2 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	17894.74
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	15699.00
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	16809.29
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.

Figure 3.3 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 3.1). 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 (ρ =0.19, p <0.001; Fig. 3.3), indicating that as shade-tree density increases, CAFS are more dominated by native shade-trees compared to planted non-native species.

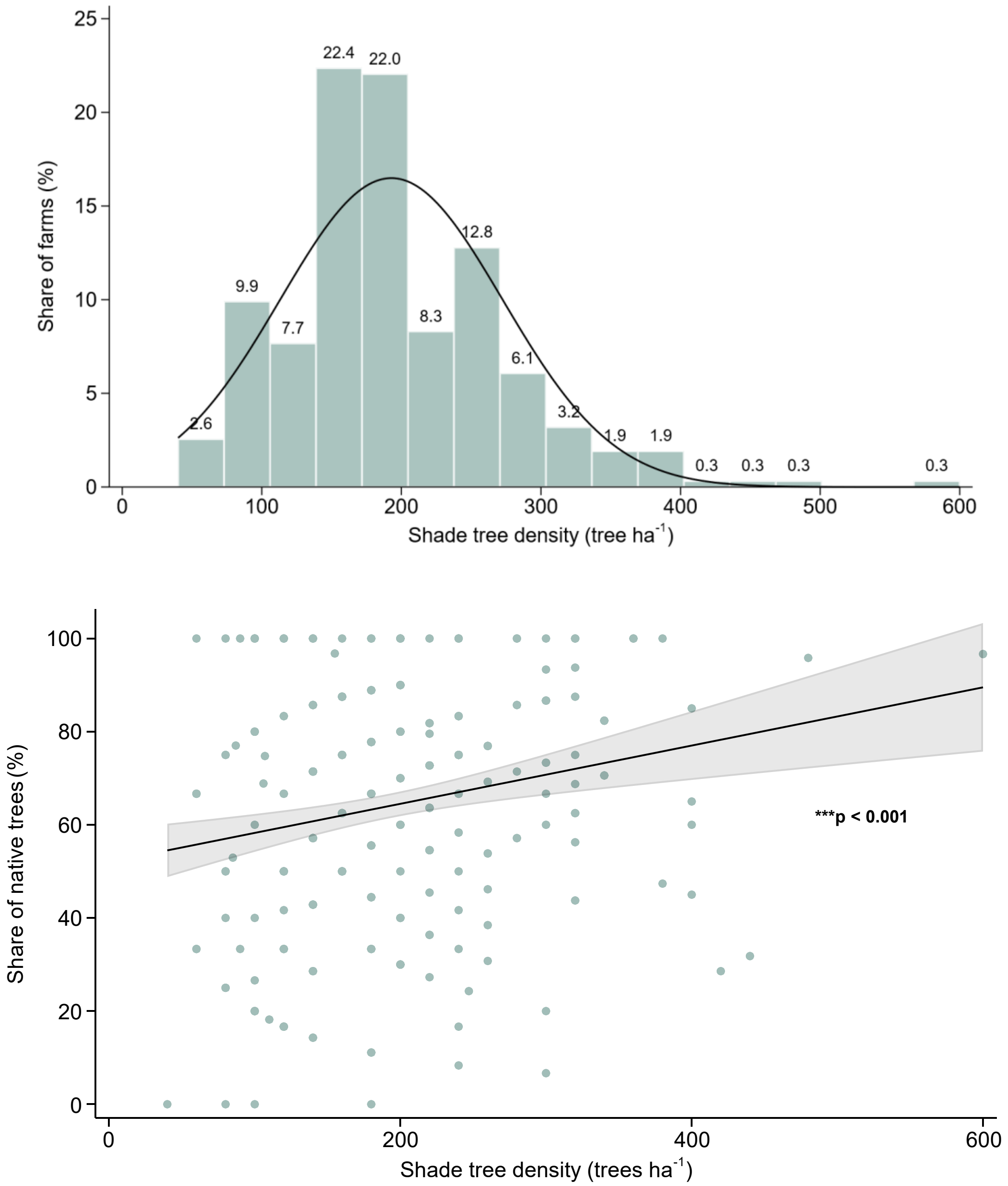

Figure 3.3 Shade-tree characteristics in 313 cocoa agroforestry systems (CAFS) in southern Bahia. Top: distribution of shade-tree density (trees ha^{-1}) across farms, ranging from 40 to 600 trees ha^{-1}. Bottom: relationship between shade-tree density and the share of native shade-tree species, showing 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}).

Figure 3.4 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).

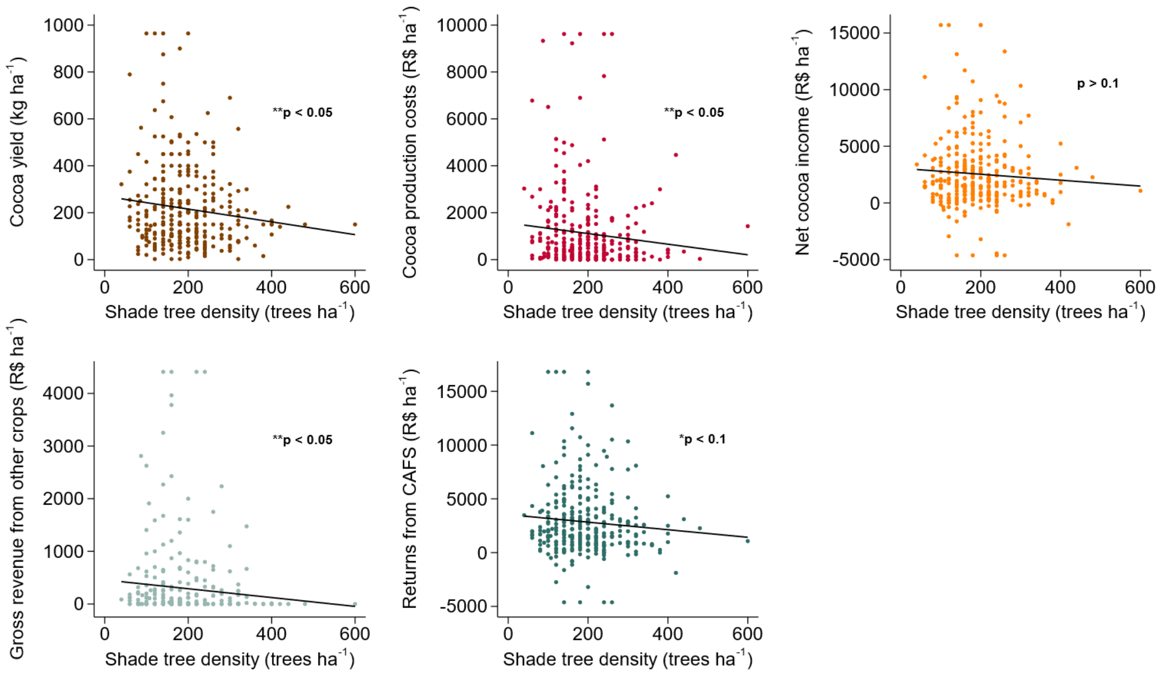

Figure 3.4 Scatterplots illustrating the relationship between shade-tree density and economic performance indicators from cocoa agroforestry systems (CAFS) in southern Bahia, Brazil. Each panel presents one economic indicator (i.e. cocoa yield, cocoa production costs, net cocoa income, gross revenue 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}). *$p < 0.10$, **$p < 0.05$, ***$p < 0.01$.

3.4.2. Regression results

Table 3.3 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 B1, in Appendix B). 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 significantly associated with the economic outcome variables (Table 3.3). 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 3.4). 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.

Table 3.3 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 of other 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 3.4 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. **p* < 0.10, ***p* < 0.05, ****p* < 0.01. Full estimation results, including coefficients of control variables, are provided in Table B3 in Appendix B.

3.5. Discussion

3.5.1. 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 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 22kg 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 2,859 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 (17ha) is substantially larger than cocoa farm sizes in Africa and Asia (Dröge et al., 2025a; Krumbiegel and Tillie, 2024). 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.

3.5.2. 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., 2016b) 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.

3.5.3. 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 density. 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 management on economic performance. Third, while we focus on shade-tree density as the principal proxy for shade 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.

3.6. 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 largely 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, yet predominantly they 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).

Chapter IV

Identifying the sweet spot: Ecological and economic trade-offs and synergies in cocoa agroforests[15]

4.1. Introduction

Ensuring that agricultural production systems can sustain farmer livelihoods while safeguarding ecosystem integrity remains one of the foremost challenges of the twenty-first century (Kremen, 2020). Agroforestry systems (AFS) exemplify a multifunctional land-use strategy that can reconcile these objectives by deliberately integrating trees with crops to deliver both economic and environmental benefits (Blaser et al., 2018; Broeckhoven et al., 2025; Clough et al., 2011; Wurz et al., 2022). Although trade-offs between agricultural yields and ecosystem services are prevalent, sustainable agricultural practices can create ecological–economic synergies as well (Berger et al., 2025; Ricciardi et al., 2021; Wurz et al., 2022). However, the contribution of AFS to sustainable land use is increasingly contested as many farmers intensify production through systematic shade-tree removal, shifting from diverse, highly shaded AFS to simplified, low-shaded or even unshaded systems in pursuit of short-term profitability (Grass et al., 2020; Niether et al., 2020; Steffan-Dewenter et al., 2007). Whether AFS can remain both economically viable and environmentally sustainable under such agricultural intensification pressures remains uncertain, as existing studies provide mixed results (Blaser et al., 2018; Steffan-Dewenter et al., 2007; Wurz et al., 2022).

Progress in evaluating the potential of AFS in generating ecological-economic synergies is constrained by several key research gaps. First, the existing literature has focused predominantly on the consequences of land-use transitions by comparing AFS to forest and monocultures (Broeckhoven et al., 2025; Grass et al., 2020; Jezeer et al., 2017; Niether et al., 2020; Wenzel et al., 2024; Wurz et al., 2022), while largely overlooking the considerable variation within AFS, particularly in terms of shade-tree density. Second, most studies address single dimensions of sustainability, focusing either on ecological (Bennett et al., 2022; Dekegel et al., 2025; Ferreira et al., 2025, 2023; Jarrett et al., 2021) or

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economic outcomes (Asare et al., 2019, 2017; Asitoakor et al., 2022; Jezeer et al., 2018) of shade-tree management. While interdisciplinary studies are available across different agroforestry crops, they remain scarce, regionally concentrated, and restricted in the ecological and economic indicators used. On the ecological side, interdisciplinary research has mainly focussed on ecosystem services (e.g., Becker et al., 2025; Blaser et al., 2018; Schroth et al., 2016; Walsh et al., 2025) and taxa such as trees (e.g., Broeckhoven et al., 2025; Clough et al., 2011; Steffan-Dewenter et al., 2007; Wurz et al., 2022), invertebrates (e.g., Bisseleua et al., 2013, 2013; Wurz et al., 2022), and birds (e.g., Blaser et al., 2018; Waldron et al., 2012). Large mammals on the other hand are rarely considered, although they are critical to ecosystem functioning and service provision in tropical landscapes and particularly sensitive to shade-tree management (Dekegel et al., 2025; Ferreira et al., 2025), and therefore represent a particularly relevant indicator taxon for assessing the ecological trade-offs associated with shade-tree thinning in CAFS. On the economic side, most assessments rely on yield (Blaser et al., 2018; Broeckhoven et al., 2025; Clough et al., 2011; Wenzel et al., 2024, p. 3; Wurz et al., 2022), without accounting for production costs and additional revenues from associated crops, which together determine overall economic performance and vary with shade tree management (Bisseleua et al., 2009, 2013; Jezeer et al., 2018). Comprehensive economic assessments exist for coffee, oil palm, and rubber (Grandez-Alberca et al., 2025; Grass et al., 2020; Jezeer et al., 2018; Walsh et al., 2025) but remain scarce for cocoa, with evidence limited to a few older small-sample analyses (Bisseleua et al., 2009, 2013; Waldron et al., 2012) and one large-scale study from Indonesia (Steffan-Dewenter et al., 2007).

In this study, we address these research gaps by evaluating under which conditions AFS can deliver ecological–economic synergies. Specifically, we aim to (i) assess the role of shade-tree density in shaping ecological–economic trade-offs and synergies; (ii) identify farmer- and farm-level characteristics associated with these ecological-economic outcomes; and (iii) analyse how farmers' perceptions of the benefits and difficulties associated to shade trees vary across ecological-economic outcomes. We combine detailed household-level economic and ecological data with field measurements from 312 cocoa-farming households across 12 municipalities in southern Bahia, Brazil. Accordingly, this study advances the literature in three ways. First, we focus exclusively on AFS, capturing their wide gradient of shade-tree density and highlighting within-system variation. Second, we use a mixed-method approach that combines household-level economic surveys with ecological field measurements, enabling a multidimensional assessment of AFS performance. Third, we employ a comprehensive measure of economic performance that captures land productivity and farm-household income, while using medium- and large-sized mammals as ecological indicator of biodiversity conservation. Taken together, these contributions provide novel insights into the conditions under which AFS can jointly deliver ecological and economic synergies.

Our focus on cocoa AFS (CAFS) in southern Bahia, Brazil, is particularly relevant, as integrated ecological-economic assessments of CAFS remain scarce for Latin-America. Moreover, cocoa is one of the leading tropical cash crops, with over 4.4 million tonnes traded annually and providing livelihoods for an estimated 40-50 million people, the majority of whom are small-scale farmers in low-income countries (Voora et al., 2019). Brazil is the world's fifth-largest cocoa producer and the second largest in Latin America, with southern Bahia as one of its principal producing regions. This region combines global ecological and socio-economic relevance: it is situated within the Atlantic Forest biodiversity hotspot (Myers et al., 2000), highly shaded cocoa agroforests still predominate, providing critical habitat for native species, and supporting the livelihoods of ~69,000 smallholder households (Cassano et al., 2009; Chiapetti et al., 2020). These characteristics make the CAFS of southern Bahia an important, yet understudied, area to examine how shade-tree management drives ecological–economic trade-offs and synergies.

4.2. Data and Methods

4.2.1. Research Area

Southern Bahia, in north-eastern Brazil, is one of the country's principal cocoa-producing regions, accounting for nearly half of national production and hosting close to three-quarters of all cocoa properties (IBGE, 2023; Chiapetti et al., 2020). Following the witches' broom outbreak (*Moniliophthora perniciosa*) in the late 1980s, Brazil shifted from a major exporter to a net importer. Although production has steadily increased over the past two decades (FAOSTAT, 2025), low productivity continues to constrain farmer livelihoods. Average yield in the region is 319 kg ha^{-1}, well below that in major West-African cocoa-producing countries Côte d'Ivoire and Ghana (500-570 kg ha^{-1}; FAOSTAT, 2025), and is even lower in traditional shaded systems, resulting in household incomes often falling short of the legal minimum wage (Chiapetti et al., 2020). Cocoa cultivation in southern Bahia is dominated by traditional AFS, locally known as *cabrucas*, which represent nearly 80% of cocoa farms (Chiapetti et al., 2020). *Cabrucas* are highly shaded AFS dominated by native tree species, providing secondary habitat and ecological corridors for native and endangered fauna while preserving cultural and historical significance (Cassano et al., 2009; Oliveira et al., 2010; Schroth et al., 2015). Despite their ecological and socio-cultural value, *cabrucas* face mounting policy and market pressures to intensify cocoa production. Limited access to credit and technical assistance, combined with persistently low yields, incentivise shade-tree removal in pursuit of higher short-term economic returns (Chiapetti et al., 2020).

4.2.2. Sampling and data collection

Between February and March 2024, we conducted a farm-household survey among 314 cocoa producers in southern Bahia (Figure 4.1). To ensure broad geographic coverage and capture the heterogeneity of CAFS in the region, we applied a two-stage random sampling strategy. In the first stage, twelve municipalities were purposively selected based on their relevance within the regional cocoa supply chain (Chiapetti et al., 2020). For these municipalities, we assembled a comprehensive sampling frame of cocoa farmers from the most recent large-scale regional census (Chiapetti et al., 2020), complemented with membership lists from cooperatives, producer associations, community groups, and agrarian reform settlements. In the second stage, between 15 and 36 farmers were randomly selected per municipality, proportional to the share of cocoa producers across municipalities (Chiapetti et al., 2020). In total, 314 farmers were interviewed, of whom 312 were retained for the analysis after data cleaning.[16]

Data were collected through face-to-face interviews conducted by a well-trained team of local enumerators. The interviews were directed at the household member responsible for day-to-day management decisions regarding cocoa production. A quantitative structured questionnaire was used, covering modules on household demographics, cocoa production and marketing, cocoa management practices and input use, and income sources from non-cocoa crops, other agricultural and non-agricultural activities. Additional modules captured farmers' perceptions of the benefits and challenges of maintaining shade trees in CAFS, as well as reports of medium- and large-sized mammal species observed within CAFS plots. After each interview, we visited the nearest CAFS plot relative to the household[17] to collect field data. Shade-tree density was measured in one randomly established vegetation plot of 25x20 m (500 m²), located at least 100m from the edge of the cocoa plot. All woody tree species with a diameter at breast height (DBH) ≥ 10.0 cm, including both native and exotic species, were identified and classified as shade trees within the plot. Additionally, GPS coordinates were taken at both the household and plot level, enabling integration of survey information with spatial data on land cover and topography.

Table C1 in Appendix C describes the summary statistics of the sampled farm households. The surveyed households are on average 55.7 years old, with women representing 22% of household heads. 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 working-age adults. Sharecropping arrangements account for 6% of the sample, while 42% of the households are located within agrarian reform settlements, where tenure is not always formally documented (Chiapetti et al., 2020). Households are generally situated at relatively low elevations, averaging 137m above sea level and are located in proximity to their CAFS, at an average distance of 610m. The average distance of households to key infrastructure is 4 km to the nearest paved road and 9 km to the nearest city. CAFS have an average area of 17ha, with substantial variation across farms. CAFS plots are situated at mean elevations of 148 m and on moderately sloping

[16] One farmer was excluded due to missing biodiversity data, while the other was removed because the production system was identified as a cocoa-rubber plantation without native shade trees, which does not qualify as *cabruca* under Bahia's legal requirement of at least 20 native shade trees per hectare (State Decree No. 15180/2014, Seção IV, Art. 15).

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

terrain (average slope 15%). Most CAFS plantations are mature, with only 13% of farmers reporting the presence of young, non-productive cocoa trees. A substantial proportion of farmers (74%) cultivate improved cocoa varieties. Post-harvest practices are widespread, with 73% of farmers fermenting cocoa beans and nearly all drying the beans before sale. Cocoa sales generated an average farmgate price of 15.75 R$ kg^{-1} in 2023, in line with the international benchmark of USD 3.35 kg^{-1} (ICCO, 2023). The cultivation of cocoa in full-sun systems alongside CAFS is rare, reported by only 6% of the farmers. Use of external inputs is relatively common, with 57% of the farmers applying pesticides, fertilisers and/or lime.

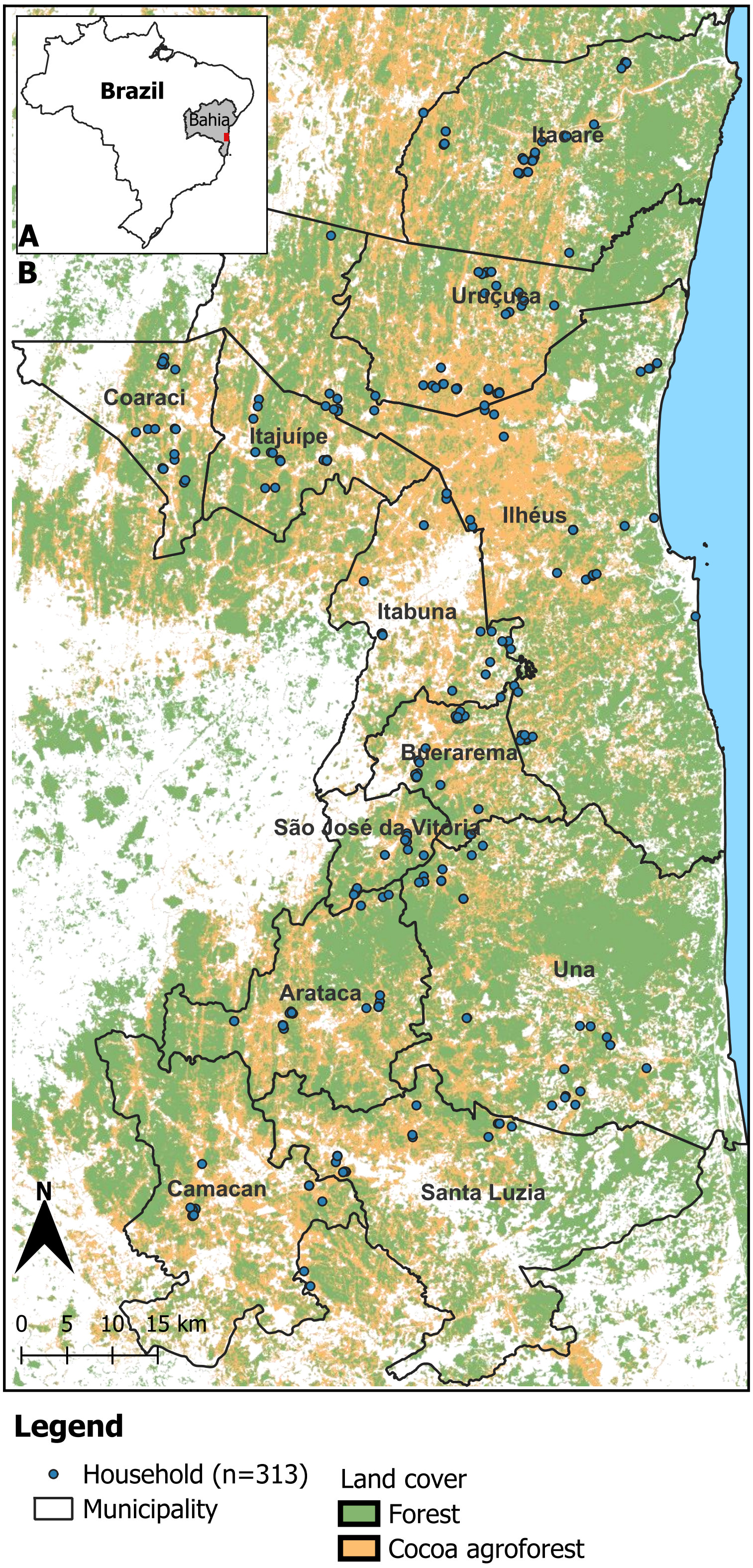

Figure 4.1 Map of the sampled households in Southern Bahia, Brazil. (A) Location of the research area (red) in the state of Bahia (grey) in Brazil. (B) Distribution of the 313 households across 12 municipalities in southern Bahia. Land cover data obtained from MapBiomas (MapBiomas Cacau, 2019).

4.2.3. Measurement of outcome variables

4.2.3.1. Economic outcome variable

Our analysis focuses on net returns per hectare of CAFS area as the main economic indicator. We use this measure to capture the overall land productivity of CAFS, accounting not only for cocoa profitability but also for the additional value of other crops cultivated within the system. Net returns from CAFS are defined as the sum of net cocoa income and revenues from non-cocoa crops cultivated in CAFS. First, 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 multiplying the self-reported cocoa yield, defined as the total quantity of dried cocoa beans harvested from the CAFS area (expressed in kilograms per hectare), by the average farmgate price that the farmer received over the past 12 months, or by using the self-reported estimation from the farmer directly. 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. Second, revenues from non-cocoa crops in CAFS are measured as the total value 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 the produce 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 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.

In addition to land productivity, we assess household-level economic outcomes to evaluate overall households' livelihood performance beyond CAFS. Total household income is calculated as the sum of all income sources earned by the household, including 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 such as pensions, remittances, or social transfers. Per capita income is calculated by dividing total household income by household size.

All reported revenues, costs, and yields refer to the 12 months preceding the survey, corresponding to the 2023 production year. To minimise the influence of outlying observations, values were trimmed at the top and bottom 1% (Bemelmans et al., 2025). The CAFS area was recorded using the farmer's preferred unit of measurement (hectares, acres, or tarefas[18]), and subsequently standardised to hectares.

4.2.3.2. Ecological outcome variable

We use mammal species richness within CAFS as the ecological outcome variable, defined as the number of medium- and large-sized native mammal species reported per farm, and employ it as a proxy for mammal conservation. Mammal presence was documented using the Wildlife–Human Survey protocol (Islas et al., 2022), a standardised and cost-efficient method for documenting medium- and large-sized mammal species through structured household interviews. This approach is well-suited for generating reliable data on mammal presence at large scales, making it particularly valuable for interdisciplinary research and in contexts where standard field-based survey methods, such as camera trapping or line transects, are logistically or financially unfeasible (Islas et al., 2022).

The survey focused on non-flying native mammal species (defined as those > 500 g), which can be reliably identified by farmers. Respondents were shown colour photographs of medium- and large-sized mammal species known to occur in the region, based on the regional species pool established in previous studies (Cassano et al., 2014; Dekegel et al., 2025; Ferreira et al., 2025). For each species, respondents were asked to indicate whether its presence in their CAFS had been identified through direct visual observation and/or indirect evidence, such as tracks or other characteristic signs, during the 12 months preceding the survey (i.e. corresponding to the 2023 production year).

Some species could not be reliably distinguished by respondents and were therefore grouped. The bristle-spined rat (*Chaetomys subspinosus*) and the Bahia porcupine (*Coendou insidiosus*) were combined, as were species belonging to the genus *Leopardus*. The survey generates binary presence–absence data (0/1) at the farm level, from which mammal richness is calculated as the total number of distinct species or species groups reported per farm.

The effectiveness of interview-based approaches for documenting the presence of medium- and large-sized vertebrate species has been previously demonstrated in tropical regions (Camino et al., 2020; Prist et al., 2012). To evaluate the reliability of our data, we compared interview-based estimates of mammal richness with independent records from camera trap surveys on a subsample of 20 farms (Dekegel et al., 2025). Spearman correlation test indicated a significant positive association ($\rho = 0.46$, $p < 0.05$), supporting the robustness of self-reported data as a proxy for field-based biodiversity assessments.

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

4.2.4. Data analysis

Spearman correlation tests are used to assess the relation between shade-tree density and mammal richness and CAFS land productivity, respectively. To perform a trade-off and synergy analysis, we defined binary thresholds for our economic and ecological indicator, which were based on the respective sample medians, allowing us to classify farms in relative terms within our sample (Riera et al., 2023). Using these thresholds, each farm was assigned to one of four quadrants:

i) Quadrant I (Ecological trade-off scenario): Lower mammal richness - Higher productivity
ii) Quadrant II (Synergy scenario): Higher mammal richness - Higher productivity
iii) Quadrant III (Lowest outcome scenario): Lower mammal richness - Lower productivity
iv) Quadrant IV (Economic trade-off scenario): Higher mammal richness - Lower productivity

To assess the determinants of farms' positioning across these four ecological-economic outcome quadrants, we estimate a multinomial probit model in which the probability that farm *i* falls into outcome category *j* is given by:

$$P(Y_i = j \mid X_i) = \mathrm{G}(\beta_0 + \beta_1 + X_i + \cdots + \beta_k X_k), \qquad j = 1, 2, 3, 4$$

where Y_i indicates the quadrant to which farm *i* belongs, conditional on X_i, a vector of explanatory variables, including shade-tree density as the main variable of interest and a set of household- and plot-level control variables[19]. At the household level, we control for the household head's gender, experience, as well as whether the household is located in an agrarian reform settlement. At the plot level, we include the area under CAFS, the use of hybrid or clonal cocoa varieties, the elevation of the CAFS plot, and the distance from the household to the nearest paved road, capturing differences in agroecological suitability and access to infrastructure and markets. Elevation and distance measures were derived by overlaying GPS data collected during the household survey with GIS data, including a Digital Elevation Model (DEM). We report average marginal effects with robust standard errors to account for potential heteroscedasticity.

While the classification of ecological–economic outcomes is based on CAFS-level indicators of biodiversity and land productivity, household-level economic variables are analysed descriptively across these outcome categories to assess how CAFS performance relates to overall household economic performance. Descriptive comparisons of continuous variables are conducted using Wilcoxon rank-sum

[19] We also estimated a multinomial probit model including additional control variables (e.g. market access and institutional factors) and find that the estimated effects of shade-tree density and other covariates remain robust in magnitude, direction, and statistical significance (Table C4, Appendix C).

tests, while binary variables are compared using χ^2 tests or Fisher's exact tests. All analyses are conducted in Stata 18 software (StataCorp, 2023).

4.3. Results

4.3.1. Quantifying shade-tree density, mammal richness and land productivity

Shade tree density varies considerably across the 312 CAFS, ranging from 40 to 600 (±4.50) shade trees ha^{-1} (Table 4.1). The values are consistent with those reported by Schroth et al. (2015) for the region. Farmers report an average mammal richness of 12.3 (±0.24) species per CAFS, with values ranging from 1 to 21 species. The most commonly reported species included the nine-banded armadillo, collared peccary, and Wied's marmoset (>85%; Table C2), reflecting the persistence of medium-sized generalist mammals in cocoa landscapes, while large carnivores such as pumas and jaguarundis are rarely reported (<10%; Table C2), indicating their sensitivity to forest conversion (Ferreira et al., 2025). CAFS land productivity averages 2864 R\$ ha^{-1} (±185.42), but with high variability across the sample, ranging from -4620 to 16809 R\$ ha^{-1}. Spearman's rank correlation test indicates a significant positive correlation between shade tree density and mammal richness (ρ =0.13, $p < 0.05$; Figure 4.2), whereas the correlation between shade tree density and land productivity was negative but not statistically significant (ρ = -0.09, p =0.12; Figure 4.2).

Table 4.1 Descriptive statistics of shade tree density, the main management variable of interest, and of mammal richness and land productivity, which serve as ecological and economic sustainability indicators, respectively, for a sample of 312 cocoa farmers across 12 municipalities in southern Bahia, Brazil.

