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Ecological dynamics in cocoa-based family farming systems in coastal Ecuador

DISSERTATION THESIS

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Declaration

I hereby declare that I have completed this thesis entitled “Ecological dynamics in cocoa-based family farming systems in coastal Ecuador” independently, all texts in this thesis are original, and that all information sources have been quoted and acknowledged by means of complete references. I also confirm that this work has not been previously submitted, nor is it currently submitted, for any other degree, to this or any other university.

In Prague, September 15th, 2026

Malena Torres Ulloa

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Abstract

Family farms are common in tropical regions and often are associated with diversified production practices. However, empirical evidence linking variation in family farm structure and crop composition to ecosystem functions and ecosystem services remains limited, particularly in perennial cropping systems. Research on family farming has often focused on production and livelihood outcomes, while ecological processes have received less attention in integrated analyses. This limits the incorporation of ecological considerations into policies and support programmes directed at family farms.

This study analysed how farm structural characteristics and crop composition in cocoa-based family farming systems relate to ecosystem functions and how these functions are associated with ecosystem service flow (service supplied), capture (service accessible to people), and benefit (potential contribution to well-being). The analysis was conducted as a case study in coastal Ecuador. Farm-level data were obtained through a census of the members of a purposively selected farmers' association and combined with spatial information derived from remote sensing and land-use datasets. Multivariate methods were used to identify family farm types, while ecosystem functions were estimated following the ECOSER protocol. Statistical and machine-learning methods were applied to analyse relationships among farm characteristics, ecosystem functions, and ecosystem service flow, capture, and benefit.

Three family farm types were identified, differing in land-use allocation, labour organisation, and crop composition. Associations between crop composition and ecosystem functions varied among functions. For soil organic carbon, the relationship with crop composition depended on farm type, and crop composition had greater predictive importance than farm type. No associations were detected for biomass carbon or erosion control. Farm type was the predictor selected for capture, while neither farm type nor crop composition was retained as a predictor of benefit.

Relationships among farm structure, ecosystem functions, and ecosystem service flow, capture, and benefit differed according to the variable considered and the scale of analysis. These findings suggest that policies and support programmes directed at family farming may benefit from considering ecological and spatial information alongside structural and productive characteristics when interpreting variation among farms. This information could contribute to the design and evaluation of interventions in cocoa-producing landscapes and comparable socio-ecological contexts.

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BEN	Ecosystem Service Benefit
BOC	Biomass Organic Carbon
CAP	Ecosystem Service Capture
CART	Classification and Regression Tree
CVB	Coefficient of Variation of Biomass
DEM	Digital Elevation Model
EC	Erosion Control
ECOSER	Collaborative Protocol for the Assessment and Mapping of Ecosystem Services and Socio-Ecological Vulnerability for Territorial Planning
EF	Ecosystem Function
EFs	Ecosystem Functions
ES	Ecosystem Service
ESs	Ecosystem Services
FF	Family Farm
FFs	Family Farms
FFS	Family Farming System
FFSs	Family Farming Systems
GAM	Generalised Additive Model
H’	Shannon Diversity Index

INEC	NATIONAL INSTITUTE OF STATISTICS AND CENSUS (ECUADOR)
IPCC	INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE
LULC	LAND USE / LAND COVER
MAG	MINISTRY OF AGRICULTURE AND LIVESTOCK (ECUADOR)
NDVI	NORMALISED DIFFERENCE VEGETATION INDEX
PCA	PRINCIPAL COMPONENT ANALYSIS
PERMANCOVA	PERMUTATIONAL MULTIVARIATE ANALYSIS OF COVARIANCE
RF	RANDOM FOREST
RMSE	ROOT MEAN SQUARE ERROR
SOC	SOIL ORGANIC CARBON

1. INTRODUCTION

1.1. Global context of family farming systems

Family farming systems (FFSs) represent one of the most widespread agricultural models worldwide. Global assessments indicate that approximately four out of five farms are family-operated and manage nearly three-quarters of agricultural land (Blondeau Simon & Korzenszky Anna, 2022; Graeub et al., 2016; Lowder et al., 2016). These systems are characterised by reliance on family labour, household-based decision-making, and the integration of economic, social, and ecological functions within the same production unit. Although highly diverse in size, production orientation, and market participation, family farms (FFs) remain important components of rural economies and food systems across both developed and developing regions (Klikocka et al., 2021; Samberg et al., 2016).

The contribution of FFs is not limited to supplying food. They sustain rural employment, preserve traditional agricultural knowledge, and maintain biological and cultural diversity within agricultural landscapes. In many countries, FFs produce a substantial proportion of locally consumed foods while contributing to the management of soil fertility, water flows, and vegetation cover (Ataei et al., 2023; Cavalli et al., 2020; Gaitán-Cremaschi et al., 2022). These functions are widely recognised in global discussions on sustainable land use and in international agendas such as the United

Nations 2030 Agenda for Sustainable Development, particularly in relation to food security, poverty reduction, and the responsible use of natural resources (Dal Moro et al., 2022; Graziano Da Silva, 2019).

Although family labour and household-based management are commonly recognised characteristics of FFs, these criteria do not correspond to a single farm size or production model. Family-operated farms may vary from small-scale holdings to larger commercial enterprises managed primarily by family members. As a result, FFs include a variety of organisational arrangements that differ in resource availability, production objectives, labour allocation, and levels of market orientation (Z. Chen et al., 2025; Kendall et al., 2022).

The diversity of FFs has been documented across different socioeconomic and geographical contexts. Differences in access to land, financial resources, infrastructure, institutional support, and market opportunities contribute to variation in farm performance and livelihood outcomes. In many cases, household livelihoods are supported by both on-farm and off-farm income sources, reflecting differences in production strategies and economic conditions. Family farming is described as a heterogeneous category of agricultural systems and not as a uniform production model (A. Amunigun et al., 2026; Fuller et al., 2021).

In many regions of Africa, Asia, and Latin America, family farming is closely associated with rural livelihoods and food production. Agricultural production frequently forms part of household livelihood strategies that may also include off-farm employment, migration, and other income-generating activities (López-Carr, 2021). The relative importance of these activities differs according to resource availability, market opportunities, infrastructure, and local development conditions, resulting in production systems with different economic objectives and varying degrees of dependence on agriculture (Silva Taveira et al., 2019).

Family-managed farms are often influenced by changing social and economic conditions. Processes such as urbanisation, demographic change, migration, market integration, and the expansion of commercial agriculture have altered production conditions across many rural areas. These changes influence labour availability, land access, production decisions, and income opportunities, affecting how households organise agricultural activities and allocate resources. In some regions, agricultural production is increasingly combined with non-farm activities, whereas in others farming continues to provide most household income and employment (Satterthwaite et al., 2010).

Differences in household objectives, access to resources, labour availability, and economic opportunities contribute to variation among family farming systems, including farms located in the same geographical region. Such differences are associated with distinct forms of farm organisation, resource use, and participation in agricultural markets (George & Ngaruko, 2017).

Recognition of farm heterogeneity has led the development of analytical approaches that classify and compare farms according to their structural characteristics, production models, agricultural practices, and levels of market integration. Farm typologies are commonly used to identify groups of farms with similar attributes and to describe variation among farming systems. These approaches contribute to understanding diversity across the agricultural sector and provide information that can support agricultural research and policy development (Costa-Pereira et al., 2025; Weersink, 2018).

The diversity observed among FFSs has contributed to the development of classification approaches aimed at describing and comparing farms according to their characteristics (Chmieliński et al., 2023). Among these approaches, farm typologies are commonly used in agricultural research to identify groups of farms that share similar attributes and production conditions. Typologies provide a means of organising heterogeneous farming populations into analytically meaningful groups and support the description of differences in resource availability, labour use, land use, production orientation, livelihood strategies, and levels of market engagement (S. Alvarez et al., 2018; Van Vliet et al., 2015).

The variables used to construct farm typologies vary according to the objectives of individual studies and the characteristics of the farming systems being analysed. Combinations of biophysical, socioeconomic, technical, and farm-management variables have been used to characterise agricultural systems and distinguish groups of farms with similar attributes. Farm typologies have been applied to describe farming-system diversity and analyse differences in farm size, land use, resource availability, production orientation, management practices, and livelihood strategies among farms (Adalbert et al., 2022).

In this context, over the past decades, transformations in global food systems have influenced the operating environment of family agriculture. Market liberalisation, urbanisation, and the growing demand for export commodities have tended to favour large-scale, capital-intensive production models, often reducing the competitiveness of smallholders (Leshchenko, 2023). In many regions, these dynamics have contributed to land concentration, rural outmigration, and the simplification of production structures. Environmental pressures, including soil degradation, limited water availability, and increasing climate variability, affect the long-term sustainability of agricultural systems including FFs (de Almeida Moura et al., 2025; Miranda et al., 2024; Urbina et al., 2024).

In response to these challenges, several international initiatives have emphasised the importance of strengthening family farming. The FAO-led United Nations Decade of Family Farming 2019–2028 promotes measures to enhance innovation capacity, improve market access, and support environmentally sound practices. Agroecological and sustainable intensification approaches also highlight the potential of diversified production systems to align productivity objectives with ecological integrity. Within these frameworks, FFs are considered as knowledge-intensive systems that integrate ecological principles into production strategies and adapt them to local conditions (Lopatynskyi et al., 2023; Shrestha Rudra Bahadur et al., 2021).

Studies frequently report benefits of agricultural diversification, such as improved food security or reduced soil erosion. However, most analyses focus on specific production systems or plot-level assessments with limited consideration of FFs as integrated socio-ecological units. Much of the global literature analyses diversification practices in isolation, without explicitly linking them to the EFs generated within FFs. Consequently, empirical evidence connecting FF management with EFs, such as soil quality, carbon accumulation, and erosion control, remains relatively scarce, particularly in tropical regions (Do et al., 2024; Vaz et al., 2025).

Interpreting FFSs in this global perspective requires an integrated understanding of their socio-ecological nature. Household strategies interact with institutional, environmental, and market dynamics to influence productivity, livelihood security, and environmental outcomes across scales. Family farming can be analysed in specific regional contexts, including tropical Latin America, where production practices, social organisation, and environmental conditions are closely connected (Apablazza et al., 2023; Niksaz et al., 2025).

1.2. Knowledge gap

Although FFSs contribute to food production and rural livelihoods, their ecological functions are less systematically addressed in empirical research. Existing studies focus mainly on socioeconomic outcomes, while ecological processes such as soil carbon dynamics, biomass accumulation, and erosion control in these systems receive less attention in integrated analyses (Aparecida da Silva et al., 2025).

Diversification, productivity, and environmental indicators are often analysed independently, without explicit links to farm-level organisation and measurable ecosystem functions (EFs) which refer to ecological processes and conditions involved in the generation of ecosystem services (ESs). As a result, the relationship between management diversity and ecological performance remains only partially explored in perennial smallholder systems (Colnago et al., 2021). An exploratory keyword co-occurrence map generated using VOSviewer from publications retrieved from Scopus shows distinct thematic concentrations in the literature on family and smallholder farming, with socioeconomic and production-related terms occupying a different area of the network from ecological terms related to biodiversity, ESs, soil, and biomass (Figure 1).

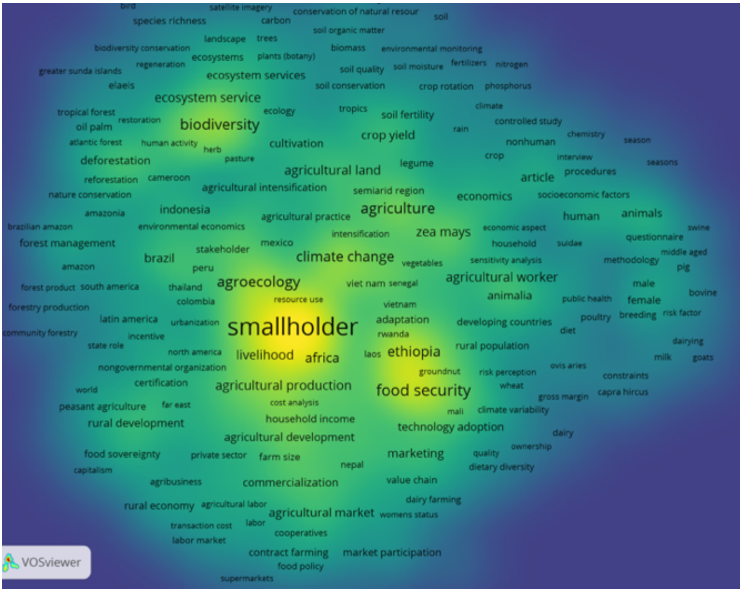

Figure 1. Global research focus on FFSs based on exploratory keyword co-occurrence analysis using VOSviewer

Empirical evidence quantifying how diversification in cocoa FFs relates to EFs and associated services remains limited (empirical gap). Research addressing ecological functions in FFs includes relatively few cases from Latin America (geographical gap) (Borja et al., 2024; Lyall & Colloredo-Mansfeld, 2024). Connections between farm typologies and ecological indicators are not consistently integrated, which limits the interpretation of how structural diversity relates to environmental outcomes (analytical gap). Spatial modelling approaches are also rarely combined with detailed farm-level data in heterogeneous tropical landscapes (methodological gap).

The gaps identified in previous studies indicate that knowledge on FFSs is distributed across thematic areas, geographical regions, and analytical approaches. Existing studies have generated valuable information on farm characteristics, diversification, ecological functions, and ESs, although few studies have examined the relationships among these dimensions at the farm level. Limited integration of these dimensions restricts understanding of how differences among FFs are associated with ecosystem functions, the availability of ESs to people, and their potential contribution to human well-being.

1.3. Problem Statement

Cocoa-based FFs (FFs with cocoa as their main crop) in coastal Ecuador have economic and social importance. Available information on how farm structure and management strategies relate to EFs such as soil organic carbon, biomass carbon, and erosion control, as well as to the distribution of associated ESs, does not allow a clear identification of how management diversity relates to ecological performance across cocoa-growing landscapes (Blanco-Gutiérrez et al., 2025; Luna Florin et al., 2025).

Coastal agroecosystems are characterised by a stronger orientation toward market production and cash crops compared to other regions, where production decisions respond to both subsistence needs and market conditions. These conditions influence land-use intensity, crop composition, and management practices, which interact with ecological processes (Zambrano et al., 2022). Limited representation of coastal Ecuadorian cocoa FFs in ecological analyses reduces the availability of context-specific evidence for these production conditions (INEC, 2024).

Relationships between farm structure, ecological processes, and spatial variation cannot be clearly identified, which limits the understanding of how management practices interact with environmental conditions across heterogeneous production systems. Connections between EFs and ESs across farms also remain unclear in relation to farm-level conditions and landscape context (Toledo et al., 2023). These limitations restrict the identification of patterns linking farm organisation, ecological processes, and ESs across cocoa-growing landscapes.

These limitations have direct implications for the design of policies and interventions. Policies and support programmes are often based on generalised farm models, which do not reflect variation in farm structure and management or spatial variation in ecological conditions. As a result, similar management practices may be promoted across heterogeneous production conditions, including farms with different levels of ecological functioning and different capacities to implement such practices (Haro Altamirano et al., 2022). This reduces the relevance of interventions for specific farm contexts and limits the consideration of how EFs and ESs vary across farms.

1.4. Research rationale

An integrated analytical approach allows the examination of how farm organisation, management practices, ecological processes, and spatial variation are connected across different levels of analysis. Research on ESs at the farm level has often focused on specific dimensions, particularly ecological and economic aspects, which can limit integrated assessments of agricultural systems. Considering these components in a single empirical analysis supports their joint evaluation and improves the interpretation of agroecosystems as socio-ecological systems (Morizet-Davis et al., 2023; Satama-Bermeo et al., 2024).

The focus on cocoa-based FFs in coastal Ecuador provides empirical evidence for production conditions that are less represented in ecological analyses. Such systems are characterised by mixed crop arrangements, structural diversity, and variable management strategies, which influence ecological processes and associated ES outcomes across farms. Analysing variation across farms supports the interpretation of how ecological patterns correspond to management practices and environmental conditions (Edelstein et al., 2024; Schmidt et al., 2025).

Differences in ecological conditions across farms and across the landscape can be identified, allowing the analysis of how ecological processes and ESs are expressed under varying management and spatial conditions. This also allows examination of how these processes vary across cocoa-growing landscapes.

These relationships support the identification of areas with different ecological conditions that may require differentiated management or policy approaches. Such differentiation includes conservation of areas with higher ecological functioning, targeted support where ecological potential is not fully expressed, and prioritisation of areas where ecological processes are present but not reflected in farm-level conditions (Heiss et al., 2025; Khanal et al., 2020; Moomen et al., 2024) .

The use of farm typologies, EFs, and ESs connects farm heterogeneity with ecological characteristics and their contribution to people. Farm typologies distinguish groups of farms with contrasting structural and management characteristics, while EFs describe ecological processes and conditions linked to ES provision. Comparing these ecological indicators across farm types examines whether differences in farm characteristics correspond with differences in ecological outcomes. This combination links ecological outcomes with farm characteristics across different FFs (Huber et al., 2024).

2. AIMS OF THE STUDY

Existing research on FFSs and diversification provides limited integration of farm structural characteristics and crop composition with EFs and their associated ESs in cocoa-based systems. In this context, the study analyses these relationships in cocoa-based FFSs in coastal Ecuador. The ES analysis is based on spatially estimated ecosystem service flow (service supplied), capture (service accessible to people), and benefit (potential contribution to well-being).

