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UNIVERSIDAD AUTÓNOMA DE SAN LUIS POTOSÍ

FACULTADES DE CIENCIAS QUÍMICAS, INGENIERÍA Y MEDICINA

PROGRAMA MULTIDISCIPLINARIO DE POSGRADO EN CIENCIAS AMBIENTALES

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TH KÖLN - UNIVERSITY OF APPLIED SCIENCES

FACULTY SPATIAL DEVELOPMENT AND INFRASTRUCTURE SYSTEMS

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Sustainability of Agroforestry Coffee Cultivation in the Cerro de Kuskawás Natural Reserve, Nicaragua

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Abstract of the Thesis

SUSTAINABILITY OF AGROFORESTRY COFFEE CULTIVATION IN THE CERRO DE KUSKAWÁS NATURAL RESERVE, NICARAGUA

GABRIEL ALEJANDRO VILLANUEVA ZAPATA, 2024

Keyword (5): sustainable coffee, smallholders, private sector interventions, outgrowers scheme, central america.

Agroforestry coffee cultivation presents a promising sustainable agricultural practice in the cerro de kuskawás natural reserve (ckNR). This study evaluates the impacts of agroforestry systems on the sustainability of smallholder farms, considering economic, environmental, social, and governance dimensions. Data were collected from 15 smallholder farms participating in agroforestry initiatives supported by private sector interventions, based on the outgrowers scheme. The research utilized mixed-method approaches, including questionnaires based on the tape tool from FAO and interviews, to assess changes in income stability, biodiversity, gender equity, and land tenure security. The findings reveal that agroforestry coffee cultivation significantly enhances sustainability across multiple dimensions. Economically, it provides increased income stability and diversification, as smallholders benefit from both the higher market value of sustainably produced coffee and the additional revenue from other integrated crops like fruits and timber. Environmentally, the agroforestry systems improve soil health, enhance biodiversity, and reduce the need for chemical inputs, contributing to a more resilient and sustainable agricultural ecosystem.

Socially, the inclusion of women in these agroforestry initiatives has led to improved gender equity and greater empowerment for female smallholders. However, the study also highlights key challenges, including the high initial costs of transitioning to agroforestry, the dependency on external support from entities from the private sector and limited autonomy for smallholders due to centralized control structures. The results suggest that while agroforestry systems have the potential to significantly contribute to sustainable development in the ckNR, achieving long-term sustainability will require addressing these challenges through cooperative models and local governance structures. This study provides valuable insights into the role of agroforestry coffee cultivation in promoting sustainability.

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RESUMEN DE LA TESIS

SOSTENIBILIDAD DEL CULTIVO AGROFORESTAL DE CAFÉ EN LA RESERVA NATURAL DEL CERRO DE KUSKAWÁS, NICARAGUA

GABRIEL ALEJANDRO VILLANUEVA ZAPATA; 2024

PALABRAS CLAVES (5): sustainable coffee, smallholders, private sector interventions, outgrowers scheme, Central America.

EL CULTIVO DE CAFÉ AGROFORESTAL PRESENTA UNA PRÁCTICA AGRÍCOLA SOSTENIBLE PROMETEDORA EN LA RESERVA NATURAL CERRO DE KUSKAWÁS (RNCK). ESTE ESTUDIO EVALÚA LOS IMPACTOS DE LOS SISTEMAS AGROFORESTALES EN LA SOSTENIBILIDAD DE LAS FINCAS DE PEQUEÑOS PRODUCTORES, CONSIDERANDO LAS DIMENSIONES ECONÓMICA, AMBIENTAL, SOCIAL Y DE GOBERNANZA. SE RECOLECTARON DATOS DE 15 FINCAS DE PEQUEÑOS PRODUCTORES QUE PARTICIPAN EN INICIATIVAS AGROFORESTALES APOYADAS POR INTERVENCIONES DEL SECTOR PRIVADO, INCLUIDAS AQUELLAS DE EXPASA Y EL PROYECTO MATRICE. LA INVESTIGACIÓN UTILIZÓ ENFOQUES DE MÉTODOS MIXTOS, INCLUYENDO ENCUESTAS BASADAS EN LA HERRAMIENTA TAPE DE LA FAO Y ENTREVISTAS, PARA EVALUAR LOS CAMBIOS EN LA ESTABILIDAD DE LOS INGRESOS, LA BIODIVERSIDAD, LA EQUIDAD DE GÉNERO Y LA SEGURIDAD DE LA TENENCIA DE LA TIERRA. LOS HALLAZGOS REVELAN MEJORAS SIGNIFICATIVAS EN LOS INDICADORES ECONÓMICOS Y AMBIENTALES, COMO UNA MEJOR ESTABILIDAD DE INGRESOS Y UN AUMENTO DE LA BIODIVERSIDAD. SOCIALMENTE, LA INCLUSIÓN DE MUJERES EN PROYECTOS AGROFORESTALES HA PROMOVIDO LA EQUIDAD DE GÉNERO Y EMPODERADO A LAS PEQUEÑAS PRODUCTORAS. SIN EMBARGO, EL ESTUDIO TAMBIÉN DESTACA DESAFÍOS, COMO LOS ALTOS COSTOS INICIALES, LA DEPENDENCIA DEL APOYO EXTERNO Y LA AUTONOMÍA LIMITADA DE LOS PEQUEÑOS PRODUCTORES DEBIDO A LAS ESTRUCTURAS DE CONTROL CENTRALIZADAS. LOS RESULTADOS SUGIEREN QUE, AUNQUE LOS SISTEMAS AGROFORESTALES TIENEN EL POTENCIAL DE CONTRIBUIR SIGNIFICATIVAMENTE AL DESARROLLO SOSTENIBLE EN LA RNCK, LOGRAR LA SOSTENIBILIDAD A LARGO PLAZO REQUERIRÁ ABORDAR ESTOS DESAFÍOS MEDIANTE MODELOS COOPERATIVOS Y ESTRUCTURAS DE GOBERNANZA LOCAL.

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ABBREVIATIONS

CKNR: Cerro de Kuskawás Natural Reserve.

CAET: Characterization of Agroecological Transition.

TAPE: Tool for Agroecology Performance Evaluation

ADDAC: Asociación para la diversificación y el Desarrollo Agrícola

EXPASA: Exportadora Atlantic, S.A.

MATRICE: Matagalpa Agroforest Resilient Landscape.

MARENA: Ministerio de Ambiente y Recursos Naturales (Nicaragua).

INIDE: Instituto Nacional de Estadísticas.

MINSA: Ministerio de Salud (Nicaragua).

COOMPROCON: Cooperativa Multisectorial Productores de Café Orgánico de Matagalpa.

SOCLA: Latin American. Society for Agroecology.

A-WEAI: Abbreviated Women’s Empowerment in Agriculture Index

MEASUREMENT UNITS

1 manzana= 0.6988 ha.

1 quintal = 100 lb.

1 lb = 2.2 kg.

1. INTRODUCTION

1.1. Problem Statement

The significant gains in agricultural productivity over the last few decades, achieved using external inputs, have created many negative ecological impacts. This has led various authors (Ikerd, 2008; Willett et al., 2019) to question the sustainability of the current system based on capitalism. The premise of unlimited growth within limited resources has brought us to a point where human health, the environment, and social welfare are at risk.

The serious challenges associated with tropical commodity agriculture, including ecological impacts, child labor, land and water conflicts, perpetuation of extreme poverty and inequality, have led to the emergence of voluntary sustainability standards such as Fair Trade and Rainforest Alliance as a promising response (Potts et al., 2015). However, these environmental management measures based on economic reward are often challenged for continuing to generate inequalities within the value chain and not representing a long-term sustainable solution for environmental conservation (Beuchelt & Zeller, 2011; Snider et al., 2017; Valkila, 2009; Wilson, 2010)

Different interventions by international retailers have been made in Nicaragua since 2000 to promote the cultivation of these commodities (mainly coffee and cocoa) under sustainable schemes (Valkila & Nygren, 2010),resulting in coffee becoming one of the three most important exports of the country, contributing 15% of the total job market (ICO, 2016).

The so-called "third wave" of coffee production in Nicaragua has stimulated the transformation of traditional crops in historically marginalized communities into sustainable coffee crops, leading to changes in the livelihoods of small farmers that directly influence the sustainability of these communities' development (Toledo & Moguel, 2012).

However, the cultivation of agroforestry coffee in a sustainable scheme has been questioned by different authors who consider it as a non-definitive answer to achieve sustainability in these communities, requiring a high investment to join this mechanism and not generating the impact that these schemes promote in their mission (Bacon et al., 2008; Salvador et al., 2011; Utting-Chamorro, 2005; Valkila & Nygren, 2010).

1.2. Justification

The communities of the Cerro de Kuskawás Natural Reserve (CKNR) have historically subsisted on traditional agriculture based on the cultivation of maize and beans or livestock production. Recently, initiatives from the private sector have promoted agroforestry coffee cultivation as a tool for the sustainable development of these communities. This transition to agroforestry systems, driven by multinational companies as part of their corporate social responsibility and sustainability initiatives, presents significant socio-environmental implications.

Understanding how this initiative, with coffee as a key crop, impacts environmental conservation and the social well-being of local communities is crucial. It is essential to evaluate and contrast the changes in the livelihoods of smallholders resulting from the implementation and promotion of agroforestry coffee cultivation. Analyzing the benefits and challenges faced by these livelihoods, and how their divergent or convergent strategies can contribute to the sustainable development of these historically marginalized communities, will allow for an assessment of the effectiveness of current tools in achieving a sustainable food production system.

In this context, it is vital to provide evidence supporting the benefits of agroforestry systems for small coffee producers. This research aims to contribute to the debate by specifically examining the impacts of these initiatives in communities within the CKNR, a region recognized for its significant ecosystem services (MARENA, 2021). Understanding the impact of agroforestry systems on the well-being of farmers and local environmental sustainability will enable a more precise evaluation of the effectiveness and scope of these practices as a strategy to improve the economic and social conditions of small coffee producers.

The findings from this study will contribute significantly to the ongoing debate about achieving more sustainable livelihoods and food systems through the integration of smallholders into sustainable global value chains, specifically within the context of agroforestry coffee systems. Moreover, this study could be valuable for the farmers themselves, who can make informed decisions about their participation in agroforestry systems, as well as for the organizations promoting these practices and decision-makers in the coffee sector. By highlighting both the strengths and limitations of agroforestry coffee systems, this research offers critical insights into how smallholders can be better supported to achieve sustainability,

1.3. Research Questions

How do agroforestry coffee systems in a global value chain compare to traditional farming in terms of sustainability?

What are the enabling factors, main challenges and limitations faced by smallholders in transitioning to agroforestry coffee cultivation?

How does the transition to agroforestry coffee cultivation impact the environmental, economic, health, governance and social dimensions of sustainability for smallholders in the CKNR?

What opportunities and challenges does agroforestry coffee production present for enhancing the sustainability of smallholder farming in the CKNR?

1.4. Objectives

To evaluate the viability of agroforestry coffee cultivation as a sustainable practice in the CKNR, Nicaragua.

- To identify the implications of transitioning to agroforestry coffee cultivation on sustainability, considering the drivers, enablers, and barriers within the context of smallholders in the CKNR.