Variable	Mean	SE	Median	Min	Max
Shade tree density (trees ha^{-1})	193.20	4.50	180.00	40.00	600.00
Mammal richness (n° species)	12.34	0.24	13.00	1.00	21.00
Land productivity (R\$ ha^{-1})	2864.18	185.42	2038.04	-4620.00	16809.29

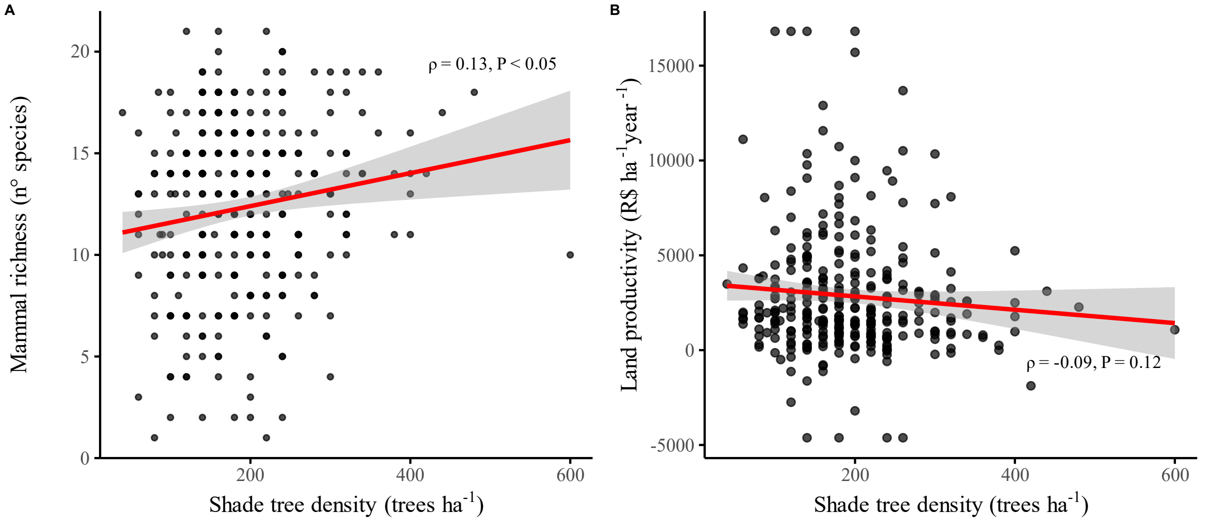

Figure 4.2 Shade tree density (main variable of interest) in relation to (a) mammal species richness (ecological sustainability indicator) and (b) land productivity (economic sustainability indicator) across 312 cocoa farms in 12 municipalities in southern Bahia, Brazil. The Spearman's rank correlation test revealed a significant positive association between shade-tree density and mammal richness ($\rho = 0.13$, $p < 0.05$) and a non-significant negative association between shade-tree density and productivity ($\rho = -0.09$, $p = 0.12$). The colour-coded area represents the 95% confidence interval for the regression line.

4.3.2. Identifying trade-offs and synergies

Farms are classified into four outcome scenarios based on sample medians of both indicators (Figure 4.3). Ecological-economic synergies (QII) are characterised by high mammal richness (15.24 ± 0.19 species) combined with high productivity (4,998 ± 349 R\$ ha^{-1}; Figure 4.4). In contrast, QIII represents the lowest-performing farms, with both low mammal richness (8.54 ± 0.35 species) and low productivity (669.53 ± 154.25 R\$ ha^{-1}). Trade-off scenarios emerge in QI (high productivity, low mammal richness) and QIV (high mammal richness, low productivity). Pairwise Wilcoxon tests confirm that mammal richness is significantly higher in QII and QIV compared to QI and QIII (all $p < 0.001$), while productivity is significantly higher in QI and QII relative to QIII and QIV (all $p < 0.001$; Figure 4.4).

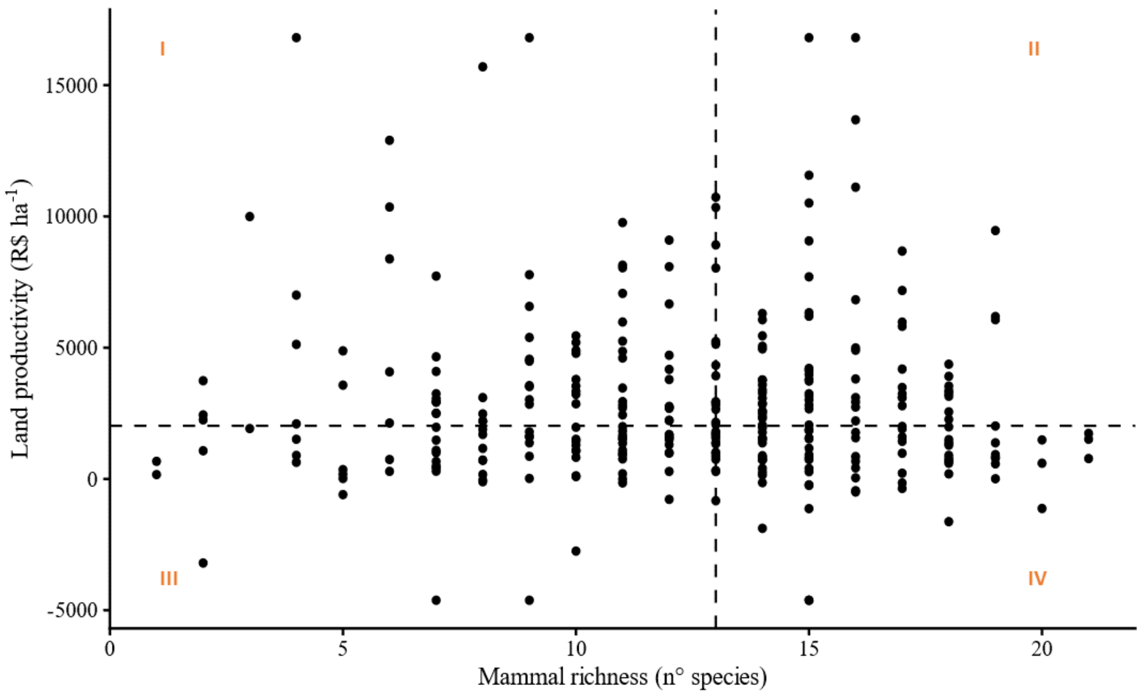

Figure 4.3 Relationship between mammal richness and land productivity of 312 cocoa agroforests in southern Bahia, Brazil. Vertical and horizontal lines represent sample medians, dividing the plot into four quadrants, each representing a distinct outcome: (I) Ecological trade-off scenario- low mammal richness with high productivity; (II) synergy scenario- high mammal richness with high productivity; (III) lowest outcome scenario- low mammal richness with low productivity; and (IV) economic trade-off scenario- high mammal richness with low productivity.

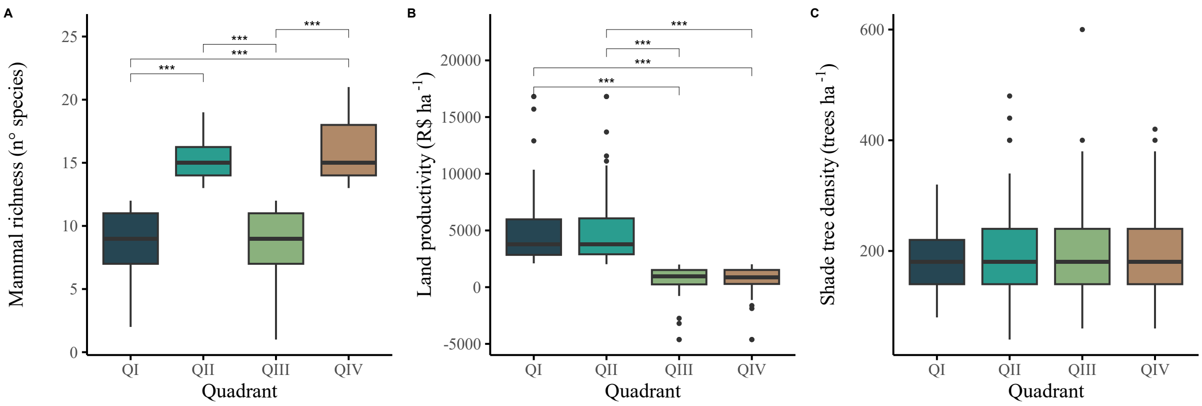

Figure 4.4 Mammal richness, land productivity and shade tree density across quadrants (QI-QIV). Pairwise differences between quadrants were tested using Wilcoxon rank-sum tests with Benjamini-Hochberg correction, with asterisks indicating significance levels (* $p < 0.10$, ** $p < 0.05$, ***$p < 0.01$).

Table 4.2 presents descriptive statistics for land productivity and household-level economic outcome variables across the four ecological-economic quadrants. Farmers in the high productivity quadrants (QI and QII) obtain significantly higher cocoa yields than farmers in QIII and QIV ($p < 0.01$). Average yields are highest in QII (326 kg ha^{-1}), representing a 2.6- to 3-fold increase relative to the low productivity scenario (QIII and QIV), respectively. Farmers in QI also receive significantly higher cocoa prices relative to those in QIII and QIV ($p < 0.10$). Cocoa production costs are significantly higher for farmers in QIV than in QII ($p < 0.10$), while value from non-cocoa crops within CAFS is significantly higher in QII compared to QIV ($p<0.05$). Consequently, farmers in QI and QII earn substantially higher cocoa net income per hectare than those in QIII and QIV ($p < 0.01$). Total household and per capita income are also significantly higher in the high productivity scenarios QI and QII ($p < 0.01$), with farmers in QI reporting the highest mean household and per capita incomes. However, none of these variables are statistically different between QI and QII, indicating that high productivity can co-exist with high mammal richness.

Table 4.2 Descriptive statistics of economic variables across ecological-economic outcomes.

Variable	Q1: Low mammal richness-High productivity		Q2: High mammal richness- High productivity		Q3: Low mammal richness- Low productivity		Q4: High mammal richness- Low productivity							
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Q1-Q2	Q1-Q3	Q1-Q4	Q2-Q3	Q2-Q4	Q3-Q4
Land productivity														
Cocoa yield (kg ha^{-1})	315.97	24.71	326.49	18.00	124.16	10.43	106.83	315.97		***	***	***	***	
Cocoa price (R$ kg^{-1})	16.55	0.38	15.98	0.27	15.29	0.37	15.14	16.55		*	*			
Cocoa production costs (R$ ha^{-1})	1126.53	198.53	1014.91	122.40	1387.25	243.52	1031.72	1126.53					*	
Cocoa net income (R$ ha^{-1})	4543.50	377.65	4561.23	318.74	487.16	170.26	625.72	4543.50		***	***	***	***	
Gross revenue other crops (R$ ha^{-1})	485.53	104.29	427.79	106.22	191.53	66.61	91.23	485.53			**			
Household-level returns														
Household income (R$)	76005.77	13678.09	69879.40	11294.52	49840.03	11597.70	43143.09	76005.77		***	***	***	***	
Per capita income (R$)	32265.04	5971.18	27451.72	3914.42	20589.47	4390.02	14913.08	32265.04		***	***	***	***	

4.3.3. Drivers of economic-ecological outcomes

Table 4.3 reports average marginal effects from the multinomial probit model estimating how shade-tree density and other characteristics are associated with farmers' positioning across ecological-economic outcomes. First, higher shade-tree densities significantly reduce the probability of being in the ecological trade-off scenario QI by 0.1% points ($p < 0.05$), while its effects on the probabilities of the other three scenarios are not statistically significant, indicating that shade-tree density has limited effects (both in magnitude and significance) in driving ecological-economic outcomes. Second, having a woman in charge of cocoa production and marketing in the household decreases the likelihood of being in the synergy scenario QII by 13% points ($p < 0.05$) and increases the likelihood of being in the lowest outcome scenario QIII by 17% points ($p < 0.01$). Moreover, greater farming experience of the household head decreases the probability of being in the lowest outcome scenario QIII ($p < 0.01$) and increases the probability of being in high biodiversity scenarios QII and QIV ($p < 0.05$). Farmers residing in an agrarian reform settlement are less likely to be in the ecological trade-off scenario QI by 9.2% points ($p < 0.10$) and more likely to be in the economic trade-off scenario QIV by 13.3% points ($p < 0.05$), indicating that agrarian reform settlement conditions are associated with high biodiversity but economically constrained outcomes. Similarly, farmers with larger CAFS areas are associated with a lower probability of being in ecological trade-off scenario QI ($p < 0.01$) and a higher probability of being in economic trade-off scenario QIV ($p < 0.01$). In contrast, using hybrid cocoa varieties significantly reduces the probability of being economic trade-off scenario QIV by 12% points ($p < 0.05$). Distance to the nearest paved road and elevation of the CAFS plot do not have statistically significant effects on achieving ecological-economic trade-off and synergies. The results indicate that socio-economic and farm structural characteristics are more strongly associated with farmers' positioning across ecological-economic outcomes than shade-tree density.

Table 4.3 Average marginal effects from the multinomial probit model estimating the probability of ecological-economic outcomes across four quadrants (QI-QIV).

Variable	Q1: Low mammal richness - High productivity	Q2: High mammal richness - High productivity	Q3: Low mammal richness- Low productivity	Q4: High mammal richness- Low productivity
Shade-tree density	-0.001 **	0.000	-0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)
Female HH head	-0.027	-0.126 **	0.165 ***	-0.012
	(0.056)	(0.054)	(0.062)	(0.057)
Experience HH head	0.002	0.005 **	-0.011 ***	0.004 **
	(0.002)	(0.002)	(0.002)	(0.002)
Settlement (dummy)	-0.092 *	-0.021	-0.021	0.133 **
	(0.050)	(0.054)	(0.052)	(0.059)
Distance HH-road	-0.007	0.002	-0.001	0.006
	(0.007)	(0.007)	(0.006)	(0.007)
CAFS size	-0.004 ***	-0.001	0.001	0.003 ***
	(0.001)	(0.001)	(0.001)	(0.001)
Elevation CAFS	-0.000	0.000	-0.000	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)
Cocoa hybrids (dummy)	0.061	0.064	-0.006	-0.119 **
	(0.052)	(0.053)	(0.052)	(0.059)

Note: Reported values are average marginal effects. Robust standard errors are shown in parentheses. **p* < 0.10, ***p* < 0.05, ****p* < 0.01

4.3.4. Perceptions of shade trees in CAFS

Table 4.4 presents perceived difficulties and benefits associated with shade trees in CAFS. Farmers identify both benefits and difficulties, with significant variation across quadrants primarily observed for difficulties. A substantial share of farmers in each quadrant (~27-48%) reports no difficulties associated with shade trees. Farmers in the high-biodiversity quadrants (QII and QIV), however, are significantly more likely to indicate the absence of difficulties compared to those in the low-biodiversity, low-productivity quadrant (QIII; $p < 0.05$ and $p < 0.01$, respectively). Among farmers who did perceive difficulties, the most frequently reported concern is resource competition between shade and cocoa trees, with more than one-third of farmers in all quadrants identifying this as a major constraint. Perceptions of pest and disease pressure are relatively uncommon (< 9%), but are significantly more frequently reported in QI and QIII, whereas no farmers in the synergy quadrant (QII) mention this concern ($p < 0.05$). Reports of physical damage to cocoa trees are also more frequent in QIII (26%), whereas farmers in QII and QIV are significantly less likely to identify this difficulty ($p < 0.05$ and $p < 0.01$, respectively).

With respect to benefits, very few farmers (<7% across all quadrants) indicate that shade trees provide no ecological or economic advantages. Ecological benefits are widely recognised, with shade provision for cocoa (~80-93%) and improvements in soil fertility (~37-54%) most frequently reported. The only significant difference among ecological benefits concerns microclimate regulation, which is generally reported by a small proportion of farmers (<9% in all quadrants) but is mentioned significantly less often in QII than in QIII ($p < 0.1$). Regarding economic benefits, farmers most commonly highlight self-consumption (~27-29%) and the provision of timber and fuelwood (~22-27%). No significant differences across quadrants are observed for any of the economic benefit categories.

Table 4.4 Share of farmers reporting perceived difficulties and benefits associated to shade trees in cocoa agroforestry systems, by quadrant of ecological–economic outcomes. Quadrants are defined by the median split of mammal species richness (ecological outcome) and returns from CAFS (economic outcome). Values represent mean percentages per quadrant.

	Q1: Low mammal richness - High productivity	Q2: High mammal richness -High productivity	Q3: Low mammal richness-Low productivity	Q4: High mammal richness- Low productivity						
Variable	Mean	Mean	Mean	Mean	Q1-Q2	Q1-Q3	Q1-Q4	Q2-Q3	Q2-Q4	Q3-Q4
Difficulty										
No difficulty	32.9	48.2	26.8	47.1				**		**
Ecological										
Physical damage to cocoa	15.1	9.6	26.8	7.1				**		***
Higher disease pressure	8.2	0	8.5	4.7	**			**		
Resource competition	41.1	33.7	46.5	34.1						
Economic										
Lower cocoa yield	19.2	20.5	12.7	25.9						
High pruning workload	2.7	1.2	1.4	0						
Benefit										
No benefit	6.8	6	7	5.9						
Ecological										
Biodiversity preservation	2.7	2.4	4.2	2.4						
Microclimate regulation	4.1	0	8.5	2.4				*		
Pest control	1.4	0	1.4	0						
Soil fertility	42.5	54.2	36.6	47.1						
Water availability	4.1	6	4.2	5.9						
Shade for cocoa trees	86.3	92.8	80.3	91.8						
Economic										
Self-consumption	27.4	28.9	28.2	29.4						
Additional income source	16.4	6	7	5.9						
Medicinal use	2.7	3.6	5.6	9.4						
Timber and fuelwood	21.9	22.9	25.4	27.1						

Note: *$p < 0.10$, **$p < 0.05$, ***$p < 0.01$ for Wilcoxon rank-sum test of continuous variables and chi² test or Fisher's exact test (i.e. when response category had <5 observations) for categorical variables, with Benjamini–Hochberg correction.

4.4. Discussion

Our results demonstrate that CAFS can deliver ecological-economic synergies, yet these outcomes are highly context-dependent. While some farmers achieve higher productivity alongside high mammal richness, others experience clear trade-offs, where gains in one dimension come at the expense of the other. Farms located in the ecological-economic synergy scenario (QII) achieve, on average, a mammal richness of 15.24 (± 0.19) species and economic returns per hectare from CAFS of 4,998 (± 349) R$ ha^{-1} $year^{-1}$. These returns translate into ~85,000 R$ $year^{-1}$ for an average 17 ha farm, corresponding to ~5.4 times the annual Brazilian minimum wage (15,840 R$ $year^{-1}$), demonstrating that biodiversity conservation can be compatible with high land productivity. At the household level, per capita income in the synergy scenario amounts to 27,452 R$ $year^{-1}$, equivalent to ~1.7 times the annual minimum wage, suggesting comparatively favourable income levels within the regional context. Importantly, economic returns per hectare from CAFS and per capita income in the ecological-economic synergy scenario (QII) are comparable to those observed in the ecological trade-off scenario (QI), indicating that higher biodiversity outcomes are not achieved at the expense of income generation from CAFS and overall households' performance. Differences in land productivity across scenarios are primarily driven by variation in cocoa yields. While yields in the synergy scenario (QII; 326 kg ha^{-1}) exceed those reported for traditional shaded systems in southern Bahia (177 ha^{-1}; Chiapetti et al. 2020), they remain below levels observed in the low-shade and full-sun production systems that predominate in West Africa (500-570 kg ha^{-1}; FAOSTAT, 2025). Yet, farmers in low-productivity scenarios (QIII and QIV) obtain even lower yield levels of 107-127 kg ha^{-1} and correspondingly low net cocoa incomes (487–626 R$ ha^{-1}), which are not compensated by higher household-level returns from other (agricultural) activities. As a result, per capita income in these low-productivity scenarios (14,913-20,589 R$) remains well below that observed in the synergy scenario (27,452 ± 3,914 R$). Land productivity in CAFS is thus directly linked to total household income and per capita income, suggesting that lower productivity is not systematically compensated by scale effects or alternative income sources. This underscores the central role of CAFS productivity in shaping overall economic outcomes for cocoa farmers in the region.

Although shade-tree density plays a role in shaping ecological trade-offs, its contribution to generating ecological-economic synergies is limited. This finding is consistent with Blaser et al. (2018), who found that strategic shade-tree management can mitigate trade-offs between biodiversity and cocoa yield. However, achieving ecological-economic synergies depends on additional household and farm-level factors beyond regulating shade-tree densities alone. Greater farming experience significantly reduces the probability of being in the lowest outcome scenario (QIII) and increases the likelihood of attaining high-biodiversity outcomes (QII & QIV). This suggests that accumulated knowledge and acquired practical farming experience play an important role in achieving higher economic and ecological performance in CAFS. Previous studies show that older and more experienced farmers are more likely to adopt agroforestry practices in Cameroon and Ghana (Gyau et al., 2014; Nkamleu and Manyong, 2005), likely because their experience has improved their understanding of the long-term benefits and sustainability of shaded AFS. Likewise, evidence from Indonesia found that agricultural and agroforestry management knowledge is primarily disseminated through farmer-to-farmer learning, informal networks and agricultural extension agents rather than formal education (Martini et al., 2012, 2017; Wartenberg et al., 2018). Moreover, households in which women are responsible for cocoa production and marketing are less likely to achieve synergy outcomes and more likely to be associated with the lowest outcome scenario, pointing to gender-based inequalities in access to asset ownership and economic opportunities (FAO, 2023).

In addition, farmers managing smaller CAFS are less likely to achieve economic-trade-offs (QIV) than ecological trade-offs (QI), supporting the inverse size–productivity relationship whereby smaller farms tend to achieve higher land productivity (Ali and Deininger, 2015; Helfand and Taylor, 2021; Kongor et al., 2018). However, this pattern contrasts with findings of Ricciardi et al. (2021), who show that small-scale farmers often combine higher land productivity with greater biodiversity outcomes, suggesting that farm size alone does not guarantee ecological–economic synergies. At the same time, farmers residing in agrarian reform settlements are more likely to achieve economic trade-offs (QIV) than ecological trade-offs (QI), pointing towards high-biodiversity but economically constrained outcomes. This pattern aligns with evidence that agrarian reform settlements contribute substantially to long-term forest restoration in Brazil (Benzeev et al., 2025) which is beneficial for biodiversity, but also face persistent structural economic constraints, such as limited transport infrastructure, weak market access and integration for agroforestry products and restricted participation in certification schemes (Shennan-Farpón et al., 2022). Overall, these findings demonstrate that ecological–economic trade-offs and synergies in CAFS are primarily associated with broader socio-economic and institutional conditions faced by cocoa farmers.

Differences in farmers' perceptions of the benefits and difficulties of shade trees partly explain the stronger association of shade-tree management with ecological trade-offs relative to ecological-economic synergies. Farmers in our study widely recognize the benefits of maintaining shade trees, highlighting their role in providing shade for cocoa trees (80-93%), improving soil fertility (37-54%), alongside supplying timber and fuelwood (22-27%), and products for self-consumption (27-29%). These findings are consistent with previous studies showing that farmers value shade trees for the protection and microclimate regulation services they provide to cocoa trees as well as for their financial benefits (Brown et al., 2025; Shennan-Farpón et al., 2022; Wartenberg et al., 2018).

However, perceptions of difficulties vary more strongly across ecological-economic scenarios. Farmers in the ecological trade-off and lowest outcome scenarios (QI and QIII) consistently report more perceived difficulties associated with shade trees, in particular regarding pest and disease pressure (8-9%) as well as physical damage to cocoa trees (15-27%). In contrast, farmers in the high-biodiversity scenarios (QII and QIV) are significantly more likely to report no difficulties associated with shade trees, indicating fewer perceived constraints associated with maintaining shade trees. Nevertheless, the most cited difficulty across all scenarios is resource competition (34-47%) and reduced cocoa yields (13-26%), which aligns with earlier evidence that many farmers associate less shaded AFS with higher cocoa yields due to competition for resources (Kaba et al., 2020; Tscharntke et al., 2011b; Wartenberg et al., 2018). Thus, farmers in our study recognize the dual effects of shade trees in CAFS, acknowledging both benefits and constraints. This is consistent with Wartenberg et al. (2018) who report similar perceptions among farmers in Southeast Sulawesi. Yet, these differences in perceptions are not reflected in actual shade-tree density differences across ecological-economic outcomes, suggesting that perceptions are more important drivers of farmers' willingness to maintain or tolerate shade trees. Reducing perceived barriers, particularly those related to lower yield and resource competition, and reinforcing widely recognised benefits could therefore facilitate the conditions under which ecological-economic synergies are achieved and sustained.

This study is subject to several limitations that should be acknowledged. First, while this study provides comprehensive economic indicators of CAFS (including yield, costs and revenues from non-cocoa crops within CAFS), the biodiversity dimension relies on a single indicator, i.e. mammal species richness. Although informative, this indicator does not capture variation in species composition or functional diversity that may also respond to shade-tree removal. Nevertheless, species richness remains a tractable and ecologically meaningful proxy for assessing the biodiversity implications of shade-tree management. Future research should integrate additional biodiversity and ecosystem service indicators to provide a more holistic understanding of the overall sustainability of CAFS. Second, our analysis does not account for landscape-scale characteristics, such as surrounding forest cover, habitat connectivity, or proximity to protected areas, which are known to influence medium- and large-sized mammal persistence in the agricultural landscape of southern Bahia (Ferreira et al., 2025, 2020; Magioli et al., 2021; Teixeira et al., 2024). As a result, part of the observed variation in mammal richness may reflect broader landscape influences rather than farm-level shade-tree management alone, highlighting the need for future interdisciplinary research integrating multi-scale landscape metrics. Third, unobserved heterogeneity related to farmers' intrinsic motivations and non-economic preferences, such as stewardship values or cultural attachment to agroforestry, remain difficult to measure. These factors may influence management decisions and partly explain variation in ecological–economic outcomes. Finally, the cross-sectional nature of our dataset limits our ability to assess temporal dynamics, as it reflects a single agricultural production year (2023). Future research employing panel data would enable a more robust evaluation of causal relationships and interannual variability in both economic and ecological outcomes.

4.5. Conclusion and policy implications

Overall, our findings demonstrate that achieving ecological-economic synergies in CAFS depend on an interplay of ecological, managerial, and socio-economic factors. Shade-tree density contributes to driving ecological trade-offs, but the realization of win–win outcomes is conditioned by farmers' experience, gender inequalities, and broader structural conditions influencing productivity and market participation. Shade-tree management alone cannot guarantee synergies, it must be embedded within broader strategies that enhance farmers' productive capacity, knowledge, and economic incentives. For policy, this implies that sustainability initiatives in cocoa-producing landscapes should move beyond generic shade-tree management strategies and instead promote flexible, context-specific approaches tailored to farmers' socio-economic and institutional realities. Addressing gender inequalities by improving women's access to productive resources and inputs (World Bank, 2012), alongside supporting productivity-enhancing practices compatible with biodiversity conservation within CAFS, remains essential given the central role of cocoa yields in shaping economic outcomes.

Farmers' perceptions of shade trees are central to this approach. Promoting more positive perceptions of shade trees through targeted extension and market incentives may be crucial to fostering ecological-economic synergies and advancing the sustainable development of CAFS. Addressing perceived difficulties while reinforcing the widely acknowledged benefits could support broader adoption of biodiversity-friendly practices. Extension services can play a key role by targeting misconceptions, providing technical support, and promoting practices that reconcile biodiversity conservation with farm-level profitability. Our results also highlight that practical farming experience is strongly associated with ecological-economic synergies, suggesting that interventions focusing solely on formal training or schooling may be insufficient. Policies should instead strengthen farmer-to-farmer knowledge exchange, field-based training, and participatory extension approaches that facilitate peer learning and trust. As emphasized by Piñeiro et al. (2020) the adoption of sustainable practices depends not only on programmes and incentives offered, but also on farmers' economic conditions, environmental preferences and cultural context. Linking programmes to tangible economic benefits, through productivity gains or profitability improvements, is essential for short-term adoption of sustainable agriculture practices. In the long term, one of the strongest motivations for sustained adoption is farmers' perception of positive environmental and farm-level outcomes.

Chapter V

When origin labels fall short: Economic and ecological sustainability of a cocoa Geographical Indication[20]

5.1. Introduction

Geographical Indications (GIs) for agri-food products, which link product quality to geographical origin, are increasingly promoted as instruments for sustainable development, particularly in emerging economies (FAO, 2025). Originally developed within the European Union, a GI is formally defined as a sign used on products that have a specific geographical origin and whose distinctive qualities or reputation are essentially attributable to that origin (FAO, 2025). Unlike third-party or in-house company voluntary sustainability standards (VSS) driven by private actors, GIs are grounded in collective, place-based public governance systems that build on territorial anchoring, active participation of local stakeholders, and the preservation of origin-linked know-how (Vandecandelaere et al., 2020). More than 9,400 products are currently registered under GI protection worldwide (FAO, 2025), with a rapidly increasing number emerging outside Europe (WIPO, 2023). Yet, the extent to which GIs can effectively contribute to sustainable development in emerging economies remains insufficiently understood (Boga, 2025; Cardoso et al., 2022; Neilson et al., 2018; Török et al., 2020).

Despite their growing prominence, empirical evidence from emerging economies remains limited and fragmented. Existing studies generally address only one dimension of sustainability, predominantly focusing on the economic outcomes for which findings are mixed. Evidence from nine worldwide case studies indicates that GIs can enhance price premiums across different product types and regions of origin, regardless of how long the GI has been established (Vandecandelaere et al., 2020). They also improve market access, increasing the share of value captured by primary producers, exert positive long-term effects on production, and strengthen value-chain resilience through market diversification (Vandecandelaere et al., 2020). However, studies focusing on cases in emerging economies often find that such economic benefits are limited or unevenly distributed, constrained by weak institutional

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frameworks, governance challenges, and misalignment with market demands (Cardoso et al., 2022; Neilson et al., 2018). The environmental dimension of GIs remains particularly understudied, with few studies evaluating their environmental implications (Bowen and Zapata, 2009; Caravaggio and Vaquero-Pineiro, 2025; Ingram et al., 2020), even in the European context (Belletti et al., 2015; Falasco et al., 2024; Froehlich and Corchuelo, 2017; Vakoufaris, 2010). These gaps underline the need for interdisciplinary, evidence-based assessments of how GIs influence both economic and environmental dimensions of sustainability in emerging economies, particularly in tropical agricultural systems where they are rapidly expanding.

With this study, we address these key research gaps by evaluating the potential of the recently established *Sul da Bahia* GI for high-quality cocoa produced in traditional shaded cocoa agroforestry systems (CAFS) in southern Bahia, Brazil. This case study provides a unique opportunity to evaluate whether origin-based certification can contribute to both ecological and economic sustainability in tropical small-scale agricultural systems. Five factors make the *Sul da Bahia* GI particularly relevant for such an assessment. First, the global cocoa sector continues to face persistent socio-economic and environmental issues (Boeckx et al., 2020; Kalischek et al., 2023; Renier et al., 2023; Van den Broeck and Akaribo, 2024), which are expected to intensify with rising global demand. Second, despite these challenges, GIs for cocoa remain uncommon worldwide (Hernandez and Granados, 2021), underscoring the importance of assessing early initiatives to inform the design and implementation of future schemes. Third, cocoa has a particularly strong potential for origin-based valorisation, as its sensory and biochemical characteristics are closely tied to geographical origin, offering a strong scientific basis for terroir recognition and traceability (Fanning et al., 2023; Hernandez and Granados, 2021). Fourth, cocoa in southern Bahia is predominantly cultivated under traditional shaded CAFS, which maintain high ecological value while providing livelihoods for small-scale farmers (Cassano et al., 2009). This production model offers a unique context to investigate how market-based instruments such as GIs can simultaneously support rural development and biodiversity conservation. Finally, the *Sul da Bahia* GI extends beyond cocoa bean production to include locally processed bean-to-bar chocolate, exemplifying how origin-based certification can foster local value addition, entrepreneurship, and the retention of economic benefits within producing regions.