2.1. Objectives

The study analyses the ecological dynamics in cocoa-based FFSs in coastal Ecuador to understand how farm structural characteristics and crop composition relate to EFs and their derived ESs.

General objective

- To analyse how farm structural characteristics and crop composition relate to ecosystem functions (soil and biomass carbon and erosion control) and how these functions are associated with ecosystem service flow, capture, and benefit in cocoa-based FFSs.

Specific objectives

- Characterise farm organisation and crop composition, including perceived benefits of crop diversification.

- Estimate ecosystem functions (erosion control, soil organic carbon, and biomass carbon).
- Analyse ecosystem functions across FFs.
- Assess ecosystem service flow, capture, and benefit across farms.

2.2. Research questions and hypotheses

The research questions (RQ) translate the objectives into analytical problems, and the hypotheses (H) define the expected patterns examined in this study. The analysis focuses on cocoa-based FFSs and considers farm structure, crop composition, EFs, and ecosystem service components.

RQ1: How are cocoa-based FFs structured and classified, and how do farm characteristics and perceived benefits of crop diversification vary across farm types?
H1: Farm types differ in structural characteristics, crop composition, and perceived benefits of crop diversification.

RQ2: How do EFs respond to crop composition?
H2: EFs are associated with crop composition.

RQ3: Do EFs differ among farm types?
H3: SOC, BOC, and EC differ among farm types.

RQ4: How is ecosystem service flow distributed, and how does variation in ecosystem service capture and benefit relate to crop composition and farm types?
H4: Variation in ecosystem service capture and benefit is associated with farm types and crop composition.

These research questions and hypotheses define an analytical structure linking farm types and characteristics (H1) with ecosystem functions (H2-H3) and their relationships with ecosystem services (H4).

3. BACKGROUND

3.1. Family farming in Ecuador

Family farming in Ecuador reflects the structural and functional diversity characteristic of smallholder systems in Latin America. National statistics indicate that 55–60 % of the agricultural labour force operates within family-based units, which manage nearly half of the cultivated land (INEC, 2024). These farms provide a significant share of domestically consumed staple crops, including maize, potatoes, rice, and plantain, and generate employment across the coastal, Andean, and Amazonian regions. They also contribute to the preservation of local seed varieties, traditional farming practices, and social cohesion in rural territories (Montúfar & Ayala, 2019; Verdugo et al., 2023).

Institutional support for family farming has expanded gradually. The Family and Peasant Farming Seal (AFC), introduced in 2017, was created to formally recognise family farmers as specific economic and social actors and to facilitate their access to differentiated markets, public procurement, and technical assistance. Despite these intentions, implementation has frequently been limited by administrative fragmentation, insufficient financing, and uneven coordination across provinces. In addition, agricultural policies have often prioritised export-oriented commodities such as banana, coffee, and shrimp, leaving many small-scale producers with reduced access to credit, infrastructure, and incentives (Cevallos & Artacker, 2025; Espinel & Solórzano, 2025).

In Ecuador, FFs include diverse territorial expressions, among them the Andean and Amazonian chakras. These family-managed production systems combine food crops, medicinal plants, fruit trees, timber species, and market-oriented crops under different arrangements. The chakra is not limited to agricultural production but is associated with household food supply, local ecological knowledge, and the organisation of family labour. In Amazonian Indigenous communities, chakras form part of livelihood systems in which productive, cultural, and environmental functions are closely interconnected (Coral-Guerrero et al., 2026).

Household organisation is commonly associated with these production systems. Agricultural activities are distributed among family members according to household needs, labour availability, and participation in non-agricultural activities. In some regions, women participate in both production and management activities, while other household members participate in wage employment, commerce, or seasonal work. In this context, family farming is associated not only with agricultural production but also with household organisation and multiple livelihood strategies (He & Ahmed, 2022; Schneider & Niederle, 2010).

Diversification is another characteristic present in many FFSs. Cultivated areas may contain annual crops, perennial species, medicinal plants, fruit trees, timber species, and small livestock managed within the same production unit. Domesticated, semi-domesticated, and wild species may coexist under different management arrangements, contributing to the maintenance of agrobiodiversity and traditional ecological knowledge. The boundaries between cultivated and non-cultivated resources are not always clearly defined, particularly in Indigenous production systems where agricultural and surrounding environments are closely connected (Lowder et al., 2021; Valliant et al., 2017).

The relationship between FFs and markets also varies across Ecuador. Some households produce mainly for self-consumption, whereas others combine household consumption with the commercialisation of agricultural products. Diversified production portfolios including cacao, guayusa, cassava, banana, vanilla, and other products are common in some Amazonian systems. These arrangements connect household production with local, national, and international markets while maintaining food production for household use (Viejó-Bautista et al., 2025).

Differences in crop composition and vegetation structure contribute to variation among FFs. Diversified agroforestry arrangements, mixed-crop systems, and more simplified production systems coexist across rural landscapes. Production units may combine crops and trees under different management intensities, generating variation in vegetation structure, species composition, and land-use configuration. This heterogeneity is associated with differences in environmental conditions and production strategies among farms (Huera-Lucero et al., 2024).

Variation among farms is also associated with the socioeconomic and environmental conditions influencing agricultural production. Migration, changing market conditions, certification requirements, technological change, land availability, water scarcity, and limited access to technical support influence household decisions regarding agricultural production and land management (Vaillant, 2018). Food acquisition commonly combines products obtained from cultivated plots with products acquired through markets and, in some regions, resources obtained from surrounding environments. These conditions contribute to the diversity of livelihood strategies and production arrangements present among FFs in Ecuador (Eche, 2018).

This diversity is also expressed through differences in resource availability, production orientation, and degree of market integration among FFs. According to the Ministry of Agriculture and Livestock of Ecuador, four categories are categorised:

- Subsistence farms, which rely almost entirely on household labour and produce mainly for self-consumption;
- Transitional farms, which combine subsistence production with partial market participation;
- Consolidated farms, which possess larger landholdings and higher levels of capital investment.
- Community-based, associated with collective or communal forms of land tenure and production.

These categories coexist within a landscape characterised by fragmented farm structures and marked differences in access to and adoption of agricultural technologies (Viera-Arroyo et al., 2025).

Regional patterns also show this diversity. In the Andean highlands, FFs occupy small and often terraced plots dedicated to tubers, cereals, and horticultural crops. Agroforestry systems in these areas have been shown to maintain higher agrobiodiversity and more stable livelihoods compared to monocultural systems(Villalba-Eguiluz et al., 2023). In the Amazon region, farmers frequently combine agroforestry systems with permanent perennial crop production, adapting their practices to ecologically sensitive environments (Caicedo-Vargas et al., 2022; Viteri Salazar et al., 2018). In the coastal lowlands, farmers cultivate perennial crops such as cocoa and coffee alongside seasonal crops like rice and maize. Across all regions, production depends mainly on family labour, supplemented by temporary workers during periods of high demand (INEC, 2024).

While this spatial and productive diversity reflects farmers' adaptive responses to Ecuador's varied agroecological conditions, it also occurs under structural conditions that influence outcomes. FFs continue to face multiple environmental and socio-economic challenges. Access to irrigation, mechanisation, and credit remains uneven across regions and farm types, limiting productive capacity and investment. In areas characterised by more intensive cultivation, production systems are frequently associated with environmental pressures, including declining soil quality (Haro Altamirano et al., 2022; Ramírez et al., 2023).

Climatic variability, expressed through irregular rainfall, droughts, and flooding, has also affected agricultural productivity, particularly in low-lying coastal areas. In response to these pressures, many FFs maintain diversified cropping structures that contribute to soil conservation, carbon storage, and water regulation. These ecological functions are increasingly considered in national discussions on sustainable land-management strategies and climate-resilient agricultural development (Fierros-González & López-Feldman, 2021; Vivar-Arrieta et al., 2023).

3.2. Cocoa production in Ecuador

Cocoa (*Theobroma cacao L.*) has long been emblematic of Ecuadorian agriculture. The country is recognised as the historical centre of origin of the Nacional variety, valued internationally for its fine flavour and unique genetic profile (Lanaud et al., 2024; Loor Solorzano et al., 2012). Cocoa, including the high-yield hybrid CCN-51, constitutes Ecuador's second most important non-oil export commodity and supports the livelihoods of more than 120,000 producers, primarily concentrated in the coastal and foothill regions (Aguirre Ilich et al., 2025).

Archaeological and genetic evidence associates cacao with some of the earliest agricultural activities documented in the territory of present-day Ecuador. Evidence from Amazonian, coastal, and Andean contexts indicates that cacao circulated through exchange networks connecting different ecological regions, illustrating its long-standing presence in food systems and human activities across the country. During the export-oriented agricultural expansion of the late nineteenth and early twentieth centuries, cocoa became one of Ecuador's principal export commodities. During this period, Ecuador became the world's leading cocoa exporter and established the international reputation of Nacional cocoa in fine-flavour markets (Montalvo-Puente et al., 2025; Southgate & Roberts, 2020).

Cocoa production in Ecuador is characterised by the coexistence of different varietal and management configurations. Nacional cocoa is traditionally associated with fine-flavour markets and is often cultivated under production systems that maintain diverse shade structures and lower planting densities (Salazar et al., 2023a). In contrast, CCN-51 has been widely adopted due to its higher productivity, earlier bearing age, and greater tolerance to pests and diseases, making it more suitable for intensive production and commercial markets (Avadí, 2023).

Cocoa cultivation is closely associated with family-based agricultural production. Across producing regions, cocoa is commonly managed on small and medium-sized farms where household labour contributes to farm operations. Production systems frequently combine cocoa with food crops, fruit trees, timber species, and other agricultural activities, generating diverse production arrangements adapted to local environmental and socioeconomic conditions (Coq-Huelva et al., 2018).

The expansion of CCN-51 since the late twentieth century has contributed to changes in the spatial organisation and management of cocoa farms, including differences in planting density, input use, and harvest cycles. As a result, farms may cultivate these varieties separately or in combination, depending on production objectives, market access, and resource availability. Mixed-variety systems are common, particularly in smallholder contexts, where farmers balance quality-oriented production with yield stability and income diversification. These configurations result in different spatial arrangements and management practices within production systems, reflecting variation in farm-level decision-making and production strategies (INEC, 2024).

The cocoa sector includes a diversity of production conditions. Farm size, access to land, producer organisation, technical assistance, post-harvest infrastructure, and market participation vary among producing areas. These differences contribute to variation in productivity, bean quality, and economic performance, generating heterogeneous production systems across the country (Purcell et al., 2018).

In addition to structural differences among producing areas, cocoa farms also differ in their management objectives and access to resources. Some farms prioritise production volume, while others focus on quality-oriented markets linked to fine-flavour cocoa. Access to physical, financial, and human resources influences production practices, post-harvest management, and market opportunities, contributing to the diversity of cocoa farming systems present in Ecuador (Middendorp et al., 2020).

Cocoa farms combine longstanding cultural traditions with opportunities for income generation, although cocoa production is associated with multiple interconnected challenges. Price volatility in international markets, limited influence within value chains, and restricted access to certification schemes continue to affect income stability. Production conditions also vary across regions, influenced by factors such as plantation age, renovation practices, and access to improved genetic material, which contribute to differences in yield levels (Burgos Villamar et al., 2025).

Environmental and socioeconomic conditions also influence the long-term viability of cocoa production. Land-use management, labour availability, access to services, and environmental pressures contribute to variation in farm performance and production outcomes. These conditions are increasingly considered in discussions concerning the sustainability of cocoa production and the future development of the sector (L. M. Tennhardt et al., 2023).

At landscape scales, cocoa production occurs in agricultural landscapes where perennial crops are combined with temporary crops and other land uses. This contributes to variation in crop composition, land-use allocation, and management practices across farms. Consequently, cocoa production systems differ in the varieties cultivated, the management strategies applied, and the composition and arrangement of crops maintained on individual farms (Kongor et al., 2024).

3.3 Crop composition in FFs

The combination of species present on farms provides a description of how agricultural production is organised in a production unit. Differences in the number of species, their relative abundance, and their allocation across the farm contribute to variation among production systems. This includes both edible and non-edible species cultivated for household consumption, market sale, livestock feeding, or other purposes. Farms differ in landholding size, labour organisation, production objectives, and degree of market integration, contributing to differences in species composition across agricultural systems (Paut et al., 2020; Verret et al., 2020).

In FFs, perennial and temporary species are frequently combined within the same production unit. In cocoa-producing systems, cocoa is often cultivated alongside temporary crops, fruit trees, and other perennial species. The relative importance of these species varies among farms and contributes to differences in land-use allocation and farm organisation (Herrera-Franco et al., 2024; Lucio et al., 2021).

Differences in species composition are also associated with decisions regarding the allocation of land, labour, and other farm resources. Farmers may prioritise food production, market-oriented crops, livestock feeding, or combinations of these objectives. Differences in species composition are observed among farms located in the same region, including differences in species combinations and in the proportion of cultivated area allocated to each crop. Species composition is associated with both environmental conditions and management decisions occurring at the farm level (Bellon et al., 2020; Snapp et al., 2019).

Species composition is closely linked to agrobiodiversity, which refers to the variety of crop species present and their management in agricultural systems. This includes different crop groups managed under practices such as monoculture, crop rotation, and intercropping. Multiple species may fulfil different functions related to food provision, income generation, animal feeding, and household needs (Melak, 2025; Vilakazi et al., 2025a).

Agrobiodiversity can be described through different indicators that capture distinct aspects of biological variation in agricultural systems. One of the most commonly reported indicators at the farm level is crop richness, which refers to the number of crop species present on a farm. Richness provides information on how many species are cultivated but does not account for differences in the relative importance of each crop. Identical richness values do not imply the same distribution of cultivated area among species (Kumari et al., 2019).

Crop composition incorporates the number of species and their relative abundance. Diversity measures distinguish between farms that cultivate similar numbers of species but allocate different proportions of land to each crop. Diversity incorporates information on both the presence of species and the distribution of cultivated area among them (Assefa et al., 2022; Seidler et al., 2026).

Among the available diversity metrics, the Shannon index combines information on richness and relative abundance into a single measure. Higher values are associated with a more balanced representation of cultivated species, whereas lower values are associated with a stronger concentration of cultivated area in a smaller number of crops. The index is frequently used to describe differences in species composition among agricultural systems and to compare farms characterised by different crop combinations (Mijatovic et al., 2018).

Richness and diversity provide complementary descriptions of species composition. Richness quantifies the number of cultivated species present, whereas diversity incorporates information on their relative representation. The combined use of these indicators allows distinctions among farms that are not evident from species counts alone. Farms with similar richness can differ in the distribution of cultivated area among crops and display different diversity values (Ng'Endo et al., 2015).

In addition to richness and diversity, the spatial distribution of species provides another description of crop composition. Farms with similar diversity values may differ in the arrangement of production areas, the allocation of crops to individual plots, and the degree to which species are cultivated separately or in combination. This spatial dimension may include mixed-cropping and intercropping arrangements in which different species are cultivated simultaneously within the same plot, or crops distributed among separate management areas. Soil characteristics, water availability, topography, and management decisions contribute to these spatial configurations and influence the combinations of species present on farms (Dupré et al., 2020; Ruillé et al., 2026).

3.4. Ecosystem functions in agricultural systems

Ecological functioning in agricultural systems is influenced by crop composition, vegetation characteristics, land use, and interactions among plants, soils, and environmental conditions. Relationships between plant diversity and ecosystem functioning have been explained through biodiversity–ecosystem functioning (BEF) theory. This theory identifies complementarity and selection effects as mechanisms through which plant diversity and composition can influence ecosystem functioning. Complementarity is associated with niche differentiation or facilitation among species, while selection effects occur when species with particular functional characteristics exert greater influence on ecosystem functioning (Loreau & Hector, 2001).

Differences in plant species and their functional characteristics can influence resource use and ecosystem functioning (Wang et al., 2024). Research on smallholder and crop production systems shows that crop arrangements, vegetation cover, and soil management contribute to EFs associated with agricultural production and rural wellbeing (Brooker et al., 2021; Guzmán et al., 2022). These functions are associated with soil conditions, vegetation continuity, and water regulation, and are documented in studies of smallholder and FFSs (Aparecida da Silva et al., 2025).

At the farm level, these processes are associated with the presence and management of vegetation. Differences in crop composition and land use are linked to variation in soil organic matter, nutrient cycling, and soil stability. Systems with sustained vegetation cover tend to retain higher organic matter, while exposed or repeatedly disturbed fields show greater susceptibility to erosion and moisture variability (Flores et al., 2020). These relationships connect crop composition, land use, and management with ecological processes associated with organic inputs, soil conditions, nutrient dynamics, and soil protection (Sanaullah et al., 2020).

In addition to farm-level management, ecological outcomes are associated with the environmental context in which farms operate. Vegetation structure, historical land use, and the distribution of forest or semi-natural areas influence environmental conditions experienced by farms, even where production practices are similar (Araújo et al., 2025; Asubonteng et al., 2021). Landscape configuration, expressed through the spatial arrangement of forests, cropland, fallows, pastures, and wetland areas, is associated with ecological functioning across tropical lowland landscapes (Raveloaritiana et al., 2023).

EFs provide information on ecological conditions associated with agricultural systems and are frequently used to characterise variation among farms and landscapes. Functions related to carbon storage, nutrient cycling, soil conservation, and water regulation are commonly studied due to their association with vegetation cover, land use, and management practices. Differences in these functions have been reported across agricultural systems with distinct structural and management characteristics, indicating that ecological processes may vary among farms (Gomes et al., 2019; Solen et al., 2018).