- To assess the multidimensional performance in sustainability of the smallholders' farms.
- To analyze the opportunities and challenges derived from agroforestry coffee production for sustainability in the CKNR.

2. Theoretical Framework

2.1. Sustainable agriculture

The global demand for food has increased fivefold in the last 50 years, primarily due to population growth and the liberalization of trade (Montoya & Rosano, 2022). This surge has brought technological challenges and conflicts over land use that impact the sustainability of the agri-food system. Consequently, international food trade has intensified its environmental requirements through private or voluntarily adopted production standards (Olmos, 2017).

Since the 1980s, there has been a growing trend towards promoting sustainable food value chains. This development began with the introduction of the term "regenerative agriculture" by Jackson and Rodale, which sparked discussions and laid the groundwork for what is now known as sustainable agriculture. This concept integrates ecological principles(Edwards et al., 1993).

The FAO defined sustainable agricultural development as:

> "The management and conservation of the natural resource base, and the orientation of technological change in such a manner as to ensure the continuous satisfaction of human needs for present and future generations. Sustainable agriculture conserves land, water, and plant and animal genetic resources, does not degrade the environment, is technically appropriate, economically viable, and socially acceptable." (FAO, 1989)

This definition highlights the importance of sustainable agriculture in protecting our natural resources and adapting to current and future needs, while also ensuring profitability, environmental health, and social and economic equity. Moreover, sustainable agriculture is considered to contribute to the four pillars of food security: availability, access, utilization, and stability (FAO, 2014b).

FAO (2014b) proposed that sustainable food value chains (SFVCs) incorporate:

- **Economic sustainability**, meaning generating higher or at least stable benefits or income for all actors in the chain over time. If this is not achievable, the value chain is not sustainable in the short term.
- **Social sustainability**, which involves proportionally distributing the generated value among all actors. There should be no objectionable social practices, such as poor working conditions, animal abuse, or violations of cultural traditions. If social sustainability is not achieved, the value chains cannot be sustainable in the medium term.
- **Environmental sustainability**, which means creating value with minimal impact on natural resources like water, land, soil, air, flora, and fauna. Without this, the chain is not sustainable in the long term.

The approach to sustainable agriculture should be grounded in five principles (FAO, 2014c):

1. Improving the efficiency of resource use.
2. Taking direct actions to conserve, protect, and enhance natural resources.
3. Protecting rural livelihoods and enhancing equity and social well-being.
4. Strengthening the resilience of people, communities, and ecosystems, particularly in the face of market volatility and climate change.
5. Good governance is essential for the sustainability of both natural and human systems.

Future sustainable agricultural systems must be technically appropriate, productive, economically viable and efficient, socially just and acceptable, and environmentally respectful, while also protecting the genetic resources of soil, water, plants, and animals (Çakmakçı et al., 2023). Therefore, sustainability strategies encompass much more than simply not harming the environment and protecting the natural resource base.

2.1.1. Measuring Sustainability in Agricultural Systems

Measuring sustainability in agricultural systems involves capturing the complex interplay between environmental, economic, and social factors(Antle & Ray, 2020). This multifaceted nature of sustainability requires a comprehensive approach that can address these dimensions simultaneously. Various frameworks have been developed to assess agricultural sustainability (Alaoui et al., 2022), each designed to focus on different aspects of these systems. For instance, the SAFA (Sustainability Assessment of Food and Agriculture systems) framework offers a holistic evaluation by integrating indicators across environmental, economic, and social dimensions, making it a versatile tool for assessing overall sustainability. On the other hand, frameworks like RISE (Response-Inducing Sustainability Evaluation) are more focused on environmental sustainability, emphasizing aspects such as resource use efficiency and ecosystem health. Selecting the appropriate framework depends on the specific goals and context of the sustainability assessment, as each framework has unique strengths in addressing particular sustainability challenges.

In this context, Darmaun et al. (2023) systematically reviewed 14 such frameworks, focusing on key criteria like adaptability to local conditions, consideration of social interactions, and the temporal dynamics of transitions. Among these, the Tool for Agroecology Performance Evaluation (TAPE) stands out for its structured approach that integrates both qualitative and quantitative methods. TAPE is particularly effective in generating harmonized global data while remaining flexible enough to be adapted to specific contexts. T

- **TAPE (Tool for Agroecological Performance Evaluation)**

The Tool for Agroecology Performance Evaluation (TAPE) is a comprehensive framework that incorporates ten key criteria: secure land tenure, productivity, income generation, value addition, pesticide exposure, dietary diversity, women's empowerment, youth employment, agricultural biodiversity, and soil health (Mottet et al., 2020). TAPE operates through four structured steps mentioned in Table 1.

Table 1. Step-by-step of TAPE assessment

Step 0: Description of Systems and Context	Primary and secondary information:	Production systems, type of household, agroecological zones
		Existing policies (including climate change)
		Enabling environment
Step 1: Characterisation of Agroecological Transitions (CAET)	On-farm/household survey:	Describe current status
		Based on 10 elements of agroecology with descriptive scales
		Can be a self-assessment by the producer
Step 2: Criteria of Performance	On-farm/household survey:	Measure progress and quantify impact
		Addressing 5 key dimensions for policymakers and SDGs
		Time/cost constraints: keep it simple!
Step 3: Analysis and Interpretation	At territory/community scale:	Review CAET results, explain with context, enabling environment
		Review Performance results and explain with CAET
		Analyze contribution to SDGs

Source: Adapted from Food and Agriculture Organization of the United Nations (2021) 'The global analytical framework of agroecology step by step'.

2.2. Coffee as a global commodity and sustainable practices

According to the OECD (2021), the global population has doubled, while food production has tripled. CEPAL et al. (2021) suggests that this significant increase in food production is not only due to improvements in productivity but also heavily influenced by international trade, which has played a crucial role in the access and availability of food. This underscores the need to transition towards more sustainable production systems that can drive improved quality of life, foster economic development, and protect natural resources in producing countries (Willett et al., 2019).

Ferro-Soto & Mili (2013) identified key ingredients for achieving the goals of this commercial system, including paying fair prices to producers in developing countries, providing financial resources to open markets for these small producers, maintaining long-term commercial relationships, and ensuring maximum transparency in business dealings.

In this context, various voluntary certifications have emerged, standardizing requirements that may include organic, social, and environmental aspects of cultivation. The first organic certification program started in the 1960s, though the concept has been practiced since the 19th century (Ferro-Soto & Mili, 2013). To date, there are numerous production standards; however, in Latin America, the most prominent social and environmental certification programs for coffee include Fair Trade, Rainforest Alliance (RFA - formerly known as Eco-OK), UTZ (now part of RFA), and the Common Code for the Coffee Community (4C). Additionally, there are private programs such as Starbucks' CAFÉ Practices certification and Nestlé's Nespresso AAA quality standards.

This movement towards certified sustainable practices in coffee production aims to create more equitable and environmentally friendly supply chains, addressing issues such as fair compensation, ecological conservation, and social responsibility.

2.2.1. NESPRESSO AAA Quality Program

The Nespresso AAA Sustainable Quality™ Program (Rainforest Alliance, 2021), launched in 2003, is an initiative aimed at improving the quality and sustainability of coffee production. The program was co-designed by Nespresso and the Rainforest Alliance, with the objective of giving coffee farmers the necessary tools, knowledge, and resources to implement sustainable farming practices. This program builds upon the social and environmental norms established by the Rainforest Alliance Sustainable Agriculture Standard, emphasizing long-term positive impacts on both the environment and coffee farming communities.

Participating farmers are rewarded with price premiums, often above standard market prices, for coffee that meets the AAA quality standards. This incentivizes sustainable practices and supports farmers financially, improving their ability to invest in long-term sustainability measures (Rainforest Alliance, 2021).

Macchiavello et al. (2019) identified some of the impact the program has had in Colombia, including:

- Improved Farming Practices: The program has led to improvements in farming practices, including better waste and water management, the adoption of agroforestry, and increased use of pest and disease control methods.
- Economic Benefits: Farmers participating in the AAA Program benefit from price premiums and technical assistance, which have contributed to increased farm incomes and greater economic stability. This support has allowed farmers to invest in better farm infrastructure and diversify their income sources, thus improving their resilience to market fluctuations.
- Environmental Conservation: The program emphasizes the protection of natural resources, with significant compliance observed in conserving forests and water bodies.

Macchiavello et al. (2019) highlight impacts of the Nespresso AAA Sustainable Quality Program in Colombia. The program has led to significant improvements in farming practices, such as better waste and water management, the adoption of agroforestry techniques, and the increased use of pest and disease control methods. These enhance the quality and yield of coffee, but also promote more sustainable agricultural practices. Economically, farmers participating in the AAA Program benefit from price premiums and technical assistance, which have helped increase farm incomes and provide greater economic stability. This financial support enables farmers to invest in better farm infrastructure and diversify their income sources, thereby improving their resilience to market fluctuations. Additionally, the program has an emphasis on environmental conservation, with compliance observed in the conservation of forests and water bodies.

2.2.2. Sustainable Global Value Chain challenges

The global coffee supply chain faces significant sustainability challenges, particularly regarding power dynamics, economic disparities, and environmental impacts. From a global perspective (Wright et al., 2024), reflexed that the coffee sector is characterized by a buyer-driven value chain where large multinational companies, roasters, and retailers often capture most of the value, leaving coffee producers with less than 10% of the total value. This imbalance is intensified by information asymmetries, where smallholder farmers lack access to essential knowledge and skills to engage effectively in the global market.

In Latin America, challenges were identified by Harvey et al. (2021) and can be catalogued on environmental, economic, and social. These challenges are particularly significant since the role of the region in global coffee production and the diverse conditions under which coffee is grown.

- **Environmental Challenges:** Climate change is a major threat to coffee cultivation, affecting both the quantity and quality of coffee production. Rising temperatures and changing precipitation patterns increase the susceptibility of coffee plants to pests and diseases such as coffee leaf rust (Bunn et al., 2015). This situation is exacerbated by the expansion of coffee cultivation into forested areas, leading to deforestation and the loss of biodiversity. Agroforestry systems, which can support a high level of biodiversity, are threatened by shifts towards more intensive farming practices that reduce shade cover and ecological diversity (Jha et al., 2014)
- **Economic Challenges:** The coffee market is highly volatile, with prices fluctuating significantly. This volatility creates financial instability for farmers, who may abandon sustainable practices in favor of more profitable, but less sustainable, alternatives. The adoption of sustainable agroforestry practices often requires substantial investment in infrastructure, training, and certification. However, many smallholder farmers lack access to the necessary financial resources or credit, making it challenging to implement these practices (International Coffee Council, 2014). Even when certifications like Fair Trade or Organic are achieved, they may not fully offset the costs or align with the specific conditions and needs of local farmers (Traldi, 2021)
- **Social and Institutional Challenges:** There is a significant gap in technical support and knowledge dissemination, which is crucial for the effective implementation of agroforestry systems. Many farmers lack the expertise required to transition to or

maintain these systems, resulting in suboptimal outcomes. Additionally, the certification process can be costly and complex, often excluding smaller farmers who cannot afford the time or resources needed. The broader governance of the coffee supply chain is dominated by large multinational companies and retailers, which can marginalize the interests of smallholder farmers and limit their access to market benefits (Perfecto et al., 2019).