Building on these motivations, this study aims to evaluate the potential of the *Sul da Bahia* GI scheme to enhance both ecological and economic sustainability at the farm level and within the broader institutional framework that supports the certification. Specifically, we examine (i) the certification framework, including its requirements, procedures, and costs; (ii) the perceived benefits and challenges experienced by participating farmers; and (iii) differences in land productivity and household-level economic performance as well as ecological outcomes between GI-certified and non-certified farms. We combine detailed household-level economic data and ecological field measurements from CAFS plots of 313 cocoa-farming households, in-depth biodiversity assessments conducted on a subsample of 18 farms, and semi-structured interviews of key GI stakeholders. We apply a propensity score matching approach to compare certified and non-certified farms in terms of economic and ecological outcomes, accounting for observable differences associated with non-random participation in the GI scheme. By simultaneously integrating economic, ecological and institutional dimensions, this study is the first to provide a comprehensive empirical, field-based assessment of a GI scheme for cocoa. It thereby offers novel insights into the role of GI certification in promoting sustainable rural development, biodiversity conservation, and local value addition in tropical CAFS.

5.2. Background

GIs are collective intellectual property rights that identify products whose quality, reputation, or other distinctive characteristics are essentially linked to their geographical origin (Barham, 2003). Recognised internationally under the World Trade Organisation's Agreement on Trade-Related Aspects of Intellectual Property Rights (TRIPS, 1994), GIs formalise the *terroir* concept by providing legal recognition and protection to producers whose traditional practices and local know-how have established reputations for regionally distinctive products (Barham, 2003). Beyond their legal function, GIs pursue a range of economic, social, cultural, and environmental objectives. The principal objective of GIs is to signal verified origin and quality, enhancing consumer trust and willingness to pay for certified products (Deselnicu et al., 2013; Vandecandelaere et al., 2020). Second, they act as instruments of product differentiation by valorising origin-linked attributes, thereby enabling producers to capture higher market value in niche and premium markets (Belletti et al., 2017; Boga, 2025; Vandecandelaere et al., 2020). Third, GIs function as strategies of cultural and economic re-localisation, re-embedding production systems within local territories and countering the homogenising and de-territorialising pressures of globalised agri-food markets (Barham, 2003; Boga et al., 2023). Fourth, they foster collective action and participatory governance, as GI ownership and reputation depend on coordination among producers and local institutions, which tend to be most effective at smaller territorial scales (Belletti et al., 2015; Boga, 2025). Finally, although GIs were not originally designed to target environmental sustainability (European Union, 2012), as environmental requirements are rarely explicit, they may nonetheless contribute indirectly. The participatory development of GI specifications reinforces producers' recognition of the ecological conditions that support product quality, thereby promoting the conservation of local environmental resources (Riccheri et al., 2007).

In practice, however, empirical evidence from emerging economies shows that the ability of Geographical Indications (GIs) to deliver tangible sustainable development outcomes is not always guaranteed and remains highly context dependent. In Latin America, evidence from five GI designations[21] shows that GIs are primarily promoted as tools for export-market access and product differentiation, and producer empowerment. Yet, their effectiveness is constrained by top-down governance, weak market alignment, and low participation of local actors, leaving some schemes largely inactive (Boga, 2025). In Indonesia, GI registration for *Kintamani* and *Flores Arabica* coffee fostered regional pride and cultural identity but yielded little evidence of farm-level price premiums or improved value capture, with benefits unevenly distributed among producers (Neilson et al., 2018). In Cameroon, the *Oku white honey* GI increased producer prices, generated short-term positive livelihood effects and improved international market access (Ingram et al., 2020). However, following the withdrawal of donor support, governance coordination weakened, counterfeit products appeared, and institutional challenges resurfaced, demonstrating that lasting GI benefits depend on strong local governance and sustained institutional support. Moreover, the expected environmental co-benefits, particularly improved conservation of the Kilum-Ijim Forest, were not achieved, as deforestation and land-use pressures persisted. The GI scheme alone failed to incentivise conservation practices due to the absence of explicit environmental criteria within its certification framework (Ingram et al., 2020). Likewise, in Colombia, the *Café de Colombia* GI has not reduced deforestation since its formal recognition. Instead, national forest loss increased by about 0.2 percentage points per year, likely driven by agricultural intensification and land expansion following improved market opportunities. Focusing mainly on quality control, traceability, and branding, the scheme lacked environmental standards and monitoring, limiting its contribution to environmental sustainability (Carvalho and Vieira, 2022). Consequently, the capacity of GIs to support ecological and economic sustainability ultimately hinges on inclusive local governance, strong institutional coordination, and sustained collective action, which are all highly context-dependent.

Although cocoa is one of the world's most traded tropical commodities, GIs in the cocoa sector remain relatively underdeveloped. Even in major producing countries such as Ghana and Côte d'Ivoire, no cocoa GI has yet been officially registered, and the first cocoa GI in Africa was only established recently in São Tomé and Príncipe in 2023 (EUIPO, n.d.). In contrast, Latin America has made greater progress in developing origin-based labels for high-quality cocoa, reflecting its dominance in the fine-flavour segment, which accounts for about 90% of global fine-flavour cocoa exports (ICCO, 2023). The first cocoa GI worldwide was *Cacao Arriba* from Ecuador, registered in 2009 and later recognised by the European Union in 2017 (EUIPO, n.d.). Other countries have registered GIs in recent years, including Peru with *Cacao Amazonas Perú* (recognised by the EU in 2022 (EUIPO, n.d.)), and *Cacao de Caripito* in Venezuela (Navarro, 2022). Brazil has also seen growing interest, with four registered

[21] Boga et al. 2025 evaluates three GI schemes in Perú (Café de Villa Rica, Pisco and Maíz Blanco Gigante de Cusco) and two in Ecuador (Cacao Arriba and Pitahaya de Palora).

cocoa GIs[22] reflecting a regional momentum toward origin-based differentiation, which further illustrates the growing interest in leveraging origin-based differentiation and quality valorisation (DataSebrae, 2025). Yet, most of these schemes are understudied, and empirical evidence on their contribution to sustainable development remains limited.

The *Sul da Bahia* GI represents a recent initiative to valorise high-quality cocoa produced in southern Bahia's traditional AFS (Ferreira, 2017a). Officially recognised as an Indication of Provenance (IP)[23] by the Instituto Nacional da Propriedade Industrial (INPI) in April 2018, it became Brazil's second GI for cocoa (DataSebrae, 2025). The INPI serves as the national authority responsible for establishing registration procedures, as defined by Resolution No. 75/2000 (INPI, 2000). At the federal level, the Ministério da Agricultura, Pecuária e Abastecimento (MAPA) oversees the promotion, supervision, and coordination of agricultural GIs. This institutional framework provides producers with a formal mechanism to protect both product quality and territorial reputation. The *Sul da Bahia* GI emerged from a collective effort involving local producers, cooperatives, and technical institutions, coordinated by the Associação Cacau Sul Bahia (ACSB) (Ferreira, 2017a). Its governance is managed by the Regulatory Council and composed of six representatives from member associations and cooperatives and two technical institutions. It is responsible for administering the GI, controlling certification procedures, maintaining producer registries, and enforcing the Regulation of Use, which defines production standards and quality criteria for the *Sul da Bahia* IP seal. The Centro de Inovação do Cacau (CIC) plays a key technical role in quality analysis and traceability, ensuring compliance with certification requirements. These requirements are detailed in the Regulation of Use, a collectively developed document that specifies production standards, quality parameters, and procedures for obtaining and using the *Sul da Bahia* IP seal.

As an IP, the GI primarily aims to protect the regional reputation and identity of cocoa from southern Bahia, enhance market differentiation, and promote sustainable local development through quality valorisation and collective governance. Beyond its economic and cultural functions, the certification framework also emphasises the ecological dimension, centred on the maintenance and legal recognition of traditional cocoa agroforests (*cabrucas*). The GI explicitly incorporates biodiversity into its territorial identity by adopting the golden-headed lion tamarin (*Leontopithecus chrysomelas*; GHLT) as a flagship species on the GI-branded chocolate, highlighting its commitment to conserving both the species and the shaded agroforestry habitats on which it depends. Collectively, these mechanisms position the *Sul*

[22] These include *Cacau Sul da Bahia* (Bahia), *Cacau de Linhares* (Espírito Santo), *Cacau de Tomé-Açu* (Pará), and *Cacau de Medicilândia* (Pará) (DataSebrae, 2025).

[23] In Brazil, two categories of Geographical Indications are legally recognized under the Industrial Property Law (Law No. 9.279/1996): Indication of Provenance (IP), which identifies a region known for the production, extraction, or manufacturing of a given product, and Denomination of Origin (DO), which applies when the product's qualities or characteristics are essentially linked to its geographical environment, including natural and human factors (INPI, 2000).

da Bahia GI as a territorial development model that integrates environmental stewardship, product quality, and rural inclusion through cooperative governance (Ferreira, 2017a).

5.3. Materials and methods

5.3.1. Research Area

The study was conducted in southern Bahia, one of Brazil's principal cocoa-producing regions. Unlike other leading cocoa-producing countries, Brazil's cocoa production is largely oriented toward the domestic market, reflecting the country's substantial domestic demand for chocolate (Hütz-Adams et al., 2022). Cocoa cultivation in southern Bahia supports more than 69,000 farming households, managing around 429,000 hectares (IBGE, 2025). Production is traditionally practised in shaded AFS known as *cabrucas*, which are unique to the Atlantic Forest biome and account for 78% of cocoa farms in the region (Chiapetti et al., 2020).

Within southern Bahia, the *Sul da Bahia* GI defines a territorial scope of 61460 km², encompassing 83 municipalities between 13°03′–18°21′ S and 38°51′–40°49′ W. This territorial delimitation anchors the GI in the region's biophysical and cultural landscape, reflecting over two centuries of cocoa cultivation traditions and post-harvest practices that define the identity and quality of southern Bahia cocoa (Ferreira, 2017b). For this study, we selected twelve major cocoa-producing municipalities within the GI's territorial boundaries for the household survey (Chiapetti et al., 2020) that overlap with the distribution range of the GHLT, which the GI adopts as a flagship species. Six of these municipalities constitute the core distribution area of the species (Teixeira et al., 2024) and were therefore selected for the biodiversity assessment survey (Figure 5.1).

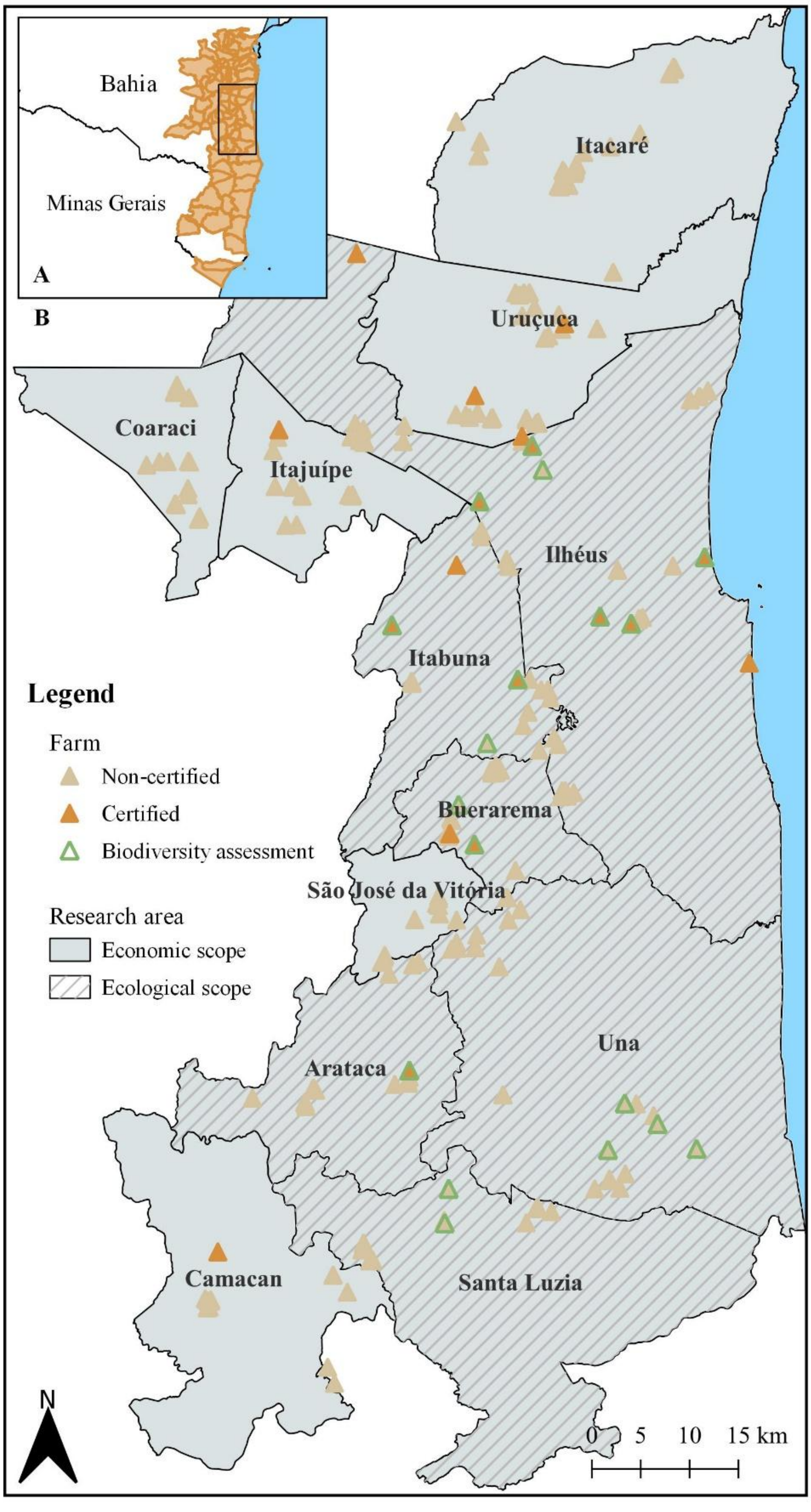

Figure 5.1 Map of the sampled households in Southern Bahia, Brazil. (A) Territorial scope of *Sul da Bahia* GI (orange) in the state of Bahia in Brazil. (B) Location of sampled households across 12 municipalities for the economic survey, including certified (n=18) and non-certified (n=295) farms. The ecological survey was conducted in a subset of six of these municipalities corresponding to the core distribution range of the golden-headed lion tamarin.

5.3.2. Data collection

5.3.2.1. Household survey

A farm-household survey was implemented between February and March 2024 among 314 cocoa producers located across southern Bahia, Brazil, of which 313 were retained for the analysis following data cleaning[24] (Figure 5.1). The sampling design followed a two-stage random sampling strategy to ensure spatial representativeness and capture the diversity of CAFS in the region. In the first stage, twelve municipalities were purposively selected based on their importance within the regional cocoa supply chain (Chiapetti et al., 2020) and the presence of farms participating in the *Sul da Bahia* GI scheme. For each municipality, we compiled a comprehensive sampling frame by integrating multiple data sources, including the most recent regional cocoa census (Chiapetti et al., 2020), the database of registered producers under the *Sul da Bahia* GI, and membership lists from cooperatives, producer associations, communities, and agrarian reform settlements. In the second stage, between 15 and 36 farmers were randomly selected per municipality, proportionate regional distribution of cocoa farmers (Chiapetti et al., 2020), with oversampling of GI-farmers.

Data were collected through face-to-face interviews conducted by a trained team of 6 local enumerators. The respondent was the household member responsible for day-to-day management decisions related to cocoa production. A quantitative structured questionnaire was used, covering modules on household demographics, cocoa production and marketing, cocoa management practices, certification, external input use, and income sources from non-cocoa crops, other agricultural and non-agricultural activities. In addition, one module captured farmers' reports of medium- and large-sized mammal species observed within CAFS plots during the 12 months preceding the survey, following the Wildlife–Human Survey protocol (Islas et al., 2022) which is well-suited for generating reliable data on mammal occurrence at large scales/large sample size, making it particularly valuable for interdisciplinary research and in contexts where standard field-based survey methods, such as camera trapping or line transects, are logistically or financially unfeasible (Islas et al., 2022).

Following each interview, the enumerators visited the household's nearest CAFS plot to collect field-level data. Within each plot, shade-tree density was measured in a single randomly positioned 25x20 m (500 m²) vegetation plot, located at least 100m from the cocoa plot boundary. All woody trees species with a diameter at breast height (DBH) ≥ 10.0 cm, including both native and exotic species, were identified and classified as shade trees within the plot. GPS coordinates were recorded at both the household and plot locations, allowing integration of survey data with spatial information on land cover

[24] One farmer was excluded because the production system was identified as a cocoa-rubber plantation without native shade trees, which does not qualify as *cabruca* under Bahia's legal requirement of at least 20 native shade trees per hectare (State Decree No. 15180/2014, Seção IV, Art. 15).

and topography. Together, the household survey provides economic indicators and ecological indicators at CAFS-level for the sample of 313 cocoa farms, including 18 GI-certified farmers.

5.3.2.2. Ecological survey

Ecological data collection was conducted from January to October 2023 in a purposively selected subsample of 18 CAFS farms located in six municipalities in the core GHLT area. The ecological sample size was determined by the limited number of GI-certified farms present in this area during the study period, combined with the high logistical demands of repeated biodiversity surveys. The final sample comprised nine GI-certified and nine non-certified CAFS farms. Sampling sites were at least 2.5 km apart and sampling design followed Almeida-Rocha et al. (2020).

Playback surveys were conducted to detect the presence of GHLTs across certified and non-certified farms. This method involves broadcasting species' long-call vocalisation to elicit territorial responses and is widely used for GHLT detection (Almeida-Rocha et al., 2020; Pinto and Rylands, 1997; Raboy et al., 2010; Teixeira et al., 2024; Kierulff and Rylands, 2003) and other primates (Gestich et al., 2017; Hilário et al., 2022). A 200 x 200 m grid was overlaid on satellite imagery of each CAFS using QGIS 3.22.5 (QGIS Development Team, 2022). Playback points were placed at grid intersections, 200 m apart, to avoid overlap within the species' auditory range (~100 m) and to detect the same group more than once on the same day (Kierulff and Rylands, 2003). Between three and ten points were surveyed per farm, proportional to farm size (de Almeida et al., 2022), covering a 100 m buffer from the agroforest edge. At each point, long-calls from an adult male and female were broadcast in four cardinal directions using a JBL Charge 5 speaker (frequency response: 60 Hz–20 kHz), followed by a four-minute listening period. The sequence was repeated three times (~15 min total). When GHLTs were detected, observers recorded location, time, and group composition (adults, juveniles, infants) to prevent double-counting of groups on the same survey day. Each farm was visited three times on non-consecutive days, with at least one week between visits, following standard detection protocols (Almeida-Rocha et al., 2020; Teixeira et al., 2024). Surveys were suspended during rainy or windy conditions. Farms without detections after three visits were classified as absent for GHLTs (Dekegel et al., 2025).

Camera traps were used to detect the terrestrial medium- and large-sized mammals (>500 g) in certified and non-certified farms. This non-invasive method effectively surveys mammal communities, recording multiple species with minimal disturbance (Bruce et al., 2018; Etana et al., 2021; Lhoest et al., 2020; Wearn and Glover-Kapfer, 2017). Camera traps (Browning Spec Ops Elite HP5) were installed at grid intersections spaced 400 m apart (Almeida-Rocha et al., 2020; Espartosa et al., 2011; Etana et al., 2024, 2021). The number of camera traps per farm ranged from 1 to 5, proportional to farm size. Each camera was fixed to a tree trunk at 20–50 cm above ground. Cameras operated continuously (24h), capturing at least five rapid-fire images per trigger with a one-second delay between triggers. Cameras remained in the field for a one-month period, depending on field conditions. Independent detection events were defined as consecutive photos of the same species separated by more than 60 minutes (Bruce et al., 2018; Tobler et al., 2008) across all cameras within the same farm. Sampling effort was expressed in camera-trap days (number of operational days per camera). Mammal detection rates were standardised as the number of independent detections per 100 effective camera-trap days (Etana et al., 2024, 2021).

Vegetation surveys were carried out in each CAFS to assess structural and compositional vegetation characteristics relevant to GHLT and terrestrial large- and medium-sized mammals. Plots of 500m² (20mx25m) were established at 400m intervals in each CAFS. Within each plot, all shade trees with a diameter at breast height (DBH) of ≥ 10.0 cm were recorded to assess shade tree richness and diversity. Shade trees were identified *in situ* to the lowest possible taxonomic level by experienced local field assistants. Among these, native species known to be used by *L. chrysomelas* for feeding and sleeping were identified based on published records (Catenacci et al., 2016, 2009; Oliveira et al., 2010, 2011; Raboy and Dietz, 2004; Couto et al., 2019) as well as jackfruit (*Artocarpus heterophyllus*), an exotic species of particular importance in the species' diet in CAFS (Oliveira et al., 2011). Other shade tree features relevant for *L. chrysomelas* were identified: i) DBH of shade trees, ii) presence of bromeliads on shade trees; iii) canopy connectivity, defined by the number of crown connections with adjacent shade trees. The number of cocoa trees within each plot was also counted. Landscape context was characterised by the percentage of surrounding forest cover within a 2 km radius buffer from the CAFS centroid was used, a spatial scale previously shown to influence medium- and large-sized mammals in the region (Faria et al., 2023; Ferreira et al., 2020). Forest cover data were obtained from MapBiomas Cacau (MapBiomas, 2024), whose classification approach has been validated in a peer-reviewed study (Souza et al., 2020).

5.3.2.3. Semi-structured interviews

To complement the quantitative survey data and provide contextual insights into the functioning of the *Sul da Bahia* GI, semi-structured interviews were conducted during 2022-2024 with key stakeholders involved in the scheme's governance, implementation, and participation. The interview sample comprised the Executive Director of the *Sul da Bahia* GI and the presidents of farmers' cooperatives represented in the household survey. The interviews sought to capture stakeholders' perspectives on the institutional functioning of the GI, the certification process, the benefits and challenges faced by participating cooperatives, and the perceived effects on market access. Qualitative insights were used to contextualise and support the interpretation of field observations and quantitative results. Additionally, the study obtained access to the official *Sul da Bahia* GI database, which includes records of all farmers who participated at least once since 2019, as well as annual data on certified cocoa volumes (2019-2024) and GI-branded chocolate sales (2021-2024). These secondary data were used to identify participating farmers and to assess the temporal evolution of the certification scheme.

5.3.3. Data analysis

5.3.3.1. Economic outcomes

We use eight economic outcome indicators derived from the household survey to assess differences in land productivity and household-level economic performance between certified and non-certified farmers: i) cocoa yield; ii) cocoa price; iii) cocoa production costs; iv) net cocoa income; v) gross revenue of non-cocoa crops cultivated within CAFS; vi) returns from CAFS; vii) household income; viii) per capita income. All values pertain to the 12 months preceding the survey (i.e. corresponding to the 2023 production year). The area under CAFS was recorded using the farmer's preferred unit of measurement (hectares, acres, or tarefas) and subsequently standardised to hectares. To reduce the influence of outlying observations, outcome variables were trimmed at the 1% values (Bemelmans et al., 2025).

Cocoa yield is defined as the total quantity of dried cocoa beans harvested from the CAFS area expressed in kilograms per hectare. Farmers reported their harvest quantities in units of kilogram, arrobas, or the number of cocoa bags, with standardised bag weights recorded. Cocoa price represents the average farmgate price that the farmer received per kilogram of dried cocoa beans sold over the past 12 months, expressed in BRL per kilogram. 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. Capital depreciation costs are negligible and therefore excluded from calculations. Net cocoa income is calculated as the difference between gross revenue from cocoa revenue and cocoa production costs, expressed in BRL per hectare of CAFS area. Gross revenue from cocoa sales was estimated by multiplying the reported cocoa yield by the average farmgate price that the farmer received over the past 12 months, or by using the self-reported estimation from the farmer directly. 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 (i.e. chocolate, nibs, and cocoa honey) when applicable. 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 identified all non-cocoa products harvested from both tree species and intercrops present in their CAFS, quantities harvested, and whether products were 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. Returns to land from CAFS is defined as the sum of net cocoa income and gross revenue of non-cocoa crops within CAFS, expressed in BRL per hectare of CAFS area. Total household income represents the total net income of the household, expressed in BRL. It includes total returns from CAFS, calculated by multiplying the returns to land from CAFS by the total CAFS area managed by the household, as well as the total net revenues from livestock rearing, crop production outside the CAFS, off-farm employment and non-labour income sources such as pensions, remittances, or social transfers. Per capita income is calculated by dividing total household income by household size.

5.3.3.2. Ecological outcomes

To assess differences in ecological performance between certified and non-certified farmers, we use ecological data collected through both the household survey (n = 313) and the ecological survey (n=18) as these two data sources provide complementary ecological information.

From the household survey, we calculate five ecological outcome indicators: i) shade-tree density; ii) the share of native shade trees; iii) farmer-reported total mammal richness; iv) farmer-reported insensitive mammal species richness; and v) farmer-reported sensitive mammal species richness. Insensitive and sensitive mammal species richness (iv–v) represent number of species classified respectively as insensitive or sensitive to forest conversion into CAFS as proposed by Ferreira et al. (2025).

From the ecological survey, we calculate five biodiversity outcome indicators to assess differences in ecological performance between certified and non-certified farmers: i) GHLT presence; ii) GHLT group density; iii) total mammal detections; iv) insensitive mammal species detections; and v) sensitive mammal species detections. To characterise structural and compositional differences in vegetation between certified and non-certified CAFS, we also calculate the following indicators: i) shade tree richness; ii) shade tree diversity (Hill-Simpson); iii) shade tree diversity (Hill-Shannon); iv) DBH of shade trees; v) basal area; vi) cocoa tree density; vii) canopy connectivity; viii) bromeliad abundance; ix) Importance Value Index (IVI) of key tree species for GHLT, x) IVI of jackfruit, and xi) forest cover.

GHLT presence represents the farm-level occurrence of golden-headed lion tamarins based on playback survey detection histories across three independent visits per farm, expressed as the proportion of visits with detections (%). GHLT group density is defined as the number of independent GHLT groups detected per square kilometre. Group density was calculated by dividing the total number of independent groups recorded per farm by the effective surveyed area, following Almeida-Rocha et al. (2020) and Ruiz-Miranda et al. (2019), and expressed as groups km^{-2}. Total mammal detection represents the total number of independent mammal detections per 100 effective camera-trap days at the farm level (Etana et al., 2021, 2024). Insensitive and sensitive mammal species detections (iv–v) represent detection rates of species classified respectively as insensitive or sensitive to forest conversion into CAFS, following Ferreira et al. (2025). Detection rates were standardised as the total number of independent detections per 100 effective camera-trap days at the farm level, excluding domestic species. Vegetation variables were first measured at the plot level, and median values were subsequently computed for each variable to obtain farm-level estimates for each CAFS. The IVI was used to quantify the contribution of individual tree species to the shade tree community composition (Curtis and McIntosh, 1951). IVI of GHLT key trees (ix) and IVI of jackfruit (x) were each computed as single composite indices per CAFS, integrating relative frequency, density, and dominance (through basal area). Higher IVI values represent greater dominance of key tree species or the jackfruit tree, respectively, within CAFS (Tesfay et al., 2022).

5.3.3.3. Descriptive analysis

Descriptive statistics are used to characterise producer, farm, and cocoa production characteristics, as well as economic and ecological outcome indicators, for the full sample of 313 households, and for certified and non-certified farms. Continuous variables are compared using Wilcoxon rank-sum tests, while binary variables are compared using χ^2 tests or Fisher's exact tests. These descriptive comparisons provide an initial overview of differences between certified and non-certified farms, but do not account for potential selection bias arising from non-random participation in GI certification.

5.3.3.4. Propensity Score Matching

Participation in GI certification is potentially subject to selection bias, as farmers who already meet cocoa quality requirements have stronger incentives to self-select into the certification scheme or to be selected by the certifier. As a result, certified and non-certified farms may differ systematically in their characteristics even prior to certification. To account for non-random participation in certification, we apply a propensity score matching (PSM) approach to compare certified and non-certified farms in the household survey (n = 313) with similar observable characteristics. Certification effects are evaluated by estimating the average treatment effect on the treated (ATET). Propensity scores are estimated using a probit model, reflecting the probability of GI certification conditional on a set of pre-treatment covariates that determine selection into certification, while not being influenced by (anticipated effects of) certification itself (Caliendo and Kopeinig, 2008). Covariates were selected based on institutional knowledge of the GI certification process and pre-certification determinants of participation. These include: (i) years of experience in cocoa production of the household head, capturing farming experience, managerial capacity, and accumulated knowledge relevant for meeting cocoa quality requirements for certification; (ii) the number of cocoa fermentation days, reflecting post-harvest quality practices that constitute a primary criterion for GI certification; (iii) distance to the GI headquarters, capturing market access and accessibility to certification-related services; and (iv) CAFS size, reflecting cocoa production potential and resource endowments. Certified and non-certified farms are matched using nearest-neighbour matching with replacement. One-to-one (1:1) nearest-neighbour matching constitutes the main specification, while one-to-two (1:2) matching is implemented as a robustness check. All estimates are restricted to the region of common support. Covariate balance is assessed using standardized mean differences (SMD) and variance ratios (VR) (Appendix D, Table D1), with balance considered satisfactory for an SMD below 0.1 and a variance ratio between 0.5 and 2 (Stuart 2010; Zhang et al. 2019). Relative to the unmatched sample, nearest-neighbour matching substantially improves covariate balance, as reflected in markedly reduced standardized mean differences and variance ratios. Improved overlap between certified and non-certified farms is further confirmed by visual inspection of the propensity score distributions (Appendix D, Figure D1).

Propensity score matching is implemented using Stata's *teffects psmatch* command, which provides Abadie-Imbens robust standard errors that account for the estimation of the propensity score and matching with replacement. In the full household survey sample (n = 313), all 18 certified farms are retained within the region of common support. For 1:1 nearest-neighbour matching, 18 non-certified farms are used as matched controls, while under 1:2 matching 22 non-certified farms contribute to the matched comparison group.