EFs describe ecological processes and properties associated with ecological conditions in ecosystems. In agricultural landscapes, these functions are linked to interactions among crops, trees, soils, water resources, and other environmental elements. EFs do not represent products obtained from ecosystems or benefits received by people. Instead, they provide information on ecological characteristics associated with environmental conditions in agricultural systems. Different functions are linked to different ecological processes and respond differently to management practices, land use, and environmental conditions (Jax, 2005).

Carbon-related functions are often used to characterise soil and vegetation conditions in agricultural systems. Soil organic carbon is associated with the accumulation and retention of organic matter in soils, while biomass carbon is linked to carbon storage in above-ground vegetation. Variation in these functions has been associated with differences in vegetation cover, land-use allocation, and management intensity across agricultural landscapes. Differences in soil and biomass carbon provide information on ecological conditions among agricultural systems (R. Chen et al., 2020; de Oliveira et al., 2025).

Soil organic carbon and biomass carbon provide complementary information, describing different parts of the carbon cycle. Soil organic carbon is associated with below-ground processes related to organic matter accumulation and retention, whereas biomass carbon describes carbon stored in living vegetation. Differences between these indicators are associated with the way vegetation and soils respond to environmental conditions and management practices over time. The combined use of soil and biomass carbon provides a more complete description of ecological conditions than either indicator considered independently (Baude et al., 2019).

Erosion control is another EF associated with ecological conditions in agricultural landscapes. Vegetation cover, root systems, litter accumulation, and soil characteristics are linked to the capacity of landscapes to reduce soil loss generated by rainfall and surface runoff. Areas maintaining continuous vegetation cover often show different erosion conditions from areas characterised by exposed soils or frequent disturbance. Soil erosion affects soil conservation, agricultural productivity, and water quality, making erosion control a relevant indicator of ecological conditions in agricultural systems (Alam, 2018).

Although carbon-related functions provide information on ecological conditions, agricultural systems are also characterised by other EFs. Functions related to soil processes, vegetation dynamics, erosion control, and agricultural emissions are associated with different biophysical and management characteristics. No single function provides a complete description of ecological conditions across farms and landscapes. Descriptions of ecological conditions commonly incorporate multiple indicators representing different EFs and environmental attributes.

Different functions provide different information about the same agricultural system. Similar values in one EF do not necessarily correspond to similar values in another, since each function is associated with particular ecological processes and environmental characteristics. Ecological assessments frequently incorporate multiple indicators describing different ecological attributes and processes in order to characterise ecological conditions across farms and landscapes (Buchadas et al., 2022).

In this context, EFs are understood as ecological processes and properties that contribute to the generation of ESs. Ecosystem-service research distinguishes between ecological functioning, service provision, service capture, and realised benefits, recognising them as different stages within the ecosystem-service pathway. This perspective distinguishes ecological processes, ecosystem-service provision, service capture, and realised benefits as separate elements of the ecosystem-service pathway. Ecological conditions and ecosystem-service outcomes are analysed as different aspects of the relationship between ecosystems and society while maintaining their conceptual connection. This distinction supports the assessment of ecological conditions independently from the ways in which people access and benefit from ESs (Barral et al., 2020; Grima et al., 2019).

3.5. Spatial dimensions of ecological processes and environmental outcomes

Agricultural landscapes contain different land uses, vegetation types, topographic conditions, and hydrological features distributed across space. Forests, wetlands, croplands, pastures, and other land-cover classes differ in vegetation characteristics, soil properties, and physical conditions. As a result, ecological conditions are not uniform across agricultural landscapes. Locations situated within the same landscape may present different ecological characteristics according to the combination of land-cover types and environmental conditions present at each site (Gebhardt et al., 2023; Landis, 2017).

Ecological processes are associated with the environmental characteristics of the locations where they occur. Biomass accumulation, soil carbon dynamics, nutrient cycling, decomposition, and water movement are related to vegetation cover, soils, climate, and topography. These processes occur across landscapes composed of different environmental conditions, resulting in differences in ecological characteristics among locations (Metzger et al., 2021; Moges & Mebrate, 2022).

Landscape elements are also connected through the movement of water, sediments, nutrients, organisms, and other materials. Water moving through a watershed may connect locations situated far apart, while vegetation cover in one area may be associated with ecological conditions in neighbouring locations. These connections create spatial relationships among different parts of a landscape and are associated with the distribution of ecological conditions across space (Pena et al., 2020). These connections contribute to the spatial distribution of ecological conditions and create relationships among locations that are not always directly adjacent. Ecological processes are linked to landscape structure and to the spatial relationships among landscape elements (Hersperger et al., 2021).

Differences in vegetation, soils, land use, and topography are associated with differences in carbon storage, erosion regulation, and other ecological attributes and ecological conditions may differ among locations even when they belong to the same agricultural landscape (Morgan et al., 2022; L. Tennhardt et al., 2022). Ecological conditions can vary across agricultural landscapes in relation to local environmental characteristics, land-cover composition, and landscape configuration (Storkey et al., 2024).

Spatially explicit information describing land use, vegetation cover, topography, and other environmental characteristics is commonly used to analyse ecological conditions across landscapes. Spatial representations allow ecological attributes to be described continuously across space and support comparisons among locations with different environmental characteristics. Such approaches are used to analyse ecological processes and ecosystem-service related attributes in agricultural landscapes (W. Chen et al., 2020; Grêt-Regamey et al., 2017).

Geospatial information from different sources can be integrated to characterise environmental and ecological attributes across agricultural landscapes. Remote sensing provides spatial and temporal information on vegetation and land-cover characteristics, while other spatial datasets can describe soils, topography, hydrological features, and farm boundaries. Satellite-derived spectral information can be used to characterise vegetation properties and temporal vegetation dynamics, and vegetation indices derived from remotely sensed imagery are frequently used to characterise vegetation condition and support spatial analyses of ecological processes and ESs (Galbraith et al., 2015; Yan et al., 2025). The integration of spatial datasets enables environmental and ecological attributes to be represented across agricultural landscapes and related to defined spatial units such as fields or farms (S. Vesterdal et al., 2026). Farm characteristics and environmental conditions are connected with ecological processes occurring in agricultural landscapes. Crop composition, land use, vegetation, and management are linked to ecological functioning, while soils, topography, land cover, and landscape structure contribute to its spatial variation. EFs contribute to the generation of ESs, connecting ecological processes with outcomes relevant to people through the ecosystem-service pathway (Brooker et al., 2021; Potschin-Young et al., 2018). Figure 2.

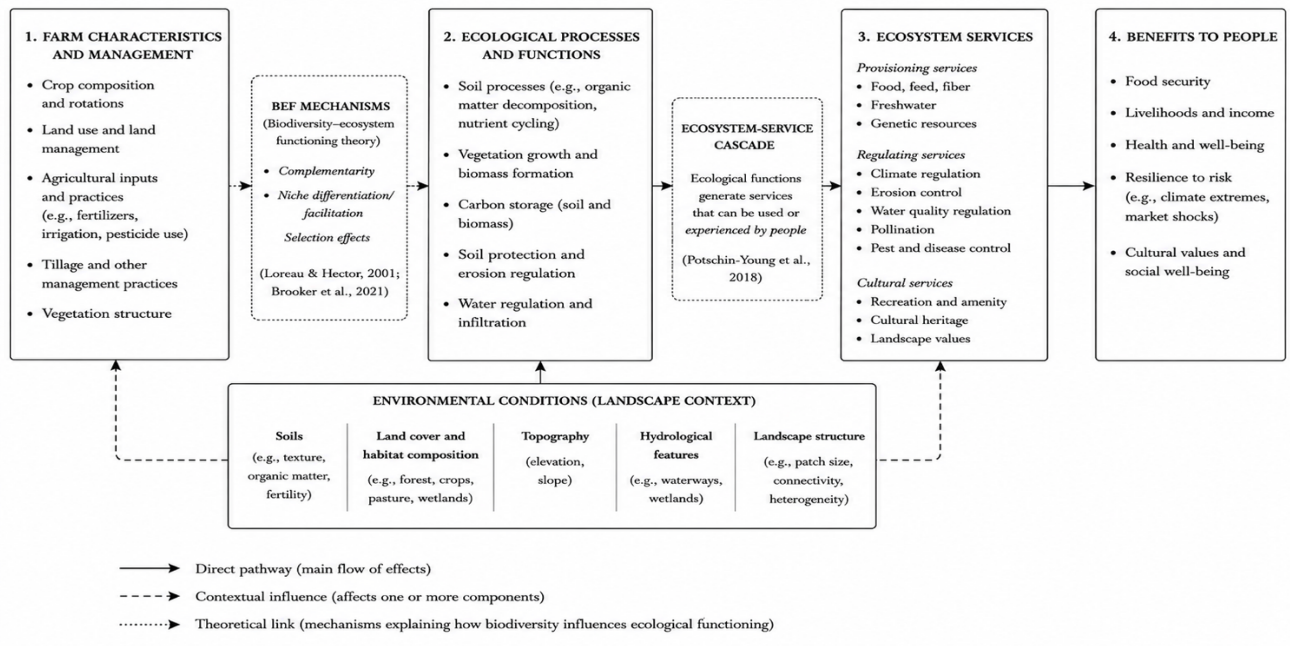

Figure 2. Conceptual framework linking farm systems, ecological functioning, and ecosystem services
Developed from the biodiversity–ecosystem functioning framework (Brooker et al., 2021; Loreau & Hector, 2001) and the ecosystem-service cascade (Potschin-Young et al., 2018).

4. METHODOLOGY

4.1. Study area

4.1.1. Location and landscape characteristics

The study was conducted in Vinces canton, Los Ríos Province, located in the coastal region of Ecuador (Figure 3). The area forms part of the Abras de Mantequilla Ramsar site, a wetland of international importance situated in the middle basin of the Guayas River system. The wetland and its surrounding agricultural zone cover approximately 22,000 ha and lie within a low-lying floodplain influenced by the Vinces and Los Tintos rivers (Dirección Generación de Geoinformación Agropecuaria, 2020).

The landscape consists of a fine-scale agricultural mosaic dominated by cocoa, rice, maize and pasture. Remnants of riparian vegetation, secondary forest and wetland fragments are interspersed throughout this matrix, providing small patches of natural cover. Fertile alluvial soils and year-round water availability support a range of perennial and annual crops, contributing to the prominence of Vinces as one of the principal cocoa-producing areas of the Ecuadorian coast (Dirección Generación de Geoinformación Agropecuaria, 2020).

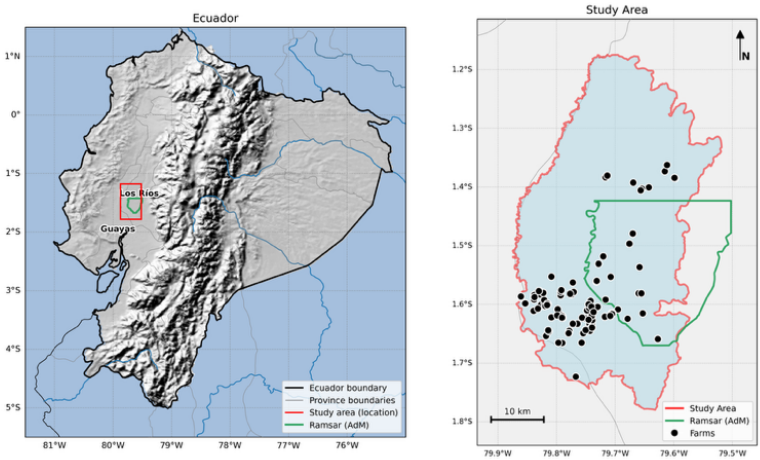

Figure 3. Location of the study area

4.1.2. Physical and climatic conditions of the study area

Vinces has a humid tropical climate, with mean annual temperatures between 24 °C and 27 °C and annual precipitation ranging from 1,500 mm to 2,500 mm. Rainfall is concentrated from January to April, while the period from May to December is markedly drier. Relative humidity remains high throughout the year (75-85 %), and evapotranspiration exceeds rainfall only during the dry months (Dirección Generación de Geoinformación Agropecuaria, 2020).

The terrain is flat to gently undulating, with elevations between 10 and 60 m.a.s.l. Soils are predominantly alluvial loams derived from fluvial deposits, typically exhibiting moderate to high fertility and relatively high organic-matter content. Periodic flooding contributes to nutrient renewal but limits cultivation in some low-lying areas. These environmental conditions support perennial crops, including cocoa, and both Nacional and CCN-51 varieties are commonly grown due to their suitability to the local hydrological and soil characteristics (García-Briones et al., 2021; Ministerio de Agricultura y Ganadería, 2022).

4.1.3. Historical and socioeconomic context

Cocoa cultivation has influenced the development of Vinces since the late nineteenth century, during the Gran Cacao period when exports of Nacional cocoa positioned the town as an economic centre known as “Paris Chiquito” (Little Paris). Although production declined after the 1920s, cocoa farming continues to be the main agricultural activity and contributes to household income (Peralta, 2011; Valdez, 2021a).

During this period, Ecuador became one of the principal exporters of fine-flavour cocoa, and the cultivation of Nacional cocoa was associated with economic activity across the coastal region. Cocoa production was linked to changes in land use, commercial activity, and trade networks connecting local production areas with international markets (Lanaud et al., 2024; Valdez, 2021b). The economic activity associated with cocoa exports was accompanied by urban growth in Vinces and expansion of commercial activity in the surrounding area.

The decline of the cocoa boom during the early twentieth century was associated with the spread of fungal diseases affecting cocoa plantations and changes in international markets following the expansion of cocoa production in West Africa. These factors reduced the competitiveness of Ecuadorian cocoa and were associated with economic changes across cocoa-producing regions (León-Bravo & Jaramillo-Villacrés, 2021).

Most holdings are small-scale farms, generally between 1 and 10 ha, managed mainly through family labour, with seasonal hired assistance during harvest periods. Recent data indicate that around 80% of agricultural households in Los Ríos operate under family-based management. Access to land, credit, and technical support remains limited, and market participation often occurs through local associations and intermediaries (INEC, 2024).

The widespread adoption of the hybrid CCN-51 in recent decades has been associated with higher productivity, whereas traditional Nacional varieties continue to be cultivated for high-quality and niche markets. The introduction and expansion of CCN-51 occurred during a period of renewed growth in cocoa production following earlier declines. Although CCN-51 and Nacional differ in agronomic and commercial characteristics, both varieties are currently cultivated across Ecuadorian cocoa-producing regions and contribute to national cocoa production (Jaimez et al., 2022).

Cocoa-based FFSs are associated with local economic activity, rural identity, and everyday livelihoods. These systems maintain perennial vegetation cover and mixed production structures associated with ecological functions in the study area (Abad et al., 2020; Salazar et al., 2023).

4.2. Farm-level data and variables

4.2.1. Study design and data collection

The study adopts a case-study approach focused on cocoa-producing households associated with the Asociación 15 de Septiembre, a producer organisation operating in the Abras de Mantequilla landscape in Vinces canton, Los Ríos Province. The research was conducted as "diversification" component of the project "Path to the Reactivation of the Ecuadorian Agri-food Sector" (CREA), which focuses on cocoa farms and promotes farmer associativity and agricultural diversification for the production of sustainable products with added value. Cocoa-based farms were defined as production units in which cocoa was the main crop, even though other crops could also be cultivated on the farm.

The farmers' association was purposefully selected as a defined and organised group of cocoa producers located in the study area, with the case-study design focusing on variability among farms under a common geographical and organisational context. Purposeful selection of farmer organisations has been applied in agricultural and rural research when the objective is to capture structural and organisational variability (Jose et al., 2023).

All registered members of the association responded to the questionnaire (N = 161), resulting in 131 valid questionnaires from cocoa-producing households. Of these, 111 were classified as FFs, while the remaining 20 were classified as non-FFs. Non-FFs were retained to maintain the complete cocoa-producing population of the selected case and to provide information on cocoa farms outside the FF classification under the same geographical and organisational context.

The questionnaire was adapted from the Continuous Agricultural Land and Production Survey (ESPAC) of the National Institute of Statistics and Census (INEC) and adjusted to the objectives of this study (available at https://www.ecuadorencifras.gob.ec/estadisticas-agropecuarias-2/). The use of an established agricultural questionnaire provided standardised definitions, variable categories, and measurement criteria for farm-level data collection. Standardised survey instruments support consistent measurement of agricultural and socioeconomic variables across respondents while accommodating questions specific to the research objectives (Van Wijk et al., 2019).

ESPAC provided standardised definitions and categories for agricultural variables in the Ecuadorian context, particularly those related to land use, crop production, labour, and agricultural inputs. The questionnaire was complemented with study-specific questions on cocoa varieties and the area cultivated with each variety, crop diversification, and farmers' perceptions of the income, food, and soil-related contributions of temporary and perennial crops (Appendix A).

Before data collection, the questionnaire was piloted with 21 association members to evaluate question clarity, comprehension, response options, and questionnaire structure. Feedback from participants was used to refine the wording and organisation of the questionnaire. This pre-testing procedure followed recommended practices for agricultural and rural surveys, in which pilot testing is used to identify problems with question interpretation and response formats before full implementation (Luke, 2025).

For the study-specific Likert-scale items addressing farmers' perceptions, internal consistency of Likert-scale items was evaluated using Cronbach's alpha, indicating good reliability for perceived benefits related to perennial crops ($\alpha = 0.88$) and temporary crops ($\alpha = 0.82$). Feedback from participants was used to refine the structure and wording of the questionnaire.