Olmos (2017) stated that, overall, the sustainability of the coffee sector governance needs to evolve towards more inclusive, adaptive, and locally relevant models that empower smallholders and consider local knowledge systems.

Addressing these challenges requires comprehensive and locally tailored solutions that consider the unique environmental, economic, and social contexts of coffee-producing regions. Enhancing the resilience and sustainability of coffee agroforestry systems involves not only mitigating environmental impacts but also ensuring economic viability and social equity for smallholder farmers. This holistic approach is essential for the long-term sustainability of coffee cultivation in the face of global changes (Harvey et al., 2021).

2.2.3. Agroforestry in Natural Protected Areas

Currently, in the Latin American and Caribbean region, strategies are being developed where natural biodiversity and productive land use coexist under sustainable management. These strategies aim to integrate marginalized communities living in these areas.

One of the benefits of coffee plantations grown under agroforestry systems is the habitat they provide for native wildlife and the conservation of surrounding landscapes. Greater trees cover and forest habitats can contribute to the preservation of native flora and fauna. It has also been identified that agroforestry coffee plantations exhibit biodiversity similar to that found in natural forests, with a notable presence of birds (Rojas Sánchez et al., 2012; Toledo & Moguel, 2012) .Additionally, the soil is protected, which positively influences coffee quality. The diversification of farmers' incomes is also enhanced, as other cultivated species within the agroforestry system can generate additional income.

However, it is important to note that these benefits are compared exclusively with conventional production, without considering the comparison with primary forest ecosystems or healthy secondary forests. Therefore, it is crucial to ensure that sustainable agroforestry coffee is not produced in recently deforested landscapes, as only then does it add real value (Jurjonas et al., 2016). The delicate balance between improving social well-being through sustainable development, conserving protected natural areas and forests, and mitigating climate change cannot be achieved without a thorough assessment of the ongoing success of the model (Jurjonas et al., 2016).

2.3. Coffee in Nicaragua

2.3.1. Context

The history of coffee in Nicaragua, as detailed in "The Chronicle of Coffee: History, Responsibility and Questions” (Jose Luis Rocha, 2001):

> Coffee cultivation in Nicaragua began in the mid-19th century, introduced by European settlers who recognized the potential of the country's fertile volcanic soil and favorable climate. This period marked the beginning of coffee's rise as a key economic driver, shaping the landscape and economy significantly.
>
> Throughout the late 19th and early 20th centuries, coffee plantations expanded rapidly, with local elites and foreign investors promoting monoculture. This expansion led to a boom in coffee exports, establishing the reputation of Nicaragua in international markets for producing high-quality beans. Coffee quickly became a critical source of foreign exchange, deeply influencing the economic structure of the country.
>
> The history of the industry has also been marked by periods of instability, including political conflicts and economic crises. The Sandinista revolution in the late 20th century, for example, brought significant changes to land ownership and coffee production systems. This period saw the expropriation of large estates and redistribution of land, which disrupted traditional coffee production and export

patterns. Despite these disruptions, the coffee sector has shown resilience, adapting to changing political and economic landscapes.

Coffee remains a cornerstone of the Nicaraguan economy, representing a significant portion of the agricultural output and employment of the country. It accounts for 25% of the land dedicated to export crops and generates a third of rural employment, providing more than 300,000 jobs. The coffee sector contributes 2% to the national Gross Domestic Product (GDP) and 21% to the agricultural GDP (Adriana Escobedo et al., 2017).

The production of coffee in Nicaragua is predominantly concentrated in three main regions. The North Central region, which includes the departments of Matagalpa, Jinotega, and Boaco, produces 83.8% of the country's total coffee output, known for its "Strictly High Grown" (SHG) beans. The Northwestern region, comprising the departments of Madriz, Nueva Segovia, and Estelí, contributes 13.6% of the national production. Meanwhile, the Pacific South region, including the departments of Carazo, Granada, Masaya, Managua, and Rivas, accounts for the remaining 2.6%. In recent years, Nicaraguan coffee has gained recognition for its quality, commanding higher prices due to a growing demand for specialty coffees. The industry's future growth centers on the differentiation strategy, primarily through farm certification, where producers play a crucial role in integrating agroecological practices with a clear market-oriented vision (Adriana Escobedoet al., 2017).

2.3.2. Legal Framework

The coffee sector in Nicaragua is managed by several legislative frameworks designed to regulate production, ensure quality, promote sustainability, and support the economic viability of the industry. These laws cover aspects related to environmental conservation, quality standards, economic incentives and market regulation. The following table provides a summary of the key laws related to the coffee industry in Nicaragua.

Table 2. Legal framework related to coffee

Legislation/Decree/NTON	***Title***	***Description***

Law No. 316	Law of the National Coffee Institute (INCAFE)	Establishes the National Coffee Institute to oversee coffee production, quality, and international promotion.
Law No. 499	General Law for the Coffee Sector	Comprehensive regulation of coffee production, including certification and quality standards.
Law No. 853	Law for the Promotion and Development of the Coffee Sector	Provides financial and technical assistance to enhance sector competitiveness.
Decree No. 25-2004	Establishment of the National Coffee Council	Creates the National Coffee Council to coordinate coffee sector policies and stakeholder interests.
Decree No. 35-2017	Law for the Protection of Nicaraguan Coffee	Protects the Nicaraguan coffee brand and combats counterfeit products.
NTON 04 063-17	Nicaraguan Technical Standard for Coffee Quality	Defines quality standards for coffee production and processing.
NTON 03 038-17	Nicaraguan Technical Standard for Organic Coffee Production	Regulates the production of organic coffee, ensuring adherence to organic farming practices.
Agreement No. 61-2016	Agreement for Coffee Rust Management	Implements measures to manage and mitigate the impact of coffee rust disease.
Agreement No. 72-2015	Agreement for the Promotion of Specialty Coffee	Aims to promote specialty coffee through improved practices and market access.

Note: Own elaboration based on publications of La Gaceta de Nicaragua (Accessed on August, 2024)

3. Methodological Framework

3.1. Study Area

The study was conducted within the buffer zone of the Cerro Grande de Kuskawás Natural Reserve (CKNR), located in the municipality of Rancho Grande, department of Matagalpa, Nicaragua (Figure 1). The reserve is located on a plateau connected to the Isabelia mountain range and is bounded by the rivers Babaska to the north, the Yaoska to the east, the Tuma to the south, and the Bijao to the west (MARENA, 2021). It is located at an altitude between 380 and 1294 m.

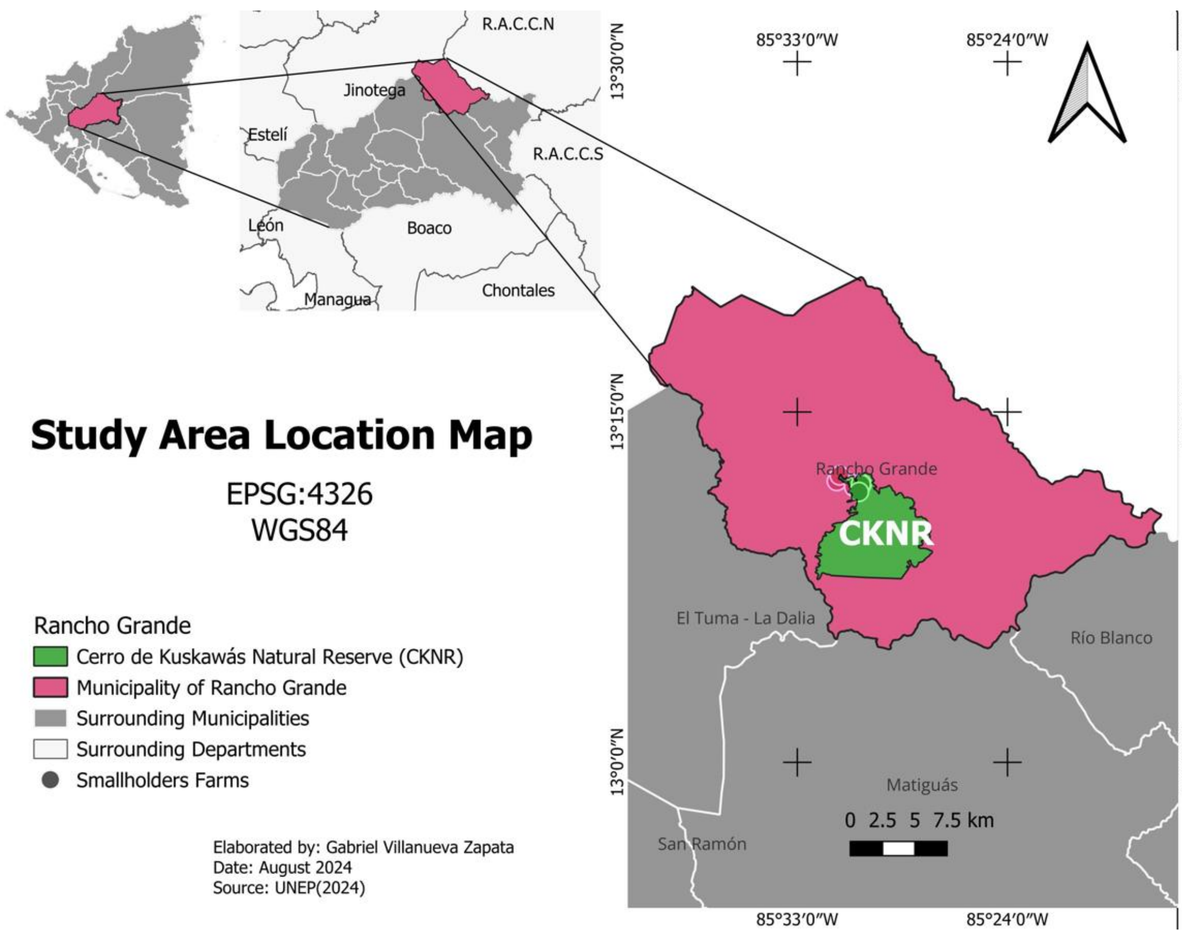


Figure 1. Location of the study area: Cerro Kuskawás Natural Reserve. Own elaboration with geodata available at Protected Planet (UNEP-WCMC & IUCN, 2024).

Designated as a protected area in 1991, the primary objective of CKNR is to conserve biodiversity, endemism, and water-producing zones that are characteristic of this mountainous region due to its unique ecological (Resolución Ministerial No. 293-2021, 2022). The reserve covers an area of approximately 5085 ha, with a buffer zone of 3878 ha, of which 61.4 % features steep slopes (25-50 %), followed by 27.4 % as steeply sloping terrain (INETER, 2016).

Climatically, the CKNR experiences two distinct seasons: the rainy season from May to January, which last about nine months, and the dry season from February to April. The reserve receives an average annual rainfall of about 2200 mm and maintains an average annual temperature of 19 °C. The variation in altitude within the reserve creates three distinct climatic zones: humid tropical, humid subtropical, and humid montane (INAFOR, 2019).

Historically, the ecological structure of the CKNR has undergone significant changes. Before the decade of 1950, the area was covered by virgin forest until the arrival of the first settlers. Initially, most communities were situated in forest areas where authorities did not permit forest utilization or hunting (MARENA, 2021). Crop production was predominantly small-scale and for self-consumption, with a lack of access roads hindering commercialization. However, in the late 1980-decade, neighboring communities began migrating in search of unclaimed land for agriculture and livestock.