To assess the robustness of the results, we additionally apply genetic matching, which combines propensity score and Mahalanobis distance matching and uses machine learning algorithms to iteratively optimize covariate balance (Diamond and Sekhon, 2013). Genetic matching is implemented using the *MatchIt* package in R (Ho et al., 2011), employing both 1:1 and 1:2 nearest-neighbour matching with replacement (Appendix D, Table D3).

While PSM is applied to estimate certification effects on economic outcomes and ecological indicators available for the full household sample (n=313), it is not applied to the subsample (n = 18) used for the ecological survey. In this subsample, limited sample size and insufficient covariate overlap preclude reliable propensity score estimation, as indicated by poor balance diagnostics and propensity score distributions. Ecological outcomes for this subsample are therefore only analysed descriptively.

5.4. Results

5.4.1. Certification framework

5.4.1.1. Certification requirements

The *IP Sul da Bahia* GI establishes a comprehensive certification framework that integrates ecological, economic and social requirements for cocoa production. The ecological component of the certification framework requires cocoa to be cultivated within AFS, in which cocoa remains the principal crop. Eligible agroforestry production systems include the traditional *Cacau Cabruca* and other AFS such as cocoa intercropped with Erythrina or rubber trees. To qualify for certification, farmers must maintain at least 50% of their total cocoa production area under the *Cabruca* system and ensure that cocoa occupies at least 30% of the total productive area[25]. The environmental classification of *cabruca* systems must follow the Bahia's Forest Decree No. 15.180, which establishes a minimum native shade tree density of 20 trees ha^{-1} (Ferreira, 2017a). Beyond compliance with these legal standards, the *Sul da Bahia* GI imposes no additional environmental criteria.

The economic component defines strict standards for cocoa bean quality and traceability. Only non-transgenic varieties of *Theobroma cacao L.* are permitted, including traditional *Forastero* and *Trinitario* types and hybrid varieties. Cocoa beans of each lot must meet the minimum physical and chemical (pH) quality standards defined in the *Regulation of Use*, requiring at least 65% fully fermented beans, a maximum of 15% partially fermented beans, and no more than 8% moisture. Cocoa lots must have a natural aroma free from foreign odours and impurities, with defective beans limited to 3% mouldy, germinated, or insect-damaged beans, and a maximum of 1% slaty beans per lot. Quality evaluation is conducted by accredited technicians from CIC, based on a cut test of 300 beans (Ferreira, 2017c). Only cocoa lots that comply with these standards receive the official *Sul da Bahia* GI seal and may be stored in approved cooperative warehouses and marketed in standardised, traceable packaging bearing the GI logo and QR code with the producer's identification. To achieve those quality standards, producers are advised to follow standardised post-harvest procedures, including a fermentation period of five to seven days, drying for 5 to 15 days, and storage in clean, well-ventilated, smoke-free facilities. Each production lot must be clearly identified, kept separate from conventional cocoa, and fully traceable throughout the process. This process has a direct influence on cocoa bean quality, extending the total post-harvest duration to approximately 15-20 days. By contrast, conventional processing is typically completed within 2-4 days, often involving incomplete or omitted fermentation, rapid drying and the mixing of beans across lots without traceability controls (Ferreira, 2017b).

[25] Exceptions are permitted for producers cultivating cocoa with Erythrina or rubber trees only if the property has a registered Legal Reserve and regularized Permanent Preservation Areas (APPs) in compliance with Brazilian environmental law. Family farmers holding PRONAF eligibility may also qualify for certification if their cocoa is cultivated in agroforestry or diversified polycultural systems, ensuring their inclusion in value-added markets.

The social component defines that certified producers must also comply with national labour legislation, including the absence of child labour, school attendance for household children, and adequate working conditions (Executive Director, *Sul da Bahia* GI, personal communication, 2025). The certification scheme also actively supports collaboration with local cooperatives, which receive assistance to strengthen production systems, improve technical capacity, and enhance market access. Interviews with presidents of the farmers' cooperatives confirmed that *Sul da Bahia* GI assists cooperatives representing agrarian reform families in organizing operations, preparing and validating project proposals, and accessing financial support, particularly through state-led development programs co-financed by the World Bank (World Bank, 2025), for equipment acquisition, training activities in agricultural and post-harvest practices and the costs of three quality analyses per producer. These initiatives have recently enabled three small-scale farmers from agrarian reform settlements to obtain certification in 2024 (of which two were included in this study).

5.4.1.2. Certification procedure and costs

According to the Executive Director of the *Sul da Bahia* GI (personal communication, 2025), the certification process begins with the producer submitting a cocoa sample to CIC in Ilhéus for physical and chemical quality analysis. Producers can submit samples individually or through cooperatives. If the sample meets the GI's physical and chemical quality standards, CIC communicates the results to the producer or cooperative, who must then contact the GI to initiate certification. Following the application, a GI technician conducts an on-site inspection to register the farm in the certification database and perform a second quality verification (cut test) to confirm compliance with GI standards. Upon approval, the cocoa is certified on-site, sealed in official GI sacks, and labelled with a QR code containing detailed traceability information. A verification sample is simultaneously sent to the CIC laboratory for confirmation. Certification requires a minimum batch size of two sacks (~60 kg), and the GI technician provides all necessary materials during the visit. The entire certification process, from initial sampling to the sealing of certified cocoa, can be completed within approximately five days. Once certified, producers are free to sell their cocoa to buyers of their choice. Follow-up inspections occur only upon submission of new certification requests, as no fixed annual inspections are required (Executive Director, *Sul da Bahia* GI, personal communication, 2025).

Producers participating in the *Sul da Bahia* GI certification bear specific costs associated with the certification process. The initial quality analysis conducted by CIC costs 17.20 USD[26] per batch (up to 500 kg). If the technician must travel more than 100 km from the GI headquarters, an additional fuel surcharge applies. Certified cocoa must be packed in official GI bags, priced at 1.30 USD each. The

[26] Based on the exchange rate at time of interview (April 2025), 1 BRL = 0.172 USD (World Bank, 2025)

second analysis, performed by the GI for verification, is financed by CIC. However, if discrepancies arise between the first and second analyses, a third test is required, for which the producer must provide a new sample and cover the associated cost. Under the state-led development programs co-financed by the World Bank, the cost of three quality analyses per cooperative member has been covered to facilitate producer participation in the certification process (M. Anunciação, cooperative leader, personal communication, 2025). Outside such initiatives, however, producers bear all certification-related costs themselves (Executive Director, *Sul da Bahia* GI, personal communication, 2025).

5.4.1.3. Processing and marketing of GI-certified cocoa and chocolate

The *Sul da Bahia* GI plays a facilitative rather than a commercial role in cocoa marketing. Beyond certification, it connects farmers with potential buyers and promotes the regional identity of *Sul da Bahia* cocoa through networking and market promotion activities. The scheme operates in close collaboration with CIC, which conducts both physical and sensory quality assessments and purchases certified cocoa directly from farmers for the production of GI-branded chocolate. Sensory evaluation is the decisive criterion for purchase, ensuring that only cocoa with the required quality and flavour profile is used in chocolate production. Although production has increased, marketing remains constrained by the absence of formal contracts and a defined commercial strategy, with chocolate sold mainly to small resellers through informal arrangements. No direct government support is provided for chocolate production, although CIC receives institutional assistance from the Instituto Arapyaú.

Bean-to-bar chocolate makers constitute the main market outlets for GI-certified cocoa, with the GI currently facilitating connections with about five small-scale producers. Buyers in this niche segment value the certification for its guarantee of traceability and consistent quality across all cocoa lots, complementing CIC's assessments, which attest only to the quality of specific cocoa samples. However, market relevance remains limited, as larger premium buyers such as Dengo Chocolates[27] rely solely on CIC's quality evaluation and do not require GI certification. The *Sul da Bahia* GI nonetheless plays an important initial role in establishing commercial links, providing assurance of origin and quality that helps farmers build credibility with speciality buyers and access differentiated markets. Over time, once trust-based relationships are established, some transactions continue without the formal use of the seal. Other sustainability certifications, such as Fairtrade or UTZ-RA, are largely absent in the region and are not directly compatible with the GI framework, which emphasises territorial origin and product quality rather than compliance with social or environmental standards. Overall, marketing of GI-certified cocoa

[27] Dengo Chocolates is one of Brazil's leading bean-to-bar and sustainability-oriented chocolate companies. It sources high-quality cocoa cultivated in *cabruca* agroforestry systems from small and medium producers in southern Bahia, offering price premiums of up to 85% above market levels and providing technical support to promote sustainable production practices. The company integrates social and environmental sustainability into its business model and has established a strong national retail presence (Fern, 2025).

remains small in scale, relying on a limited network of artisan buyers and the promotional activities of the GI and CIC. The certification adds value primarily through traceability, product differentiation, and symbolic recognition of origin.

5.4.2. Evolution of GI-certified cocoa and chocolate

The *Sul da Bahia* GI for high-quality cocoa has experienced fluctuating growth since its implementation in April 2018. Between 2019 and 2021, the volume of certified cocoa increased more than twofold, from 28.2 to 60.2 tons (Figure 5.2), reflecting the initial uptake of certification in the region. After this initial expansion, certified volumes declined to 55.6 tons in 2022, 22.5 tons in 2023, and only 3.4 tons in 2024 (Figure 5.2). The sharp decline in certified volumes after 2022 can be linked to evolving market dynamics. In 2024, international cocoa prices reached their highest levels ever recorded, averaging 7.40 USD ton^{-1}, more than threefold the average cocoa price observed between 2019 and 2022 (Figure 5.2). Before the price surge, farmers received a premium of 60–70% for GI-certified cocoa relative to conventional cocoa. By April 2025, however, this premium had declined to around 25–30%, as conventional cocoa prices increased sharply on the domestic market. These estimates were reported by the Executive Director of the *Sul da Bahia* GI and by cooperative leader M. Anunciação (personal communications, 2025). The convergence of conventional and certified cocoa prices during this period substantially reduced the added value of GI certification.

At least 43 registered producers provided certified cocoa between 2019-2024. The actual number of participating individual producers is likely much higher, as farmers within a cooperative or agrarian reform settlement can pool their small production volumes to reach the minimum quantities required for certification (i.e., 60 kg). This system enables small-scale farmers who produce limited amounts of high-quality cocoa to access GI certification and speciality markets through cooperative commercialisation. While such collective arrangements facilitate participation and promote inclusion of small-scale producers, they also limit full traceability at the individual farmer level within cooperatives or settlements.

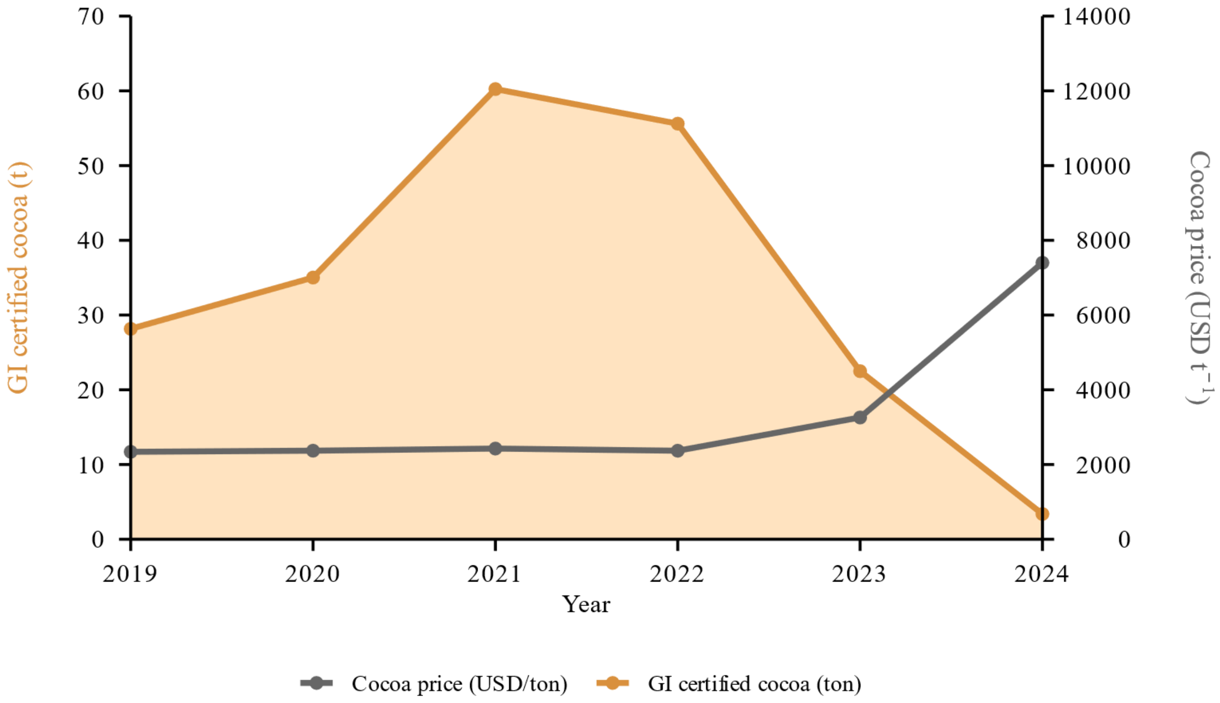

Figure 5.2 Evolution of cocoa certified under the *Sul da Bahia* scheme and international cocoa price between 2019 and 2024. Annual volume of GI-certified cocoa (t) is shown on the left y-axis, and average international cocoa price (US$ t^{-1}) on the right y-axis. Data sources: *Sul da Bahia* GI (Personal communication) and ICCO (2025) for international cocoa prices.

In parallel, the commercialisation of *Sul da Bahia* GI-certified chocolate has grown steadily since its market launch in 2021, reaching a total of 5.15 tonnes sold between 2021 and 2024. Annual sales volumes increased from 1109 kg in 2021 to 1248 kg in 2022, 1355 kg in 2023, and 1442 kg in 2024 (Figure 5.3). This represents a 30% increase in the volume of certified chocolate commercialised over the 2021-2024 period, reflecting the gradual strengthening of downstream value-added activities under the GI scheme.

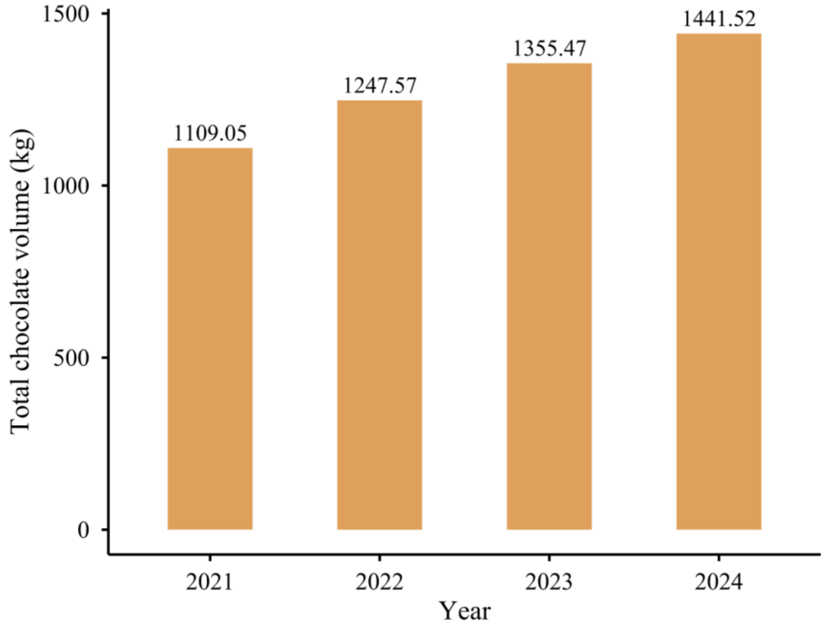

Figure 5.3 Evolution of GI-certified chocolate commercialisation between 2021 and 2024. Annual volume of *Sul da Bahia* GI-certified chocolate sold (kg).

5.4.3. Awareness and perception of the *Sul da Bahia* GI

Awareness of the *Sul da Bahia* Geographical Indication (GI) among cocoa farmers in the study region remains limited. Out of 313 surveyed farmers, only 27% (n = 85) reported having heard of the GI (Figure 5.4). Awareness levels varied considerably across municipalities, ranging from 5% in Coaraci to 44% in Ilhéus and Arataca. The highest awareness was recorded in Ilhéus, where the GI headquarters and the CIC are located, and in municipalities where certified farmers and cooperatives involved in GI certification are located.

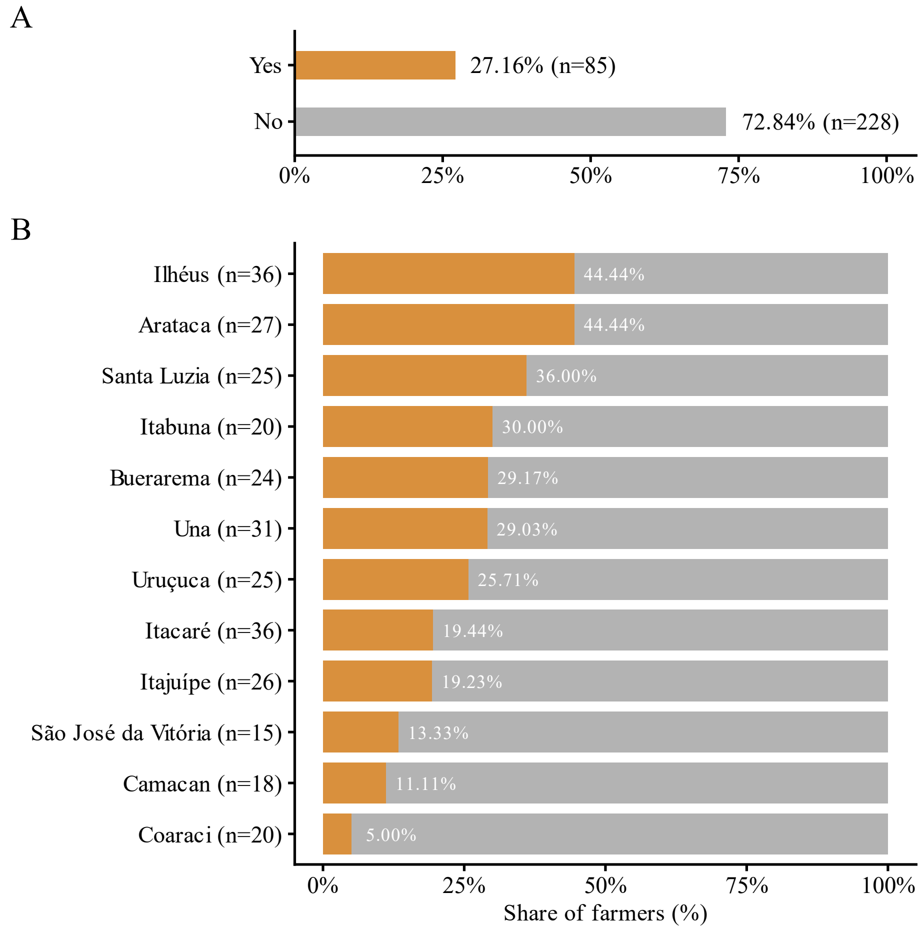

Figure 5.4 Awareness of the *Sul da Bahia* Geographical Indication (GI) among cocoa farmers in the study region. (A) Overall share of surveyed farmers who reported awareness of the GI (n = 313). (B) Share of farmers aware of the GI across 12 municipalities.

Among farmers who had certified their cocoa under the *Sul da Bahia* GI scheme since 2019[28], a small share (13%) reported experiencing no tangible benefit, while the remainder identified advantages that were primarily economic and market-related (Figure 5.5). More than half (56%) identified improved commercialisation as the main benefit of certification, referring to stronger product image, improved reputation, and better commercialisation opportunities. Other frequently mentioned benefits included higher selling prices (44%) and recognition of the region's cultural identity, particularly related to the long tradition of producing cocoa within traditional CAFS (44%). Additional perceived benefits included guaranteed market access (25%), improved traceability and transparency (19%), and low

[28] Two certified farmers were excluded from the analysis of perceived benefits and challenges of associated to GI participation because they did not recall their prior participation at the time of interview.

certification costs (13%). Several farmers also emphasised that GI certification initially facilitated entry into high-value niche markets by fostering trust with buyers, although this trust often persisted independently of continued certification once relationships had been established.

Regarding challenges, 13% of respondents reported no difficulties related to GI certification. Among those who did report difficulties and reasons to discontinue participation, they were mainly related to market access and certification costs (Figure 5.5). The most frequently cited issue was the low demand for GI-certified cocoa (63%). Several producers reported that, due to limited market outlets, they were forced to sell their high-quality certified cocoa through conventional channels, receiving lower prices despite the additional effort and time invested in meeting certification standards. Other commonly reported challenges included high certification costs (25%) and lengthy certification procedure (25%). Other difficulties included the minimum cocoa volume required for certification (13%), limited technical support (13%), and administrative burdens (13%).

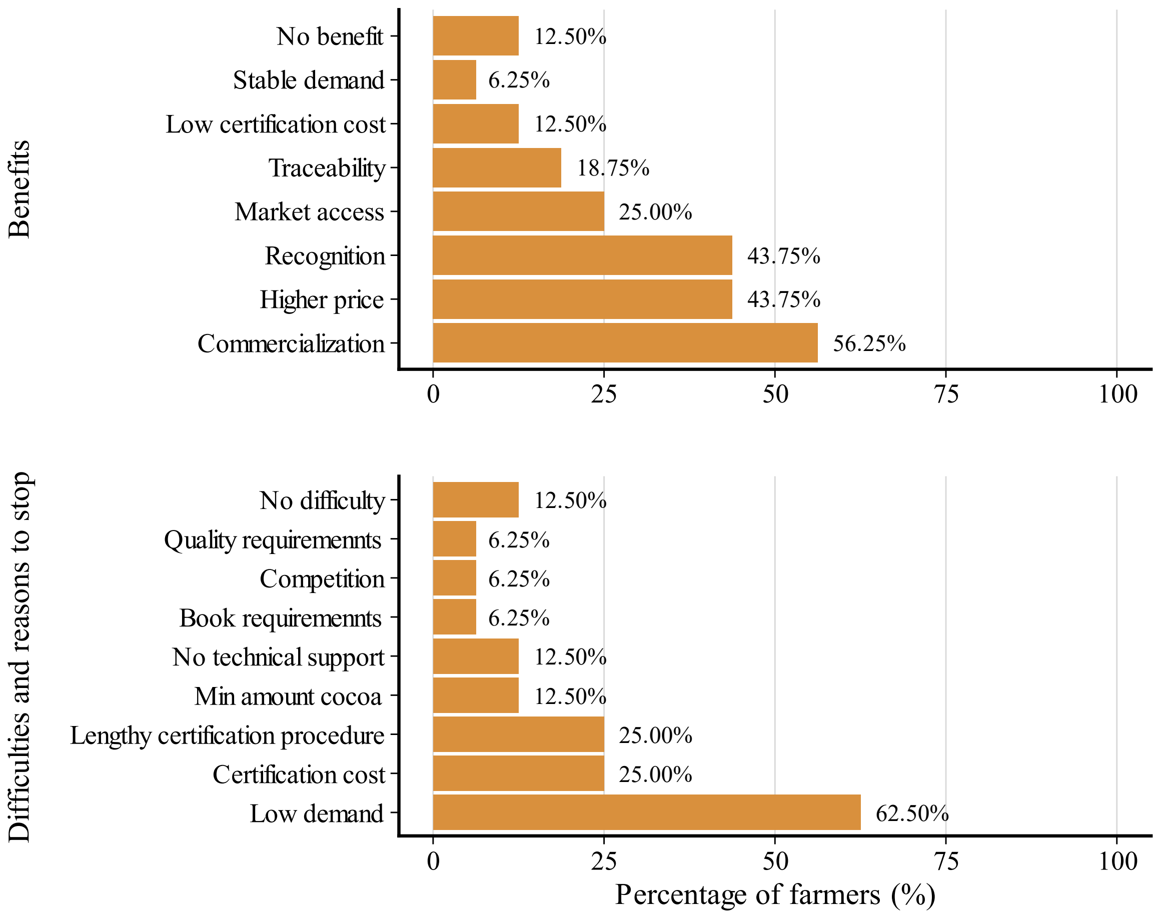

Figure 5.5 Farmers' perceived benefits and challenges associated with the *Sul da Bahia* Geographical Indication (GI) scheme. The figure presents the share (%) of farmers (n=16) who have certified their cocoa with *Sul da Bahia* GI at least once. The upper panel shows the percentage of farmers identifying perceived benefits, while the lower panel presents perceived difficulties and reasons for discontinuation.

5.4.4. Producer and farm characteristics of certified and non-certified households

Table 5.1 shows the descriptive statistics of the total sample of cocoa farming households as well as certified and non-certified producers under the *Sul da Bahia* GI scheme. Compared to their non-certified counterparts, certified farmers have, on average, three more years of education. They also have a higher dependency ratio, indicating a higher share of working-age members within the household. Only 11% of certified farmers are located within agrarian reform settlements, compared to 43% of non-certified farmers. In contrast, both groups were similar in terms of gender and age of household head, farming experience, and household size. While certified farmers are twice as likely to derive income from livestock activities, no significant differences are observed in income from other crops (inside or outside CAFS), off-farm employment, or non-labour income sources. Non-certified households are located relatively closer to their CAFS than certified farmers, but farther away from the GI headquarters. Distances to roads and urban cities are similar between groups.

Certified farmers manage substantially larger CAFS (73ha) than non-certified farmers (13ha) and, in addition to cultivating cocoa within these systems, are more likely to also manage plots with cocoa in full sun. They also use more external inputs, including pesticides, fertilisers and lime. Regarding post-harvesting practices, all certified farmers report fermenting their cocoa, compared to 77% of non-certified producers, and the average fermentation duration was also notably longer (6 days) compared to non-certified farmers (4 days), a practice aimed at improving cocoa quality. Drying practices do not differ significantly between groups, although all certified farmers dried their cocoa beans compared to 98% of the non-certified producers, which is also consistent with good practice for high-quality cocoa. Market integration and value-chain engagement also differ between certified and non-certified farmers. Overall participation in third-party certification schemes (e.g. UTZ/Rainforest Alliance, Organic, Demeter) is limited, with only 3% of the overall sample of farmers currently holding such certifications. Certified farmers, however, are 15 percentage points more likely to hold additional third-party certifications. Certified farmers are also significantly less likely to market their cocoa through middlemen and more likely to sell directly to milling companies or specialty bean-to-bar buyers, indicating deeper integration into differentiated value chains. In addition, they are more engaged in value-added processing, with a significantly higher share producing cocoa derivatives such as nibs, cocoa honey, or chocolate. The labour structure further reflects this commercial orientation. While the use of family labour was comparable, certified farmers employed substantially more hired labour, indicating a more labour-intensive and commercially oriented production model. In contrast, the prevalence of young cocoa trees, the presence of hybrid or clonal varieties and the proximity of CAFS to forest remnants are similar across groups.

Table 5.1 Descriptive statistics for the total sample of cocoa farmers (n = 313), including non-certified (n = 295), and certified (n = 18) farmers under the *Sul da Bahia* GI.

	Total sample (n= 313)		Non-certified farmers (n=295)		Certified farmers (n=18)		
Variable	Mean	se	Mean	se	Mean	se	P-value
Producer characteristics							
Female HH head (%)	21.73	2.33	22.71	2.44	5.56	5.56	
Age HH head (yrs)	55.70	0.79	55.75	0.81	54.89	3.57	
Education HH head (yrs)	9.26	0.25	9.06	0.25	12.44	1.43	***
Experience HH head (yrs)	19.04	0.70	19.22	0.72	15.94	2.40	
HH size	3.03	0.09	3.05	0.09	2.72	0.25	
Dependency ratio[1]	0.73	0.02	0.72	0.02	0.85	0.05	**
HH head is sharecropper (%)	5.75	1.32	6.10	1.40	0.00	0.00	
HH head is part of agrarian reform settlement (%)	41.53	2.79	43.39	2.89	11.11	7.62	***
Farm characteristics							
Income from other crops in CAFS (%)	49.20	2.83	48.14	2.91	66.67	11.43	
Income from other crops outside CAFS (%)	18.21	2.18	18.64	2.27	11.11	7.62	
Income from livestock (%)	24.92	2.45	23.39	2.47	50.00	12.13	**
Income from off-farm employment[3] (%)	29.07	2.57	28.14	2.62	44.44	12.05	
HH head has non-labour income source[4] (%)	66.13	2.68	66.78	2.75	55.56	12.05	
Distance HH-CAFS (km)	0.61	0.10	0.57	0.10	1.27	0.40	***
Distance HH-road (km)	3.98	0.22	4.04	0.23	2.93	0.79	
Distance HH-city (km)	9.11	0.34	9.18	0.35	7.81	0.95	
Distance HH-GI headquarters (km)	4.04	1.14	41.33	1.17	25.76	4.39	***
Cocoa production							
CAFS size (ha)	16.61	2.14	13.18	1.69	72.68	21.30	***
Young cocoa trees (%)	12.92	1.08	12.68	1.11	16.78	4.38	
Presence of cocoa hybrids/clones (%)	73.48	2.50	72.54	2.60	88.89	7.62	
Cocoa full sun (%)	6.07	1.35	5.42	1.32	16.67	9.04	*
Cocoa fermentation (%)	77.32	2.37	75.93	2.49	100.00	0.00	**
Cocoa fermentation duration (days)	4.48	0.11	4.34	0.11	6.17	0.20	***
Cocoa drying (%)	98.08	0.78	97.97	0.82	100.00	0.00	
Third party certification (%)	2.56	0.89	1.69	0.75	16.67	9.04	***
Middlemen channel (%)	83.39	2.11	85.76	2.04	44.44	12.05	***
Cocoa derivates (%)	14.70	2.00	12.88	1.95	44.44	12.05	***
Full-Time Equivalent family labour devoted to cocoa	0.73	0.02	0.73	0.02	0.64	0.10	
Full-Time Equivalent hired labour devoted to cocoa	0.75	0.13	0.45	0.10	5.64	1.21	***
Pesticide use (%)	56.87	2.80	55.59	2.90	77.78	10.08	*
Fertilizer and lime use (%)	56.87	2.80	54.92	2.90	88.89	7.62	***
Distance CAFS-forest (km)	0.10	0.01	0.10	0.01	0.10	0.03	
Altitude CAFS (m)	147.71	4.32	147.90	4.39	144.67	22.24	
Slope CAFS (%)	15.48	0.57	15.64	0.59	12.86	2.40	

Note: * ($p < 0.1$), ** ($p < 0.05$) and *** ($p < 0.01$) for Wilcoxon rank-sum test of continuous variables and chi² test for categorical variables.