Data were collected through direct interviews with household heads to maintain consistency in responses. Geographic coordinates were recorded for each farm using handheld GPS units, enabling spatial linkage with environmental datasets. The study combined the questionnaire data with spatial and remotely sensed data used for the estimation of ecosystem functions and services, as described in Section 4.5.

4.2.2. Farm characteristics

Farm characteristics included structural and labour variables, cocoa variety, fertilisation strategy, and farmers' perceptions of crop diversification.;

- Structural variables (quantitative) included farm size, the area allocated to cocoa, temporary crops and other crops, and the number of cultivated crops. These variables describe land-use arrangement and crop composition. In addition, information was collected on cocoa variety (CCN-51, Nacional, or mixed) and on the identity of cultivated crops other than cocoa, allowing the characterisation of crop composition using both area and crop-specific information. Cocoa variety was included as a categorical attribute of farm organisation. Temporary crops refer to short-cycle crops that can be sown and harvested more than once per year, while perennial crops persist for multiple years without replanting after each harvest.
- Labour variables (quantitative), which distinguish family and hired labour based on the number of persons involved in each group.
- Fertilisation strategy (categorical) was classified according to the type of fertiliser used: organic, synthetic, or combined inputs.

4.2.3. Crop composition

Cash crop composition was quantified using the Shannon Diversity Index (H'), which accounts for both the number of cultivated crops and their proportional area within each farm. This metric allows the analysis to consider not only crop richness but also the relative distribution of cultivated areas, offering a more detailed description of diversification levels (Mijatovic et al., 2018). The H' has also been applied to assess agricultural diversification in Ecuador using crop-area data, supporting its suitability for analysing diversification patterns in this context (Pacheco et al., 2018).

The index was calculated considering all cultivated crops reported by farmers, including cocoa, temporary crops, and other crops. Values of H' increase with both the number of crops and the evenness of their distribution across the farm.

4.3. Typology construction

To identify groups of cocoa-based FFs with comparable structural and management characteristics, a multivariate procedure was applied. Farm types are commonly used to organise heterogeneity among smallholder farms into similar configurations for analytical purposes (Benitez-Altuna et al., 2023; Siddique et al., 2022).

Prior to multivariate analyses, all quantitative variables were standardised using z-scores to ensure comparability across different units and to prevent variables with larger numerical ranges from dominating the analysis (Mohamad & Usman, 2013). Standardisation is widely recognised as a necessary preprocessing step for exploratory data analysis and clustering techniques (Al-Mekhlafi et al., 2024). Although H' is mathematically derived from crop composition and area distribution, it was retained as an integrative indicator of diversification that captures both crop richness and evenness, complementing area-based measures without replacing them (Gómez-Limón et al., 2024; Hassall et al., 2023; Paranjak et al., 2025).

K-means cluster analysis was applied to the standardised variables. This approach groups farms based on similarity in their multivariate profiles while minimising within-cluster variance. The number of clusters was selected using the elbow criterion, which evaluates the reduction in within-cluster variance as the number of clusters increases. Three clusters were selected at the point where adding another cluster produced little additional reduction in within-cluster variance (Cui, 2020; Humaira & Rasyidah, 2020). The resulting clusters were interpreted as farm types and characterised using the original variables.

Principal Component Analysis (PCA) was applied to the same standardised variables to summarise the main gradients of variation and provide a two-dimensional representation of the resulting farm types (Papić Milojević & Bogdanov, 2024).

4.4. Analysis of farmers' perceptions of crop-related benefits

Farmers' perceptions of crop diversity were analysed to assess whether perceived benefits varied according to farm type or cocoa variety. Perceptions were recorded using ordinal response categories ("Never", "Sometimes", "Often", "Always") for the contributions of temporary and perennial crops other than cocoa to additional income, household food provision, and soil improvement. These variables represented farmers' perceptions of the economic, household food, and environmental contributions of crops cultivated in addition to cocoa (Vilakazi et al., 2025b).

Perception data were analysed using contingency-table approaches. Associations between perception categories and farm types were tested using Fisher's Exact Tests, given the ordinal nature of the responses. The same approach was applied to evaluate associations between perceptions and cocoa-variety groups (CCN-51, Nacional, and mixed plantings) (Daya, 2002; Gebiso et al., 2023).

Where overall tests indicated statistically detectable associations, post-hoc pairwise Fisher tests were used to identify contrasts between specific groups.

4.5. Ecosystem functions and services

4.5.1. ECOSER framework

The ECOSER protocol (Laterra et al., 2015; Laterra & Castellarini, 2011), is a spatially explicit approach for mapping and evaluating ecosystem functions, ecosystem service flows, and their benefits across landscapes. It combines biophysical and socio-economic information to connect ecosystem functioning, service provision, and potential beneficiaries. The protocol was previously applied by Portalanza et al. (2024) in the Abras de Mantequilla wetland, providing a context-specific basis for its use in the present study.

ECOSER adopts a socio-ecological approach that connects ecological functioning, ecosystem service provision, and potential beneficiaries. Similar connections between ecological service generation, flow, and use by people are represented in ecosystem-service approaches that distinguish potential service supply from realised service use (Bagstad et al., 2013; Wu et al., 2024).

The protocol distinguishes the following components (Laterra et al., 2015):

- Ecosystem functions (EFs): ecological processes and attributes quantified through indicators or models. The EFs considered for each ES are used to estimate its flow.
- Ecosystem service flow: the provision or supply of an ES generated from natural capital. For its estimation, the EFs contributing to each ES are

transformed to relative values and integrated according to their contribution to that service.

- Ecosystem service capture (CAP): the relative capacity of potential beneficiaries to access or make use of the available ES flow. The factors used to estimate CAP depend on the characteristics of each ES.
- Ecosystem service benefit (BEN): the fraction of ES flow potentially available as a benefit after accounting for the capacity of potential beneficiaries to access or use the service. BEN represents the potential benefit associated with the ES flow and does not constitute a direct measurement of human well-being.

The following subsections describe the estimation of these components according to the ECOSER protocol.

4.5.2. Spatial data and preprocessing

Spatial data were used to estimate EFs across the study area and to derive the relative flow of ESs. The analysis was based on satellite imagery and terrain data, including vegetation indices and topographic attributes.

A multi-temporal Normalised Difference Vegetation Index (NDVI) dataset was generated from cloud-free Landsat 9 images acquired during 2022. Images affected by cloud cover, cloud shadows, or atmospheric distortion were excluded. NDVI was used as a proxy for vegetation condition and biomass, and temporal variation was used to characterise the stability of vegetation cover throughout the year.

Topographic information was derived from a Digital Elevation Model (DEM), from which slope was calculated. Slope was included to account for terrain effects relevant to erosion processes.

All spatial datasets were harmonised to a common spatial resolution and coordinate reference system prior to analysis. Raster values were extracted at the farm level using the geographic coordinates recorded during field data collection.

4.5.3. Ecosystem functions estimation

Three EFs were estimated: soil organic carbon (SOC), biomass organic carbon (BOC), and erosion control (EC). These functions were used to derive the relative flow of ESs.

Soil organic carbon

Following the protocol, SOC was estimated using its Tier 1 parameterisation based on the IPCC Guidelines for National Greenhouse Gas Inventories. Reference SOC stocks were assigned according to climate and mineral-soil class and adjusted using the land-cover correction factors specified in the protocol (Laterra et al., 2015b):

$$SOC_i = SOC_{ref} \times F_{LU} \times F_{MG} \times F_A$$

where, SOC_i is the estimated soil organic carbon stock for pixel (t C/ha), SOC_{ref} is the reference SOC stock associated with the corresponding climate and mineral-soil class (t C/ha), F_{LU} is the stock-change factor for land use, F_{MG} is the stock-change factor for management practices, F_A and is the stock-change factor for carbon inputs to the soil.

Soil classes from SIGAGRO, originally classified according to USDA Soil Taxonomy, were reclassified into the mineral-soil classes used by the IPCC. Reference SOC stocks corresponding to tropical moist conditions were assigned to these classes. The reference stocks were adjusted according to the LULC categories used in the protocol (cropland, pasture, forest, wetland, floodable lowlands, and urban), using the correction factors specified by the protocol, as detailed in Table 1. The correction factors act as multipliers of the reference SOC stock. F_{LU} represents the land-use factor, F_{MG} the management factor, and F_A according to carbon inputs to the soil. The protocol assigns these factors according to the corresponding LULC class; individual farm management practices and carbon inputs were not used to parameterise the factors. A value of 1.00 leaves the stock unchanged for the corresponding factor, values below 1.00 reduce the estimated stock, and values above 1.00 increase it. The combined effect of the three factors determines the SOC stock assigned to each pixel according to its corresponding spatial classes.

Table 1. Correction factors specified by the ECOSER protocol for soil organic carbon estimation by land-cover type (Laterra et al., 2015b).

Cover type	F_{LU}	F_{MG}	F_{A}
Crop	0.69	1.08	1.00
Pasture & Grassland	0.95	1.00	1.00
Forestry	1.00	1.00	1.00
Wetland	1.00	1.00	1.00
Floodable Lowlands	1.00	1.00	1.00
Urban	0.00	0.00	0.00

F_{LU}: Correction factor corresponding to existing changes in carbon stocks. F_{MG}: Correction factor corresponding to different management (cultivation) practices. F_{A}: Correction factor corresponding to different levels of carbon inputs to the soil.

The reference SOC raster and the LULC-based correction factors were combined pixel by pixel following the protocol. Spatial approaches integrating remotely sensed land-cover information with soil and environmental variables are commonly used for SOC mapping, although their accuracy depends on the spatial inputs, environmental conditions, and availability of field observations (Pouladi et al., 2023; Vaudour et al., 2022).

All calculations were performed using harmonised raster inputs with consistent spatial resolution and projection. The resulting SOC surface is expressed in tonnes of carbon per hectare, from which farm-level values were extracted.

Biomass carbon

BOC was estimated using the land-cover-specific biomass carbon coefficients specified by the protocol, which uses IPCC default biomass coefficients when local values are unavailable. These coefficients, expressed in tonnes of carbon per hectare, represent reference biomass carbon stocks assigned to the LULC classes used in the spatial analysis. Land-cover-based approaches combining spatial land-cover information with biomass coefficients are used for spatial biomass estimation, although uncertainty is associated with the generalisation of vegetation characteristics within land-cover classes and the use of reference biomass values (Abbas et al., 2020).

Using the LULC raster, each pixel was assigned the corresponding biomass carbon coefficient for its land-cover category. The LULC classification was retained for the spatial calculation and was not reclassified according to the crops recorded in the farm questionnarie. Pixel-level biomass carbon (BOC_i) was calculated as:

$$BOC_i = C_{LULC,i} \times A_i$$

where, $C_{LULC,i}$ is BOC coefficient assigned to the LULC class represented by pixel i (t/ha) and A_i is pixel area.

All spatial layers were harmonised to a consistent spatial resolution and projection. Raster algebra was applied to generate pixel-level BOC stocks, and the resulting raster was overlaid with the farm polygons. BOC values within each farm polygon were summed and standardised by farm area to obtain farm-level BOC estimates expressed in tonnes of carbon per hectare. As the calculation retained the pixel-level LULC classification, the farm-level estimates incorporated the spatial BOC values represented within each farm boundary.

Table 2. Biomass organic carbon coefficients specified by the ECOSER protocol from IPCC reference values by land-cover type (Laterra et al., 2015b; IPCC, 2006).

Land cover type	Carbon storage (t C/ha)
Crop	5.67
Pasture & grassland	1.22
Forestry	6.34
Wetland	0.00
Floodable lowland	0.00
Urban	0.00

Erosion control

EC was estimated integrating vegetation condition, temporal variability, and terrain. NDVI is used as a proxy for vegetation condition, and its temporal variability can be represented by the coefficient of variation of NDVI (Vatandaşlar & Yavuz, 2023a).NDVI was calculated as:

$$NDVI = (NIR - RED)/(NIR + RED)$$

Temporal variability in vegetation was represented by the coefficient of variation calculated from the NDVI time series (CVB):

$$CVB = \sigma_{NDVI}/\mu_{NDVI}$$

EC was then calculated as:

$$EC = B \times (1 - CVB) \times \left(1 - F_{slp}\right)$$

Where B represents vegetation condition, expressed using satellite-derived NDVI, CVB represents its temporal variability calculated from the NDVI series, and F_{slp} accounts for the influence of slope steepness. EC is expressed as a relative value.

4.5.4. Ecosystem services flow

The EFs (SOC, BOC, and EC) were integrated according to the protocol to estimate the spatial distribution of ES flow. The resulting ES flow values were used in the estimation of CAP and BEN, as described in the following sections.

Relative flow of ecosystem services

SOC, BOC, and EC raster layers were transformed into relative values, expressing the intensity of each function on a 0-100 scale across the landscape.

This transformation enables comparison and combination of functions expressed in different units. Relative values were calculated using min–max normalisation:

$$FSE_i = \frac{(V_i - V_{min})}{(V_{max} - V_{min})} \times 100$$

where FSE_i= Relative value of the ecosystem function at pixel i (0-100), V_i is the pixel value, and V_{min} and V_{max} are the minimum and maximum values of the corresponding ecosystem function.

The spatial distribution of ES flow was derived by combining the relative values of EFs using a weighting matrix developed for the study area by Portalanza et al. (2024). This matrix was obtained through a participatory process in which respondents assigned weights to reflect the degree to which each function contributes to the ESs considered.

$$ES_i = \sum_j w_j \times FSE_{ij}$$

where ES_i is the composite relative ES flow at pixel i, w_j is the weight assigned to the ecosystem function j, and FSE_{ij} is the relative value of the ecosystem function j at pixel i.

This procedure generated spatially explicit composite map of relative climate-regulation ES flow, based on the weighted integration of SOC, BOC, and EC. At each pixel, the resulting value represents the relative level of ESs supplied by the underlying EFs. A higher flow value represents a location with greater relative ESs supply, while a lower value represents lower relative supply. These values are relative to the conditions represented across the study area and do not correspond to a physical quantity of ESs.

EFs were estimated at the pixel level, and ES flow was represented as a continuous surface across the landscape. Farm-managed vegetation, soils, and land uses contribute to this surface through their influence on underlying EFs. Flow values were not assigned to farms as discrete units; farm boundaries were used only to derive CAP and BEN.

Ecosystem service capture

CAP was estimated by linking ES flow with the spatial distribution of beneficiaries. The number of beneficiaries associated with each farm was used as to represent beneficiary presence and potential demand for the service.

These values were distributed across the landscape using a distance-decay function, so that the potential for service capture decreased with increasing distance from beneficiaries. CAP outputs were normalised to a 0-1 scale, representing the relative proportion of ES flow potentially captured by beneficiaries.

Ecosystem service benefit

BEN represents the ESs available to beneficiaries after accounting for both ES flow and CAP. BEN was calculated as the pixel-level product of ecosystem service flow and capture:

$$BEN_{ij} = flow_{ij} \times CAP_{ij}$$

where, BEN_{ij} is the benefit is the benefit associated with ecosystem service $i$at pixel j, $flow_{ij}$ is the relative flow of the service *i* at pixel j, and CAP_j is the proportion of that flow captured at pixel j. The index *i* denotes the ESs included in the integrated ES-flow calculation, and j denotes the spatial pixel.

This calculation identifies locations where ES flow and capture combine to generate higher or lower benefit values.

4.6. Statistical analysis

4.6.1. Farm structure and cocoa variety

An exploratory analysis was conducted to describe variation in farm structure in relation to cocoa varieties cultivated (Vigni et al., 2013) This grouping was used to characterise the production context associated with CCN-51, Nacional, and mixed cocoa production. A correlation-based network analysis was used to examine relationships among continuous structural, labour, and crop-composition variables across all studied farms (Langfelder & Horvath, 2008; Masuda et al., 2025).

All quantitative variables were retained in the network analysis, including the H', despite its mathematical dependence on both crop-area distribution and the number of cultivated crops. Including this index allowed associations between crop diversity, crop richness, area allocation, and labour characteristics to be considered in the same analysis. The network was used as an exploratory graphical representation of the association structure among farm characteristics (Huber et al., 2024).

Pairwise associations among variables were quantified using Spearman rank correlation coefficients (ρ), given the non-normal distribution of the data. Correlations were calculated using pairwise complete observations. A network representation was constructed in which nodes correspond to variables and edges represent the strength of association between variable pairs, with edge weights defined as the absolute value of ρ (Huber et al., 2024; Schober & Schwarte, 2018). The corresponding Spearman correlation matrix was retained to report the direction and magnitude of the individual pairwise associations.

Fertilisation strategy was analysed by cocoa variety to evaluate whether cocoa variety was associated with the type of fertilisation used among family farms. The comparison was included to determine whether cocoa variety was related to this specific management characteristic, complementing the structural and crop-composition characteristics used to describe the farms.

Fertilisation strategies (organic, synthetic, or combined inputs) were evaluated across cocoa-variety groups using Fisher's Exact Test, as this was the only categorical variable analysed in relation to cocoa variety (Daya, 2002; Tevenart & Brunette, 2021; Wawire et al., 2021).

4.6.2. Modelling of ecosystem functions

A combination of descriptive, multivariate, semi-parametric, non-parametric, and machine-learning methods was used to analyse relationships among EFs, CAP, BEN farm types, and crop composition.

For analyses in which H' was included as an explanatory variable, the farm typology was reconstructed without H' to avoid using the same variable both in defining farm types and as an explanatory variable. The resulting farm classification was unchanged from that obtained when H' was included in the typology construction.