The construction of access roads led to exponential population growth and a consequent transformation in land use, impacting the reserve's ecological system. Data from (INIDE & MAGFOR, 2012) indicate a 261% population increase in the Cerro Grande community, the most significant within the area. These populations engage in productive activities within the buffer zone, including coffee cultivation on 14.96% of the total area, livestock production on 24.67% of the protected area, and smaller-scale cacao cultivation.

The level of marginalization within the communities of the Reserve, which includes Cerro Grande, La Cuyuca, Caño Blanco, Caño Negro I, Caño Negro II, Rancho Alegre, and San Antonio de Kuskawás, is predominantly high to severe, except for San Antonio de Kuskawás, which experiences a low level of poverty (INIDE & MAGFOR, 2012).

There are 11 schools within the Natural Reserve area (MARENA, 2021). These educational institutions primarily focus on elementary education and operate under a multigrade system, where one or two teachers simultaneously instruct students across multiple grade levels, including preschool.

This population growth and agricultural expansion have resulted in inappropriate land use. According to the land use map of the CKNR prepared by (INETER, 2018), only 64.91% of the territory is utilized appropriately, while 29.43% is overused, and a mere 5.66% is underutilized. It is anticipated that, with continued migration and the adoption of agricultural systems, the proportion of overused areas will increase in the coming years.

3.2. Methodology

This study employed a mixed-methods approach, combining both qualitative and quantitative methods to assess the viability of agroforestry coffee as a sustainable practice within the CKNR. The primary tool used for this evaluation was the TAPE designed by (FAO, 2019), chosen for its framework that facilitates a multidimensional analysis of sustainability. Although TAPE is traditionally applied to agroecological systems, its adaptability makes it well-suited for assessing agroforestry practices, which share key objectives with agroecology (Pandey et al., 2024), such as enhancing soil health, promoting biodiversity, and supporting sustainable livelihoods. Additionally, TAPE is particularly suitable because it allows for close comparison between different crops, enabling an assessment of agroforestry coffee in relation to previous practices before its integration.

The decision to use TAPE over other sustainability assessment tools, such as MESMIS, RISE, GTAE, and SAFA, was based on its holistic perspective. TAPE integrates essential attributes from over 12 different frameworks, which provides a comprehensive vision for sustainability assessment. Additionally, its development involved an inclusive, multi-stakeholder process, including a consultation phase, ensuring that the tool is both comprehensive and user-friendly. Its operational flexibility allows for easy adaptation by end-users, making it particularly useful in diverse contexts (Darmaun et al., 2023).

The study utilized a Judgement Sampling method to select participants, ensuring that the smallholders chosen provided relevant insights into the various stages of agroforestry integration. Semi-structured interviews were also conducted with key stakeholders to gather primary data, for an understanding of the socio-economic and environmental contexts in which these farming systems operate. Figure 2 illustrates the steps followed in the methodology, the tools employed at each stage, and the specific objectives addressed by each step.

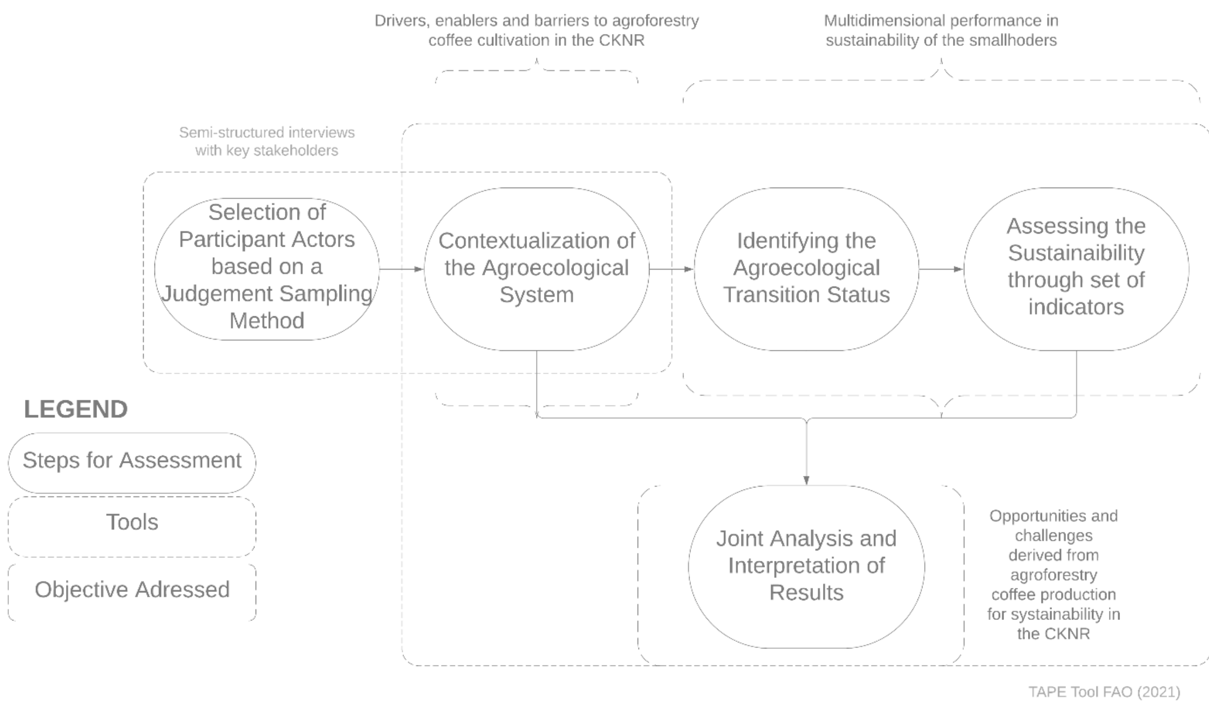


Figure 2. Methodological Framework for Assessing Agroforestry Coffee Sustainability in the CKNR

3.3. Selection of Participant Actors

The criteria to select key actors was based in a Judgement Sampling method (Thornhill et al., 2012), since the aim of this study is not to obtain a representative sample, but rather to collect detailed information from a group selected intentionally. The following criteria were established for selection:

1. Active Participation: Smallholders who have actively participated in projects aimed at sustainable agriculture or are keen to participate in future projects.

2. Accessibility: Smallholders who are easily accessible, as well as those in more difficult-to-reach areas.
3. Cooperative Membership: Smallholders who are part of cooperatives and those who work independently.
4. Project Continuity: Smallholders who have continued with the projects and those who are working separately.
5. Crop Diversity: Smallholders who cultivate a range of crops or have livestock production
6. Certification scheme: those currently working under a sustainability certification, those in transition towards certification, and those not currently involved in any certification scheme.

The selection of smallholders meeting the criteria was conducted in collaboration with an agronomic technician from an active NGO. This technician has been actively engaged in transforming traditional farming systems to agroforestry systems incorporating coffee and cocoa. A total of 15 smallholders were chosen to participate and the application of the TAPE tool.

The smallholders belong to three different communities (Table 3), however, these communities are very close to each other and connected through the same road. As a result, the environmental and socioeconomic conditions are quite similar.

Table 3. Socio-demographic data of the interviewees' communities based on MARENA (2021)

Community Name	Total inhabitants	Poverty Level	Smallholders interviewed	Illiterate % (Men-Women)	Main economic activities
Cerro Grande	476	High	8	34.2-35.7	Commercial crops include coffee, cacao, and cattle farming. Maize and beans, plantains,
La Castilla 1	604	High	5	36.9-48.1	

Rancho Alegre	1104	High	2	32.3-39.5	yucca, and vegetables such as tomatoes and peppers, are also cultivated.

3.3.1. Selected Typology

The smallholders selected for this study were grouped based on similar characteristics. This typological approach allows for a deeper analysis of general phenomena rather than focusing on individual case specifics (Alvarez et al., 2014). The study identified three groups based on their level of agroforestry integration and their developmental paths, as well as two smallholders planning to incorporate coffee agroforestry into their crops. The number of smallholders for each category was also chosen in collaboration with the key stakeholders' members of two NGOs working on sustainable agriculture in the region, to ensure that the chosen groups accurately represent the diversity and relevance of the agricultural practices under the study. The smallholders were classified into the following categories:

- **Traditional agriculture (2):** Smallholders in this category primarily produce maize and beans, which are the typical crops in the region. They use common management practices for growing these crops prevalent locally. These smallholders can be considered the baseline from which many agroforestry systems have evolved through interventions. Both smallholders in this group are planning to convert one manzana (1 manzana ≈ 0.698 hectares) of their annual crops into agroforestry coffee soon.
- **Incipient agroforestry with EXPASA (8):** These smallholders transitioned in 2021 from annual crops like maize and beans to agroforestry coffee with the support of a major regional retailer named EXPASA. It is important to note that most of these smallholders were selected to participate in the project for only one manzana, meaning they continue to cultivate other crops within their family farming systems. The company covered the establishment and maintenance costs. Since the transition was made only four years ago, at the time of the interview they had only

experienced a small harvest, corresponding to their first yield. A significant harvest is expected next year, marking the best in the cropping cycle.

- **Established agroforestry with EXPASA (3):** This group began transitioning in 2017, shifting from bare land crops (such as maize and beans) or livestock production. They have since experienced the most productive yields in their coffee agroforestry system and now they are starting with pruning and stunning making the plantation less productive in the recent past years. Most of these smallholders are part of the Nespresso's AAA program and are currently certified by Rainforest Alliance. They continue to grow different crops and/or engage in livestock production on other parcels within their family farming system.
- **Established agroforestry without EXPASA (2):** These systems have been primarily maintained using traditional knowledge and additional support from various institutions, but without being market-driven. Support has come from organizations such as ADDAC and COMPROCON, the first one focused on building capacity in topics to agroecology and the second one focused on expanding their production as a smallholder cooperative. Currently they don't work directly with any specific institution to sell their harvest. Like the other groups, these smallholders also cultivate other types of crops that are not necessarily part of an agroforestry system.

Through these grouping criteria (Figure 3), the study aims to assess the influence of agroforestry on the sustainability of farming systems within the natural reserve. This categorization allows for a comparative analysis between traditional agricultural practices and various stages of agroforestry adoption. By including smallholders practicing traditional agriculture, the study can establish a baseline for measuring sustainability. The groups representing incipient agroforestry with EXPASA and established agroforestry with EXPASA offer insights into how external support and resources contribute to the development and sustainability of agroforestry systems over time. On the other hand, the group of established agroforestry without EXPASA permits an evaluation of how independent adoption of agroforestry practices compares in terms of sustainability outcomes.