[1] Household ratio of working age adults to HH size.

[2] A mandatory state-level registry of rural properties used to verify land tenure and compliance with environmental legislation.

[3] Any type of job in the non-farm sector (both wage and self-employment), as hired labour on other farms.

[4] Income from other non-labour sources, such as pension, remittances, renting out land and/or houses.

5.4.5. Associations between economic performance and certification

Table 5.2 presents descriptive statistics of the economic outcome variables between non-certified and certified farmers. Cocoa yields are on average 218 kg ha^{-1}, but do not differ between certified and non-certified farmers. Certified farmers receive a higher average cocoa price, earning 3.59 USD kg^{-1} compared to 3.13 USD kg^{-1} for non-certified producers. Certified farmers also have substantially higher cocoa production costs per hectare, which are more than twice those of non-certified farmers (2539 and 1041 R$ ha^{-1}, respectively). As a consequence, net cocoa incomes are similar between certified and non-certified farmers. Gross revenue of other crops cultivated in CAFS and overall returns from CAFS are also comparable between certified and non-certified farmers. Certified farmers, however, have markedly higher total household incomes, averaging 227,626 R$ compared to 49,104 R$ among non-certified farmers, reflecting their larger production scale and greater engagement in diversified income-generating activities such as livestock rearing. This difference is also reflected in per capita income, which is more than four times higher among certified households (82,234 R$) than among non-certified households (19,975 R$). The share of household income derived from CAFS averages 66% among certified farmers and 52% among non-certified farmers, with no statistically significant difference between the two groups.

Table 5.2 Descriptive statistics of economic outcome variables of the sample of non-certified and certified farmers across 12 municipalities in southern Bahia, Brazil

	Total sample (n = 313)		Non-certified farmers (n = 295)		Certified farmers (n = 18)		
Economic outcome variable	Mean	se	Mean	se	Mean	se	P-value
Cocoa yield (kg ha^{-1})	217.57	10.02	216.08	10.08	241.98	56.85	
Cocoa price[1] (USD kg^{-1})	3.15	0.04	3.13	0.04	3.59	0.20	**
Cocoa total production costs (R$ ha^{-1})	1126.84	97.31	1040.66	95.42	2539.19	563.01	***
Net cocoa income (R$ ha^{-1})	2552.14	173.71	2548.50	171.49	2611.80	1137.28	
Gross revenue from other crops than cocoa (R$ ha^{-1})	295.92	41.65	303.34	44.01	174.21	60.35	
Returns from CAFS (R$ ha^{-1})	2858.57	184.92	2859.23	183.53	2847.69	1168.52	
Household income (R$)	59370.15	5619.78	49103.67	4431.94	227626.35	52391.49	***
Per capita income (R$)	23555.44	2136.47	19975.03	1715.97	82234.26	20179.85	***
Share of household income derived from CAFS[2] (%)	52.58	1.90	51.79	1.96	65.64	7.51	

Note: * ($p < 0.1$), ** ($p < 0.05$) and *** ($p < 0.01$) for the Wilcoxon rank-sum test of continuous variables. Outcome variables trimmed at 1% extreme values.

[1] The average annual exchange rate in 2023 was 1 USD = 4.994 BRL (World Bank, 2025)

[2] 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 is calculated by multiplying the returns from CAFS by the total CAFS area managed by the household (expressed in BRL).

Table 5.3 reports the propensity score matching estimates of the ATET of GI certification for all economic outcome indicators, estimated using one-to-one nearest-neighbour propensity score matching (1:1). After accounting for selection into certification, no statistically significant effects are observed for economic outcomes in terms of land productivity, including cocoa yield, cocoa price, total production costs, or net cocoa income, gross revenue from other crops, and total returns from CAFS. Similarly, certification does not significantly affect household-level economic outcomes, including total household income and per capita income. The PSM results indicate that certification is not associated with significant differences in economic performance once observable differences between certified and non-certified farmers are controlled for. These findings are robust to alternative matching specifications, with no consistent evidence of statistically significant certification effects across outcome variables (Appendix D, Table D3).

Table 5.3 Average treatment effects on the treated (ATET) of *Sul da Bahia* GI certification on economic outcome indicators related to land productivity and household-level economic returns, estimated using one-to-one nearest-neighbour propensity score matching.

	Nearest-neighbour matching 1:1		
Outcome	ATET	Std. Error	P-value
Cocoa yield (kg ha^{-1})	23.25	85.94	
Cocoa price (R$ kg^{-1})	0.66	1.93	
Cocoa total production costs (R$ ha^{-1})	862.52	810.29	
Net cocoa income (R$ ha^{-1})	155.48	1497.80	
Gross revenue from other crops than cocoa (R$ ha^{-1})	-44.35	36.03	
Returns from CAFS (R$ ha^{-1})	-4.31	1537.57	
Household income[2] (R$)	45216.22	67271.22	
Per capita income (R$)	18784.00	21292.17	

Note: * ($p < 0.1$), ** ($p < 0.05$) and *** ($p < 0.01$). No estimated effects are statistically significant at conventional levels.

5.4.6. Associations between ecological performance and certification

Figure 5.6 demonstrates the considerable variation in shade tree characteristics between certified and non-certified farmers (n=313). Non-certified farms have a significantly higher shade tree density (197.4 ± 4.6 trees ha^{-1}) compared to certified farms (117.6 ± 11.2 trees ha^{-1}). Likewise, the share of native shade trees is higher in non-certified farms (64.8 ± 1.4%) than in certified farms (51.1 ± 6.4%), indicating that CAFS managed by certified farmers are more dominated by non-native shade tree species.

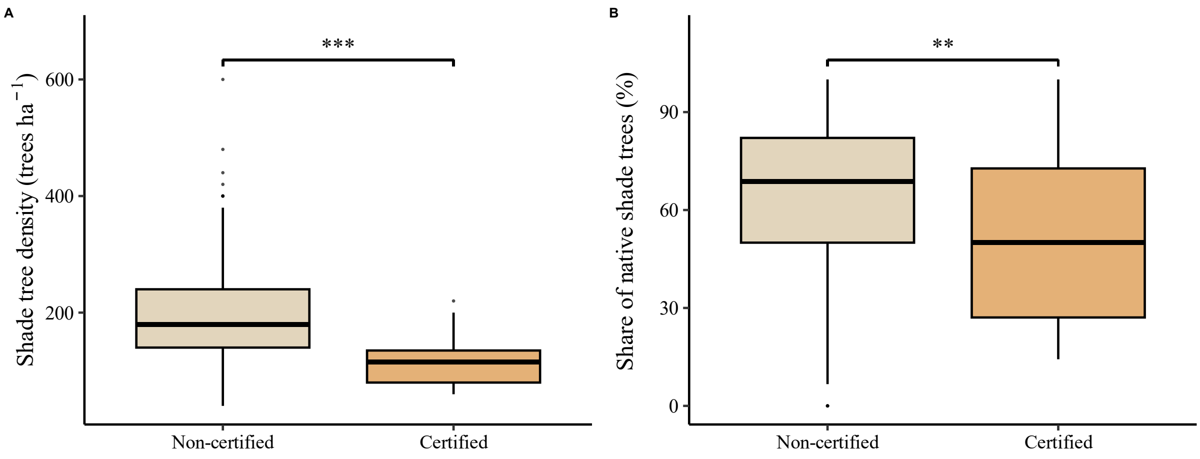

Figure 5.6 Comparison of shade tree characteristics within cocoa agroforestry systems between non-certified and certified farms (n=313) in terms of (A) shade tree density (trees ha^{-1}) and (B) the share of native shade trees (%). * ($p < 0.1$), ** ($p < 0.05$) and *** ($p < 0.01$) for Wilcoxon rank-sum test of continuous variables.

Table 5.4 presents propensity score matching estimates of the ATET of GI certification on ecological outcome indicators related to shade-tree structure and mammal richness. After accounting for non-random selection into certification, GI certification is associated with a significant reduction in shade-tree density compared to matched non-certified farms ($p < 0.1$). In contrast, the share of native shade trees does not differ significantly between certified and non-certified farms. GI certification is also associated with significantly lower mammal species richness ($p < 0.01$) and this negative effect is observed across both insensitive and sensitive mammal species ($p < 0.01$). These results are robust to alternative matching specifications, which yield consistent effect directions and statistical significance across ecological indicators (Appendix D, Table D4).

Table 5.4 Average treatment effects on the treated (ATET) of *Sul da Bahia* GI certification on ecological outcome indicators related to shade-tree structure and mammal richness, estimated using one-to-one nearest-neighbour propensity score matching.

	Nearest-neighbour matching 1:1		
Outcome	ATET	Std. Error	P-value
Shade-tree density (trees ha^{-1})	-30.00	18.06	*
Native shade tree (%)	-10.19	9.05	
Total mammal richness (n° species)	-4.06	0.30	***
Insensitive mammal species richness (n° species)	-1.28	0.25	***
Sensitive mammal species richness (n° species)	-2.78	0.35	***

*Note: * (p < 0.1), ** (p < 0.05) and *** (p < 0.01).*

Table 5.5 presents the structural and compositional characteristics of CAFS between the non-certified and certified farms (n=18). Certified farms have lower shade-tree species richness (4.8 vs. 3.6 species) and shade-tree species diversity (4.3 vs. 3.2) compared to non-certified farms. Mean DBH of shade trees is comparable between groups (~40 cm), whereas basal area is significantly higher in non-certified farms (29.6 vs. 18.8 m^2 ha^{-1}). Cocoa tree density is similar across farms, averaging 719 trees ha^{-1}. Regarding CAFS characteristics important for GHLT, canopy connectivity and bromeliad presence do not differ significantly between certified and non-certified farms. In contrast, the Importance Value Index (IVI) of key tree species for golden-headed lion tamarins is significantly higher in non-certified CAFS (173.9 vs. 109.8). The IVI of jackfruit trees, representing an exotic yet ecologically important food source during periods of native fruit scarcity (Costa et al., 2022; Oliveira et al., 2011), is higher in non-certified farms (33.1 vs. 8.2; $p < 0.05$). Forest cover within the surrounding landscape averages 38.5% and does not differ significantly between groups.

Table 5.5 Structural and compositional characteristics of cocoa agroforestry systems on GI-certified and non-certified farms in southern Bahia, Brazil.

	Total sample (n= 18)		Non-certified farmers (n=9)		Certified farmers (n=9)		
Ecological outcome variable	Mean	se	Mean	se	Mean	se	P-value
Shade tree richness (species)	4.19	0.35	4.78	0.46	3.61	0.46	*
Shade tree diversity (Hill-Simpson)	1.51	0.10	1.40	0.06	1.62	0.19	
Shade tree diversity (Hill-Shannon)	3.73	0.29	4.30	0.39	3.16	0.34	*
DBH (cm)	39.87	2.52	39.42	3.7	40.32	3.63	
Basal area (m^2 ha^{-1})	24.17	2.21	29.55	3.38	18.79	1.44	**
Cocoa density (trees ha^{-1})	718.89	38.74	722.22	51.45	715.56	61.06	
Canopy connectivity (crown connections)	2.26	0.22	2.44	0.34	2.08	0.27	
Bromeliads (index)	0.38	0.10	0.31	0.12	0.44	0.16	
IVI GHLT	141.85	15.36	173.87	19.66	109.84	18.98	**
IVI Jackfruit	20.64	5.60	33.10	8.79	8.17	4.13	**
Forest cover (%)	38.51	3.68	40.62	5.61	36.39	4.99	

Note: * ($p < 0.1$), ** ($p < 0.05$) and *** ($p < 0.01$) for the Wilcoxon rank-sum test of continuous variables and the chi² test for categorical variables.

Table 5.6 demonstrates the variation in golden-headed lion tamarin (GHLT) presence and group density, as well as terrestrial mammal detections, across GI-certified and non-certified cocoa farms in southern Bahia, Brazil. GHLTs are detected on 61.1% of the surveyed farms, with detections on 77.8% of non-certified farms and 44.4% of certified farms. Estimated GHLT group density averaged 5.06 ± 1.30 groups km^{-2} on non-certified farms and 2.78 ± 1.22 groups km^{-2} on certified farms, however, these differences are not statistically significant. Across all farms, the mean number of terrestrial mammal detections is 40.5 ± 6.6 detections per 100 trap days. Total mammal detections are similar between certified (48.2 ± 10.8) and non-certified farms (32.52 ± 7.1). Likewise, detections of sensitive mammal species do not differ significantly between certified (14.4 ± 4.15) and non-certified farms (11.6 ± 4.51) and a comparable pattern is observed for insensitive mammal species (33.7 ± 10.1 vs. 20.6 ± 4.9).

Table 5.6 Golden-headed lion tamarin (GHLT) presence (%) and group density (groups km^{-2}) based on playback survey, and camera trap detections of total, sensitive, and insensitive terrestrial mammal species on non-certified and GI-certified cocoa farms in southern Bahia, Brazil. Mean values for terrestrial mammals represent the number of independent detection events per 100 trap days.

	Total sample (n= 18)		Non-certified farmers (n=9)		Certified farmers (n=9)		
Biodiversity outcome variable	Mean	se	Mean	se	Mean	se	P-value
GHLT							
GHLT presence (%)	61.11	11.82	44.44	17.57	77.78	14.70	
GHLT group density (groups km^{-2})	3.92	0.91	2.78	1.22	5.06	1.30	
Terrestrial mammals							
Total mammal detections	40.36	6.57	32.52	7.13	48.19	10.83	
Insensitive mammal species detections	27.14	5.66	20.59	4.93	33.69	10.06	
Sensitive mammal species detections	13.03	2.99	11.64	4.51	14.43	4.15	

Note: * ($p < 0.1$), ** ($p < 0.05$) and *** ($p < 0.01$) for the Wilcoxon rank-sum test of continuous variables.

5.5. Discussion

5.5.1. Market dynamics and producers' perception of the *Sul da Bahia* GI scheme

The evolution of the certified cocoa under the *Sul da Bahia* GI scheme reflects the institutional fragility of niche certification systems in maintaining attractive market incentives for producer participation within a volatile global commodity context. The volume of certified cocoa expanded rapidly between 2019 and 2021, suggesting an initial phase of institutional consolidation and producer engagement. However, certified volumes contracted sharply after 2022, coinciding with record increases in international cocoa prices in 2024 (ICCO, 2025). As global cocoa prices tripled between 2023 and 2024, the price premium offered for GI-certified cocoa narrowed from 60-70% to only 25-30%, substantially reducing its attractiveness to producers. Many farmers consequently prioritised conventional sales channels that offered immediate liquidity and required no additional effort and certification costs, leading to a marked reduction in participation. This pattern indicates that the recent decline in certification reflects underlying institutional weaknesses in the *Sul da Bahia* GI scheme, whose current institutional design provides limited economic incentives to sustain farmer engagement when market-driven price differentials diminish.

At the same time, the low level of awareness of the *Sul da Bahia* GI among cocoa farmers highlights its limited institutional diffusion within the regional value chain. Only 27% of surveyed farmers had heard of the scheme, indicating that it remains weakly integrated at the producer level. Among those who had certified their cocoa at least once since 2019, only 13% reported no difficulties, while the majority identified market- and procedure-related challenges as the main barriers to participation. Farmers indicated low demand for GI-certified cocoa (63%), high certification costs (25%), and lengthy certification procedure (25%) as the most important difficulties, which further discourage sustained participation and limit the scheme's scalability. Low demand, in particular, reflects the narrow market for GI-certified cocoa in the region, as few buyers explicitly demand certification for purchase, offering limited assurance of regular sales. Similar constraints have been observed in other Latin American GI initiatives, where weak alignment with supply chains, limited demand from downstream actors and high compliance costs create entry barriers for farmers (Boga et al., 2025; Cardoso et al., 2022). This partly explains why several certified producers reported selling their high-quality GI cocoa through conventional channels, receiving mainstream prices despite the additional effort and investment required to meet certification standards. Although the growing sales of GI-branded chocolate illustrate the scheme's success in enhancing regional visibility, the limited share of certified cocoa transformed into GI-branded chocolate is unlikely to offset the low demand for GI-certified cocoa. This reflects a broader pattern among Brazilian consumers, whose awareness and willingness to pay for certified or origin-based products remain low due to limited familiarity with certification schemes, insufficient dissemination of label meanings, and high price sensitivity (Silva et al., 2017).

Despite these challenges, the majority of the farmers who perceive benefit from participating in the scheme emphasise primarily market-oriented advantages such as improved commercialisation opportunities and higher selling prices. These perceptions suggest that producers view the GI primarily as an economic and reputational tool, offering access to speciality markets and building trust with quality-focused buyers, including bean-to-bar chocolate makers seeking traceable, high-quality cocoa. Moreover, nearly half of certified farmers highlight the recognition of the region's cultural identity of growing cocoa in traditional CAFS as an important advantage. This highlights the symbolic potential of the *Sul da Bahia* GI to strengthen territorial identity and preserve traditional agroforestry practices. Similar findings have been reported in other GI schemes, where certification not only improves market access but also fosters regional pride, cultural valorisation, and the preservation of local heritage (Boga 2025; Cardoso et al., 2022; Neilson et al., 2018).

5.5.2. Economic profile and performance of farmers participating in the GI scheme

Certified farmers differ markedly from non-certified farmers and from the regional averages reported by Chiapetti et al. (2020) in their household and farm characteristics. They are characterised by higher education levels, greater household labour availability, and more secure land tenure, as reflected in their higher registration rate in CEFIR. Their production systems also reflect a distinctly commercial orientation, as certified farmers manage substantially larger CAFS, employ significantly more hired labour while maintaining comparable levels of family labour, and are more frequently engaged in value-added processing and income diversification through livestock rearing. In addition, the higher prevalence of third-party certifications and greater reliance on direct sales to milling companies or specialty buyers among certified farmers indicates that participation in the *Sul da Bahia* GI scheme tends to concentrate among producers already integrated into formal and differentiated cocoa markets, and engaged in broader sustainability-oriented initiatives. These characteristics point to a more capitalised and market-integrated profile among certified farmers, highlighting structural differences that may enhance their capacity to meet certification and quality requirements. Evidence from studies on smallholders engaged in direct trade and specialty markets shows that these farmers typically have greater access to agricultural training, technical assistance, credit, and market information, as well as stronger social networks through cooperative or buyer relationships, compared with farmers selling through mainstream marketing channels (Hernandez-Aguilera et al., 2018; Middendorp et al., 2020). This pattern is consistent with evidence from other sustainability certification schemes, which often exhibit limited inclusiveness by favouring better-resourced farmers and creating structural barriers to participation for more marginalised producers (Enthoven et al., 2025; Meemken et al., 2021).

The absence of significant economic effects associated with GI certification in terms of cocoa price, land productivity and household-level economic returns indicates that, despite clear engagement in quality-oriented production practices, these efforts do not translate into measurable economic advantages for participating cocoa producers. Certified farmers adhere closely to post-harvest practices consistent with fine-flavour cocoa standards, most notably extended fermentation periods within the recommended range of five to seven days, reflecting quality differentiation aligned with the technical specifications of the *Sul da Bahia* GI. While investments in post-harvest quality improvement are expected to provide higher farm-gate prices, as documented by previous studies (Cadby and Araki, 2021; Middendorp et al., 2020; Rueda et al., 2023), our findings indicate that adherence to fine-flavour standards and *Sul da Bahia* GI participation alone are insufficient to secure consistently higher cocoa prices. One plausible explanation is that only a share of certified farmers' total cocoa output is certified and sold under GI or specialty arrangements, such that price premiums obtained for specific batches may not be fully reflected in annual average cocoa prices reported at by the farmer.

These findings suggest that the *Sul da Bahia* GI primarily recognises and formalises pre-existing quality-oriented production practices, rather than functioning as a driver of improved economic performance. This interpretation is consistent with previous studies on GI highlighting the role of geographical indications in product differentiation and reputation building rather than in delivering direct economic gains (Boga, 2025; Neilson et al., 2018). At the same time, research on specialty cocoa markets highlights weakly defined quality standards, heterogeneous quality metrics, and limited standardisation, which allow buyers to set prices and quality requirements unilaterally and often place farmers at a bargaining disadvantage (Cadby and Araki, 2021). By providing a transparent quality framework, GIs may help address the need for clear system-level definitions of cocoa quality required for sustainable market development. Nevertheless, the economic additionality of the *Sul da Bahia* GI remains limited, as the capacity to benefit from certification appears closely tied to pre-existing structural advantages and production standards, which is consistent with findings from other certification schemes (Dietz and Grabs, 2022).

5.5.3. Lower ecological performance in certified CAFS

The ecological outcomes associated with GI certification indicate that certified CAFS exhibit lower ecological performance relative to non-certified systems. Farms participating in the Sul da Bahia GI scheme were characterised by significantly lower shade-tree density, a pattern typically associated with shade-tree removal for productivity gains in CAFS (Blaser et al., 2018; Steffan-Dewenter et al., 2007). However, the lack of yield differences between certified and non-certified farms suggests that this reduction in shade trees is unlikely to reflect yield intensification and may instead be linked to quality-oriented management practices, whereby farmers selectively reduce shade to facilitate harvesting operations or to mitigate pest and disease pressures that can adversely affect cocoa bean quality. Irrespective of underlying motivation, reductions in shade-tree density can substantially undermine both biodiversity conservation and the climate-mitigating functions of CAFS (Bennett et al., 2022; Blaser et al., 2018; Dekegel et al., 2025; Ferreira et al., 2023). Notably, one third of GI-certified farms had less than 100 shade trees per hectare, the threshold identified by Dekegel et al. (2025) as necessary for the presence of the GHLT in CAFS, suggesting that current levels of shade-tree densities in certified CAFS may already be associated with reduced habitat suitability for this endangered primate species. By contrast, no significant differences are observed in the proportion of native shade trees after accounting for observable differences between certified and non-certified farms.

This pattern is partly reflected in the results of the biodiversity assessment survey conducted on the subsample of 18 farms. Within this subsample, certified farms exhibit significantly lower shade-tree density, richness and diversity, indicating less structurally and diverse CAFS. In addition, non-certified farms were characterised by a greater basal area of shade trees, pointing to the presence of larger and more mature trees, which are particularly important for providing preferred sleeping sites for GHLTs (De Almeida-Rocha et al., 2020). Non-certified farms also supported a higher prevalence of key tree species used by GHLT as well as jackfruit trees, an exotic yet complementary food source during periods of native fruit scarcity (Costa et al., 2022; Oliveira et al., 2011). Together, these characteristics suggest that non-certified farms maintain higher habitat suitability for GHLTs, although this did not translate into significantly higher GHLT presence or group densities on non-certified farms. This lack of statistical significance may partly reflect the limited sample size of the biodiversity subsample, a constraint that similarly affects the detection of differences in medium- and large-sized terrestrial mammal activity based on camera trap data.

After accounting for observable differences between certified and non-certified farms, certified farms support significantly lower mammal species richness, with declines observed among both sensitive and insensitive species to forest conversion. By contrast, no significant difference is observed in the proportion of native shade trees between certified and non-certified farms. Yet, as this measure does not capture shade-tree species richness or diversity, it remains possible that structural simplification is associated with shifts in tree species composition.

These findings support evidence that participation in high-quality or specialty cocoa markets does not automatically lead to improved ecological outcomes. Middendorp et al. (2020) found no difference in shade-tree richness, abundance and cover between farmers engaged in high-quality cocoa direct trade and those selling through mainstream markets, highlighting that quality-based market differentiation alone is insufficient to enhance ecological performance in the absence of explicit environmental requirements in buyer-producer arrangements. By contrast, Rueda et al. (2023) document higher shade tree species richness among farmers participating in direct trade of high-quality cocoa networks, underscoring that ecological outcomes are highly context-dependent. Evidence from other GI and VSS schemes similarly indicates that limited or absent environmental criteria have failed to deliver measurable ecological benefits (Caravaggio and Vaquero-Pineiro, 2025; Dröge et al., 2025a; Ingram et al., 2020; Wätzold et al., 2025).

Nonetheless, both certified and non-certified farms in southern Bahia maintain relatively high ecological value, characterised by substantial shade-tree density and cover compared to other cocoa-producing regions, as well as the presence of terrestrial mammals and species of conservation concern. At the same time, these findings indicate that the current shade-tree threshold of 40 trees ha^{-1} within the GI framework is insufficient to prevent further structural simplification and biodiversity loss, highlighting the need for more stringent shade-tree density criteria to strengthen ecological outcomes.

5.6. Conclusion

This study delivers the first integrated, field-based assessment of a GI scheme for cocoa in an emerging economy, combining farm-level economic and biodiversity survey data and semi-structured interviews. Focusing on the *Sul da Bahia* GI in Brazil as a case study, we demonstrate that origin-based certification can formalise mechanisms of quality differentiation and traceability while reinforcing territorial identity and regional reputation. Nevertheless, despite these achievements, its effective sustainability outcomes remain limited.

Our findings reveal that the *Sul da Bahia* GI scheme remains at an early and fragile stage of institutional consolidation, constrained by limited farmer awareness, restricted market uptake, and unstable economic incentives for participation. Its current institutional design offers limited capacity to sustain producer engagement, relying primarily on volatile price differentials rather than on consistent market demand or stable governance structure. Economically, the GI scheme appears to attract better-resourced and market-oriented producers already equipped to meet quality standards and integrated in differentiated markets, but does not generate measurable economic gains beyond those associated with pre-existing advantages. Although the scheme actively supports cooperative-based initiatives to improve access for smaller producers, these efforts remain dependent on external financial support. From an ecological perspective, GI-certified cocoa farms show lower environmental performance than non-certified systems, indicating that certification has not translated into ecological benefits. Instead, GI-certified farmers appear to favour structural simplification of AFS, which may undermine the long-term biodiversity value and climate adaptation potential of CAFS. Although both certified and non-certified farms continue to provide habitat for forest-dependent fauna, including species of conservation concern, current environmental criteria in the GI framework is insufficient to prevent structural simplification and biodiversity loss.

This study is not without limitations. The ecological assessment is based on a relatively small sample of farms, which constrains the statistical power to detect potentially subtle differences in biodiversity or vegetation structure outcomes across certification status. In addition, the number of certified farms is limited, reflecting the reality on the ground that the recently established GI scheme fails to attract many participating farmers. The temporal context of data collection, in which cocoa prices were substantially higher than usual, also matters to interpret the potential economic additionality of the GI scheme.

The findings highlight several priorities for strengthening the long-term sustainability and inclusiveness of the *Sul da Bahia* GI scheme. If the GI scheme is to be maintained and up-scaled, ensuring smallholder participation will require continued financial and technical support to overcome structural barriers to entry, while maintaining rigorous quality and traceability standards. Achieving inclusiveness without compromising quality remains imperative to preserve the scheme's credibility and market trust. The GI standards specifications should explicitly integrate minimum shade-tree density thresholds that go beyond compliance with existing environmental legislation to align product quality objectives with ecological sustainability and biodiversity conservation. Such stricter requirements would strengthen the ecological credibility of the GI and link quality recognition more directly with conservation outcomes. Equally important is building locally anchored governance and institutional capacity that endures beyond donor support. Policy efforts should also extend beyond farmer support to broader value chain development, fostering stronger integration among producers, cooperatives, processors, and buyers. Stimulating market demand through targeted outreach, local consumer awareness, stable buyer commitments, and domestic market development would be necessary to consolidate differentiated markets to provide stable incentives for producers. Yet, given the limited additionality of the current GI scheme, there might be other more effective initiatives for sustainable development. Ultimately, realising the potential of GIs to support sustainability transitions in tropical commodity sectors will require moving beyond symbolic differentiation toward governance models that consolidate differentiated markets, foster institutional inclusivity, and embed quality, equity, and environmental stewardship as coequal pillars of sustainable territorial development.

Chapter VI

General conclusion

6.1. Main findings

This dissertation examines how shade-tree management in CAFS shapes ecological and economic outcomes, the extent to which these outcomes involve trade-offs or synergies, and whether governance instruments such as the *Sul da Bahia* GI can promote the sustainable development of these systems. By combining ecological field surveys, household-level economic data, and institutional analysis, the dissertation provides an integrated assessment of how biodiversity conservation, farm-level economic performance, and governance interact in traditional CAFS in southern Bahia, Brazil.

Building on this integrated assessment, the findings highlight substantial *within-system* variation in cocoa agroforestry systems. Shade-tree management plays an important role in shaping ecological and economic outcomes, but its effects vary across outcomes and interact with farm-level, social, and institutional conditions. Across chapters, this points to shade-tree management as a necessary but insufficient lever for sustainability, underscoring the need to move beyond simplified farm-level management approaches.

From an ecological perspective, shade-tree management plays a key role in shaping biodiversity outcomes in CAFS, particularly for species of high conservation concern. Results from **Chapter II** show that reduced shade cover is associated with lower occupancy of the endangered GHLT as well as decreased detections of medium- and large-sized terrestrial mammals. The results further indicate that a minimum of approximately 65% shade cover, corresponding to ~100 shade trees per hectare, is required to sustain GHLT persistence in CAFS, while also providing benefits for the terrestrial mammal community. This estimated threshold is especially relevant in light of Bahia’s shade-tree management decree, which permits thinning of cabrucas down to a minimum of 40 native trees per hectare. While this legal threshold may allow continued cocoa production, the findings suggest that it is insufficient to adequately support biodiversity conservation within CAFS. Taken together, these results demonstrate that ecological sustainability in CAFS of southern Bahia is constrained by a well-defined ecological threshold, with direct implications for land-use regulation, conservation planning, and sustainability standards

From an economic perspective, the findings demonstrate that the performance of CAFS cannot be assessed on the basis of cocoa yields alone, but instead should reflect the combined effects of yields, production costs, and income diversification. Results from **Chapter III** show that although higher shade-tree densities are associated with lower cocoa yields, these yield reductions are partly offset by lower production costs, leaving net cocoa income largely unaffected. As a result, increasing shade-tree density entails limited economic trade-offs. Revenues from the cultivation of non-cocoa crops remain weakly valorised in the study context and decline with increasing shade-tree density, indicating that income diversification currently plays a limited role in enhancing overall returns under higher shade-tree densities, while pointing to underexploited opportunities for improving value capture from non-cocoa agroforestry products.

Taken together, the ecological and economic results suggest that retaining at least 100 shade trees per hectare within CAFS, as required to sustain biodiversity conservation, imposes limited economic losses on farmers, and that non-cocoa agroforestry crops can further offset these losses, adding additional value to these CAFS. Given that shade-tree retention contributes to the long-term ecological resilience of CAFS, these findings challenge the economic rationale underlying the current Bahian shade-tree management decree and suggest that stricter shade-tree retention requirements could remain economically feasible, particularly for small-scale farmers. More broadly, they underscore the need for economic assessments that accounts for multiple economic components shaping farm-level returns in CAFS, as well as for policy interventions that create incentives for retaining shade trees to better align farm-level economic performance with long-term sustainability objectives.