Distribution of SOC, BOC and EC across farm types

Comparisons of SOC, BOC, and EC among farm types were conducted using the Kruskal–Wallis test, which is appropriate for non-normal distributions and unequal group sizes. When significant differences were detected, pairwise comparisons with Holm correction were applied to identify contrasts between groups.

Joint modelling of carbon pools

To analyse the joint response of SOC and BOC to farm type and crop diversity, a permutational multivariate analysis of covariance (PERMANCOVA) was fitted. This analysis incorporated the two carbon pools in a single multivariate model and accounted for H' when estimating differences among farm types. The analysis was based on a Euclidean distance matrix constructed from untransformed SOC and BOC values (t C/ha). Farm type was included as a fixed factor and H' as a covariate (Anderson, 2017; Hanna et al., 2020).

Generalised additive models (GAM)

Generalised additive models were fitted separately for SOC, BOC, and EC to evaluate their responses to crop diversification and farm structure. GAMs allow non-linear relationships to be modelled through smooth functions applied to continuous predictors, while categorical predictors are included as parametric terms (Huang et al., 2022).

The general form of the model was:

$$\mathbb{E}[Y_i] = \beta_0 + \sum_{j=2}^{k} \beta_j \cdot \mathbb{I}\left(Farm\_type_j = Level_j\right) + f(Shannon\_index_i, Farm\_type_i) + \varepsilon_i$$

where:

- $\mathbb{E}[Y_i]$ is the expected value of SOC, BOC or EC for the i-th farm.
- β_0 = is the intercept term in the model.
- $\sum_{j=2}^{k} \beta_j \cdot \mathbb{I}(Farm\_type_j = Level_j)$ represents the parametric effect of the farm type, where $\mathbb{I}(Farm\_type_j = Level_j)$ is an indicator function for the j-th level of the farm type.
- $f(Shannon\_index_i, Farm\_type_i)$ represents the smooth function modeling the relationship between H' (as a continuous predictor) and farm type (as a categorical factor).

ε_i is the error term for the i-th observation, accounting for unexplained variance.

Given the high inherent variability of ecological response variables, model explanatory performance was interpreted in relation to the ecological context (Johannesson et al., 2024; Lai et al., 2024; Møller & Jennions, 2002).. GAMs with an $R^2 \geq 0.10$ were examined using Random Forest analysis to investigate predictor importance. Models below this value were reported but were not used for the Random Forest analysis.

Random forest model

For GAMs with $R^2 \geq 0.10$, Random Forest models were fitted to investigate the relative contribution of the predictors identified in the same set of explanatory variables. This non-parametric approach complemented the GAM analysis by quantifying predictor importance without specifying the shape of the relationships between predictors and the response variable. Predictor importance was assessed using permutation-based measures, which quantify the loss in predictive performance when the values of each predictor are permuted (Kim & Grunwald, 2016; Liaw & Wiener, 2002; Salinas et al., 2023).

CART models for CAP and BEN

Classification and Regression Tree (CART) models were used to analyse variation in CAP and BEN in relation to farm type and crop composition. Farm type and H' were included as separate predictors to determine whether CAP and BEN were associated with the categorical farm characteristics, crop composition, or both variables. CART was selected to identify which of these predictors separated farms into groups with different CAP and BEN values and whether additional separation occurred through sequential splits. This structure also allowed specific thresholds in H' associated with changes in CAP or BEN to be identified. This approach accommodates both categorical and continuous predictors and allows non-linear relationships and interaction thresholds to be identified (Obiang Ndong et al., 2021; Rositano et al., 2018).

Initial trees were grown without restrictions to evaluate all potential splits. Farm type was included as a categorical predictor and H' as a continuous predictor.

Trees were pruned using cost–complexity procedures, with ten-fold cross-validation used to estimate predictive error. Final models were selected using the one-standard-error rule to reduce tree complexity while maintaining cross-validated predictive performance.

4.7. Software

Spatial data preparation and processing were conducted in QGIS-LTR version 3.34.15 Prizren, including raster processing, calculation of spatial indicators, harmonisation of spatial layers, raster algebra, and extraction of values at farm level.

Statistical analyses were conducted in R version 4.5.0. The main packages used were vegan for permutational multivariate analyses, mgcv for Generalised Additive Models, randomForest for Random Forest models, and rpart for Classification and Regression Tree models. The packages dplyr and tidyr were used for data organisation and ggplot2 for data visualisation.

4.8. Ethical considerations

The study followed ethical procedures. Participation was voluntary, and respondents provided informed consent prior to each interview. Individual data are presented in aggregated form to preserve anonymity.

5. RESULTS

5.1. Farm structure and cocoa variety

Cocoa production was combined with a variety of other crops, and farm characteristics showed heterogeneity within each cocoa-variety group. Cocoa was grown in three cocoa-variety groups: exclusively CCN-51, exclusively Nacional, or a mixture of both. These categories were used to describe how farm characteristics were distributed according to the cocoa variety cultivated and were not intended to define separate production types.

Family labour was most frequently represented by two to four household members across the three cocoa-variety groups, although higher values were also recorded. Hired labour was generally low, with most farms reporting no hired workers or a single worker.

Total cash-crop area included farms with less than 1 ha as well as holdings exceeding 20 ha. CCN-51 farms contained both smaller and larger holdings, while Nacional farms were concentrated at lower and intermediate values, with some larger holdings also present. Mixed-variety farms also included farms with different total cash-crop areas.

Cocoa area was concentrated at lower values in all three cocoa-variety groups, although some farms dedicated several hectares to cocoa production. Observations from CCN-51, Nacional, and mixed-variety farms were present across the cocoa-area distribution.

Temporary crops and other crops generally occupied smaller areas than cocoa. In all three cocoa-variety groups, many observations were located near the lower end of the scale, while fewer farms devoted larger areas to these crops.

Crop richness was between one and five cultivated crops across farms. Farms cultivating CCN-51, Nacional, or both varieties included cases with one or two crops as well as farms managing larger numbers of cultivated crops.

H’ showed overlap among the three cocoa-variety groups, with both lower and higher diversity values recorded for CCN-51, Nacional, and mixed-variety farms (Figure 4).

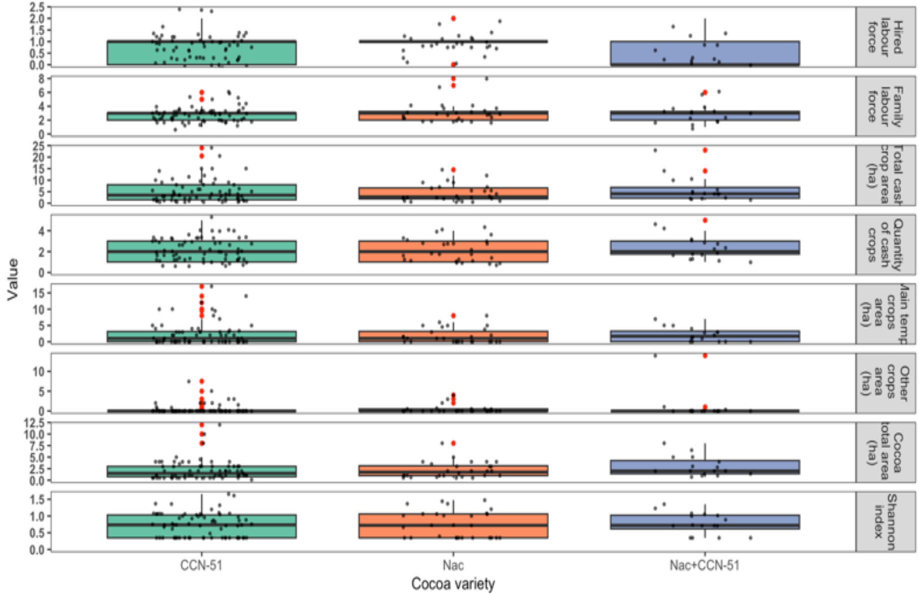

Figure 4. Distribution of labour force, cultivated area, crop number and H' for farms within each cocoa-variety category.

Boxes summarise the distribution of observations within each cocoa-variety group, horizontal lines indicate median values, black points represent individual farms, and red points indicate group means.

In addition, households reported three fertilisation strategies: organic inputs, synthetic inputs, or a combination of both. All three practices occurred across all cocoa-variety categories. Organic inputs were more frequent among Nacional and mixed-variety farms, whereas combined organic-synthetic fertilisation was more common among farms cultivating only CCN-51. Fisher's Exact Test did not identify a statistically significant association between fertilisation strategy and cocoa variety (p = 0.1429). The correspondence analysis shows the observed relationships between fertilisation strategies and cocoa-variety categories (Figure 5).

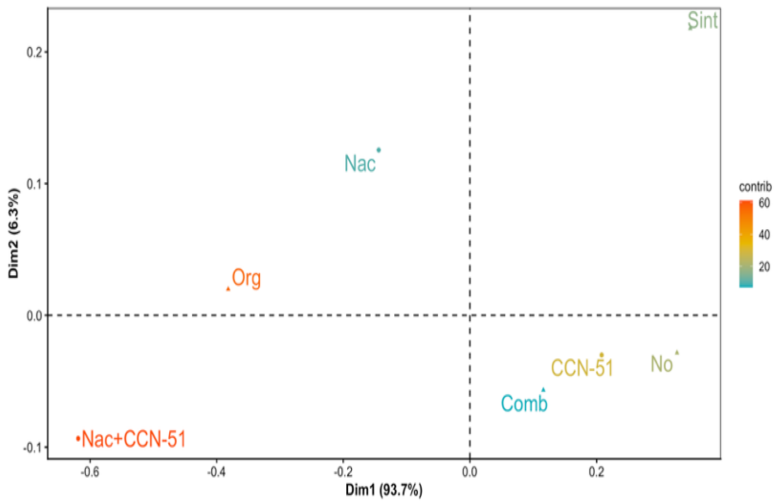

Figure 5. Correspondence analysis of cocoa-variety groups and fertilisation strategies reported by households.

Crop number and H' showed the strongest association among farm characteristics. Total cash-crop area was positively associated with cocoa area, temporary-crop area, crop number, and H′, while associations involving family and hired labour were generally lower. Among the Kruskal-Wallis statistics calculated across cocoa-variety groups, hired labour had the highest value (Figure 6).

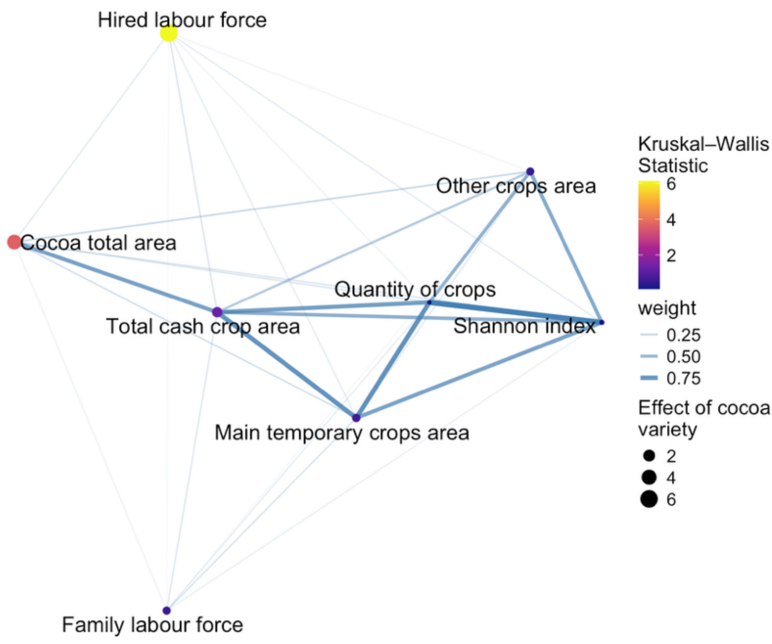

Figure 6. Correlation network of structural and diversification variables across cocoa-based FFs.

Edges indicate Spearman correlations (thicker = stronger) Node colour and size show the degree of variation among cocoa-variety groups (higher Kruskal-Wallis statistic = larger and brighter nodes).

Correlations calculated separately for each cocoa-variety group showed differences in the magnitude and direction of associations among farm characteristics (Figure 7). Total cash-crop area was positively associated with crop number across cocoa-variety groups, with the strongest association in mixed-variety farms. The association between hired labour and total cash-crop area was strongest in mixed-variety farms, while other associations involving hired labour varied among cocoa-variety groups. Crop number and H′ were strongly related across groups; as these variables are intrinsically related through the calculation of H′, no further interpretation was made. The coefficients were presented descriptively and were not statistically compared among cocoa-variety groups.

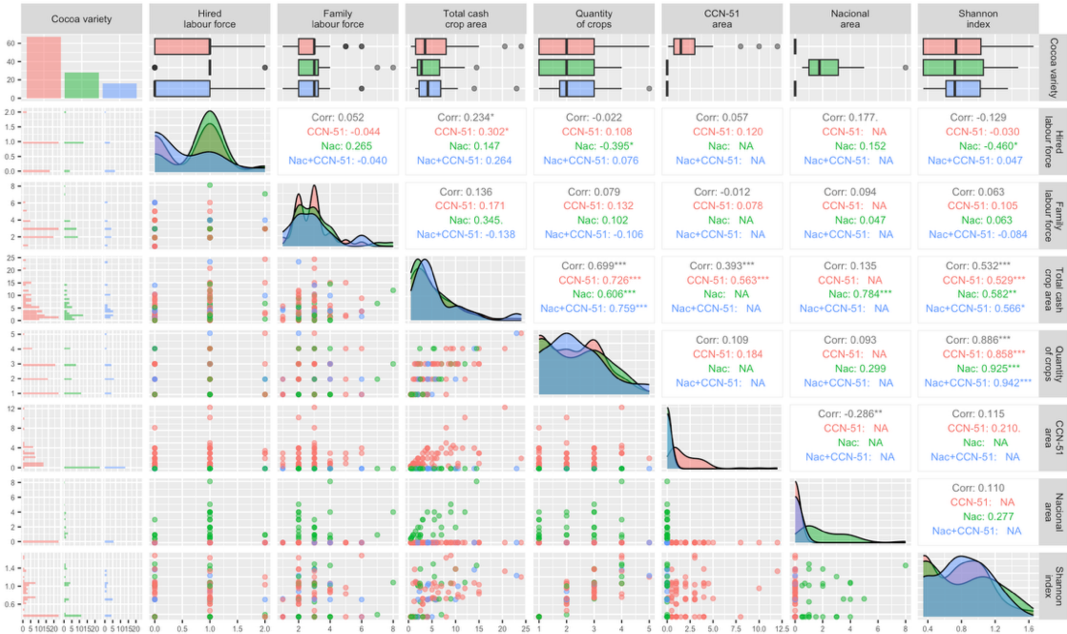

Figure 7. Correlation matrix of farm structural and diversification variables by cocoa-variety group

The figure shows relationships between cocoa varieties (CCN-51 and Nacional), labour force (hired and family), number of crops, and Shannon diversity index in cocoa FFSs. Correlations (Corr) are colour-coded by cocoa variety and statistical significance is indicated ($* \ p < 0.05$, $** \ p < 0.01$, $*** \ p < 0.001$). Density plots, scatterplots, and boxplots illustrate distributions and relationships between variables.

5.2. Farm types

K-means clustering of the standardised farm variables identified three types of cocoa-based FFs differing in land-use allocation, labour organisation, and crop diversification. PCA summarised the multivariate structure of the variables used in the classification and provided a two-dimensional representation of the three farm types. The first two principal components explained 50.0% of the total variance. PC1 (31.2%) represents a gradient from cocoa-centred systems to more diversified configurations, while PC2 (18.8%) captures variation in labour composition (Figure 7). The resulting farm types are summarised in Table 1. The standardised cluster centroids show the profile of each farm type across the variables used in the K-means classification (Figure 8).

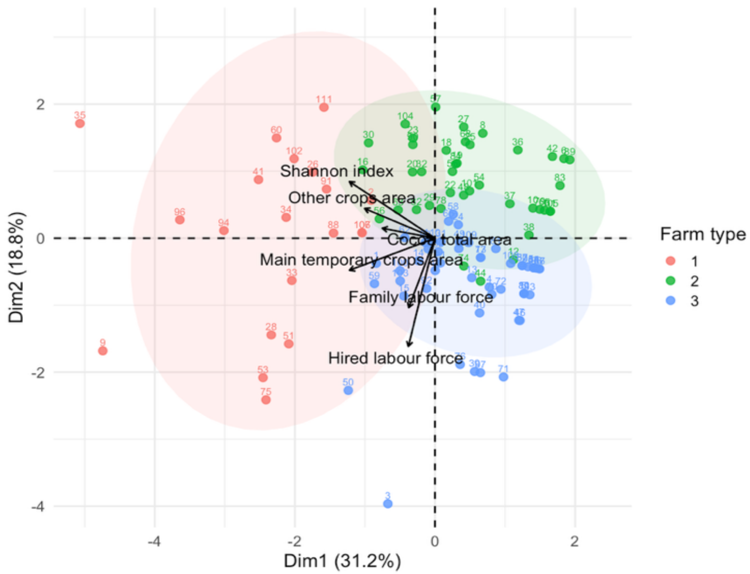

Figure 8. Principal PCA visualisation of farm types identified by k-means

Points represent individual farms and vectors represent the variables included in the PCA. Colours identify the farm types obtained from k-means clustering

Type 1 corresponds to farms with larger cultivated areas and higher levels of diversification. These households combined family and hired labour and allocate more land to both cocoa and additional crops. CCN-51 is more frequent in this group, either alone or in combination with Nacional, indicating a stronger market-oriented profile.