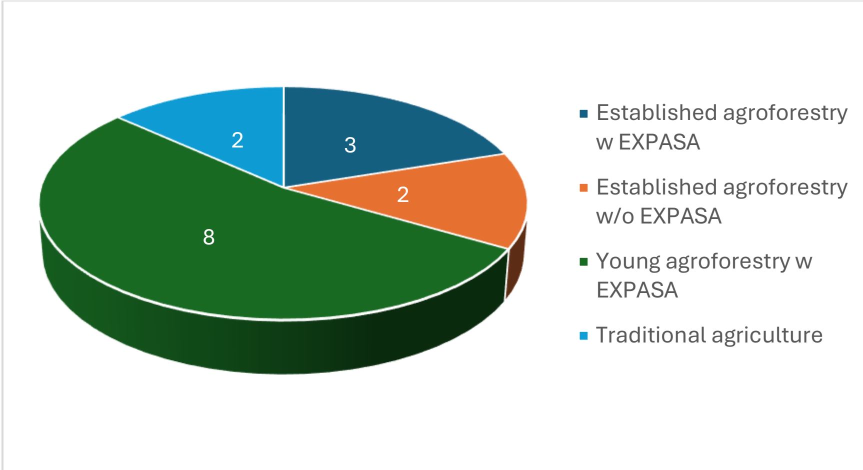


Figure 3. Selected typology of smallholders for this study

3.4. Contextual Analysis

To gather information about the production systems, household characteristics, agroecological zones, key local actors, and policies and interventions related to the transition toward sustainable agriculture, a combination of secondary and primary data was utilized.

- **Secondary Data:** A desk review was conducted, using official documents from the natural reserve, including the natural reserve management plan and previous studies conducted in the region, such as master's thesis and mission reports from various projects undertaken in the area. This review aimed to gather detailed information on the types of production systems, general household demographics, agroecological zones, key local actors, and an overview of ongoing projects that drive the transition towards sustainable agriculture.
- **Primary Data:** Qualitative data were collected through a series of semi-structured interviews with key local stakeholders (Table 4). The first interview was conducted online on April 5th with the leader of the Nicafrance Foundation, a prominent NGO involved in integrating smallholders into the global value chain (GVC) of coffee through partnerships with Exportadora Atlantic S.A. (EXPASA). This interview provided preliminary insights into the ongoing projects and sociodemographic details

of the smallholders involved. The second interview took place on May 11th in the field with a technician from the Nicafrance Foundation who works in the day-to-day implementation of the projects. This discussion focused on operational details, challenges faced during implementation, and the objectives of the project. The third interview was conducted with the coordinator of another NGO, named ADDAC, that is focused on developing agroecological knowledge in the region's diverse crop sectors and operates independently of private sector stakeholders. This interview explored the NGO's projects, the challenges encountered, and the driving forces that support the transition to sustainable agriculture.

Table 4. List of interviews and addressed information with relevant local stakeholders

Date	Organization interviewed	Position in the organization	Points addressed
05.04.2024	Nicafrance Foundation	Community Development Director	▪ Description of the projects ▪ Role of the NGO in the transition to agroforestry cultivation ▪ General sociodemographic data of the participants of the project
11.05.2024	Nicafrance Foundation	Agronomist Technician	▪ Main economic activities of the region ▪ Operational functions of the NGO ▪ Carried out projects ▪ Activities for establishment and maintenance of the coffee plantation
16.05.2024	ADDAC	Regional Coordinator	▪ Their role in the sustainable development of the smallholders ▪ Agronomic context and current challenges ▪ Durability of sustainable projects

- Constraints and Challenges for project implementation

3.5. Multidimensional Sustainability Performance

The steps outlined in this section were selected to assess the sustainability performance of smallholders within the Reserve. The first and second steps of the TAPE Tool provided a structured approach to evaluating the farms' progress in agroecological transition and overall sustainability.

The first step, Characterization of Agroecological Transition (CAET), established a baseline by giving a general overview of the current state of agroecological practices.

The second step included a more detailed assessment using a questionnaire adapted to the multidimensional framework of the TAPE Tool. This approach enabled a multidimensional evaluation of the sustainability practices of the smallholders.

3.5.1. Characterization of Agroecological Transition (CAET)

The current state of agroecological transition for the 15 farms was assessed using the first step of the TAPE Tool. This evaluation was conducted through semi-structured interviews with smallholders, each lasting approximately 30 minutes. The assessment focused on the 10 key elements of agroecology as outlined by the (FAO, 2018), providing a general overview of the farms' agroecological practices in relation to an ideal benchmark.

- Diversity: Evaluated the diversity within the agroecosystem, considering the number and types of crops, animal species, and trees present, as well as the variety of productive activities and the integration of crops and animals.
- Synergies: Analyzed the integration and connection of different elements within the agroecosystem, such as the relationship between crops, animals, and trees, and how they supported each other in the system.
- Efficiency: Examined the use of external resources, such as purchased inputs, and how soil fertility and pest and disease management were handled, aiming to minimize dependence on external inputs.

- Recycling: Focused on the reuse and recycling of waste and by-products within the farm, as well as water management and the handling of seeds and breeds to ensure a sustainable cycle.
- Resilience: Considered the stability and recovery capacity of income and production in the face of disturbances, as well as the production and use of renewable energies.
- Food Culture and Tradition: Assessed food security, nutritional knowledge, cultural identity, and the use of local varieties and traditional knowledge in food preparation.
- Co-creation and Knowledge Sharing: Measured access to agroecological knowledge, the participation of producers in knowledge networks, and the degree of knowledge exchange, with a focus on the inclusion of women.
- Human and Social Values: Analyzed the empowerment of women, working conditions, the relationship of young people with agriculture, and animal welfare within the system.
- Circular Economy and Solidarity: Focused on the local marketing of products, the existence and functioning of producer networks, and the community's self-sufficiency in food production and processing.
- Responsible Governance: Examined the respect for producers' rights, transparency, and equity in producer organizations, and the participation of producers in land and natural resource governance, with a gender perspective.

3.5.2. Sustainability Performance

A second, more structured interview was conducted using a questionnaire adapted to the second step of the TAPE Tool. This follow-up interview, lasting approximately 80 minutes, provided a more detailed assessment of the farmers' practices in terms of sustainability following the initial evaluation. It considered five key dimensions, encompassing a total of 10 core performance criteria (Table 5), to generate evidence on the multidimensional performance of sustainability. These dimensions included governance, economy, health and nutrition, society and culture, and environment.

Table 5.Core criteria of performance of agroecology and their link to SDG indicators

Main Dimension	Core Performance Criteria	Method of Assessment	SDG	SDG Indicators
Governance	Secure land tenure	Type of tenure over land: property, lease duration, verbal, not explicit	1, 2, 5	1.4.2, 2.4.1, 5.a.1
Economy	Productivity	Farm output value per hectare	2	2.3.1, 2.4.1
Economy	Income	Outputs - Inputs - operating expenses - depreciation + other income	1, 2	1.1.1, 1.2.1, 2.3.2, 2.4.1, 10.2.1
Economy	Added value	Net income + rents + taxes + interest - subsidies	10	10.1.1, 10.2.1
Health & Nutrition	Dietary diversity	Minimum Dietary Diversity for Women (FAO & FHI 360, 2016)	2	2.1.2, 2.2.1, 2.4.1
Society & Culture	Women's empowerment	Abbreviated Women's Empowerment in Agriculture Index (IFPRI, 2015)	2, 5	2.3.2, 5.a.1
Society & Culture	Youth employment opportunity	Access to jobs, training, education, or migration	8	8.6.1
Environment	Exposure to pesticides	Quantity applied, area, toxicity, and existence of risk mitigation equipment and practices	3	3.9.1, 3.9.2, 3.9.3
Environment	Agricultural biodiversity	Relative importance of crops varieties, livestock breeds, trees and semi-natural environments on farm	2, 15	2.4.1, 15.5.1
Environment	Soil health	Adapted SOCLA rapid and farmer-friendly agroecological method to assess soil health (M. Altieri & Nicholls, 2005)	2, 15	2.4.1, 15.3.1

Source: Adapted from Food and Agriculture Organization of the United Nations (2021) '10 Core Criteria of Performance of Agroecology and Their Links to SDG Indicators'.

For each of the Core Performance Criteria a set of indicators was used to classify them according to the level of sustainability they currently are: **Desirable**, **Acceptable** or **Unsustainable**. A detailed explanation of the calculation made for each of the Core Performance Criteria is presented below.

Secure Land: The desirable category was assigned when the landholder possesses a formal document with their name on it, has a perception of secure access to the land, and holds at least one right to sell, bequeath, or inherit the land. The acceptable category was applied if the landholder either had a formal document with their name on it but perceived insecure access to the land, or had no rights to sell, bequeath, or inherit; it also included cases where the holder had a document without their name on it, or had no document but perceived secure access and had at least one of the aforementioned rights. Finally, the unsustainable category was used for cases where the landholder had no formal document, perceived insecure access, and/or had no rights to sell, bequeath, or inherit the land.

Productivity: The calculation was conducted by categorizing productivity based on both productivity per hectare and productivity per person considering all the crops transformed in currency, using national averages indicated by the World Bank (2015). The desirable category for productivity per hectare was assigned when the productivity value per hectare was equal to or greater than two-thirds of the national average value of production per hectare per year, which is US$717. For productivity per person, the desirable category was applied when the productivity value per person was equal to or greater than two-thirds of the national average value of production per person, which is US$3800. The acceptable category for productivity per hectare was determined when the productivity value per hectare was equal to or greater than one-third but less than two-thirds of the national average value of production per hectare. Similarly, for productivity per person, the acceptable category was applied when the productivity value per person fell within the same range of one-third to two-thirds of the national average value. The unsustainable category for productivity per hectare was used when the productivity value per hectare was less than one-third of the national average value of production per hectare per year. The unsustainable category for productivity per person was assigned when the productivity value per person was less than one-third of the national average value of production per person.

Income: The desirable category was assigned when the family net income per family worker exceeded the median income from farm activities, which is US$1291.74 according to data from FAO (2014a). The acceptable category was applied when the family net income per family worker was below the median income from farm activities but still higher than the national poverty line, which is US$997. The unsustainable category was used when the family net income per family worker fell below the national poverty line, as defined by the World Bank.

Added Value: The gross added value per family worker was categorized into the three classifications based on comparisons with the national agricultural GDP per agricultural worker, which is US$1489 according to FAO (2014a). The desirable category was assigned when the gross added value per family worker was greater than 1.2 times the national agricultural GDP per agricultural worker. The acceptable category was applied when the gross added value per family worker was less than 1.2 times but greater than 0.8 times the national agricultural GDP per agricultural worker. The unsustainable category was used when the gross added value per family worker was less than 0.8 times the national agricultural GDP per agricultural worker or, if not available, less than 0.8 times the median gross added value in similar agroecosystems.

Dietary Diversity: The indicators used are based on those selected for the Minimum Dietary Diversity for Women (FAO & FHI 360, 2016), where women serve as a proxy for assessing the nutritional status of the household. Data is collected directly from women, with their dietary diversity score calculated by counting the consumption of 10 specific food groups over the previous 24 hours. These food groups included grains, roots, and tubers; pulses; nuts and seeds; dairy; meat, poultry, and fish; eggs; dark green leafy vegetables; other vitamin A-rich (yellow) fruits and vegetables; other vegetables; and other fruits. The dietary diversity score was then categorized as desirable if it was 7 or higher, acceptable if it was between 5 and 7, and unsustainable if it was less than 5.