Integrating ecological and economic dimensions, the analysis of trade-offs and synergies shows that high economic performance can, under specific conditions, coexist with biodiversity conservation in CAFS, but that such outcomes are not driven by shade-tree density alone. Results from **Chapter IV** demonstrate that lower shade-tree density strongly influences the likelihood of ecological trade-offs, defined as outcomes combining high economic performance with low biodiversity. In line with the findings from Chapters II and III, lower shade-tree densities are associated with negative biodiversity outcomes, while still allowing for relatively high economic performance. Conversely, increasing shade-tree density alone does not guarantee “win–win” outcomes, indicating that shade-tree retention is a necessary but insufficient condition for generating ecological–economic synergies. The analysis further shows that producer and farm characteristics are associated with the likelihood of achieving different ecological–economic outcomes. Practical farming experience is positively associated with synergistic outcomes, while ecological–economic synergies are less frequently observed in female-headed households, suggesting that women face constraints that limit their ability to attain simultaneous economic and biodiversity benefits within CAFS. Smaller CAFS tend to combine higher economic performance with lower biodiversity outcomes, whereas agrarian reform settlements show high biodiversity potential but face substantial economic constraints, highlighting both the conservation value of these systems and the structural barriers limiting their economic viability. Farmers’ perceptions of shade trees, particularly concerns about yield competition, may also influence farmers’ willingness to retain or tolerate shade trees in CAFS, underscoring the importance of behavioural and social factors in sustainability outcomes.

Overall, these findings challenge simplified narratives that frame CAFS as inherently capable of delivering “win–win” outcomes through shade-tree retention alone. Instead, they demonstrate that ecological–economic synergies are contingent on supportive social and institutional conditions, including measures that promote equality and improve farmers’ access to resources relevant for farm-level decision-making. Recognising this conditionality is essential for designing policies and interventions that reconcile biodiversity conservation with farm-level economic viability in cocoa agroforestry landscapes.

Finally, the findings of **Chapter V** show that origin-based governance instruments are not a silver bullet for aligning economic and ecological outcomes in CAFS. The *Sul da Bahia* GI strengthens cocoa quality recognition, product differentiation, traceability, and regional identity. However, these functions do not translate into improvements in economic returns or social equity for cocoa farmers. Consistent price premiums remain absent, and participation in the scheme is largely concentrated among better-resourced producers, constrained by weak market demand and limited institutional support. From an ecological perspective, the findings further show that farms participating in the GI exhibit lower ecological performance, including greater biodiversity loss and more structurally simplified cocoa agroforestry systems characterised by lower shade-tree densities. Overall, these findings indicate that the GI does not operate as an effective instrument to deliver simultaneous economic and ecological sustainability in CAFS.

Overall, the findings of this dissertation demonstrate that sustainability of CAFS cannot be achieved through farm-level management practices alone, but requires inclusive value-chain governance arrangements that enable, support and reward farmers in maintaining biodiversity-friendly production systems.

6.2. Contributions to the literature

This dissertation advances the interdisciplinary literature on sustainable cocoa production, biodiversity conservation, and rural development by integrating ecological, economic, and institutional perspectives through a comprehensive case-study approach in southern Bahia. Rather than comparing CAFS to alternative land-use types, this dissertation shifts the analytical focus toward *within-system* variability, demonstrating that sustainability outcomes in CAFS are highly heterogeneous and shaped by shade-tree management, producer- and farm-level characteristics, and institutional contexts. Across its four empirical chapters, the dissertation generates novel, context-specific evidence that improves the understanding of the mechanisms linking biodiversity, productivity, and governance in tropical agroforestry landscapes.

Chapter II contributes to the ecological and conservation science by providing farm-level evidence on biodiversity responses to shade-tree management within CAFS. It offers the first empirical quantification of a shade-tree density threshold necessary to sustain the presence of the endangered GHLT within CAFS. By linking species-level habitat requirements to farm-level shade-tree management, this dissertation generates actionable evidence for revising Bahia's shade-tree management decree and for informing biodiversity-oriented certification and incentive schemes, thereby filling a critical empirical gap in understanding biodiversity responses to variability *within* AFS.

Chapter III contributes to the economic literature on tropical agroforestry by providing one of the first quantitative assessments of how shade-tree density influences farm-level economic performance *within* CAFS. Moving beyond the dominant focus on cocoa yields, this analysis jointly examines cocoa yields, production costs, and revenues from associated crops to assess overall farm-level economic returns from CAFS. By showing that high shade-tree densities entail only limited economic loss due to cost offsets, this dissertation challenges yield-centred assessments that implicitly frame shade-tree retention as economically costly. This contribution refines the concept of economic sustainability in AFS and provides evidence-based insights for designing incentive mechanisms that better align farm profitability with long-term sustainability objectives.

By integrating ecological and economic indicators within a single empirical framework, **Chapter IV** extends the emerging body of research on ecological–economic trade-offs and synergies in AFS to identify conditions under which they can arise. It moves beyond the dominant focus on shade-tree management and highlights the role of contextual factors in mediating sustainability outcomes. It also contributes to a more nuanced understanding of the mechanisms that enable win–win outcomes between biodiversity conservation and farm-level economic performance.

Chapter V makes an important contribution to the literature on GIs as governance instruments for sustainable rural development in emerging economies by providing one of the first field-based, interdisciplinary empirical evaluations of a cocoa GI. By integrating institutional, economic, and ecological perspectives, it addresses a critical empirical gap in the global GI literature, which has relied on conceptual or single-dimension analysis. It advances this literature by demonstrating the limitations of relying on product differentiation and regional identity alone to achieve sustainability objectives, and by highlighting the risk that GIs may reinforce existing inequalities and ecological simplification when market demand and institutional support are weak. In doing so, the dissertation contributes with a more critical and empirically grounded perspective on the role of GIs in sustainability transitions.

Viewed in relation to broader debates on sustainable agricultural transitions, the findings of this dissertation indicate that CAFS cannot be adequately captured by a single analytical framework of either sustainable intensification or agroecology. The ecological results align with agroecological principles by demonstrating that biodiversity conservation in AFS depends on maintaining structural complexity above clear ecological thresholds, rather than on yield-oriented intensification alone. At the same time, the economic and governance findings highlight issues that are insufficiently addressed in both sustainable intensification and agroecology, showing that farm-level economic viability is shaped not only by productivity and production costs, but also by value-chain conditions and institutional arrangements. Rather than supporting a dichotomous framing, the findings show that each approach captures only part of the conditions required for sustainability in CAFS. The results further suggest that CAFS function as production systems in which ecological structure and biodiversity are foundational to sustainability, and whose long-term viability therefore depends on integrating biodiversity-friendly management practices with governance and market arrangements that enable, reward, and sustain them. In this sense, CAFS emerges as a pathway that bridges sustainable intensification and agroecology, while also exposing the limitations of each when pursued in isolation.

Overall, these contributions position cocoa agroforestry systems as a key empirical case for understanding sustainability transitions in tropical agriculture, showing how the alignment of ecological requirements for biodiversity conservation, farm-level economic viability, and value-chain governance shapes sustainable transition pathways.

6.3. Research limitations and scope for further research

As with any empirical research, the findings of this dissertation should be interpreted in light of several limitations and deliberate scope choices. Reflecting on these aspects helps clarify the conditions under which the findings apply and points to important directions for future research. Several of the limitations discussed below reflect methodological and practical constraints inherent to field-based, interdisciplinary research, while others represent conscious choices aligned with the objectives of this dissertation.

First, the analysis is based on cross-sectional data collected during a single agricultural year, providing only a snapshot of economic conditions in CAFS. Given substantial inter-annual variability in cocoa yields, prices, and certification outcomes, longitudinal data would be required to capture temporal dynamics and evaluate how ecological and economic outcomes respond to market cycles and climatic variability.

Second, because the study focused on traditional CAFS, the findings primarily reflect ecological–economic relationships within forest-to-agroforestry transitions. They may be different from outcomes of systems established on degraded land or converted from monocultures, where ecological recovery processes and economic trade-offs likely differ substantially.

Third, while the dissertation integrates ecological and economic dimensions of sustainability, it does not explicitly address social aspects. Variables such as labour conditions, intra-household labour allocation, and gender dynamics were not measured, despite their potential importance for understanding both economic performance and ecological outcomes. Future research would benefit from incorporating more detailed social indicators to better capture trade-offs and synergies across sustainability dimensions. Similarly, the economic analysis did not include labour productivity as an explicit indicator, as collecting sufficiently detailed and reliable information on hired and household labour inputs was not feasible within the survey time constraints. Labour is a central component of cocoa production systems and is likely to mediate both economic performance and gender-differentiated outcomes. Incorporating labour productivity and labour allocation into future economic analyses would provide a more complete picture of farm-level performance and help clarify trade-offs between income, labour requirements, and management intensity.

Fourth, the analysis relies on shade-tree density as the primary indicator of agroforestry management. While this metric is objectively measurable and directly relevant for policy, its use entails several limitations. Tree species differ substantially in crown architecture and canopy structure, such that similar shade-tree densities can generate different levels of shade cover and structure complexity. Consequently, density-based thresholds may not fully capture the ecological heterogeneity of CAFS when species composition is not taken into account. Future research should therefore complement density measures with indicators that capture shade-tree species composition, canopy structure, or functional diversity, and evaluate how such indicators relate to biodiversity outcomes, economic performance, and their feasibility for inclusion in regulatory and certification frameworks.

Fifth, landscape-level influences on biodiversity were not addressed beyond forest cover, which was used as a proxy for surrounding habitat availability. The potential influence of landscape connectivity, or matrix quality, which are known to shape species presence at the farm level was not investigated. Future research integrating fine-scale landscape metrics with farm-level management data would help disentangle the relative contributions of local and landscape-scale factors to biodiversity outcomes in agroforestry landscapes.

Sixth, the economic analysis likely underestimates the full value of agroforestry products other than cocoa. While revenues from non-cocoa crops were captured in the economic analysis, the medicinal and timber values associated with shade trees were not explicitly quantified. This likely leads to an underestimation of the full economic value of agroforestry systems, particularly with respect to non-market or opportunistic uses of shade trees. At the same time, the importance of such values is highly context-specific. In the Atlantic Forest region of southern Bahia, cocoa production has historically been highly specialised, and the harvesting of fruits from native shade trees appears limited compared to regions such as the Amazon, where a wide range products of native shade trees is utilised. Future research should therefore adopt context-specific valuation approaches of AFS products that reflect regional livelihood strategies.

Finally, several methodological lessons emerge from the design of the ecological and governance analyses. The ecological assessment relies on observational data analysed using GLMMs and occupancy models, which allows the identification of statistically robust associations but limits causal inference regarding the effects of shade-tree management on biodiversity. While such correlational approaches remain common in conservation science, they do not permit attribution of observed outcomes to shade-tree management in the absence of a credible counterfactual. This aligns with emerging calls for greater use of impact evaluation approaches in conservation research in order to better inform policy and practice. Similarly, the analysis of the Sul da Bahia Geographical Indication was constrained by limited participation and sample size. Farmers were classified as GI participants based on having certified cocoa at least once between 2019 and 2024, although certification typically applies to only a subset of total annual cocoa production. This binary treatment definition may dilute estimated effects on price premiums and related economic outcomes. Future research could address this limitation through difference-in-differences or panel-based designs that exploit variation in certification over time to more accurately capture the economic impacts of participation in origin-based certification schemes. More generally, future studies would benefit from sequencing economic household surveys prior to ecological fieldwork and conducting ecological assessments on matched subsets of farms, thereby strengthening causal inference through the construction of more credible counterfactual comparisons.

6.4. Policy implications

The findings of this dissertation demonstrate that the ecological and economic sustainability of CAFS in southern Bahia depends not only on optimal shade-tree management but also on policies and market mechanisms that effectively recognise, support, and reward farmers' contributions to sustainability. To achieve this, current policy and market frameworks must provide stronger guidance on shade-tree management and institutional, market, and governance support, ensuring coherence and coordination across multiple governance levels. The following policy recommendations outline how different actors can contribute to better aligning production, conservation, and rural development objectives.

6.4.1. Government

The government plays a central role in establishing the regulatory and incentive framework that enables the long-term sustainability of CAFS. The state's current shade-tree management decree needs to be revised to establish an ecologically grounded threshold by increasing the minimum total shade-tree density to at least 100 trees per hectare, while maintaining a minimum of 40 native trees per hectare. This adjustment would better align legal requirements with empirically derived ecological thresholds for species of conservation concern, such as the golden-headed lion tamarin, while generating co-benefits for the broader mammal community within CAFS.

However, regulatory requirements alone are insufficient to ensure the long-term sustainability of CAFS if they are not accompanied by viable economic pathways for farmers. Beyond regulation, sustaining biodiversity-friendly CAFS depends on their economic viability, which is primarily driven by productivity. As this dissertation demonstrates, variation in cocoa yields is the principal determinant of differences in net returns per hectare from CAFS. Therefore, for AFS to be effective, yield-enhancing strategies must precede market-based incentives. Importantly, under high shade conditions, cocoa yields can be increased through improved agronomic management, especially pruning, soil fertility management, weed control and pollination management (Figueiredo et al., 2026; Toledo-Hernández et al., 2023, 2020). Accordingly, governments should prioritise research, training, and extension programs that enable farmers to implement these practices under high shade-tree densities, thereby improving economic performance without incentivising shade-tree removal. Moreover, improving the economic viability of CAFS will also require greater diversification of income sources from non-cocoa agroforestry products. At present, shade trees in CAFS primarily generate indirect value through ecosystem services, while their direct economic contribution remains limited. A common response has been the replacement of native shade trees with commercially attractive exotic species, a strategy that risks undermining biodiversity conservation objectives. Instead, policy and extension efforts should prioritise income diversification strategies that maintain native shade-tree cover while increasing economic returns through complementary crops. This includes the promotion of understory crops such as vanilla, whose productivity is not affected by higher shade levels (Wurz et al., 2022), as well as native fruit tree species such as cajá (*Spondias mombin*), jabuticaba (*Myrciaria cauliflora*), jenipapo (*Genipa americana*) and *Inga edulis* that can generate additional income through local markets without compromising ecological integrity.

Building on this productivity base, governments should promote positive incentive mechanisms, such as Payments for Environmental Services (PES), access to green credit, or fiscal benefits, that reward farmers for maintaining structurally complex AFS. Although Bahia's environmental legislation defines criteria for PES, excluding AFS with fewer than 40 native trees per hectare from eligibility (State Decree No. 15180/2014, Art. 15), the absence of an operational framework has limited its implementation. Evidence from PES initiatives across the Atlantic Forest shows that such schemes can effectively promote forest conservation when supported by clear institutional arrangements, stable funding, and strong monitoring systems (Montero-de-Oliveira et al., 2023; Ruggiero et al., 2019). Integrating PES as a complementary incentive mechanism to the shade-tree management decree could therefore strengthen compliance and encourage farmers to maintain and restore higher shade-tree densities. To be effective, PES implementation in Bahia should ensure long-term financial sustainability, transparent conditionality, and equitable access for farmers (Montero-de-Oliveira et al., 2023; Ruggiero et al., 2019).

In addition to PES, governments should facilitate the development of transparent and inclusive carbon credit mechanisms that reward the maintenance and protection of existing shade trees in CAFS, rather than solely incentivising new shade tree planting (Pappo et al., 2025). Integrating CAFS conservation into regional land-use and rural development plans would further strengthen ecological connectivity within the Atlantic Forest landscape, consistent with calls for landscape-level governance approaches to AFS and forest conservation (Cammelli et al., 2025). Moreover, strengthening rural extension services is essential to disseminate knowledge on shade-tree management practices that balance productivity with ecological sustainability and to foster more positive farmer perceptions of shade trees. Finally, reinforcing the institutional framework of the *Sul da Bahia* GI by aligning it with shade-tree management policies and ensuring the inclusion of small and less-endowed farmers would strengthen its contribution to sustainable rural development in southern Bahia.

6.4.2. Certification bodies

Certification bodies play a crucial role in translating sustainability objectives into market-based incentives that reward environmentally responsible cocoa production. To enhance their ecological effectiveness, certification schemes should adopt region-specific shade-tree management criteria that reflect empirically derived thresholds for biodiversity conservation, rather than applying generic global standards. Integrating ecological monitoring, using indicators such as shade-tree density, into certification audits and protocols would improve accountability and transparency. At the same time, certification schemes must become more socially inclusive. Most current certification schemes are designed around large-scale producers and fail to differentiate among actors in the value chain, overlooking the economic, technical, and organisational constraints of smaller producers (Carballido et al., 2025). In the regional context, the *Sul da Bahia* GI has strengthened product differentiation and regional identity but has failed to reach its potential as a driver of sustainable territorial development. To enhance its effectiveness, the GI should reinforce its institutional framework by improving coordination among the Regulatory Council, cooperatives, and buyers, while expanding producer outreach as well as technical and financial support to include smaller and less-endowed producers and agrarian reform farmers. The GI should also play a more active role in value chain coordination and development by fostering stable buyer commitments, supporting local processing capacity, and developing collective marketing and branding strategies that emphasise quality and origin in the domestic market. Increasing consumer awareness is equally important, through targeted campaigns that communicate the meaning and value of the GI seal, highlight the ecological and cultural heritage of *cabruca* systems, and differentiate high-quality cocoa and chocolate from mass-produced alternatives. Finally, integrating environmental indicators such as shade-tree density into the Regulation of Use would align the GI with environmental sustainability objectives, enabling it to function as a genuine mechanism linking quality, sustainability, and inclusive rural development in southern Bahia.

6.4.3. Cocoa buying companies

Cocoa-buying companies occupy an important position in advancing sustainability across the cocoa value chain through shaping the incentives and market conditions that influence farmers' management decisions. As midstream actors, they connect producers with markets and therefore hold strategic leverage to align economic incentives with environmental objectives (Grabs et al., 2024). To promote environmentally sustainable cocoa production, companies should explicitly reward cocoa production in AFS through differentiated pricing, long-term contracts and implementation of the shade-tree management decree. Their local presence and logistical capacity position them to deliver training, provide access to credit, and strengthen farmers' technical capacities. Strengthening traceability and data transparency is equally important while ensuring data rights for producers. Furthermore, companies can co-finance environmental incentive programs in collaboration with public institutions and NGOs to maintain ecosystem services across cocoa landscapes.

6.4.4. Farmer associations

Farmer organisations are key intermediaries for achieving collective action, equitable benefit-sharing, and the adoption of sustainable production practices. Strengthening cooperative structures can enhance farmers' bargaining power, facilitate collective marketing under sustainability or origin-based labels such as the *Sul da Bahia* GI, and improve price negotiation capacity. By coordinating access to financial incentives, training, and certification programs, associations can help producers overcome the economic and technical barriers that often limit participation in sustainability initiatives. They also play a crucial role in disseminating shade-tree management strategies that balance productivity with ecological sustainability and in promoting farmer-to-farmer learning. Through active engagement in governance mechanisms such as the *Sul da Bahia* GI, farmer associations can ensure that sustainability programs remain inclusive, context-specific, and responsive to farmers' needs.

6.4.5. Non-governmental organisations (NGOs)

NGOs and conservation organisations occupy a strategic position at the science–policy interface. They can translate empirical research, such as ecological thresholds for shade-tree density, into practical guidelines for policymakers, companies, and certification schemes. By implementing landscape-level conservation programs that connect high-shade CAFS with forest remnants, NGOs can enhance biodiversity corridors and ecosystem resilience. Moreover, capacity-building initiatives should empower farmers to adopt improved agronomic management practices. Continued monitoring of ecological and socio-economic outcomes will be crucial to ensure that sustainability interventions deliver equitable and measurable benefits. NGOs are also well-positioned to facilitate coordination among government agencies, certification bodies, and private companies, ensuring that sustainability initiatives are coherent and complementary. However, their impact is often limited by short-term project cycles and fragmented interventions. Long-term partnerships and co-financing mechanisms with public and private actors are therefore essential to ensure continuity and scaling of successful initiatives. Finally, NGOs can play an important role in raising consumer awareness of the ecological and cultural value of *cabruca* systems, helping to strengthen market demand for biodiversity-friendly products.

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Appendix A

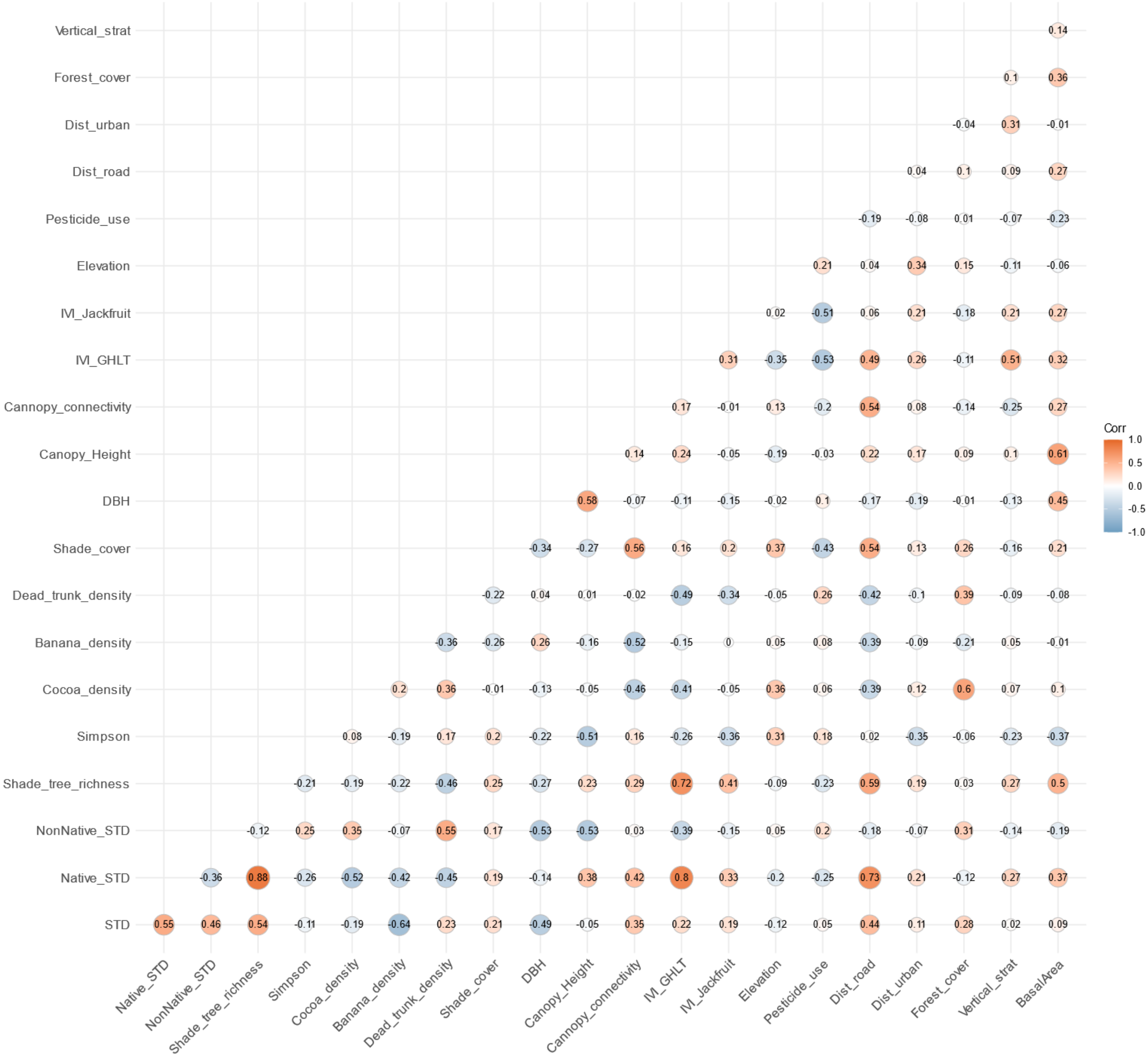


Figure A1 Spearman correlation matrix showing pairwise relationships between farm-level covariates. Correlation coefficients range from –1 (strong negative correlation) to +1 (strong positive correlation), with colour intensity indicating the strength and direction of the correlation.

Table A1 Shade tree species identified in the 18 CAFS surveyed in this study and their use by *L. chrysomelas* as a food source (F) and/or sleeping site (SS).

id	Family	Species	Common name	Type	Use	Reference
1	Anacardiaceae	*Spondias mombin* L.	cajazeira	native		
2	Anacardiaceae	*Tapirira guianensis* Aubl.	pau-pombo	native	F; SS	(Cardoso et al., 2011; Catenacci et al., 2016; Oliveira et al., 2011, 2010; Raboy and Dietz, 2004)
3	Annonaceae	*Annona salzmannii* A.DC.	pinha-da-mata	native	F	(Oliveira et al., 2010; Raboy and Dietz, 2004)
4	Annonaceae	*Guatteria oligocarpa* Mart	pindaíba-preta	native	SS	(Oliveira et al., 2010)
5	Apocynaceae	*Himatanthus bracteatus* (A. DC.) Woodson	janaúba	native	SS	(Oliveira et al., 2010)
6	Araliaceae	*Schefflera morototoni* (Aubl.) Maguire et al.	matataúba	native	F	(Couto and Oliveira, n.d.)
7	Arecaceae	*Euterpe edulis* Mart.	juçara; palmito	native		
8	Arecaceae	*Euterpe oleracea* Mart.	açaí	non-native		
9	Bignoniaceae	*Sparattosperma leucanthum* (Vell.) K.Schum.	caroba-branca	native		
10	Bombacaceae	*Eriotheca macrophylla* (K.Schum.) A.Robyns	imbiruçu	native	SS	(Catenacci et al., 2009)
11	Caricaceae	*Carica papaya* L.	mamão	non-native	F	(Oliveira et al., 2011)
12	Clusiaceae	*Tovomita brasiliensis (Mart.) Walp.*	mangue da mata	native	SS	(Oliveira et al., 2010)
13	Combretaceae	*Terminalia mameluco* Pickel	araça-d'água	native	SS	(Catenacci et al., 2009; Oliveira et al., 2010)
14	Cordiaceae	*Cordia* L.	claraíba	native	F?	(Catenacci et al., 2016; Oliveira et al., 2010; Raboy and Dietz, 2004)
15	Elaeocarpaceae	*Sloanea obtusifolia* (Moric.) Schum.	gindiba	native	F; SS	(Catenacci et al., 2016; Oliveira et al., 2010)
16	Euphorbiaceae	*Alchornea glandulosa subsp. iricurana* (Casar.) Secco	lava-prato	native		
17	Euphorbiaceae	*Aparisthmium cordatum* (A.Juss.) Baill.	lava-prato-branco; frieira	native		
18	Euphorbiaceae	*Hevea brasiliensis* (Willd. ex A.Juss.) Müll.Arg.	seringueira	non-native		
19	Euphorbiaceae	*Mabea brasiliensis Müll.Arg.*	leiteira	native	F	(Catenacci et al., 2016)
20	Fabaceae	*Andira anthelmia* (Vell.) Benth.	angelim coco	native	SS	(Oliveira et al., 2010)

Table A1 (Continued)

id	Family	Species	Common name	Type	Use	Reference
21	Fabaceae	*Andira* sp. Lam.	angelim	native		
22	Fabaceae	*Andira vermifuga* (Mart.) Benth.	angelim amargosa	native		
23	Fabaceae	*Arapatiella psilophylla* (Harms) R.S.Cowan	arapati; faveca-vermelha	native	SS	(Oliveira et al., 2010)
24	Fabaceae	*Bauhinia longifolia* (Bong.) Steud.	pata-de-vaca	native		
25	Fabaceae	*Bowdichia virgilioides* Kunth.	sucupira	native	SS	(Oliveira et al., 2010)
26	Fabaceae	*Clitoria fairchildiana R.A.Howard*	sombreiro	non-native		
27	Fabaceae	*Copaifera sp.* L.	copaíba	native	F[?]; SS[?]	(Catenacci et al., 2016, 2009)
28	Fabaceae	*Erythrina sp.* L.	eritrina	non-native		
29	Fabaceae	*Gliricidia sepium* (Jacq.) Kunth ex Walp.	mãe-do-cacau	non-native		
30	Fabaceae	*Inga sp.* Mill.	ingá	native	F[?]	(Cardoso et al., 2011; Catenacci et al., 2016; Oliveira et al., 2011, 2011; Raboy and Dietz, 2004)
31	Fabaceae	*Plathymenia foliolosa* Benth.	vinhático	native		
32	Fabaceae	*Senna multijuga* (Rich.) H.S.Irwin & Barneby	cobi	native		
33	Fabaceae	*Swartzia macrostachya* Benth.	jacarandá branco	native		
34	Fabaceae	*Dialium guianense* (Aubl.) Sandwith	jitaí	native	F; SS	(Catenacci et al., 2009; Oliveira et al., 2010; Raboy and Dietz, 2004)
35	Lauraceae	*Nectandra membranacea* (Sw.) Griseb.	louro-sabão	native	F; SS	(Couto and Oliveira, n.d.; Oliveira et al., 2010)
36	Lauraceae	*Nectandra sp.* Rol. ex Rottb.	louro-prego	native	F[?]; SS[?]	
37	Lauraceae	*Persea americana* Mill.	abacateiro	non-native	F	(Oliveira et al., 2011)
38	Lecythidaceae	*Cariniana estrellensis* (Raddi) Kuntze	jequitibá-cipó	native		
39	Lecythidaceae	*Cariniana legalis* (Mart.) Kuntze	jequitibá-rosa	native		
40	Lecythidaceae	*Eschweilera ovata* (Cambess.) Mart. ex Miers	biriba	native	F; SS	(Catenacci et al., 2016, 2009)