Type 2 represents medium-sized, diversified farms. includes farms with smaller areas allocated to cocoa, temporary crops, and other crops than Type 1.

Hired labour is particularly low in this group, while family labour is similar to that of the other farm types. Crop diversification is intermediate between Types 1 and 3. Nacional is more frequent in this group, consistent with a combination of subsistence production and market participation.

Type 3 includes smaller farms with limited land availability and lower diversification. Although small areas of other crops are present, cocoa remains the dominant land use. Hired labour is higher than in Type 2, while family labour is similar among the three farm types. Crop diversification is lower than in Types 1 and 2.

Land allocation, labour, and crop diversification showed distinct patterns among the three farm types. Post-hoc comparisons showed higher cocoa area, main temporary crops area, and other crops area in Type 1 than in Types 2 and 3, while Types 2 and 3 did not differ for these variables. Family labour did not differ among farm types ($p = 0.623$), while hired labour was lower in Type 2 than in Types 1 and 3 ($p < 0.001$). The Shannon index differed among all three types ($p < 0.001$), with the highest value in Type 1 and the lowest in Type 3. Cocoa-variety composition also differed among types ($\chi^2 = 9.42$, $df = 4$, $p = 0.05$), with CCN-51 more frequent in Type 1, Nacional in Type 2, and mixed varieties in Type 3.

5.3. Farmers' perceptions of crop diversification

Fisher's exact tests indicated no association between farm type and perception category across the six benefit variables. The proportions of responses ("Never", "Sometimes", "Often", and "Always") were similar across farm types for all benefits ($p > 0.05$). The proportion plots presented in Appendix B show the response patterns for each farm type. No statistical association was detected between the identified farm types and farmers' perceptions of the benefits associated with additional crops.

When perceptions were analysed by cocoa variety, response patterns were also similar across categories. Among the six benefit variables, only "soil improvement" related to permanent crops showed a statistically detectable association with cocoa variety ($p = 0.0378$). Post-hoc pairwise tests identified a difference between CCN-51 and Nacional producers ($p = 0.040$), with Nacional producers selecting the highest perception category ("Always") more frequently and "Never" less frequently than households cultivating CCN-51. Mixed plantings did not differ from either group. No other benefit variables showed evidence of association with cocoa variety ($p > 0.10$).

5.4. Spatial distribution of ecosystem functions

SOC, BOC and EC varied across the study area in relation to differences in land cover and vegetation dynamics. Studied farms were concentrated mainly in the central and southern sectors of the landscape (Figures 9, 10).

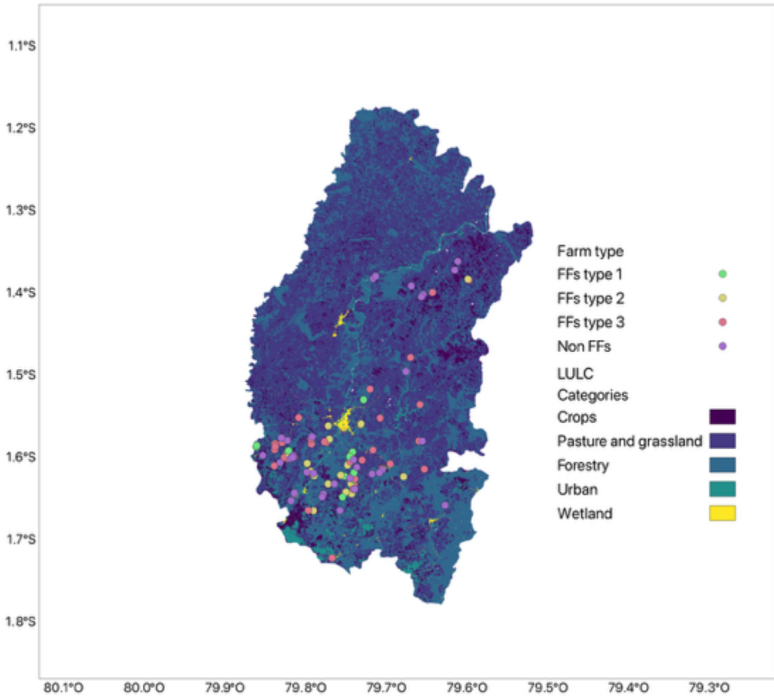

Figure 9. Land-use and land-cover classes and spatial distribution of studied farms

SOC values differed in relation to the land-cover mosaic. Lower values occurred in areas classified as crops and pasture, while higher values were observed in zones mapped as forestry or wetland, particularly toward the western and northern sectors. Most farms were located within crop and pasture areas, and farm-level SOC values fell mainly within the lower to intermediate portion of the overall range. Only a small number of farms intersected areas with tree cover or wetland vegetation, where higher SOC values were present. Across farms, SOC values ranged approximately from 3 to 62 t C/ha.

BOC followed a spatial pattern similar to that of SOC. Higher values were associated with areas classified as forestry, while lower values predominated in crops and pasture. Although the studied farms were agricultural production units and were located mainly in areas classified as crops, the remote-sensing LULC classification identified other land-cover classes within some farm polygons, including forestry and pasture and grassland.

For EC, higher values occurred in areas higher NDVI and lower temporal variability in NDVI. The spatial pattern also incorporates the slope component included in the EC calculation. In some cases, EC varied within individual farm areas, reflecting local variation in vegetation dynamics or slope conditions.

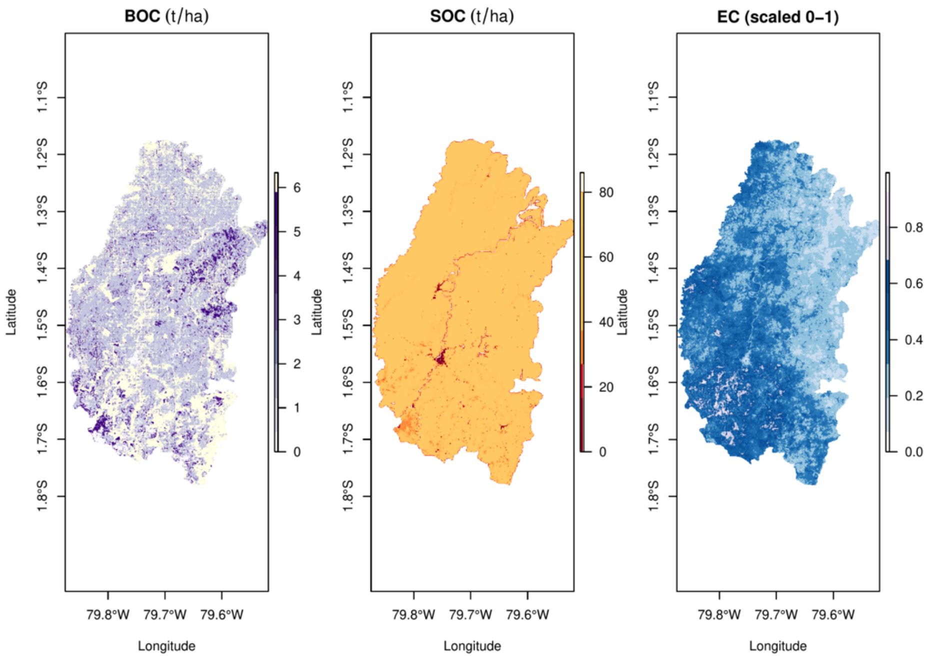

Figure 10. Spatial distribution of ecosystem functions

The ES flow map, derived from SOC, BOC, and EC, presented differences across the landscape (Figure 11). Values ranged from 44.3 to 83.6 on the 0-100 scale, with most areas characterised by intermediate values. Higher values occurred mainly in the central and southern sectors, with additional high-value areas toward the north, while lower values were present in several spatially defined areas across the landscape. Since ES flow was modelled at the pixel level, the map represents spatial differences in ES flow across the landscape and does not provide a comparison among farm types.

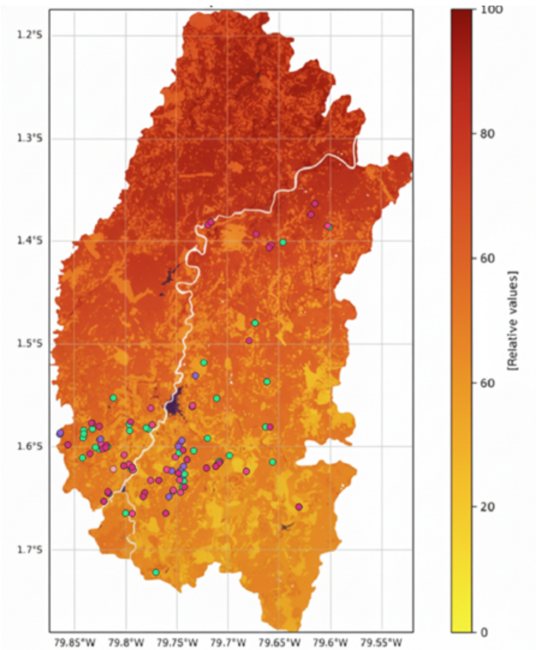

Figure 11. Spatial distribution of ecosystem service flow derived from SOC, BOC, and EC

CAP also varied spatially. Higher CAP values occurred where farms were more closely located, especially in the central part of the study area. Lower CAP values occurred in more isolated sectors, particularly toward the southern and northeastern margins. These spatial differences indicate higher capture of ES flow in areas with a greater concentration of the farm households considered as beneficiaries (Figure 12).

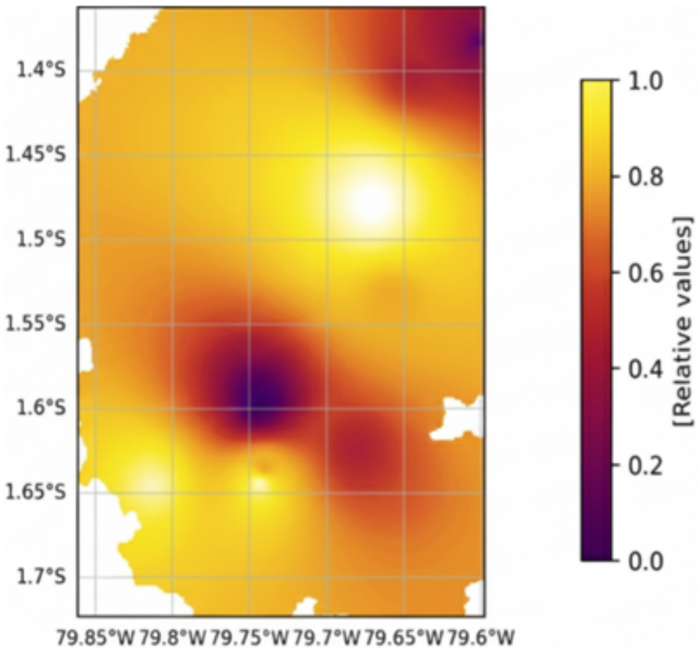

Figure 12. Spatial distribution of ecosystem service capture across the study area

The BEN map reflected the spatial overlap between ES flow and CAP. Medium to high BEN values occurred where relatively high ES flow coincided with higher CAP. Lower BEN values occurred in areas where either ES flow or CAP was lower. BEN values were higher where service flow and its capture by the farm households considered as beneficiaries coincided spatially (Figure 13).

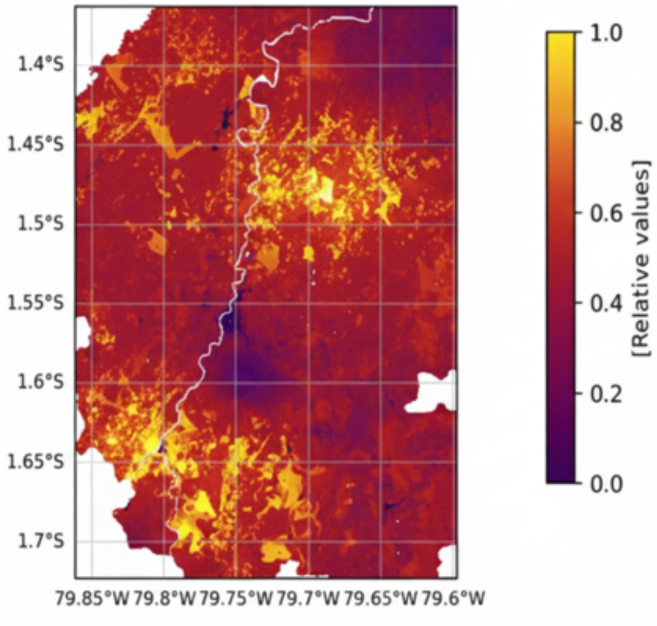

Figure 13. Spatial distribution of ecosystem service benefit across the study area

5.5. Ecosystem functions across farm types

SOC, BOC, and EC differed in their distributions across farms. SOC values ranged approximately from 3 to 62 t C/ha. BOC values were generally lower, with most farm-level observations concentrated at lower values and fewer observations at higher values. EC values occupied the intermediate and upper portions of the 0–1 scale across most farms.

Differences among farm groups were detected for SOC and BOC, while no differences were detected for EC. Post-hoc comparisons showed that Market-oriented FFs (Type 1) had lower SOC and BOC values than Small-scale FFs (Type 2), Balanced FFs (Type 3), and non-FFs. Small-scale FFs (Type 2), Balanced FFs (Type 3), and non-FFs did not differ from each other for either function (Figure 14).

For EC, no differences were detected among Market-oriented FFs (Type 1), Small-scale FFs (Type 2), Balanced FFs (Type 3), and non-FFs (Figure 15).

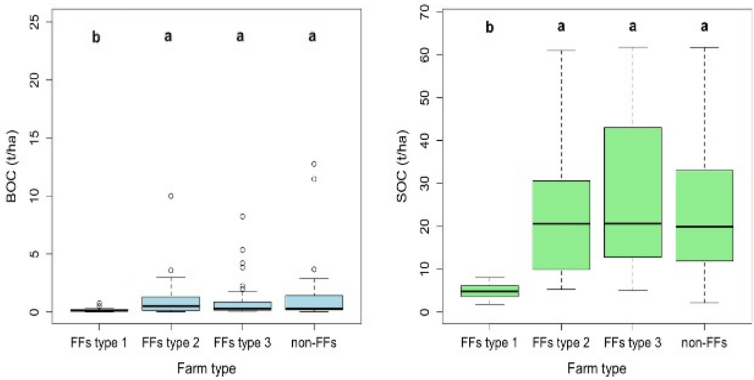

Figure 14. Distribution of BOC and SOC across farm types

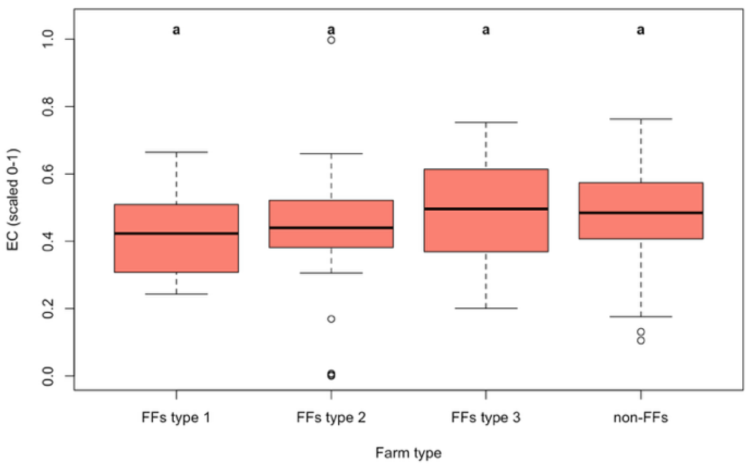

Figure 15. Distribution of EC across farm types

CAP values varied across farms, ranging from near zero to above 0.90. Among FFs, Market-oriented FFs (Type 1) were concentrated at higher CAP values, with most observations around 0.70 or above. Small-scale FFs (Type 2) included observations from approximately 0.30 to above 0.90, although most values were concentrated around 0.50–0.75. Balanced FFs (Type 3) included values across almost the entire CAP scale, with most observations between approximately 0.50 and 0.75. Non-FFs also presented a concentration at intermediate to high values, with a few observations near zero. CAP did not differ among farm groups ($p = 0.154$; Figure 16).

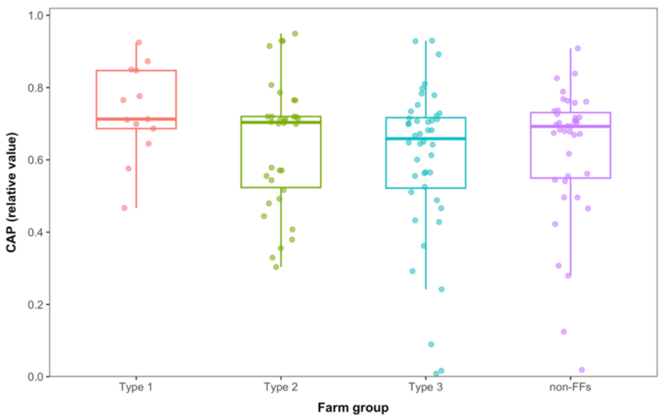

Figure 16. Ecosystem-service capture by farm type. Points represent individual farms, the horizontal line within each box represents the median

BEN values were between values close to zero and 1.00 across farms. Among FFs, Market-oriented FFs (Type 1) and Small-scale FFs (Type 2) had similar median BEN values (0.624 and 0.627, respectively), while Balanced FFs (Type 3) had a slightly lower median (0.590). Non-FFs had a median BEN of 0.582. BEN did not differ among farm groups ($p = 0.382$; Figure 17).