Women's empowerment: The survey collected data by following the Abbreviated version of the Women's Empowerment in Agriculture Index (A-WEAI) (IFPRI, 2015), retaining its five domains of empowerment. However, the original 10 indicators were reduced to 6, with one indicator per domain: (i) Input in productive decisions, (ii) Ownership of assets, (iii) Access to credit, (iv) Control over use of income, (v) Group membership, and (vi) Workload. Each domain was weighted at 20 percent of the overall average score for A-WEAI. The score for each domain was calculated using specific rules and then standardized on a percentage scale. The criteria were then scored according to the following thresholds: a desirable classification was given when the A-WEAI score was 80% or higher, an acceptable classification was used for scores between 60% and 79.9%, and an unsustainable classification was assigned for scores below 60%

Youth migration: Data were collected on the number of young people working in agricultural activities within the assessed system, the number of youths in education, those working outside but still residing within the system, and those who had emigrated. Additionally, young people's perceptions of agricultural work were gathered. These data were then used to calculate a final average score for employment and emigration, with thresholds set as follows: a desirable score was 70% or higher, an acceptable score ranged from 50% to below 70%, and an unsustainable score was below 50%.

Use of pesticides: The classification of pesticide use was based on the types and quantities of pesticides applied, as well as the use of mitigation techniques. A desirable classification was assigned when the quantity of organic pesticides used was equal to or greater than the quantity of synthetic pesticides used, no pesticides of class I or II (highly and moderately toxic) were used, and at least four of the specified mitigation techniques were employed during the application of chemical pesticides. An acceptable classification was given when the quantity of synthetic pesticides used exceeded that of organic pesticides, but no class I (highly toxic) pesticides were used, at least four mitigation techniques were followed, and organic pesticides or other integrated techniques were also utilized. Finally, an unsustainable classification was assigned when producers used highly hazardous pesticides (Class I) or illegal pesticides, or when they used pesticides of class II or III (moderately toxic and slightly or relatively non-toxic) with fewer than four of the listed mitigation techniques.

Agricultural biodiversity: During the transect walk conducted as part of the survey, data were collected on the number of species and varieties of crops and trees grown within the assessed system, as well as the number of animal species and breeds raised. The survey also gathered information on the area occupied by each crop. Using this data, a Gini-Simpson index of diversity (Eq. 1) was calculated for both crops and animals. Additionally, a third index, termed "Natural vegetation, trees, and pollinators," was calculated as the average presence of pollinators, beekeeping activities, and the productive area covered by natural or diverse vegetation.

$$1 - D = 1 - \Sigma \, pi^2 \text{ Eq. 1}$$

A desirable classification was assigned when the average score was 70% or higher. An acceptable classification was given when the average score ranged between 50% and 69.9%. Finally, an unsustainable classification was used when the average score was below 50%.

Soil Health: The assessment of soil health was based on the 10 indicators developed by the Latin American Society for Agroecology (SOCLA) and presented in M. Altieri & Nicholls (2005). These indicators included soil structure, degree of compaction, soil depth, status of residues, color, odor, and organic matter, water retention, soil cover, signs of soil erosion, presence of invertebrates, and microbiological activity. The results were then summarized by calculating an average soil health score. The following thresholds were applied: a desirable classification was given when the average score was 3.5 or higher; an acceptable classification was used for scores between 2.5 and 3.4; and an unsustainable classification was assigned for scores below 2.5.

3.6. Joint Analysis and Interpretation of Results

The quantitative and qualitative data collected in the field were processed and analyzed to identify the challenges and opportunities associated with agroforestry coffee cultivation for smallholders in achieving sustainability. The results from the context analysis, the CAET (presented in a radar graph), and the multidimensional sustainability assessment were integrated to contextualize the performance outcomes. The analysis enabled the comparison of sustainability performance between agroforestry coffee practices and traditional agricultural methods of annual crops in the region.

4. RESULTS

4.1. Contextual Analysis

4.1.1. Smallholders' characterization

Size of the production systems and crop diversity

The crop diversity among the smallholders is shown in Figure 4, according to their land extension and the previously mentioned classifications: traditional agriculture, incipient agroforestry with support from EXPASA, and established agroforestry without EXPASA.

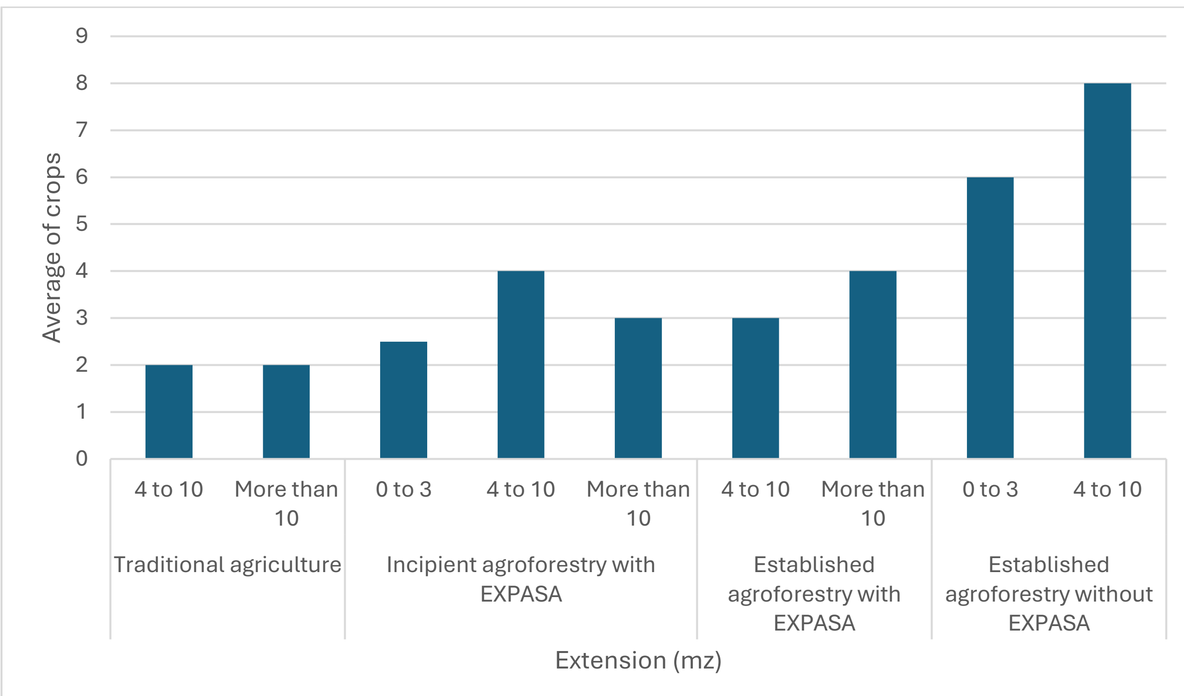


Figure 4. Crop diversity by size of production systems, grouped by category.

In general, smallholders possess similar amounts of land, with a few exceptions where land is inherited from family, resulting in larger extensions used for livestock production. The land use of smallholders, categorized as traditional agriculture, often focuses on growing maize, beans, and one additional cash crop, typically resulting in an average of two crops per farm considering a spatial analysis

An increase in crop diversity is observed among smallholders engaged in incipient agroforestry, initiated with the support of EXPASA. These smallholders maintain the cultivation of annual crops for self-consumption, in addition to coffee and other small intercropped species like fruit trees, plantains, and timber. Similarly, smallholders who have been working with EXPASA and have already established systems demonstrate similar levels of crop diversity. Established agroforestry systems without EXPASA support show the highest crop diversity, with up to eight different crops.

It is relevant to also notice that most of the actors interviewed continue to grow maize and beans for self-consumption in small parcels, but two smallholders from the established agroforestry group with EXPASA and one from the incipient agroforestry with EXPASA group (Figure 5).

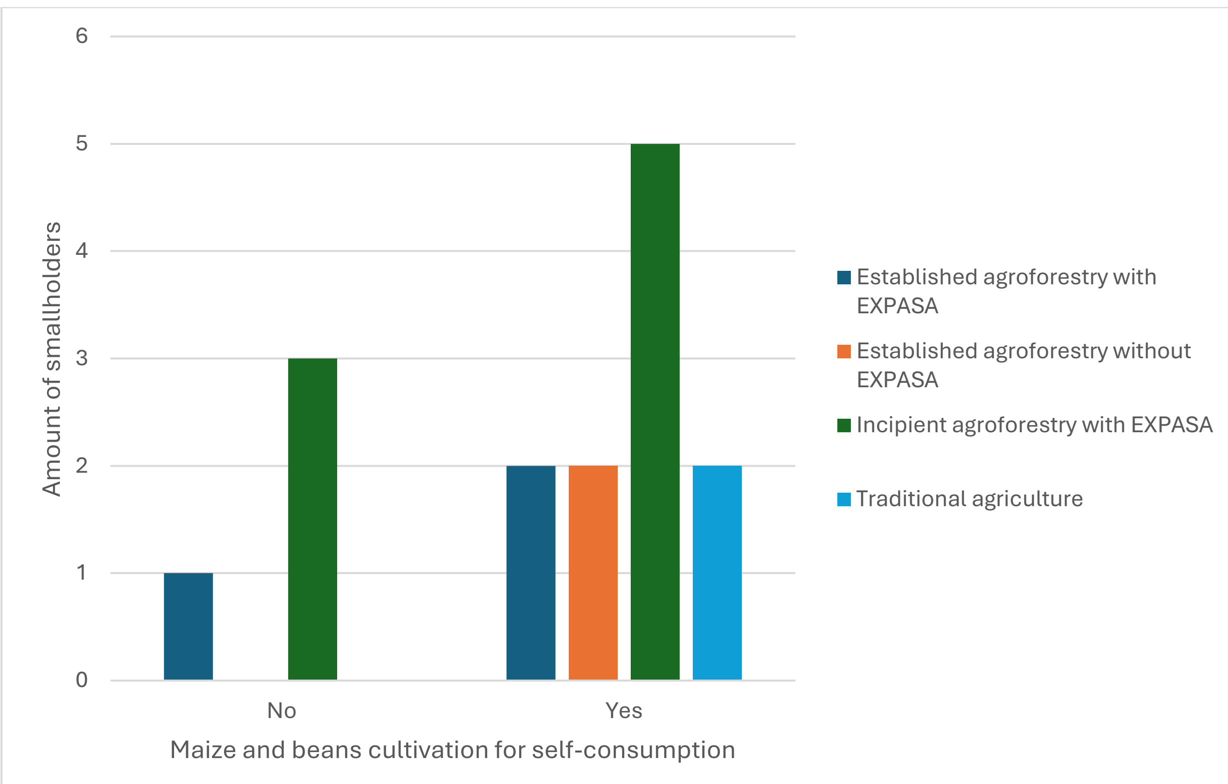
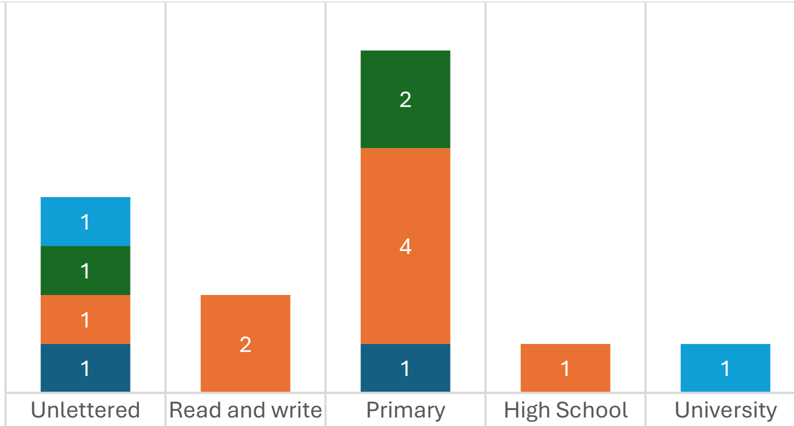


Figure 5. Smallholders that remain cultivating maize and beans as a staple crop

Education Level

The next graph (Figure 6) represents the education levels of the interviewed smallholders grouped by the select classification.