Table A1 (Continued)

id	Family	Species	Common name	Type	Use	Reference
41	Lecythidaceae	*Lecythis lurida* (Miers) S.A. Mori	inhaíba	native	F; SS	(Catenacci et al., 2009; Couto and Oliveira, n.d.; Oliveira et al., 2010)
42	Lecythidaceae	*Lecythis pisonis* Cambess.	sapucaia	native	SS	(Catenacci et al., 2009; Oliveira et al., 2010)
43	Malvaceae	*Apeiba tibourbou* Aubl.	pau-de-jangada	native		
44	Melastomataceae	*Henriettea succosa* (Aubl.) DC.	mundururú-ferro	native	F	(Cardoso et al., 2011; Catenacci et al., 2016; Oliveira et al., 2010; Raboy and Dietz, 2004)
45	Meliaceae	*Cedrela odorata* L.	cedro-rosa	native		
46	Meliaceae	*Guarea guidonia* (L.) Sleumer	carrapeta-verdadeira	native	F	(Couto and Oliveira, n.d.)
47	Moraceae	*Artocarpus heterophyllus* Lam.	jaqueira	non-native	F; SS	(Catenacci et al., 2016; Oliveira et al., 2011, 2010; Raboy and Dietz, 2004)
48	Moraceae	*Ficus sp.* L.	gameleira	native	F; SS	(Cardoso et al., 2011; Catenacci et al., 2016; Oliveira et al., 2011, 2010; Raboy and Dietz, 2004)
49	Moraceae	*Helicostylis tomentosa* (Poepp. & Endl.) Rusby	amora-preta	native	F	(Cardoso et al., 2011; Catenacci et al., 2016)
50	Myristicaceae	*Virola gardneri* (A.DC.) Warb.	bicuíba-vermelha	native	SS	(Oliveira et al., 2010)
51	Myristicaceae	*Virola officinalis* Warb.	bicuíba-branca	native	F; SS	(Catenacci et al., 2016, 2009)
52	Myrtaceae	Unidentified species 1	Unidentified species 1	native		
53	Myrtaceae	Unidentified species 2	araçá	native	F; SS	(Cardoso et al., 2011; Catenacci et al., 2016; Oliveira et al., 2011, 2010; Raboy and Dietz, 2004)
54	Nyctaginaceae	*Guapira obtusata* (Jacq.) Little	farinha-seca	native	F	(Oliveira et al., 2010; Raboy and Dietz, 2004)
55	Phytolaccaceae	*Gallesia integrifolia* (Spreng.) Harms	pau-d'alho	native		

Table A1 (Continued)

id	Family	Species	Common name	Type	Use	Reference
56	Rubiaceae	*Genipa americana* L.	jenipapeiro	native		
57	Rutaceae	*Citrus sp.* L.	laranjeira	non-native		
58	Sapotaceae	*Manilkara sp.* Adans.	maçaranduba	native	F; SS	(Cardoso et al., 2011; Catenacci et al., 2016, 2009; Oliveira et al., 2010; Raboy and Dietz, 2004)
59	Sapotaceae	*Pouteria grandiflora* (A.DC.) Baehni	bapeba-de-nervura	native	F; SS	(Catenacci et al., 2016, 2009)
60	Simaroubaceae	*Simarouba amara* Aubl.	pau-paraíba	native	F	(Oliveira et al., 2010; Raboy and Dietz, 2004)
61	Urticaceae	*Cecropia sp.* Loefl.	embaúba	native	F$^{?}$	(Catenacci et al., 2016; Oliveira et al., 2011)
62	Verbenaceae	*Aegiphila integrifolia* (Jacq.) Moldenke	fidalgo	native	SS	(Oliveira et al., 2010)
63	Lauraceae	Unidentified species 3	louro-comuja	native	SS	Observation in the field by field assistants
64	Unidentified	Unidentified species 4	Unidentified species 4	native		

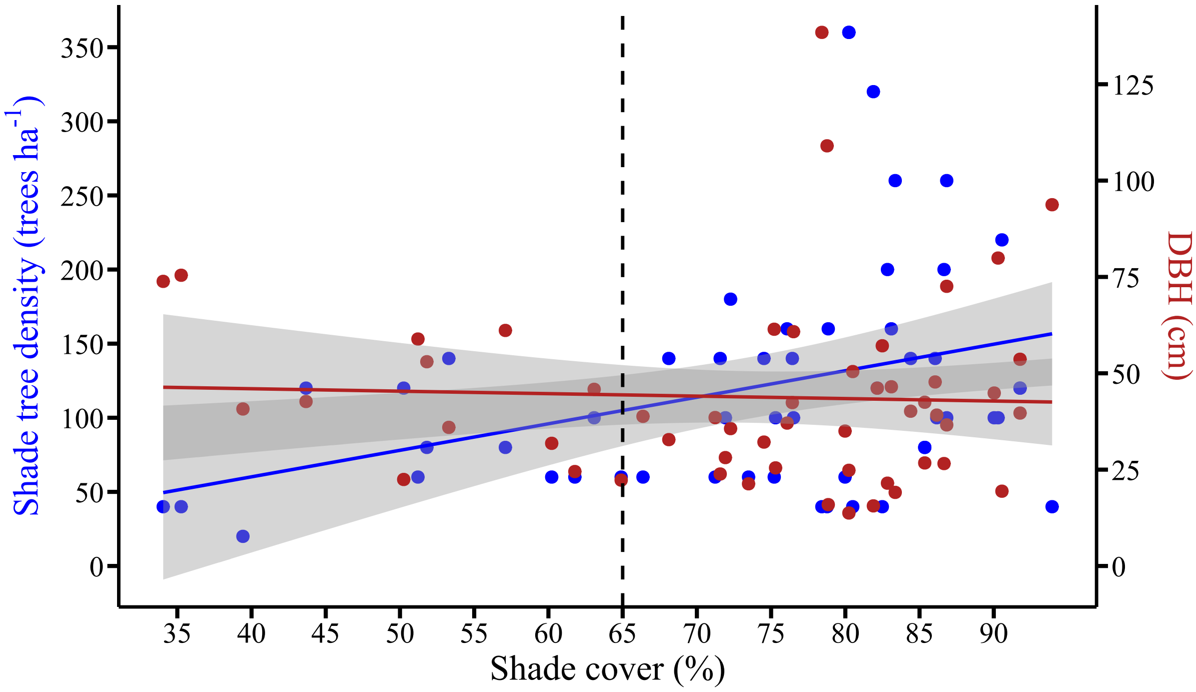


Figure A2 Shade cover (%) in relation to shade-tree density (trees ha^{-1}) and DBH of shade trees (cm) in each plot. A Spearman correlation test on plot-level measurements revealed a significant positive correlation between shade-tree density and shade cover ($\rho = 0.34$, $p < 0.05$) and no significant relationship correlation between shade cover and DBH of shade trees ($r = -0.04$, $p = 0.776$). The color-coded area represents the 95% confidence interval for the regression line.

Table A2. Model selection for the best-fitting model ($\Delta AIC = 0.00$) of detection probability *(p)* and occupancy (Ψ) of *Leontopithecus chrysomelas* in 18 cocoa agroforestry systems in southern Bahia, Brazil. The table shows the values of the number of parameters (K_i), the Akaike Information Criterion corrected for small samples (AICc), the difference between the AICc value of each model and the top-ranked model (ΔAICc) and the Akaike weight (AICcW). The best-supported model (bold) has ΔAICc = 0.00, with the lower ΔAICc values indicating stronger support with higher Akaike weights (AICcW) signify greater relative model strength.

Detection models	K_i	AICc	ΔAICc	AICcW
***p* (Forest cover) ~ ψ(1)**	**3**	**157.13**	**0.00**	**0.16**
p (1) ~ ψ(1)	2	158.30	1.17	0.09
p (Forest cover + sampling effort) ~ ψ(1)	4	158.64	1.51	0.08
p (Forest cover + time of visit) ~ ψ(1)	4	158.97	1.85	0.07
p (Forest cover + humidity) ~ ψ(1)	4	159.08	1.95	0.06
Occupancy models	K_i	AICc	ΔAICc	AICcW
***p*(Forest cover) ~ ψ(Shade cover + IVI Jackfruit)**	**6**	**148.58**	**0.00**	**0.35**
p(Forest cover) ~ ψ(Shade cover)	6	148.69	0.10	0.33
p(Forest cover) ~ ψ(Shade cover + Pesticide use)	5	151.42	2.84	0.08

Table A3 Local vegetation and landscape characteristics among 18 CAFS sites surveyed in southern Bahia, Brazil. Values are based on estimates at the CAFS-level, which were calculated from plot-level data.

Variable	**Mean**	**SD**	**Median**	**Min**	**Max**
Management characteristics					
Pesticide use (R$ ha^{-1})	34.79	48.54	16.91	0.00	169.00
Cocoa density (trees ha^{-1})	724.20	156.94	690.00	465.00	990.00
CAFS characteristics					
Shade cover (%)	73.51	11.06	78.48	46.18	88.33
Shade tree density (trees ha^{-1})	121.39	59.42	100.00	60.00	310.00
Native shade tree density (trees ha^{-1})	71.59	40.72	60.00	20.00	185.00
Non-Native shade tree density (trees ha^{-1})	48.41	51.21	20.00	0.00	220.00
Species richness (n° species)	4.07	1.34	3.75	2.00	6.50
Shade tree diversity (Hill-Simpson Index)	1.52	0.45	1.42	0.95	3.04
Vertical stratification (m)	5.83	2.65	5.34	2.00	13.29
Canopy height (m)	19.09	3.71	17.55	12.44	27.07
Shade tree characteristics					
DBH (cm)	48.35	14.26	38.67	31.54	73.94
Basal Area (m^2 ha^{-1})	25.54	10.51	23.05	14.98	46.45
Key habitat characteristics for *L. chrysomelas*					
Canopy Connectivity (n° tree crown connections)	2.49	0.81	2.12	1.25	3.88
Banana density (trees ha^{-1})	97.83	127.00	40.00	0.00	447.00
IVI key tree species	141.85	65.17	135.97	39.07	269.62
IVI jackfruit trees	20.64	23.75	20.96	0.00	80.53
Bromeliads (Index)	0.42	0.37	0.25	0.00	1.00
Landscape characteristics					
Elevation (m)	100.00	51.48	79.00	35.00	244.67
Distance to urban area (m)	3390.70	2167.43	3330.78	688.92	8988.64
Distance to roads (m)	562.44	388.00	431.07	148.08	1723.78
Forest cover (%)	38.51	15.61	38.60	10.77	68.75

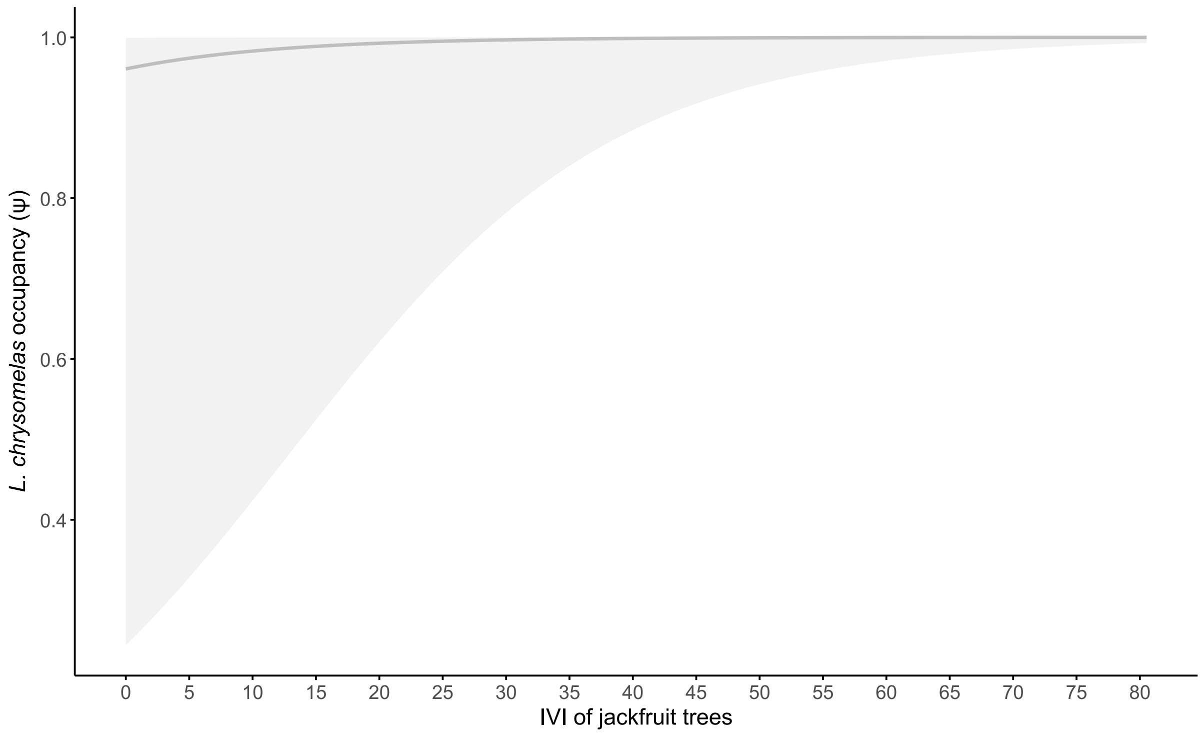


Figure A3 Predicted occupancy (Ψ) of *L. chrysomelas* within cocoa agroforestry systems as a function of IVI of jackfruit. The prediction was based on the model from Table 1. The grey line and the color-coded area represent the estimates and the 95% confidence intervals, respectively.

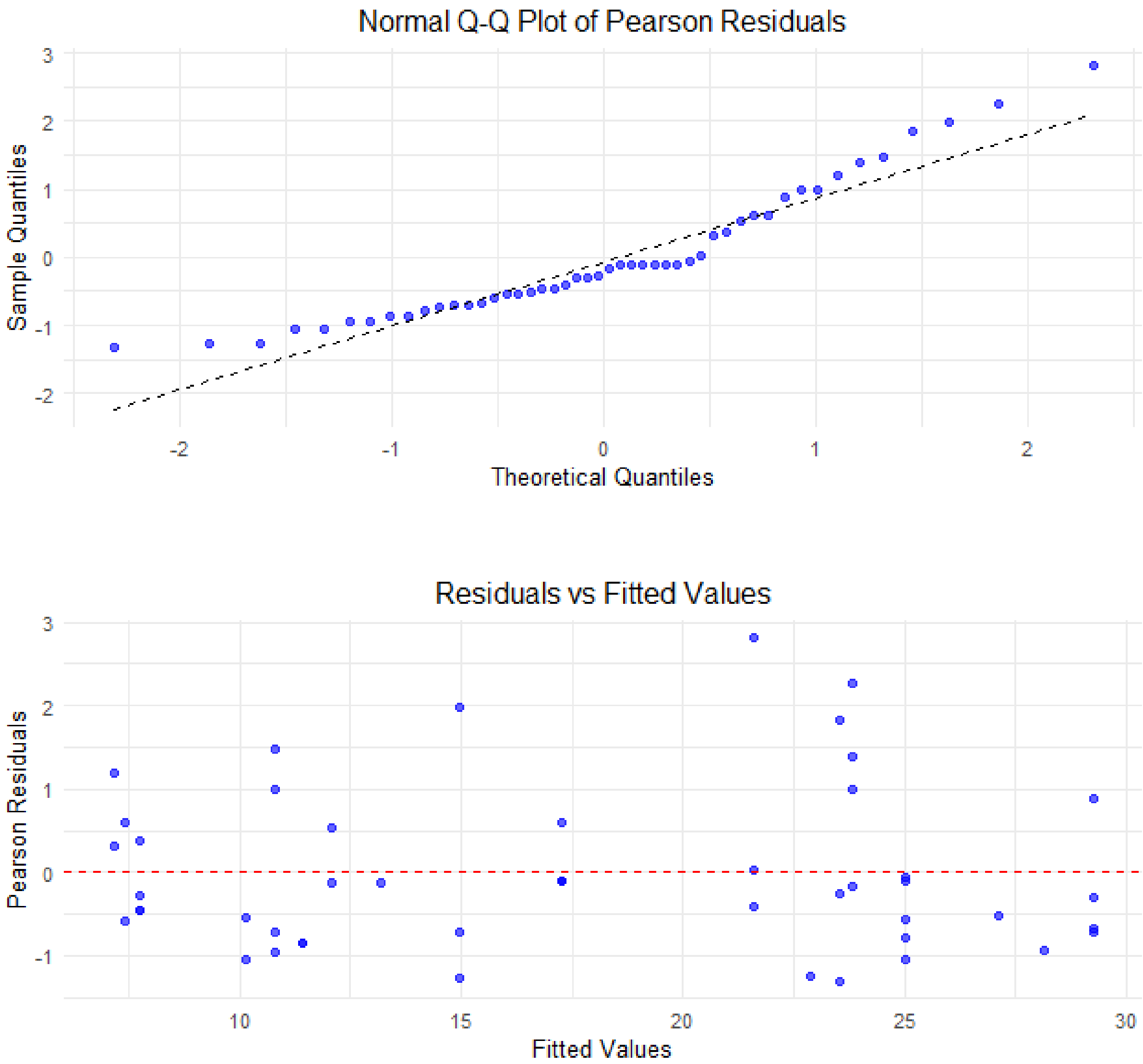
Table A4. Model selection for the best-fitting model (ΔAIC = 0.00) for mammal detection rate as response variable.

Models	K_i	AIC	ΔAICc	AICwt
Shade cover + Total basal area	**3**	**362.11**	**0.00**	**0.08**
Shade cover + Total basal area + Distance to road	4	363.31	1.20	0.04
Shade cover + Total basal area + Pesticide use	4	363.58	1.47	0.04
Shade cover + Total basal area + Shade tree diversity	4	363.80	1.69	0.03
Shade cover + Total basal area + Forest cover	4			

Table A5 Estimates of parameters predicting detections for mammal species classified as sensitive and insensitive to forest conversion into cocoa agroforestry systems (Ferreira et al. 2025) as a function of shade cover (%) and total basal area of shade trees (m^2 ha^{-1}) analysed using a Generalized Linear Mixed Model (GLMM; family = Negative Binomial).

Response variable	Covariates	Estimate	SE	Z	P-value
Insensitive mammal species detections	Intercept	-0.36	0.15	2.39	< 0.05
	Shade cover	0.24	0.15	1.62	0.105
	Total basal area	-0.55	0.16	-3.42	< 0.001
Sensitive mammal species detections	Intercept	-0.86	0.14	-6.20	< 0.001
	Shade cover	0.37	0.15	2.47	< 0.05
	Total basal area	-0.40	0.13	-3.15	<0.01

Figure A4 Diagnostic plots for the best-fit Generalized Linear Mixed Model with a Negative Binomial error structure: (a) Normal QQ plot of Pearson residuals, and (b) Residuals vs. Fitted Values plot, used to assess model fit and detect overdispersion.



Appendix B

Table B1 Coefficient stability analysis of the effect of shade tree density on economic outcomes.

Economic outcome	β(short)	β(medium)	Breakdown point
Cocoa yield	-0.273	-0.220	33.7%
Cocoa production costs	-2.261	-1.685	27.1%
Gross revenue of other crops	-0.838	-0.908	32.2%
Returns from CAFS	-3.515	-3.093	25.6%

Notes: β(short) and β(medium) are the estimated coefficients for shade tree density obtained using the coefficient stability approach of Diemert et al. (2023). β(short) benchmarks the potential strength of unobserved confounders against the explanatory power of a smaller baseline set of observed covariates, while β(medium) benchmarks against an extended set of observed covariates. The breakdown point indicates the proportion of the selection on observables that unobservables would need to have to reduce the estimated effect to zero.

Table B2 Robustness check of OLS regression estimates on economic performance indicators of cocoa agroforestry systems with additional control variables.

	Cocoa yield		Cocoa production costs		Net cocoa income		Gross revenue of other crops		Returns from CAFS	
Shade tree density	-0.227	**	-1.634		-2.548		-1.159	***	-3.769	**
	(0.103)		(1.018)		(1.800)		(0.393)		(1.891)	
Female HH head	-50.013	**	-82.734		-1097.813	***	-129.638		-1209.314	***
	(21.913)		(232.754)		(352.904)		(108.317)		(369.456)	
Age HH head	0.679		7.995		0.752		0.650		1.713	
	(0.729)		(7.198)		(12.974)		(3.709)		(13.257)	
Education HH head	0.631		61.172	***	2.733		14.346		15.481	
	(2.516)		(22.800)		(44.868)		(9.755)		(46.359)	
Settlement (dummy)	-66.943	***	-819.443	***	-855.218	**	-175.933	*	-1048.243	**
	(22.598)		(241.978)		(432.625)		(104.064)		(458.214)	
Distance HH-road	3.783		18.721		17.152		-7.790		11.797	
	(3.143)		(31.050)		(52.553)		(11.030)		(54.130)	
CAFS size	-0.660	***	-4.591	**	-7.552	*	-1.580	***	-8.993	**
	(0.240)		(1.814)		(3.844)		(0.524)		(3.935)	
Elevation CAFS	0.155		-1.464		2.931		-0.603		2.369	
	(0.159)		(1.320)		(2.849)		(0.478)		(2.956)	
Cocoa hybrids/clones (dummy)	47.226	**	390.701	**	452.318		110.225		567.629	
	(20.304)		(168.235)		(350.402)		(92.194)		(363.416)	
Middlemen channel (dummy)	3.924		-326.938		381.313		194.685	***	582.398	
	(28.121)		(291.223)		(527.912)		(72.472)		(554.056)	
Producers' organisation	13.485		288.388		558.691		384.971	***	958.652	**
	(22.258)		(205.546)		(411.422)		(90.422)		(432.320)	
Constant	183.521	***	822.829		2215.395	*	128.453		2330.989	*
	(68.365)		(662.032)		(1178.802)		(263.836)		(1213.230)	
Number of observations	313		313		313		313		313	
R^2	0.12		0.12		0.07		0.10		0.08	

Note: Coefficient estimates for the economic outcome variables are shown with robust standard errors between parentheses. Outcome variables trimmed at 1% values.

Table B3 Results of OLS regression estimates on economic performance indicators of cocoa agroforestry systems, 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)	
Female HH head	-54.209	***	-111.406		-1092.668	***	-73.900		-1146.199	***
	(20.606)		(230.528)		(331.462)		(111.675)		(345.239)	
Age HH head	0.642		7.274		0.649		0.879		1.847	
	(0.722)		(7.259)		(12.681)		(3.843)		(13.043)	
Education HH head	0.759		65.811	***	9.128		19.490	*	27.224	
	(2.433)		(23.581)		(43.820)		(9.946)		(45.172)	
Settlement (dummy)	-66.063	***	-805.885	***	-661.675	*	-12.743		-685.252	*
	(19.021)		(212.298)		(371.299)		(85.898)		(394.150)	
Distance HH-road	3.992		15.633		22.683		-6.650		18.495	
	(3.114)		(30.543)		(51.130)		(11.341)		(53.230)	
CAFS size	0.776	*	6.974	*	11.573	*	-1.640		10.041	
	(0.423)		(4.172)		(6.646)		(1.055)		(6.786)	
Elevation CAFS	0.178		-1.001		3.283		-0.494		2.834	
	(0.155)		(1.370)		(2.845)		(0.489)		(2.964)	
Cocoa hybrids/clones (dummy)	49.612	**	402.175	**	467.846		93.593		565.819	
	(19.989)		(168.446)		(348.574)		(94.078)		(362.129)	
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 between parentheses. Outcome variables trimmed at 1% values. *$p < 0.10$, **$p < 0.05$, ***$p < 0.01$.

Appendix C

Table C1 Descriptive statistics of sample cocoa farmers (n=313) across 12 municipalities 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 a sharecropper (%)	5.75		0.00	100.00
HH head is part of an agrarian reform settlement (%)	41.53		0.00	100.00
Farm characteristics				
HH head has income from other crops in CAFS (%)	49.20		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				
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
Cocoa price[5] (USD/kg)	3.16	0.63	0.47	5.34
Young cocoa trees (%)	12.92		0.00	100.00
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
FTE[4] family labour devoted to cocoa	0.73	0.41	0.00	2.74
FTE 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] Off-farm employment is any type of job in the non-farm sector (both wage and self-employment), as hired labour on other farms.

[3] Non-labour income is income from other non-labour sources, such as pension, remittances, renting out land and/or houses.

[4] Full-Time Equivalent (FTE)

[5] The average annual exchange rate in 2023 was 1 USD = 4.994 BRL (World Bank, 2025)

Table C2 Number and percentage of cocoa farmers (n = 312) reporting the presence of medium- and large-sized mammals within their cocoa agroforestry systems in southern Bahia, Brazil, based on household interviews.

Species	Common name	N° reports	Relative frequency (%)
Dasypus novemcinctus (Linnaeus, 1758)	Nine-banded armadillo	291	92.68
Pecari tajacu (Linnaeus, 1758)	Collared peccary	277	88.22
Callithrix kuhlii (Coimbra-Filho, 1985)	Wied's marmoset	267	85.03
Cerdocyon thous (Linnaeus, 1766)	Crab-eating fox	265	84.39
Euphractus sexcinctus (Linnaeus, 1758)	Six-banded armadillo	256	81.53
Cuniculus paca (Linnaeus, 1766)	Spotted paca	252	80.25
Nasua nasua (Linnaeus, 1766)	South American coati	241	76.75
Tamandua tetradactyla (Linnaeus, 1758)	Southern tamandua	238	75.80
Didelphis aurita (Wied-Neuwied, 1826)	Black-eared opossum	223	71.02
Coendou & Chaetomys sp.	Porcupine species	214	68.15
Coendou insidiosus (Lichtenstein, 1818)	Bahia hairy dwarf porcupine		
Chaetomys subspinosus (Olfers, 1818)	Thin-spined porcupine		
Eira barbara (Linnaeus, 1758)	Tayra	200	63.69
Mazama sp. & Passalites sp.	Brocket deer species	168	53.50
Procyon cancrivorus (G. Cuvier, 1798)	Crab-eating raccoon	156	49.68
Sylvilagus brasiliensis (Linnaeus, 1758)	Brazilian rabbit	154	49.04
Leontopithecus chrysomelas (Kuhl, 1820)	Golden-headed lion tamarin	136	43.31
Leopardus sp.	Ocelots	118	37.58
Leopardus wieddi (Schinz, 1821)	Margay		
Leopardus pardalis (Linnaeus, 1758)	Ocelot		
Leopardus guttulus (Schreber, 1775)	Southern Tiger Cat		
Sapajus xanthosternos (Wied-Neuwied 1826)	Buff-headed capuchin	117	37.26
Potos flavus (Schreber , 1774)	Kinkajou	112	35.67
Dasyprocta leporina (Linnaeus, 1758)	Red-rumped agouti	108	34.39
Puma concolor (Linnaeus, 1771)	Puma	32	10.19
Herpailurus yagouaroundi (É. Geoffroy Saint-Hilaire, 1803)	Jaguarundi	26	8.28

Table C3 Descriptive statistics of producer, farm and CAFS characteristics across ecological-economic outcomes.

	Q1: Low mammal richness High productivity		Q2: High mammal richness- High productivity		Q3: Low mammal richness- Low productivity		Q4: High mammal richness- Low productivity							
Variable	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Q1-Q2	Q1-Q3	Q1-Q4	Q2-Q3	Q2-Q4	Q3-Q4
Producer characteristics														
HH head Female (%)	19.18	4.64	14.29	3.84	30.99	5.53	23.81	4.68						
Age HH head (yrs)	56.9	1.69	56.95	1.45	51.75	1.77	56.79	1.41		**		**		**
Education HH head (yrs)	9.49	0.58	8.29	0.47	10.03	0.55	9.33	0.43	*			**		
Experience HH head (yrs)	20.03	1.29	21.94	1.37	13.01	1.21	20.57	1.43		***		***		***
HH size	2.89	0.19	3.15	0.19	2.76	0.17	3.25	0.16						
Dependency ratio[1]	0.79	0.03	0.69	0.03	0.78	0.03	0.67	0.03	*		**	*		*
HH head is sharecropper (%)	5.48	2.68	7.14	2.83	4.23	2.4	5.95	2.6						
HH head part of settlement (%)	38.36	5.73	41.67	5.41	36.62	5.76	48.81	5.49						
Farm characteristics														
Third-party certification (%)	2.74	1.92	0	0	1.41	1.41	5.95	2.6						
Producer organisation (%)	60.27	5.77	59.52	5.39	50.7	5.98	63.1	5.3						
Distance HH-CAFS (km)	0.56	0.11	0.42	0.08	0.92	0.38	0.56	0.09						
Distance HH-road (km)	3.86	0.5	4.27	0.45	3.74	0.41	3.98	0.43						
Cocoa production														
CAFS size (ha)	9.33	1.53	11.1	2.61	20.33	5.77	25.36	5.47		*	**	**	**	
Young cocoa trees (%)	14.28	2.22	11.45	2.2	13.24	2.24	13.08	2.02						
Presence of cocoa hybrids (%)	78.08	4.88	78.57	4.5	71.83	5.38	65.48	5.22						
Middlemen channel (%)	82.19	4.51	88.1	3.55	70.42	5.45	91.67	3.03						
Altitude CAFS (m)	151.9	10.07	156.22	8.4	140.26	9.49	142.11	6.98						
Distance CAFS-forest (km)	0.09	0.02	0.12	0.02	0.08	0.01	0.09	0.01						
Native shade tree (%)	59.22	3.05	62.72	2.66	63.35	2.89	70.64	2.31			**		*	

Table C4 Robustness check with additional control variables reporting average marginal effects from a multinomial probit model.

Variable	Q1: Low mammal richness - High productivity	Q2: High mammal richness - High productivity	Q3: Low mammal richness- Low productivity	Q4: High mammal richness- Low productivity
Shade-tree density	-0.001 **	0.000	-0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)
Female HH head	-0.030	-0.127 **	0.182 ***	-0.024
	(0.056)	(0.054)	(0.061)	(0.055)
Experience HH head	0.002	0.005 **	-0.011 ***	0.004 **
	(0.002)	(0.002)	(0.002)	(0.002)
Settlement (dummy)	-0.094 *	-0.037	0.040	0.091 **
	(0.054)	(0.057)	(0.053)	(0.059)
Distance HH-road	-0.007	0.001	0.001	0.004
	(0.007)	(0.007)	(0.006)	(0.007)
CAFS size	-0.004 ***	-0.001	0.001	0.004 ***
	(0.001)	(0.001)	(0.001)	(0.001)
Elevation CAFS	-0.000	0.000	-0.000	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)
Cocoa hybrids (dummy)	0.061	0.062	-0.007	-0.116 **
	(0.051)	(0.053)	(0.051)	(0.057)
Middlemen channel (%)	-0.057	0.077	-0.22 ***	0.2 ***
	(0.073)	(0.068)	(0.076)	(0.050)
Producer organisation	0.026	0.008	-0.060	0.027
	(0.052)	(0.054)	(0.051)	(0.052)

Note: Reported values are average marginal effects. Robust standard errors are shown in parentheses. *p < 0.10, **p < 0.05, ***p < 0.01

Appendix D

Figure D1 Boxplots and kernel density plots of propensity scores before and after matching, comparing nearest-neighbour matching in Stata (top panels) and genetic matching in R (bottom panels).