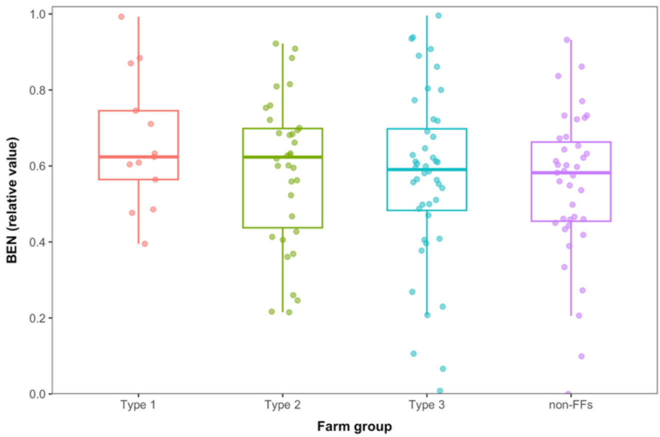

Figure 17. Ecosystem service benefit by farm type. Points represent individual farms, the horizontal line within each box represents the median.

5.6. Influence of farm type and cash crop diversity on ecosystem functions

The multivariate analysis of SOC and BOC indicated that farm type and crop diversity were associated with part of their joint variation ($R^2 = 0.24$, F

= 9.97, p = 0.001), indicating an association between these farm characteristics and SOC and BOC values.

Results from the GAM analyses differed across EFs. For SOC, the model explained 28.7% of the variance. The parametric terms indicated higher baseline SOC values for Small-scale FFs (Type 2) and Balanced FFs (Type 3) relative to Market-oriented FFs (Type 1). For non-FFs, baseline SOC was also higher than for Market-oriented FFs (Type 1). The smooth terms indicated a significant relationship between SOC and crop diversity for Balanced FFs (Type 3), while no significant relationship was detected for Market-oriented FFs (Type 1) or Small-scale FFs (Type 2). A significant relationship between SOC and crop diversity was also detected for non-FFs.

For BOC, the GAM did not reach the explanatory threshold (adjusted $R^2 = 0.0585$). Although differences in BOC were detected among farm groups in the univariate analysis, farm type and crop composition accounted for little of the variability in BOC in the GAM. BOC was not included in the RF analysis.

For EC, the GAM explained 1.4% of the variance. No differences in EC were detected among farm groups in the univariate analysis, and farm type and crop composition accounted for little of the variability in EC in the GAM. EC was not included in the RF analysis.

Table 3. GAM results assessing relationships between soil organic carbon, farm type, and crop composition

Component	Term	Estimate	EDF	SE	Ref.df	t-value	p-value
Parametric coefficients							
	(Intercept)	3.926		8.13		0.483	0.63
	Farm_type: FFs type 2	19.552		8.502		2.3	0.023 *
	Farm_type: FFs type 3	26.242		9.027		2.907	0.004 **
	Farm_type: non-FFs	19.753		8.47		2.332	0.021 *
Smooth terms							
	s(Shannon_index): FFs type 1		1.001		1.00	0.014	0.909
	s(Shannon_index): FFs type 2		1.666		2.02	2.308	0.108
	s(Shannon_index): FFs type 3		2.247		2.61	5.064	0.003 **
	s(Shannon_index): non-FFs		1.38		1.65	7.382	0.002 **
Model fit							
	R^2						0.287
	Deviance explained						33.80%

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

RF analysis was applied only to SOC, which met the criterion defined for RF modelling. The model explained 35.4% of the variance in the test dataset, with a normalised RMSE equivalent to 23.92% of the SOC range. Variable-importance scores indicated that crop composition had higher importance for SOC prediction than farm type (Table 5).

Table 4. Variable importance and performance metrics from the RF model for soil organic carbon

Component	Metric/Variable	Value	Notes
Model fit			
	Number of trees	500	Training data
	Mean of squared residuals	244.56	Training data
	Variance explained (%)	18.70%	Test data
	RMSE	13.01	Test data
	R^2	0.354	
	Normalised RMSE	23.92%	Based on observed SOC range
Variable importance			
	Shannon_index	%IncMSE: 29.19; IncNodePurity: 9655.19	Higher importance
	Farm_type	%IncMSE: 13.73; IncNodePurity: 3634.79	

The CART analysis for CAP identified farm type as the primary predictor. Cross-validation retained farm type as the splitting variable in the pruned tree. The tree produced three terminal nodes, with predicted CAP values of 0.58, 0.66, and 0.93 (Figure 18). Market-oriented FFs (Type 1) formed the node with the lowest predicted CAP, Small-scale FFs (Type 2) formed the intermediate node, and Balanced FFs (Type 3) and non-FFs were grouped in the node with the highest predicted CAP. Observed CAP values associated with the three terminal nodes are presented in Figure 19.

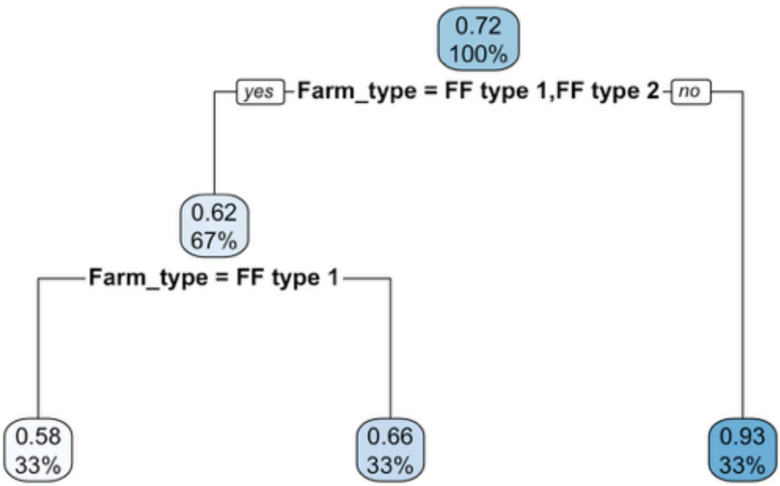

Figure 18. Classification and regression tree showing stable splits for ecosystem service capture

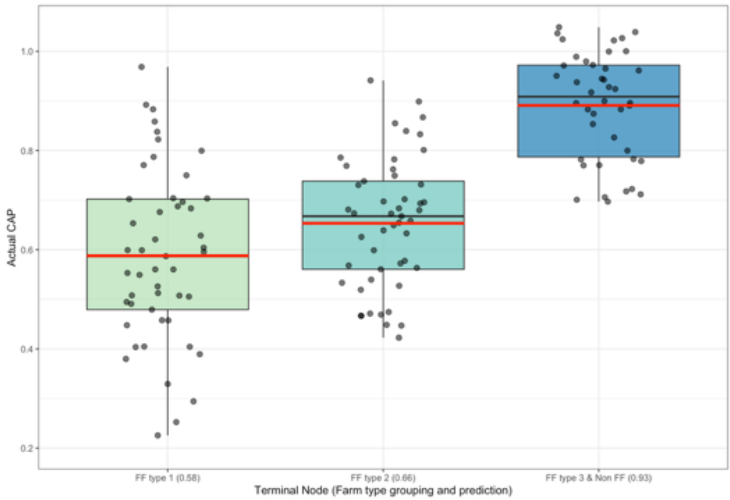

Figure 19. Ecosystem service capture across CART-terminal nodes

In contrast, for BEN, the CART analysis resulted in a single-node pruned model. Neither farm type nor crop composition produced a split that improved predictive accuracy under cross-validation. he final model predicted a single BEN value for all farms, indicating that the predictors considered did not improve BEN prediction in the pruned CART model.

6. DISCUSSION

6.1 Discussion

Cocoa-based FFs in the study area are organised through different combinations of land allocation, labour arrangements, and crop composition. These variables do not form a tightly structured system, as distributions across cocoa-variety categories indicate overlapping ranges of cultivated area, crop number, and H’. Correlation patterns reinforce this, with low associations among most structural variables aside from the expected relationship between crop number and the H’. Comparable patterns of heterogeneity have been described in smallholder systems, where farm organisation reflects the interaction of labour availability, production objectives, and contextual factors and is not explained by a single structural dimension (Hayden et al., 2021; Pacheco de Castro Flores Ribeiro et al., 2021). Farm organisation results from concurrent decision processes at household level, where land allocation, labour use, and crop selection respond multiple changing conditions and do not follow a single organising principle (Foguesatto et al., 2019; B. V. Miranda & Grandori, 2020). These patterns are associated with the characteristics of the studied production system and may differ in systems with alternative institutional arrangements, market integration, or land-use histories, limiting direct transfer of results to other contexts.

Under these conditions, diversification does not align consistently with structural variables, as farm characteristics vary independently and do not follow a systematic pattern across farms. Crop composition does not align consistently with farm size, labour availability, or cocoa variety, indicating that structural attributes do not determine diversification patterns. Similar configurations have been reported in smallholder systems combining perennial and temporary crops, where variation in management and production conditions results in heterogeneous arrangements (Hashmiu et al., 2022; Song & Cai, 2024). Diversification is associated with management decisions linked to resource allocation, risk distribution, and short-term adjustments and is not restricted to fixed structural conditions (Azarov et al., 2024; Daxini et al., 2019).

Regarding farm classification, typological differences correspond to variation in land-use allocation and labour organisation. Diversification distinguishes farm types statistically, particularly between highly diversified and less diversified systems, while other variables such as family labour remain similar across groups. Cocoa variety is distributed unevenly across farm types, although cocoa variety is not associated with the level of diversification.

Typologies capture contrasts in how resources are arranged, while variation in crop composition persists within each group, indicating that classification does not fully represent how production components are combined in practice (Kurdyś-Kujawska et al., 2021; Tacconi et al., 2022; Taramuel-Taramuel et al., 2023).
Perceptions follow the same pattern of limited differentiation, as reported benefits of diversification do

not differ across farm types and vary across cocoa varieties. Response distributions showed similar frequencies across farm structures. Crop combinations are evaluated through general expectations and show little differentiation in perceived outcomes according to specific farm conditions. Perceived advantages appear diffuse or influenced by factors not captured in structural variables (Agrawal et al., 2021; Rosa-Schleich et al., 2024). Variation in crop composition is associated more closely with practical considerations such as labour allocation, risk distribution, or market conditions while perceived benefits show less consistent relationships with these differences. Decision-making appears oriented toward maintaining flexibility in production, with no clear emphasis on maximising specific perceived outcomes (Ge et al., 2023; Nahar et al., 2024).

Fertilisation practices follow a similar pattern. The absence of association between cocoa variety and fertiliser strategy shows that fertiliser use was not differentiated according to the cocoa variety cultivated. This aligns with findings in smallholder systems, where fertilisation practices are influenced by resource availability, management preferences, and risk considerations (Hoffmann et al., 2020; Zheng et al., 2022). Farms cultivating both Nacional and CCN-51, as well as those specialising in Nacional, show a higher tendency to apply organic fertilisers. This pattern is consistent with management approaches linked to certification schemes or to perceived agronomic and ecological advantages of organic amendments (Avane et al., 2022; Saravia-Matus et al., 2020; Yang et al., 2024).

At the same time, the use of organic fertilisers may also be associated with resource limitations, as reliance on farm-derived inputs can indicate limited access to external inputs due to financial restrictions (Aryal et al., 2021; Benson & Mogues, 2018).

For EFs, relationships with farm characteristics differ across variables, indicating that ecological responses are not uniformly associated with farm organisation. SOC, BOC and EC differ in their relationships with farm characteristics. Differences among farm types are observed for SOC and BOC, while EC remains similar across categories. Divergent responses among functions indicate that ecological processes operate through distinct mechanisms that are not equally sensitive to farm-level variation

Among these functions, soil organic carbon is the only variable consistently associated with farm-level differences. Variation in soil carbon is associated with organic matter inputs and soil disturbance, which differ across farms combining perennial cocoa with temporary crops and hired labour and those relying on household labour and more stable crop composition. Under these conditions, the relationship between crop diversity and SOC is influenced by vegetation, soil, and management characteristics that are not represented by crop number or proportional area. Similar context-dependent relationships have been reported in smallholder systems (Babu et al., 2023; Reichert et al., 2022; Zhang et al., 2023). Crop diversity metrics describe composition, while soil carbon is associated with management practices, indicating that both operate at different analytical levels (R. Alvarez, 2024).

In addition, SOC estimates varied among farms in association with the spatial information and reference values incorporated into the calculation. The IPCC Tier 1 approach uses empirically derived reference values and adjustment factors representing land use, management, and carbon inputs, grouped into relatively general soil, climate, and management categories (Paustian et al., 2019). The estimated values are useful for comparing SOC patterns among farms using consistent reference values and adjustment factors. Differences in estimated SOC can be interpreted across the production systems, while incorporating local field data could improve the precision of farm-level estimates (Sperow, 2020).

In contrast, BOC was not associated with crop composition. The estimated BOC values were derived from biomass carbon coefficients assigned to the LULC classes represented across the farms. Although the questionnaire identified agricultural land uses and crops reported by farmers, the remotely sensed LULC layer represented additional land-cover classes across some farm polygons. The questionnaire describes production according to reported crops and land uses, while remote sensing characterises land cover from spectral and spatial information. Tree cover and other vegetation associated with cocoa production can contribute to the remotely sensed characteristics of the farm area (Kalischek et al., 2023). Classification uncertainty also needs consideration, as mixed pixels and spectral similarities among vegetation types can complicate the separation of LULC classes (Moraiti et al., 2024).

The biomass coefficients assigned to these classes incorporate spatial variation in land cover across farm polygons that is not represented by crop composition variables derived from the questionnaire. LULC-based carbon estimation has also been applied when local carbon-pool data are unavailable, using carbon-density values assigned to land-cover classes. The resulting BOC estimates are useful for comparing spatial differences among farms under a consistent estimation procedure, while local biomass information could refine farm-level estimates (Mallick et al., 2022). In perennial agricultural systems, aboveground biomass carbon can vary with vegetation structure, stand characteristics, and management history (Riquetti et al., 2022). Characteristics of this type were not explicitly represented in the BOC estimation and could contribute to variation among farms (Beka et al., 2023; Kassa et al., 2022).

EC depends on terrain, rainfall patterns, soil properties, and vegetation continuity, factors not represented in the farm-level variables included in the analysis. Crops are managed in separate plots instead of intercropped arrangements, so variation in crop composition does not translate into continuous ground cover (Vianney Nsabiyumva et al., 2025). The EC estimation incorporated spatial information on vegetation condition, temporal vegetation variability, and slope. NDVI has been used in erosion-control assessments and is associated with vegetation characteristics linked to soil protection, including canopy cover, vegetation structure, and litter cover (Vatandaşlar & Yavuz, 2023b). In the EC estimation, NDVI was used as a proxy for vegetation condition and its temporal variation, not as a direct measurement of biomass. NDVI primarily captures spectral characteristics of surface vegetation and has limited capacity to represent differences in vegetation structure, soil properties, and erosion-regulation mechanisms among vegetation types (Zhao et al., 2026). The estimated EC values are useful for comparing spatial differences in erosion-control conditions among farms using a consistent estimation procedure. The lack of differences across farm types and the low explanatory performance of the models suggest that the farm-level variables included in the analysis did not capture much of the spatial variation represented in EC. Differences in spatial scale between erosion processes and farm-level variables can also limit the capacity of statistical models to represent these relationships (Colnago et al., 2021; Gao et al., 2023).

In addition to farm-level characteristics, EFs vary according to spatial context. EFs differ across land cover types, with higher values in areas with tree cover and lower values in cropland and pasture. Comparable spatial patterns have been reported in tropical agricultural landscapes (Lohbeck et al., 2016; Qiu et al., 2020). Ecological conditions result from the interaction between farm management and surrounding land cover, linking farm-level processes with landscape configuration. Such relationships depend on the spatial configuration of the studied landscape and may not occur in more homogeneous systems or in contexts with different land-use mosaics, which limits the extent to which these findings can be generalised.

When ESs indicators are considered, relationships among variables are structured differently. ES flow represents the relative spatial availability of the selected EFs, CAP represents the proportion of that flow spatially accessible to potential beneficiaries, and BEN represents the potential benefit resulting from the interaction between flow and capture. These components distinguish the spatial generation of the service from its accessibility and potential contribution to beneficiaries (Schultner et al., 2021; Vialatte et al., 2019). Separation between these components indicates that ecological processes and socio-economic outcomes follow distinct mechanisms (Katusiime & Schütt, 2020; Silva et al., 2024).

Capture represents the portion of ES flow accessible to potential beneficiaries, while benefit represents the interaction between ES flow and capture. Differences in capture among farms are associated with spatial access to the service, while differences in benefit depend on both the available flow and its capture. Socio-economic conditions can influence how ESs contribute to human well-being in relation to their spatial availability (W. Chen et al., 2020). Model outcomes showing limited predictive structure indicate that the selected variables and modelling approaches are insufficient to capture the processes determining benefit, pointing to the need for integrating socio-economic and institutional variables in future analyses (Morgan et al., 2022).

These results indicate limitations associated with modelling complex social–ecological systems. Model complexity can exceed the information represented in the available data, reducing parameter identifiability and making it possible for different parameter combinations to produce similar outcomes (Castro et al., 2025). Noisy observations and processes occurring at temporal or spatial scales not represented in the model can add uncertainty to model estimates. ESs assessments use simplified representations of dynamic systems, where abstraction reduces representational accuracy and explanatory capacity (Evans, 2019).