	Unlettered	Read and write	Primary	High School	University
Established agroforestry w/o EXPASA	1				1
Established agroforestry w EXPASA	1		2		
Young agroforestry w EXPASA	1	2	4	1	
Traditional agriculture	1		1		

Figure 6. Level of education of the smallholders

The education level among the sampled smallholders is quite low, primarily due to a lack of educational infrastructure. Most individuals are either illiterate or have only completed primary school. Only one smallholder, who is part of the established agroforestry system without support from EXPASA, has achieved a university-level education.

Composition by age and gender

Figure 7 displays the composition of the interviewed smallholders by age and gender. The graph details the distribution of both men and women across different age groups, highlighting the representation within incipient agroforestry systems and other categories.

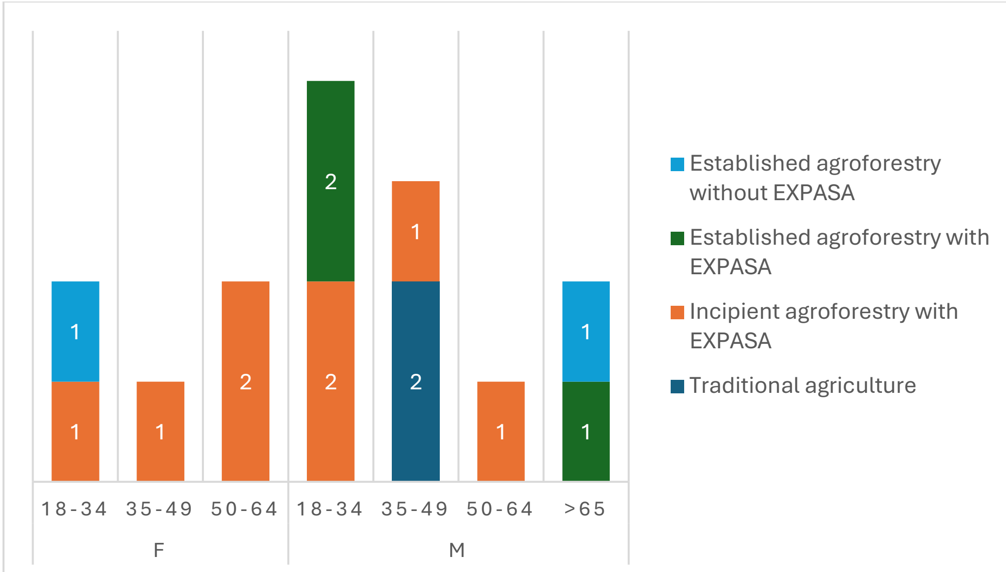


Figure 7. Composition by age and gender

A total of five women were interviewed, primarily representing incipient agroforestry systems and almost evenly distributed across different age groups. Ten men were interviewed, representing all four groups and almost evenly distributed among the various age groups. Two of the men were above 65 years old.

4.1.2. Interventions for transitioning to agroforestry

The local economy in the communities has historically been based on the production of basic grains, such as maize and beans, along with livestock farming. However, as noted by the local stakeholders interviewed and MARENA (2021), the past decade has seen a significant increase in the cultivation of agroforestry cocoa and coffee. This shift has been driven primarily by external projects, as many farmers initially lacked the resources and capacity to undertake these crops independently. A description of these interventions for transitioning to agroforestry cultivation based on the data obtained during the interviews is presented below.

Matrice project (Matagalpa Agroforest Resilient Landscape program)

In 2017, the MATRICE project begun with 17 producers working over a total of 35 manzanas, with the goal of transitioning from basic grains or livestock to a coffee agroforestry system.

Operating under the outgrowers scheme with EXPASA, one of the country's leading retailers, the project provides small producers with assistance for establishment, inputs, technical support, and labor. Hence, MATRICE supplied the smallholders with Marsellesa or in some cases Starmaya variety coffee plants, technical support, and seedlings for shade trees, including timber trees (e.g., *Platymiscium pinnatum*) and fruit trees (e.g., lemons (*Citrus* spp. 'limón'), oranges (*Citrus* spp. 'naranja'), and mandarins (*Citrus reticulata*). The program also covered the costs of inputs and labor. Producers gradually repay the debt they incur to the Trust through a system of payment using a portion of the coffee harvested, with a 5-year contract featuring a 50-50 profit split.

The establishment was mainly on a planting frame of 1.5x2 m for Marsellesa, and in some cases where Starmaya was cultivated, the frame was 1.5x3 m. Marsellesa has shown good results, although Starmaya is still under development. For the agroforestry system, timber varieties such as coyote (*Platymiscium pinnatum*) are included, with less use of mahogany.

The agricultural labor included preventive foliar applications for common affectations produced by fungus, like canker and rust, done four times a year and up to six or seven in case curative applications are needed, along with foliar insecticides applied during wet seasons to control pests such as weevils. There were four to five annual mowings, and one herbicide application using glyphosate. Empty agrochemical containers were returned to commercial companies after triple washing, with collection managed by the company. Farmers in the project were provided with personal protective equipment, although not all of them habitually used it.

Matrice II stage and Climate Change resilience improvement with coffee and Cacao (GIZ)

In 2020 the project was replicated with changes in the contract to a profit distribution of 60% for the company and 40% for the producer, adding seven more producers. Also, a GIZ project was implemented, working an additional 30 manzanas with 24 producers to improve resilience to climate change by transitioning to agroforestry systems for coffee and, to a lesser extent, cocoa.

In the first projects there were some difficulties with outsourced labor, which affected crop development. This issue was corrected by using family labor, which improved the quality of the work and increased family income. However, as of May 2024, only four of the original growers remained from the initial project in 2017. Those who left the project continued to grow coffee independently and sold their product to local buyers who also offered credit at 5% interest for the harvest.

In interviews with the smallholders, uncertainty about the continuity of the program was highlighted, given the low level of assistance for the crop development by the company and the delay in the payment of the harvests carried out in February of this year, which had not yet been completed by mid-May. This has created uncertainty between the smallholders, since similar projects in the region fostered by the same company but focused on cocoa were cut two years ago.

However, a new project is being discussed in cooperation with a transnational company, which is planned to involve small producers with three manzanas: two for coffee cultivation with 190 shade trees and one manzana for forestry only, starting in the middle of this year. This program assigns more than 900 manzanas exclusively for forestry.

4.1.3. Drivers, Enablers, and barriers to Agroforestry Coffee

As highlighted in the interviews, the transition to agroforestry for smallholders faces significant barriers, making it difficult for many to adopt these practices. However, some drivers and enablers, including local NGOs and a company, have played a role for supporting this transition. These enablers have been driven both by market forces and for human development motivations. The interviewees identified the following barriers, drivers and enablers contributing to the ongoing efforts for transitioning in a regional level perspective, meaning in the communities of the CKNR.

Barriers

- **Financial constraints**

Establishing a new agroforestry coffee plantation presents significant financial constraints for smallholder producers living in extreme poverty. With costs potentially reaching up to 2100 USD per hectare, including labor expenses if workers are not family members, the initial investment required for transitioning to a coffee agroforestry system is often prohibitively high. Additionally, during the establishment period, which can extend to four years, the income of the farmers is primarily limited to annual crops used for intercropping and providing shade. This prolonged period without direct returns from the coffee plants can further strain their already limited financial resources.

Additionally, smallholder producers are often reluctant to acquire debt for such medium-term investments due to the high risk involved. The stability of annual income from traditional crops, although minimal, is perceived as more reliable and less risky compared to the uncertain returns from coffee agroforestry systems. Consequently, the modest yet consistent revenue from traditional farming practices offers a sense of security that medium-term, higher-risk agroforestry investments do not. This financial constraint poses a significant barrier to the adoption of agroforestry systems, highlighting the need for targeted interventions such as financial support, subsidies, and risk mitigation strategies to facilitate this transition.

- **Knowledge and Technical Skills**

It is important to consider the limited educational access in these communities, where, in most cases, only primary school education is available nearby. While traditional knowledge related to the cultivation of staple foods is valuable, it is often limited and does not extend to the technical requirements of coffee plantation management. Most smallholders lack the necessary expertise to effectively cultivate coffee, a crop that requires specific skills and knowledge.

Years of training focused on the use of external inputs such as fertilizers and other agrochemicals have ingrained certain practices in these communities. This reliance on external inputs can be a barrier, as transitioning to agroforestry systems requires a different approach. Proper training in good agricultural practices is essential to equip farmers with the knowledge and skills needed to manage the various stages of the coffee crop without relying heavily on financial resources. This includes understanding tree-crop interactions, integrated pest management, soil health improvement, and other sustainable practices that are crucial for the success of agroforestry systems. Without such training and capacity-building efforts, the lack of technical knowledge and skills remains a significant barrier to adopting agroforestry practices.

- **Migration**

Migration to Costa Rica and now increasingly to the United States, especially with the Humanitarian Parole program launched in 2023, presents a significant challenge. In recent years, many young people have opted to migrate to other countries or to pursue careers unrelated to agriculture, avoiding the labor-intensive work involved in managing a farm. This trend has made local labor scarce and more expensive, raising labor costs from 200 to 250-300 córdobas per day. The increasing migration has also led to the sale of agricultural land or a shift to livestock farming, which requires less manual labor.

Furthermore, the continuity of projects initiated by NGOs and the private sector is disrupted as the community loses key participants who could have benefited from and contributed to these initiatives. This outmigration weakens the workforce from the community and economic stability, meaning a significant barrier to the long-term sustainability and success of transitioning to agroforestry systems.

- **Lack of government interventions**

The small producers located in the buffer zone of a designated protected area receive little to no support from government institutions for transitioning their current practices to diversified crops or models like agroforestry. Institutions such as INTA (Nicaraguan Institute of Agricultural Technology) and the Ministry of Family, Community, Cooperative, and Associative Economy (MEFCCA) have not actively engaged in the zone to create opportunities for promoting alternative agricultural practices or enabling new markets for development. Although MARENA (Ministry of Environment and Natural Resources) has conducted some training sessions focused on reserve management and fire prevention, there has been no substantial support or initiatives aimed at assisting these producers in transitioning to more sustainable agricultural practices. This lack of government intervention and support further exacerbates the challenges smallholders face in adopting new, resilient, and sustainable farming systems.

- **Leadership Gaps and Innovation Reluctance**

Even though efforts in capacity building have been made by ADDAC throughout the years, it remains challenging to encourage innovation and initiative among producers, so they do not wait for external projects to take the lead. Developing local leadership that proactively seeks and adopts new agricultural practices is difficult due to a combination of risk aversion and a history of dependency on external assistance. Some projects have focused on creating and promoting reference farms with the goal of influencing other producers who are more reluctant to change. However, actions that involve risk are often avoided by most producers. This hesitancy to engage in innovative practices or to lead community-driven agricultural initiatives presents a significant barrier to the successful and wide-scale adoption of agroforestry systems.