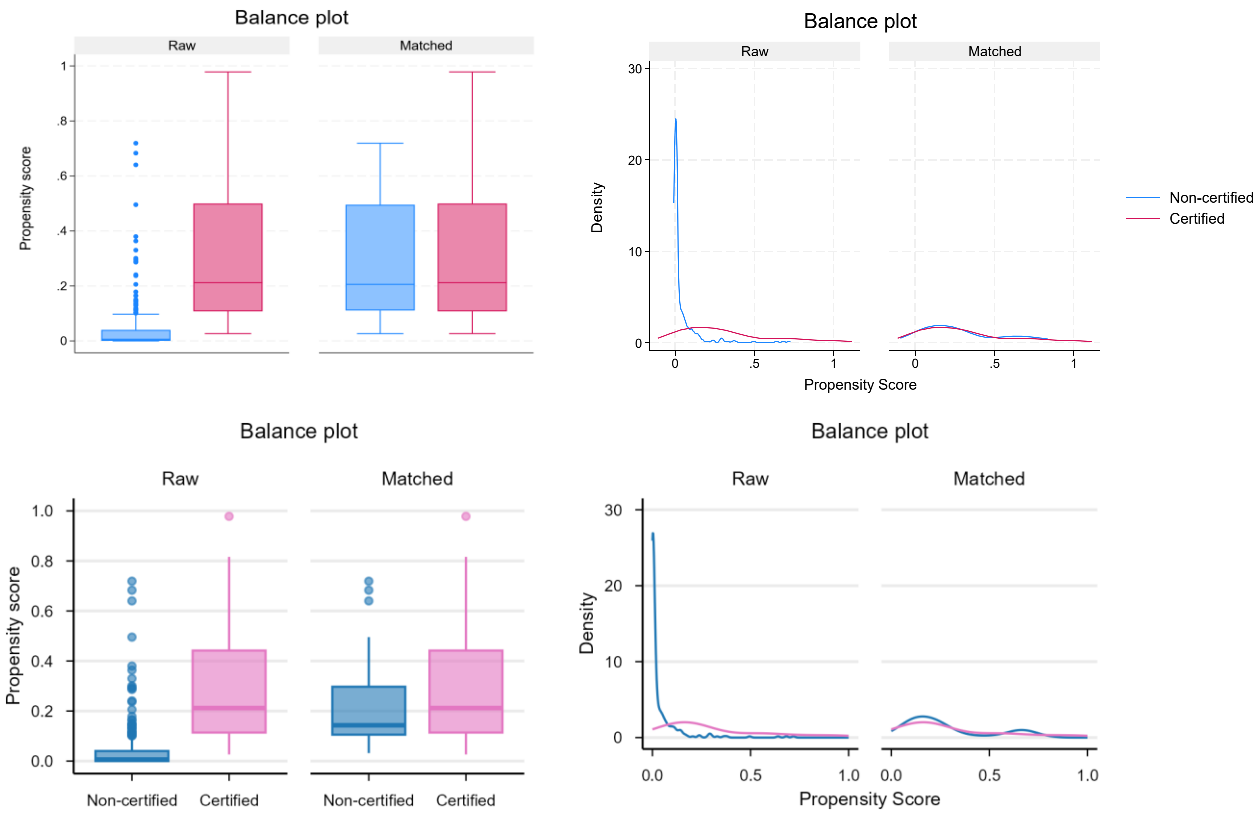


Table D1 Standardized mean differences (SMDs) and variance ratios (VRs) of matching covariates for certified and noncertified producers in the unmatched sample and in the matched samples, using nearest neighbourhood matching (1:1 and 1:2).

	Unmatched		Nearest neighbour 1–1		Nearest neighbour 1–2	
Covariate	SMD	VR	SMD	VR	SMD	VR
Experience HH head (yrs)	-0.289	0.671	0.154	1.414	0.150	1.272
Cocoa fermentation (days)	1.633	0.135	0.124	0.836	-0.048	0.378
Distance to GI headquarters (km)	-0.806	0.865	-0.101	3.375	-0.090	3.291
CAFS size (ha)	0.886	9.651	0.013	1.234	0.161	1.147
Number of non-certified	295		18		22	
Number of certified	18		18		18	

Table D2 Robustness check: Standardized mean differences (SMDs) and variance ratios (VRs) of matching covariates for certified and noncertified producers in the unmatched sample and in the matched samples, using genetic matching (1:1 and 1:2) with replacement.

	Unmatched		Genetic matching 1–1		Genetic matching 1–2	
Covariate	SMD	VR	SMD	VR	SMD	VR
Experience HH head (yrs)	-0.32	0.671	0.038	1.133	0.046	1.035
Cocoa fermentation (days)	3.349	0.135	0	0.312	0.097	0.553
Distance to GI headquarters	-0.84	0.865	-0.04	1.613	0.025	2.92
CAFS size (ha)	0.658	9.651	0.116	1.538	0.127	1.5
Number of non-certified	295		14		22	
Number of certified	18		18		18	

Table D3 Robustness check for average treatment effects on the treated (ATET) of *Sul da Bahia* GI certification on economic outcome indicators, estimated using nearest-neighbour matching (1:2) and genetic matching (1:1 and 1:2).

	Nearest neighbour (1:2)			Genetic matching (1:1)			Genetic matching (1:2)		
Outcome	ATET	Std. Error	P-value	ATET	Std. Error	P-value	ATET	Std. Error	P-value
Cocoa yield (kg ha^{-1})	-1.90	71.15		20.191	62.761		21.02	49.37	
Cocoa price (R$ kg^{-1})	0.76	1.23		0.284	1.374		0.94	1.01	
Cocoa total production costs (R$ ha^{-1})	1148.92	615.37	*	1144.027	670.990	*	801.03	589.71	
Net cocoa income (R$ ha^{-1})	-1037.94	1211.83		-467.611	1553.880		60.84	1132.20	
Gross revenue from other crops than cocoa (R$ ha^{-1})	-71.70	37.18	*	-95.998	181.294		-149.40	140.34	
Returns from CAFS (R$ ha^{-1})	-1383.27	1298.25		51907.936	64400.646		71876.88	44733.88	
Household income (R$)	73512.43	38371.04	*	21091.550	21798.508		26010.63	18056.43	
Per capita income (R$)	29984.01	17463.96	*	20.191	62.761		21.02	49.37	

*Note: Nearest-neighbour matching estimates are obtained using Stata (teffects psmatch), while genetic matching estimates are obtained using the MatchIt package in R. * (p < 0.1), ** (p < 0.05) and *** (p < 0.01)*

Table D4. Robustness check for average treatment effects on the treated (ATET) of *Sul da Bahia* GI certification on ecological outcome indicators, estimated using nearest-neighbour matching (1:2) and genetic matching (1:1 and 1:2).

	Nearest neighbour (1:2)			Genetic matching (1:1)			Genetic matching (1:2)		
Outcome	ATET	Std. Error	P-value	ATET	Std. Error	P-value	ATET	Std. Error	P-value
Shade-tree density (trees ha^{-1})	-53.97	10.05	***	-47.17	18.78	**	-48.31	14.84	***
Native shade tree (%)	-8.36	7.43		-4.47	7.31		-5.99	5.96	
Total mammal richness (n° species)	-3.14	1.00	***	-2.58	1.10	**	-2.42	0.95	**
Insensitive mammal species richness (n° species)	-0.81	0.18	***	-0.81	0.45	*	-0.76	0.39	*
Sensitive mammal species richness (n° species)	-2.33	0.24	***	-1.77	0.79	**	-1.66	0.67	**

*Note: Nearest-neighbour matching estimates are obtained using Stata (teffects psmatch), while genetic matching estimates are obtained using the MatchIt package in R. * (p < 0.1), ** (p < 0.05) and *** (p < 0.01)*

Appendix E

Questionnaire household survey

The questionnaire was administered in Portuguese. The English version of the questionnaire is presented below.

Module 0: Preliminary survey information

Q1. Enumerator

Q2. Municipality

Q3. Name of the person responsible for cocoa production and managament of the cocoa farm

Q4. Name of the farm or agrarian reform settlement

Q5. Coordinates

Q6. Phone number

Module 1: Farm-household characteristics

Q7. How old are you?

Q8. Sex (Male/Female)

Q9. What is your level of education?

- No certificate/diploma
- Illiterate
- Primary school certificate
- High school certificate
- Bachelor's degree or licentiate
- University diploma (Master or above)

Q10. How many members does your household have (including yourself)?

Q11. How many members able to work does your household have (including yourself)?

Q12. What is the highest school diploma or certificate that a household member other than you hold?

- No certificate/diploma
- Illiterate
- Primary school certificate
- High school certificate
- Bachelor's degree or licentiate
- University diploma (Master or above)

Module 2: Land ownership and total landholdings

Q13. Is the land that you use, own or hold use rights for part of a settlement? (No/Yes)

Q14. Are you a sharecropper? (No/Yes)

Q15. What is the total size of land of this property?

Q16. Measurement unit (hectare/m²/tarefa)

Q17. What is the size of land that you own?

Q18. Measurement unit (hectare/m²/tarefa)

Q19. Are you registered in the CEFIR system? (No/Yes)

Q20. Why not?

- No formal land ownership document
- Registration procedure is too expensive
- Does not know registration procedure
- Conflict over property boundaries
- Other (specify)
-

Q21. Are the river banks forested on this property? (No/Yes/Partially/Not applicable)

Q22. How many plots do you use, own or hold use rights for, either alone or with someone else?

Q23. Information regarding each plot

Q24. Name of the plot

Q25. How has this {plot name} been used during the past 12 months?

- Cocoa in AFS (with or without other crops)
- Full sun cocoa (with or without other crops)
- Other crops (than cocoa) in full sun
- Fallow
- Pasture
- Orchard (perennial crops)
- Cocoa-rubber
- Cococa with erythrina
- Forest
- Other (specify)

Q26. What is the total size of ${plot name}?

Q27. Measurement unit (hectare/m²/tarefa)

Q28. What share (%) of ${plot name} is occupied with crops?

Q29. Which cocoa agroforestry plot is the clostest to the homestead?

Q30. How long does it take (in minutes) to walk from the homestead to the clostest cocoa agroforestry plot?

Q31. What is the distance (km) from home to clostest cocoa agroforestry plot?

Q32. What is the distance (km) from clostest cocoa agroforestry plot to the forest?

<u>Module 3: Cocoa production and commercialization</u>

Q33. When did you start producing cocoa?

Q34. Cocoa production in cocoa agroforestry systems

Q35. What share (%) of your cocoa trees is young and not yet productive in your CAFS?

Q36. What variaties of cocoa do you use on your CAFS?

- Common varieties
- CCN51
- PS 1319
- CEPEC2002
- Ipiranga 01
- PS 1030
- PH 16
- SR162
- TSH1188
- BN34
- VB1151
- SJ02
- Hybrid
- Other (specify)

Q40. In the past 12 months, what was the total amount of cocoa harvested on your CAFS?

Q41. Measurement unit (arroba/kg/bag)

Q42. How much does one bag weigh?

- 30 kg
- 60 kg
- 2 arrobas
- 4 arrobas

Q47. Does the quantity harvested cocoa refer to dry or wet (fresh) beans?

Q48. Do you have cocoa in full sun, cocoa with only rubber trees and/or cocoa with only erithrina trees? (No/Yes)

Cocoa production in full sun / cocoa with rubber trees / cocoa with erithrina trees?

Q50. What share (%) of your cocoa trees is young and not yet productive in your full sun/ cocoa-rubber/ cocoa-ertithrina area?

Q51. What variaties of cocoa do you use on your full sun/ cocoa-rubber/ cocoa-ertithrina area?

- Common varieties
- CCN51
- PS 1319
- CEPEC2002
- Ipiranga 01
- PS 1030
- PH 16
- SR162
- TSH1188
- BN34
- VB1151
- SJ02
- Hybrid
- Other (specify)

Q53. In the past 12 months, what was the total amount of cocoa harvested on your full sun/ cocoa-rubber/ cocoa-ertithrina area?

Q54. Measurement unit (arroba/kg/bag)

Q55. How much does one bag weigh?

- 30 kg
- 60 kg
- 2 arrobas
- 4 arrobas

Q56. Does the quantity harvested cocoa refer to dry or wet (fresh) beans?

Q57. How much of your total production of cocoa did you manage to sell?

Depending on what the producer can tell you, ask them for the price (R$ per @/kg/bag) or the total revenue (R$) from cocoa production.

Q59. On average, what price (R$/@/kg/bag) did you receive for your cocoa?

Q60. Measurement unit (arroba/kg/bag)

Q61. How much revenues did you receive for your cocoa production (R$)?

Q62. To whom did you sell your cocoa beans?

- Cooperative
- Local middlemen
- Dengo
- Olam
- Barry Callebaut
- Cargill
- Other (specify)
- Barry Callebaut

Q64. Do you ferment your cocoa? (No/Yes)

Q65. Why do you ferment your cocoa? (Higher selling price/Other (specify))

Q67. Why do you not ferment your cocoa?

- No added value to the product
- A lot of work
- Do not know procedure
- Too little volume of cocoa
- Urgency to commercialize product for financial return
- No (adequate) infrastructure
- Too little demand
- Difficult requirements
- Other (specify)
- No (adequate) infrastructure

Q69. Where do you ferment cocoa beans?

- Wooden boxes
- Bags
- Within the plantation (a stack of cocoa beans, either covered with banana leaves or not)
- Raised platform
- Other (specify)
-

Q71. How many days do you ferment your cocoa?

Q72. Do you dry your cocoa? (No/Yes)

Q73. What drying structure do you use?

- Raised platform
- Greenhouse
- Mixed
- Firewood
- Other (specify)
-

Q75. What were the total investment costs (R$) you made to buy equipment for fermentation and drying during the past 5 years?

Q76. Do you produce "*mel de cacao*" (cocoa honey) for selling purpuses? (No/Yes)

Q77. How much of mel de cacau did you manage to sell (in liters)?

Q78. What were the total net revenues (R$) from selling mel de cacau?

Q79. Do you re-sell (part of) your cocoa that is processed into cocoa nibs? (No/Yes)

Q80. How much of the cocoa nibs did you manage to sell?

Q81. What were the total net revenues (R$) from selling cocoa nibs?

Q82. Do you re-sell (part of) your cocoa that is processed into chocolate? (No/Yes)

Q83. How much of the chocolate did you manage to sell?

Q84. Measurement unit (kg/bars)

Q85. What were the total net revenues (R$) from selling chocolate?

Module 4: Production and commercialization of other crops (besides cocoa) in CAFS

Q87. Do you have other crops in your cabruca that you sell or use for own consumption? (No/Yes)

Note: Here we are interested in the harvest and quantity produced of other crops (besides cocoa) in the CAFS (with shade trees). This includes products from planted and naturally occurring trees, annual and permanent crops.

Q115. Please list ALL trees and crops, including planted trees, annual and permanent crops.

Q91. In the past 12 months, what was the total amount of {name of crop or tree} harvested?

Q92. Measurement unit (kg/other measurement unit)

Q94. How much does one {other measurement unit} weight in kilograms?

Q95. How much of the production of {name of crop or tree} did you manage to sell?

Depending on what the producer can tell you, ask them the price (R$/kg) or the revenue (R$) they received from harvesting the {name of crop or tree} last year.

Q97. Measurement unit (kg/other measurement unit)

Q99. How much revenues did you receive from the sale of {name of crop or tree}?

Q100. In the last 12 months, did your household use any of the harvested {name of crop or tree} for own consumption? (No/Yes)

Q101. In the last 12 months, what was the total amount of {name of crop or tree} consumed by your household?

Q102. Measurement unit (kg/other measurement unit)

Shade trees

Q105. How do you categorise the level of shade in your cocoa agroforestry system?

- Low
- Medium
- High

Q106. What is your estimation of the number of shade trees in your cocoa agroforestry system?

Q107. Measurement unit (hectare/m²/tarefa)

Q108. What is the proportion (%) of naturally occurring native trees compared to planted/exotic trees (syringa/erithrina/jaqueira) in your CAFS?

Q109. What dificulties do you associate to these naturally occuring trees in your cocoa area?

- No difficulty
- Competition with cocoa
- Reduced crop yield
- Susceptibility to fungal attacks
- Other (specify)

Q111. What benefits have you experienced from the naturally occuring shade trees in your cocoa area?

- No benefit
- Shade for cocoa trees
- Food (fruits, leaves, etc.) for own consumption
- Food for additional sources of income
- Medicinal properties
- Timber/fuelwood
- Soil fertility preservation or enhancement
- Other (specify)

Module 5: Production of other crops outside CAFS (without cocoa and shade trees)

Q114. Do you cultivate other crops outside CAFS (without any naturally occuring shade tree) for production purpuses, including harvesting, collecting or using any products from them? (No/Yes)

Note: Here we are interested in the quantity of produced and harvested crops (other than cocoa) outside CAFS, for exemple in unshaded plots.

Q115. Please list ALL trees and crops, including planted trees, annual and permanent crops.

Q118. In the past 12 months, what was the total amount of {name of crop or tree outside cafs} harvested?

Q119. Measurement unit (kg/other measurement unit)

Q121. How much does one {other measurement unit} weigh in kilograms?

Q122. How much (%) of the production of {name of crop or tree outside cafs} did you manage to sell?

Depending on what the producer can tell you, ask them the price (R$/kg) or the total revenue (R$) they received for harvesting the ${crop_trees_outside_cafs_name} last year.

Q124. On average, what price (R$/kg) did you receive for ${crop_trees_outside_cafs_name}?

Q125. Measurement unit (kg/other measurement unit)

Q127. What was the total revenue received from the sale?

Q128. In the last 12 months, did your household use any of the harvested {name of crop or tree outside cafs} for own consumption? (No/Yes)

Q129. In the last 12 months, what was the total amount of {name of crop or tree outside cafs} consumed by your household?

Q130. Measurement unit (kg/other measurement unit)

Module 6: Labour and management practices

Q133. In the last 12 months, how many HH members worked on your farm (yourself included)?

Q134. On average, how many days per month did your hh member(s) work during the past 12 months (including yourself)?

Q135. How much (%) of this work was devoted to cocoa-related work?

Q136. During the last 12 months, did you hire any full-time, non-family employees to work on your farm? (No/Yes)

Q137. How many full-time, non-family employees worked on your farm during the last 12 months?

Q138. How much (%) of this work was devoted to cocoa-related work?

Q139. What was the average wage paid (R$)?

Q140. During the last 12 months, did you hire any temporary workers to work on your farm? (No/Yes)

Q141. How many daily temporary workers did you hire during the last 12 months to work on your farm?

Q142. During the last 12 months, how many days on average did you hire (a) temorary worker(s)?

Q143. How much (%) of this work was devoted to cocoa-related work?

Q144. What was the average daily wage paid (R$)?

Q145. In the past 12 months, did you use fungicide for your crop production? (No/Yes)

Q146. How much did you pay for fungicide during the past 12 months (R$)?

Q147. In the past 12 months, did you use insecticide for your crop production? (No/Yes)

Q148. How much did you pay for insecticide during the past 12 months (R$)?

Q149. In the past 12 months, did you use herbicide for your crop production? (No/Yes)

Q150. How much did you pay for herbicide during the past 12 months (R$)?

Q151. How much (%) of the costs of pesticides were devoted to cocoa production?

Q152. In the past 12 months, did you use fertilizer for your crop production? (No/Yes)

Q153. How much did you pay for fertilizer during past 12 months?

Q154. How much (%) of the costs of fertilizers was devoted to cocoa production?

Q155. In the past 12 months, did you use lime for your crop production? (No/Yes)

Q156. How much did you pay for lime during the past 12 months (R$)?

Q157. How much (%) of the costs of lime was devoted to cocoa production?

Q158. How much did you pay for seeds/seedlings during past 12 months (R$)?

Q159. How much (%) of the costs of seeds/seedlings was devoted to cocoa production?

Q160. Do you own agricultural implements (brush cutter and chainsaw)? (No/Yes)

Q161. What was the total investmennt cost (e.g. maintenance, fuel) of using your agricultural implements (brushcutter and chainsaw) (R$)?

Q162. How much did you pay for renting agricultural implements (brushcutter and chainsaw) last year (R$)?

Q163. How much (%) of the costs of this machinery was used for cocoa-related work?

Q164. Do you irrigate your cocoa in AFS? (No/Yes)

Q165. What were the total investment costs you made for buying irrigation equiment during past 12 months (R$)?

Q166. What were your total costs for irrigation (water, elec benzine) during the last 12 months?

Q167. How much (%) of the costs of irrigation was devoted to cocoa production?

Q168. Do you have any other costs (R$) related to cocoa production (e.g. buying bags of cocoa, transport costs, etc.)? (No/Yes)

Q169. How much did you pay for these costs in total?

Q170. Here we will ask the sharecropper about the percentage of the cocoa revenue that he has to share with the owner of the property, as well as other costs that he shares with the owner (e.g. pesticides).

Q171. How much (%) of the cocoa revenue do you receive from the owner?

Q172. How much (%) of the costs of fungicide, insecticide, herbicide and fertiliser do you have to pay?

Q173. How much (%) of the revenue from other crops (e.g. rubber) do you receive from the owner?

Q174. Are there any sharecropper(s) working on your farm? (No/Yes)

Q175. How many sharecroppers work on your farm?

Q176. How much (%) of the cocoa revenue will go to you?

Q177. How much (%) of the costs of fungicide, insecticide, herbicide and fertiliser do you pay?

Q178. How much (%) of the income from other crops (e.g. rubber) will go to you?

Module 7: GI certification and other certification schemes

Q180. Have you ever analyzed the quality of your cocoa beans in a laboratory? (e.g. CIC) (No/Yes)

Q181. Did the cocoa sample meet the required fysiqual quality standards? (No/Yes)

Q182. When was the first time you send a sample of cocoa beans for quality analysis?

Q183. How many times have you sent a sample of your cocoa beans for analysis?

Q184. When was the last time you sent a sample of cocoa beans for quality analysis?

Q185. Have you ever heard about "Indicação Geográfica Sul da Bahia"? (No/Yes)

Q186. During the past 12 months, has (part of) your cocoa been GI certified? (No/Yes)

Q187. Since when has your cocoa been GI certified?

Q188. During the past 12 months, how much of your cocoa has been GI certified?

Q189. Measurement unit (arroba/kg/bag)

Q190. How much does one bag weigh in kilograms?

- 30 kg
- 60 kg
- 2 arrobas
- 4 arrobas

Q191. How much did you pay for one quality assessment of the cocoa beans?

Q192. Did you have to make any investments/renovations to meet the quality requirements? (No/Yes)

Q193. What type of investments/renovations/expansions did you have to make?

- Storage
- Dryers
- Fermentation houses
- Other (specify)

Q195. Did you receive financial support from government/NGOs/cooperative to cover (one of) these fees (i.e. fee for quality assessment and/ or use of GI seal)? (No/Yes)

Q196. How much did you receive (R$)?

Q197. What are the benefits of selling your cocoa beans under the GI label?

- No benefits
- Higher selling price
- More stable demand
- Better reputation
- Better commercialization
- Guaranteed market
- Safer working conditions
- Other (specify)

Q199. Did you receive technical assistance from the association linked to GI Sul da Bahia? (No/Yes)

Q200. What type of technical assistance did you receive?

- Harvesting process
- Fermentation process
- Drying process
- Cocoa classification (quality)
- Other (specify)

Q202. Which difficulties do you experience about GI certification?

- No difficulties
- Difficulties in achieving quality requirements
- Difficult requirements for book keeping
- Too little demand for quality cocoa
- Too low selling price
- Too high certification fee to obtain GI seal
- Lack of technical support
- High investment costs
- Too high minimum amount of cocoa required
- Other (specify)

Q204. Has your cocoa ever been GI-certfied in the past? (No/Yes)

Q205. Why did you stop using the GI seal for your cocoa?

- Difficulties in achieving quality requirements
- Difficult requirements for book keeping
- Too little demand for quality cocoa
- Too low selling price
- Too high certification fee to obtain GI seal
- Lack of technical support
- High production costs
- Too high minimum amount of cocoa required
- Other (specify)
- Lack of technical support

Q207. Would you be interested in obtaining the GI label for your cocoa beans (again)? (No/Yes)

Q208. Why?

- Higher selling price
- More stable demand
- Better reputation
- Better commercialization
- Guaranteed market
- Safer working conditions
- Other (specify)
- Guaranteed market

Q210. Why not?

- Difficulties in achieving quality requirements
- Difficult requirements for book keeping
- Too little demand for quality cocoa
- Too low selling price
- Too high certification fee to obtain GI seal
- Lack of technical support
- High investment costs
- Too high minimum amount of cocoa required
- Other (specify)

Q212. Are you member of a cooperative or a farmers' organization? (No/Yes)

Q213. Since when are you member of a cooperative or a farmers' organization?

Q214. Are you certified under any (other) certification scheme? (No/Yes)

Q215. Which certification scheme?

- UTZ & Rainforest Alliance
- Demeter
- Orgânico Brasil
- IBD (organic)
- USDA Organic
- EU-organic
- Povo da Mata
- Other (specify)

Q218. Since when are you certified under {name of other certification}?

Q219. During the past 12 months, how much did you pay for the certification fee of {name of other certification}?

Q220. Did you receive financial support from government/NGOs/cooperative for the certification fee? (No/Yes)

Q221. How do you benefit from {name of other certification}?

- No benefits
- Higher selling price
- More stable demand
- Better reputation
- Better commercialization
- Guaranteed market
- Safer working conditions
- Lower investment costs
- Other (specify)

Q223. Which difficulties do you experience about{name of other certification}?

- No difficulties
- Difficult requirements for book keeping
- Too little demand for quality cocoa
- Too low selling price
- Too high certification fee to obtain GI seal
- Lack of technical support
- High investment costs
- Too high minimum amount of cocoa required
- Delayed payments
- Difficult requirements for input use
- Other (specify)

Module 8: Biodiversity (with picture for each species)

Q226. How important is it for you to preserve biodiversity on the farm?

- Not important at all
- Slightly important
- Important
- Moderately important
- Very important

Q227. Have you ever noticed the golden-headed lion tamarin here in the CAFS on this property? (No/Yes)
Q228. How did you identify the golden-headed lion tamarin? (Direct observation/signs/reported by worker)
Q229. Have you ever seen Wied's marmoset here in the CAFS on this property? (No/Yes)
Q230. How did you identify Wied's marmoset? (Direct observation/signs/reported by worker)
Q231. Have you ever seen capuchin monkey here in the CAFS on this property? (No/Yes)
Q232. How did you identify capuchin monkey? (Direct observation/signs/reported by worker)
Q233. Have you ever seen crab-eating fox here in the CAFS on this property? (No/Yes)
Q234. How did you identify crab-eating fox? (Direct observation/signs/reported by worker)
Q235. Have you ever seen lowland paca here in the CAFS on this property? (No/Yes)
Q236. How did you identify lowland paca? (Direct observation/signs/reported by worker)
Q237. Have you ever seen nine-banded armadillo here in the CAFS on this property? (No/Yes)
Q238. How did you identify nine-banded armadillo? (Direct observation/signs/reported by worker)
Q239. Have you ever seen six banded armadillo here in the CAFS on this property? (No/Yes)
Q240. How did you identify six banded armadillo? (Direct observation/signs/reported by worker)
Q241. Have you ever seen red-rumped agouti here in the CAFS on this property? (No/Yes)
Q242. How did you identify red-rumped agouti ? (Direct observation/signs/reported by worker)
Q243. Have you ever seen brazilian common opossum here in the CAFS on this property? (No/Yes)
Q244. How did you identify brazilian common opossum? (Direct observation/signs/reported by worker)
Q245. Have you ever seen *Leopardus sp*. here in the CAFS on this property? (No/Yes)
Q246. How did you identify *Leopardus sp*.? (Direct observation/signs/reported by worker)
Q247. Have you ever seen jaguarundi here in the CAFS on this property? (No/Yes)
Q248. How did you identify jaguarundi? (Direct observation/signs/reported by worker)
Q249. Have you ever seen puma here in the CAFS on this property? (No/Yes)
Q250. How did you identify puma? (Direct observation/signs/reported by worker)
Q251. Have you ever seen tayra here in the CAFS on this property? (No/Yes)
Q252. How did you identify tayra ? (Direct observation/signs/reported by worker)
Q253. Have you ever seen tamandua here in the CAFS on this property? (No/Yes)
Q254. How did you identify tamandua? (Direct observation/signs/reported by worker)
Q255. Have you ever seen *mazama sp*. here in the CAFS on this property? (No/Yes)
Q256. How did you identify *Mazama sp*.? (Direct observation/signs/reported by worker)
Q257. Have you ever seen coati here in the CAFS on this property? (No/Yes)
Q258. How did you identify coati? (Direct observation/signs/reported by worker)
Q259. Have you ever seen crab-eating raccoon here in the CAFS on this property? (No/Yes)

Q260. How did you identify crab-eating raccoon ? (Direct observation/signs/reported by worker)

Q261. Have you ever seen collared peccary here in the CAFS on this property? (No/Yes)

Q262. How did you identify collared peccary? (Direct observation/signs/reported by worker)

Q263. Have you ever seen common tapeti here in the CAFS on this property? (No/Yes)

Q264. How did you identify common tapeti? (Direct observation/signs/reported by worker)

Q265. Have you ever seen bristle-spined rat here in the CAFS on this property? (No/Yes)

Q266. How did you identify bristle-spined rat? (Direct observation/signs/reported by worker)

Q267. Have you ever seen Bahia porcupine here in the CAFS on this property? (No/Yes)

Q268. How did you identify Bahia porcupine? (Direct observation/signs/reported by worker)

Q269. Have you ever seen kinkajou here in the CAFS on this property? (No/Yes)

Q270. How did you identify kinkajou? (Direct observation/signs/reported by worker)

Module 9: Other income sources

Q272. Did you keep livestock during past 12 months? (No/Yes)

Q273. How much did you earn from keeping livestock during the last 12 months?

Q274. During past 12 months, were you or somebody else in the household off-farm employed? (No/Yes)

Q275. How much did you or any other HH-member earn from off-farm employment during the past 12 months?

Q276. During past 12 months, did you receive income from other sources, such as pension, remittances, renting out land/houses, etc? (No/Yes)

Q277. How much did you or any other HH-member receive from other sources during the past 12 months?

Q278. Compared with five years ago, how do you consider that your income from cocoa production has evolved?

- It has decreased a lot
- It has decreased a little
- It has stayed the same
- It has increased a little
- It has increased a lot

Q279. Compared with five years ago, how do you consider that your total household income has evolved?

- It has decreased a lot
- It has decreased a little
- It has stayed the same
- It has increased a little
- It has increased a lot

Q280. Take a photo of the consent form (front)

Q281. Take a photo of the consent form (back)

Q282. Take a photo of the CAFS plantation closest to the respondents' home

Q283. Coordinates of the plot

Q284. Number of native trees within the plot

Q285. Number of exotic trees within the plot

Q286. Is the density of shade trees in the entire CAFS compared to that of the plot?

- Lower
- Equal
- Higher