Differences between CAP and BEN indicate spatial differences in ecosystem-service access and potential benefit. Access to ESs depends on farm location, while potential benefit depends on the relationship between service flow and capture. Improvements in ecological conditions do not automatically translate into higher potential benefits at the farm level, showing a distinction between ecological supply and the potential contribution of ESs to well-being (Khosravi Mashizi & Sharafatmandrad, 2021; Liu et al., 2023).

Across these levels, relationships among farm structure, EFs, and ESs indicators do not follow a single explanatory structure. Farm-level organisation is associated with some EFs, particularly soil carbon, while ES flow, capture, and benefit are linked to spatial processes and access to services. Farm types describe structural configurations in the study area, supporting H1. H2 received partial support, as associations between crop composition and EFs depended on farm configuration and function type. H3 also received partial support, as differences among farm types were found for specific functions, particularly soil organic carbon. H4 received limited support, with ES flow, capture, and benefit showing limited relationships with farm type and crop composition.

Joint analysis of farm organisation, EFs, ES flow, CAP, and BEN show that relationships among these components vary across analytical levels. Farm structure is associated with selected EFs, while ES flow, CAP, and BEN correspond to the spatial distribution of functions and their accessibility and potential contribution to beneficiaries. Ecological processes and service outcomes require interpretation at different analytical levels and cannot be addressed through a single perspective.

6.2. Policy implications

Cocoa-based FFs considered differ in land-use allocation, labour organisation, and crop composition, while diversification varies independently from these structural characteristics. Differences in labour use and crop distribution show variation in production conditions that is not captured by uniform support measures, and similar levels of diversification across farm types show that crop composition is not consistently associated with these organisational patterns. Policy design based on simplified categories or general diversification targets does not correspond to how production is structured across farms with similar characteristics, reducing the capacity to adjust interventions to existing conditions.

Interventions can be differentiated by combining information on labour organisation and crop distribution within farms. Training and technical assistance can be structured according to labour availability, accounting for the presence or absence of hired labour, while participation requirements and deliver y formats can be adapted to the scale of operations and crop distribution. Differentiating extension delivery according to farmers' characteristics has also been proposed for cocoa production, where household and farm-related factors influence preferences for extension delivery methods (Aniagyei et al., 2024). These adjustments support alignment between programmes and farm organisation, avoiding delivery formats that do not fit labour arrangements or farm scale and supporting implementation across different contexts. Existing crop combinations can inform programme design, avoiding standardised diversification targets that do not correspond to current systems.

Differences across EFs indicate that environmental performance cannot be represented by a single indicator. SOC varies across farm contexts, while BOC and EC do not follow the same pattern. Programme evaluation can differentiate indicators according to the ecological process being addressed, supporting the interpretation of outcomes across farms with similar conditions and reducing the risk of assigning similar environmental performance where EFs differ. The allocation of incentives and evaluation of programme effectiveness can then consider the specific EF targeted by the intervention.

Access to ESs adds a spatial component to these differences. EFs vary in relation to land-cover distribution, while ESs access depends on the position of farms and their proximity to service flows. Farms with similar organisational characteristics may differ in access to ESs, which is not captured by farm type or crop composition alone. Incorporating spatial information into agricultural planning can help identify areas with lower ESs vice access and support prioritisation instead of uniform allocation across producers with similar characteristics. Spatial targeting has been applied to agricultural and agri-environmental interventions, including the prioritisation of water, agricultural inputs, technical assistance, and environmental management measures (Biffi et al., 2021; Kpienbaareh et al., 2019; Robin et al., 2019; Uthes et al., 2010).

Access to ESs does not correspond directly to realised outcomes. Distinguishing between CAP and BEN can help monitoring systems to evaluate whether interventions influence ecological conditions, spatial access, or potential benefits. This separation prevents overestimation of programme impact in situations where service availability does not translate into outcomes at the farm level, including in contexts with comparable farm structures.

Farmers report similar perceptions of diversification across production contexts, indicating that crop composition is not associated with clearly differentiated perceived benefits. Interventions aligned with existing crop combinations are more consistent with observed practices, which is consistent with implementation in farms with similar characteristics, reducing the need for changes in farm organisation and increasing the likelihood of adoption.

Differences in the relationships of farm characteristics with EFs, ES flow, CAP, and BEN show that ecological conditions and service outcomes do not respond in the same way to farm-level characteristics. Distinguishing between these dimensions in policy design and evaluation contributes to clearer assessment of programme effects and avoids treating improvements in ecological conditions as equivalent to improvements in farmer-level outcomes across contexts with comparable conditions.

Consideration of farm organisation, EFs, access to ESs, and realised outcomes may provide additional information for the design and evaluation of initiatives directed at family farming. In contexts characterised by variation among farms, distinguishing these dimensions can contribute to a more differentiated interpretation of environmental performance, recognising that ecological processes and ecosystem-service outcomes may differ across farms with similar characteristics.

6.3. Limitations of the study

The analysis is based on cocoa-based FFs located within a specific coastal region of Ecuador, where land-use history, cocoa varieties, and farm organisation generate particular social and ecological conditions. The participating farms belong to one producer association, adding specificity to the production and socioeconomic conditions represented in the analysis. The farm types identified, capture variation in this context, while structural and ecological patterns may differ in other cocoa-producing regions with different environmental or socio-economic conditions. The analytical approach can be reproduced in other locations by applying the same methods and adapting context-specific inputs, including spatial environmental data. Interpretation of the results needs to consider the production, socioeconomic, and environmental conditions of each location.

The assessment of crop composition relies on reported information and represents the crops present and their relative representation across farms. It does not include field-level information on vegetation attributes such as crop age, planting density, or canopy structure, which were not required as input variables for the spatial estimation of EFs. Including these attributes as complementary farm-level information could support the analysis of relationships between vegetation characteristics and the estimated EFs.

EFs were estimated using spatial environmental information at moderate spatial resolution. SOC estimation used reference values and adjustment factors, while BOC estimation used biomass carbon coefficients assigned to the LULC classes represented across the farms. Uncertainty in the reference values and LULC classification can influence farm-level estimates.

Processes influencing BOC and EC, including microtopography, small drainage features, and vertical vegetation structure, are not fully represented by the spatial information used. Local soil and biomass measurements and finer-scale vegetation information could complement the spatial estimates and support their interpretation at the farm level.

The analysis represents was cross-sectional. Farm management, vegetation structure, and soil properties change over time as crop composition and environmental conditions vary. Repeated collection of farm-level information on crop composition and management could complement the spatial analysis and support the evaluation of their relationships with EFs and ecosystem service indicators over time.

The study focuses on ecological and spatial dimensions of ESs and does not incorporate direct measures of livelihood outcomes. Variation in CAP and BEN is not linked to indicators such as income, food security, or risk exposure, BEN represents potential benefit and does not constitute a direct measure of household outcomes. Household-level socioeconomic indicators could complement the analysis by exploring relationships between ecosystem service benefits and household well-being.

Finally, the analysis focuses on selected EFs and their associated ESs. Other ecological functions and services were not evaluated. Future research on family farming can incorporate technical and ecological characteristics of production systems alongside the social and socioeconomic dimensions commonly addressed in family farming studies.

7. CONCLUSIONS

Cocoa-based FFs combine different configurations of land allocation, labour arrangements, and crop composition across a heterogeneous coastal landscape. These organisational differences describe how production is arranged, while relationships between farm organisation and EFs differ among the functions evaluated. Soil organic carbon varies across farm contexts, while biomass carbon and EC do not differ among farm types. The different relationships observed for SOC, BOC, and EC show that farm organisation and EFs are not consistently associated across the functions evaluated.

Crop composition forms part of management across all farm configurations and does not act as a uniform mechanism associated with soil organic carbon. Relationships between crop composition and estimated SOC differ among farm contexts. Crop composition is not a general indicator of soil-related conditions, and its relationships with EFs differ according to the function evaluated and the farm context.

BOC and EC did not differ among farm types and were not associated with crop composition. Biomass carbon and EC incorporate spatial environmental information that is not represented by farm-level characteristics. Their estimation includes land cover and, for EC, vegetation condition, temporal vegetation variation, and slope. Interpretation of these EFs at the farm level requires consideration of both farm characteristics and the spatial environmental conditions represented in their estimation.

Ecological conditions, access to ecosystem services, and potential benefits represent distinct dimensions of the studied production systems. EFs and ecosystem service indicators did not show the same relationships across farms. Differences in ecological conditions were not directly associated with differences in CAP and BEN. Farm type and crop composition also showed different relationships across provision, CAP, and BEN.

Farm typology captures differences in the organisation of cocoa-based FFs without defining their ecological and ecosystem service conditions. Farm types differed in estimated SOC, with no differences in BOC or EC, and similar perceptions of diversification were found across farm types. Relationships between farm characteristics and ecosystem service indicators also varied across provision, CAP, and BEN. Farm typology is useful for characterising production organisation, although it does not represent a general classification of ecological performance or ecosystem service conditions.

The integration of farm organisation, crop composition, estimated EFs, and ecosystem service indicators connects production characteristics with ecological conditions, ecosystem service access, and potential benefits in a single analytical approach. Considering these dimensions in the same analysis makes it possible to distinguish how their relationships change from farm organisation and EFs to ecosystem service access and potential benefits.

Spatial information can contribute to differentiated planning and programme design in cocoa-producing landscapes. Ecosystem-function indicators can support the identification of areas according to ecological conditions, and ecosystem-service indicators can distinguish access from potential benefits. Farm organisation can inform how interventions are delivered without being used to define ecological performance. Future research can incorporate temporal information on crop composition and management, complementary field-level vegetation information, and household socioeconomic indicators to explore relationships among farm characteristics, EFs, ecosystem service access, and potential benefits over time.

Findings are derived from cocoa-based FFs located in a specific coastal region belonging to one producer association and correspond to the organisational and ecological conditions present in that context. Transferability depends on similarity in farm structure, land use, socioeconomic conditions, and landscape configuration across cocoa-producing systems. Cocoa-based production systems can be interpreted as socio-ecological systems in which farm organisation, ecological conditions, ecosystem service access, and potential benefits represent related but distinct dimensions.

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9. APPENDIXES

Appendix A. Questionnaire for farm characterization and perceived benefits of non-cocoa cash crops

Note: The questionnaire was administered using Kobo Toolbox. Additional questions were included but are not reproduced here, as they served analytical purposes outside the scope of this study. Only information relevant to the present research is reported in this appendix.

Section 1. Identification

1. Locality: ______________________________
2. GPS Coordinates:
   - Latitude: _________________
   - Longitude: ________________

Section 2. Labour force

3. Number of hired labourers: ____________
4. Number of household (family) labourers: ____________

Section 3. Cash crops (different than cocoa)

For each cash crop cultivated on the farm, please complete:

Crop name | Cultivated area (ha)

Section 4. Cocoa varieties

5. Which cocoa variety/varieties do you cultivate?

- CCN-51
- Nacional
- Both

6. Cultivated area under each cocoa variety (ha):
   - CCN-51: ____________
   - Nacional: ____________

Section 5. Perceived Benefits of temporary and perennial crops (Other than cocoa)

Response categories: Never / Sometimes / Often / Always

Ben 1. Crops provide additional income:
- Temporary crops: ___________________
- Perennial crops: ___________________

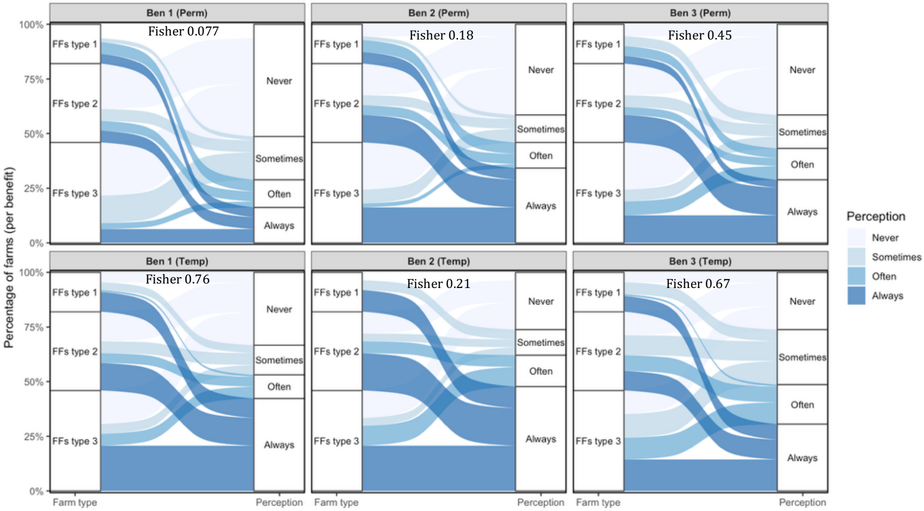
Ben 2. Crops provide food for family:
- Temporary crops: ___________________
- Perennial crops: ___________________

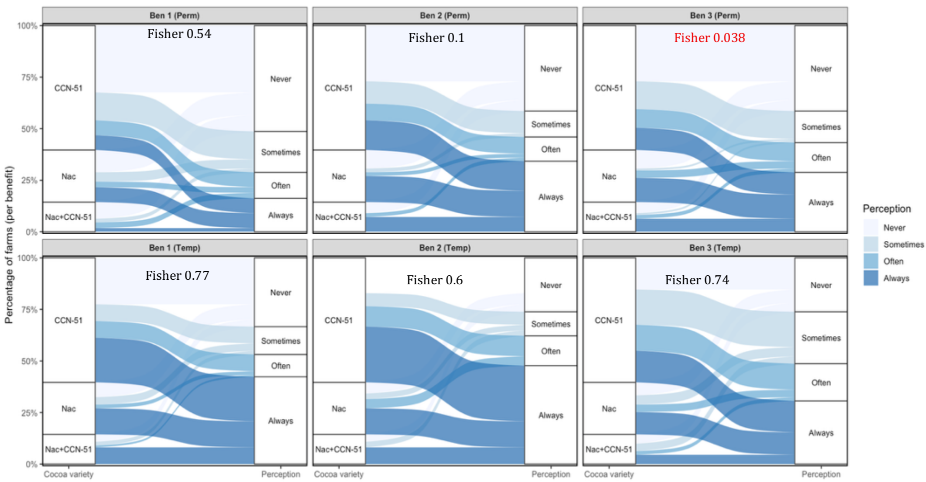
Ben 3. Crops provide soil improvement:
- Temporary crops: ___________________
- Perennial crops: ___________________

Section 6. Type of fertilization

7. What type of fertilization do you use?
   - Organic
   - Synthetic
   - Both

Appendix B. Perceived benefits farm type and cocoa variety





Appendix C. Author academic CV

Angélica Malena Torres Ulloa
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Angélica Malena Torres Ulloa is an agricultural engineer and researcher specialising in tropical agroforestry systems, family farming, and climate–agriculture interactions. She holds a Master of Science degree in Tropical Agroforestry from the Tropical Agricultural Research and Higher Education Center (CATIE), Costa Rica, and an undergraduate degree in Agricultural Engineering from ESPOL. She is a full-time lecturer at ESPOL, teaching courses related to tropical crop production.

She was a member of the project CREA: Pathway to the Reactivation of the Ecuadorian Agri-Food Sector – Diversification Component (2023–2025) led by the Rural Research Center of ESPOL, which focuses on the implementation of accountability mechanisms within farmers' associations. The data analysed in this doctoral research form part of the CREA project. She is also a member of a trained cocoa sensory evaluation panel at ESPOL.

The present thesis led the publication of one paper. The database developed during the research has been used for two submitted manuscripts.

Torres-Ulloa, M., Verner, V., Espinel, R., Portalanza, D., Álava, E., Feijoó, M. J., ... & Van Damme, P. (2026). Combining satellite and farm-collected data to assess ecosystem functions in family-run cocoa production systems: a case study from the Abras de Mantequilla Ramsar site in Ecuador. Environmental and Sustainability Indicators, 101159.

In addition to the doctoral research, she contributed to the following peer-reviewed publications during the PhD period:

Portalanza, D., Torres-Ulloa, M., Alava, E., Facuy, J., Zuluaga, C., Bucaram, R., ... & Ferraz, S. (2025). Impacts of climate change on extreme weather indices in Ecuadorian cities: A socioeconomic analysis. Weather and Climate Extremes, 100810.

Portalanza, D., Torres-Ulloa, M., Arias-Hidalgo, M., Piza, C., Villa-Cox, G., Garcés-Fiallos, F. R., et al. (2024). Ecosystem services valuation in the Abras de Mantequilla wetland system: A comprehensive analysis. Ecological Indicators, 158, 111405.

Portalanza, D., Torres, M., Rosso, F., Zuluaga, C. F., Durigon, A., Horgan, F. G., et al. (2024). Climate variability and change in Ecuador: Dynamic downscaling of regional projections with RegCM4 and HadGEM2-ES for informed adaptation strategies. Frontiers in Climate, 6, 1344868.

Note: Portalanza et al. (2024) applied the ECOSER framework to the Abras de Mantequilla wetland system at landscape scale and analysed multiple ecosystem services using spatial and remotely sensed data. The author's contribution included investigation and data curation. Torres-Ulloa et al. (2026) presents the farm-level research reported in this thesis, integrating spatial and remotely sensed data with information on farm characteristics and crop composition to analyse relationships among farm characteristics, crop composition, estimated EFs, and ESs.