Drivers

- **Low Yields of Traditional Crops:**

The unsustainable low yields of maize and beans due to climate stress result in insufficient income for farmers. For instance, a producer with one manzana of maize who obtains 20 quintals and sells them at NIO 400 (≈ USD 10.85) , achieves an income of NIO 8000 (≈ USD 217). However, the total costs can amount to approximately NIO 6900 (≈ USD 187) per manzana, leaving a small profit of only NIO 1100 (≈ USD 29.84), and sometimes even causing losses if yields are lower.

This adverse financial context means that many producers do not even cover their costs, creating economic pressure and needing a shift to more profitable and resilient farming systems. The uncertainty and discouragement stemming from these low yields drive farmers to seek alternatives, such as transitioning to coffee cultivated under agroforestry systems, which promise better economic stability and resilience to climate change.

- **Increased profitability and income diversification**

Agroforestry coffee, when well managed and sold in a value market, represents almost ten times the profit that can be achieved from a plot destined for maize and beans. Additionally, it allows for the cultivation of multiple crops, including timber (e.g., *Platymiscium pinnatum*) and fruits (such as oranges, bananas, plantains, and cocoa) for self-consumption. This diversified approach enhances economic returns and improves food security and environmental sustainability. The uncertainty and discouragement of low yields in traditional crops drive farmers to seek these more stable and lucrative alternatives, making agroforestry coffee a good choice for ensuring long-term viability.

- **Climate adaptation and ecosystem health**

The smallholders in the region face significant challenges due to poor soil management leading to low fertility, intensified by decreasing rainfall over the past three years. This reduction in precipitation has resulted in decreased yields, making traditional farming practices no longer economically viable. As one farmer expressed, "In the last 3 years, it has been more difficult due to the lack of rain; the harvests are no longer the same."

Agroforestry systems address these issues by integrating different tree species and crops, which improve biodiversity and ecosystem health. This integrated approach leads to more resilient agricultural systems. For example, in response to decreased rainfall, farmers in agroforestry systems, utilize banana trees to provide shade, which helps retain soil moisture and mitigates the adverse effects of drought.

Enablers

According to the interviews and direct observation, the presence of public institutions that promote the transition is very limited. In theory, the MEFCCA, INTA, IPSA, MAG, MARENA and INAFOR are the ministries and institutes that are responsible for developing capacities, providing technical assistance and resources to promote sustainable development in the reserve. However, there are some private institutions that are actively working in the region to achieve agroecological transitions (Figure 8).

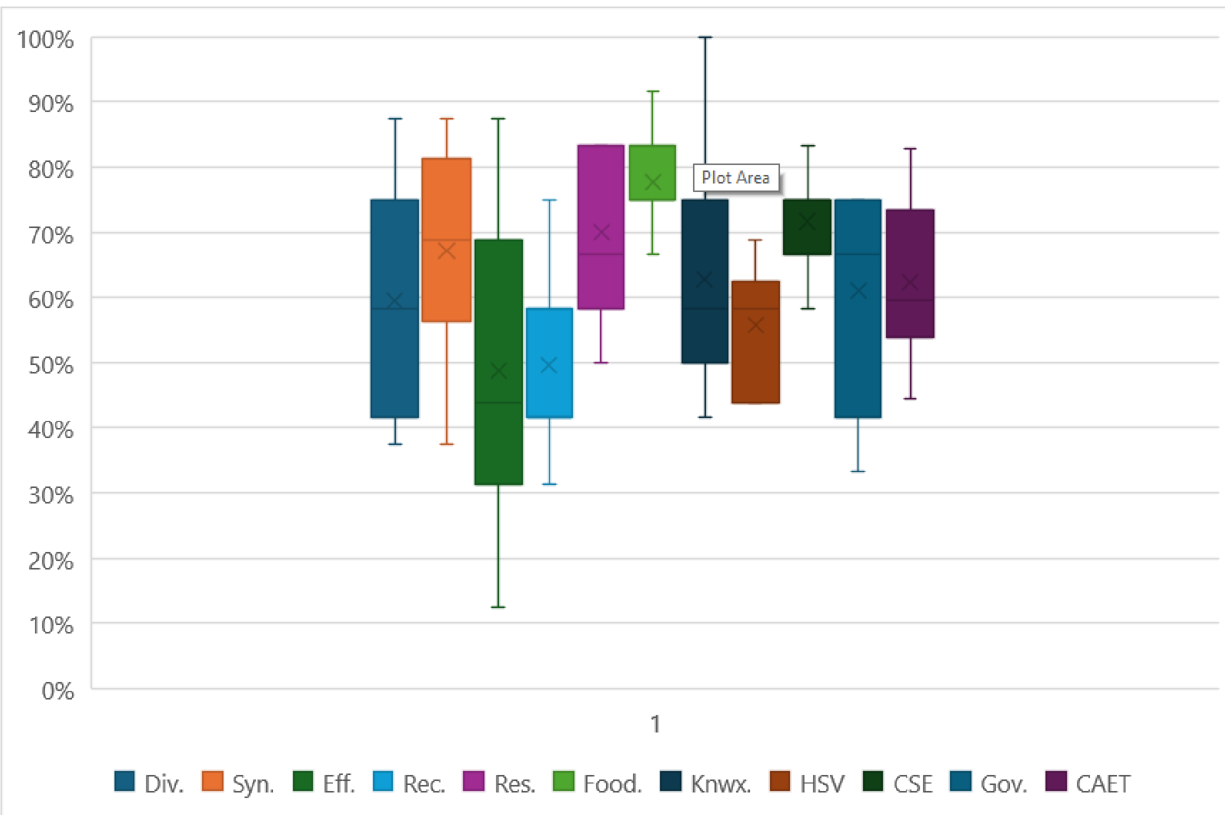
ADDAC (20 years of work in the region)	Focused on achieving sustainable development through agroecology, organic agriculture, and fomenting capacity building.
	Provides land to disadvantaged producers and collaborates with community organizations on generational succession, gender issues, and agroecology.
	It has established biofactories for producing organic inputs, resulting in two operational biofactories.
	It has established cooperatives for giving finnacial assistance and fomented agroecological approaches for cultivating tradional crops
	Encourages income diversification through the establishment of family gardens for enhancing food security and economic sustainability
	It has contributed on the development of cacao cooperatives inside of the CKNR with essential training in organic production and improving market access
EXPASA (7 Years of work in the region)	Promotes integration of coffee agroforestry system in smallholders who used to have bareland-growed crops or livestock, through an outgrowers scheme.
	Covers initial costs of inputs and labor, reducing financial and operational barriers to adopting new agricultural practices.
	Implements structured repayment plans and profit-sharing models
	Facilitates access to value markets, enabling farmers to achieve higher profits compared to traditional maize and bean plots.
GIZ (2020-2023)	Installed agroforestry systems wtih resilient coffee hybrids and native forest species in the buffer zone of CKNR, aligning with the existing EXPASA scheme.
	Provided training in good agricultural practices over three years, enhancing farmers' capacity to manage and improve their agroforestry systems sustainably.
	Offered technical expertise and resources, supporting the transition towards sustainable and resilient agricultural practices within the local context.

Figure 8. Enablers of the agroforestry transition in the CKNR

4.2. Agroecological Transition Status

The following section presents the results obtained from the first step of the TAPE tool, which assesses the level of agroecological transition within the production systems under study.

In general, the interviewed farmers did not perform poorly overall (Figure 9), as the sample mainly includes smallholders who have been working for at least four years with various initiatives. These initiatives have encouraged them to adopt agroforestry practices linked to the ten elements of agroecology (FAO, 2018). It is relevant to reiterate that the study does not include a representative sample, hence the results shown in the Figure 9 are not intended to represent the broader population but rather gives some insights on the central tendency within this specific group of smallholders.



#	Diversity	Synergies	Efficiency	Recycling	Resilience	Food traditions and Culture	Co-creation & sharing of knowledge	Human & Social Values	Circular & Solidarity economy	Responsible Governance	CAET
Mean	59%	67%	49%	50%	70%	78%	63%	56%	72%	61%	62%

Figure 9. Characterization of Agroecological Transition (CAET) for the entire sample of the buffer zone of CKNR: Disaggregated results for the 10 Elements of Agroecology.

A lower score was obtained in Efficiency (49%), which reflects the continued use of external inputs such as synthetic fertilizers and chemical pesticides for the cultivation of annual crops for self-consumption. Even on farms where agroforestry systems have been implemented through EXPASA intervention, many smallholders continue to use external inputs for growing their staple crops.

Recycling also had a lower score (50%), indicating room for improvement in the use and production of renewable energy. The utilization of renewable energy is often only feasible for smallholders who are not connected to the national energy grid, as these systems are frequently too expensive for them to afford. Water saving was not considered due to the types of agroecosystems where, they only work with rainfall

On a positive note, good average scores were achieved in Food Tradition and Culture (78%), as well as in Circular and Solidarity Economy (72%), due to a strong sense of community in most cases and the cultivation of a diverse range of staple crops.

4.2.1 Most Relevant Elements of Agroecology and CAET

For an exploratory analysis aimed at identifying patterns within this specific group, statistical correlation coefficients were calculated between the CAET and each individual element of agroecology. This approach allows for the assessment of the relationships between these elements, providing insights into the relative significance of each element in contributing to the overall progress of the agroecological transition within the studied group of smallholders (Table 6).

Table 6. Most relevant elements of agroecology and their influences in the level of agroecological transition of the sample.

Agroecology	Syn.	Eff.	Rec.	Res.	Food.	Knwx.	HSV	CSE	Gov.	CAET
Diversity	**0.80**	**0.89**	0.67	0.59	0.45	0.87	0.56	0.66	0.71	**0.92**
Synergies		**0.82**	0.69	0.61	0.39	0.80	0.59	0.89	0.85	**0.93**
Efficiency			0.75	0.57	0.39	0.85	0.37	0.75	0.77	**0.92**
Recycling				0.50	0.67	0.65	0.29	0.71	0.57	**0.79**
Resilience					0.36	0.69	0.65	0.62	0.46	**0.73**
Culture & food traditions						0.49	0.27	0.42	0.11	**0.51**

Co-creation & sharing of knowledge	0.62	0.67	0.63	**0.92**
Human & social values		0.62	0.33	**0.62**
Circular & Solidarity Economy			0.77	**0.86**
Responsible Governance				**0.80**

All 10 elements contribute to the overall improvement towards agroecological transition. However, certain elements are more closely related to the CAET within these specific communities. The 'synergies' element, which includes the level of integration within the farm system, soil coverage with residues, integration with trees, and connectivity between elements of the agroecosystem and the landscape, shows a significant impact on CAET with a correlation of 0.93. This high correlation is attributed to the positive effects of agroforestry, which ensures a permanent layer of residues on the soil and enhances landscape connectivity, especially when native species are utilized.

Diversity, which takes into account not only crop and animal diversity but also tree diversity and diversity of economic activities, also shows a strong correlation with CAET (0.92). Agroecological systems demand a high level of diversity, including various crops, animals, and trees, as well as multiple sources of income that promote a more synergistic system. This is reflected in the 80% correlation between these two variables.

A higher level of agroecological transition is closely linked to efficiency, which measures the farm's ability to be self-sufficient through integral and organic pest and fertility management. Co-creation and knowledge sharing are directly correlated with farms that are closer to achieving agroecology, due to the technical knowledge on how to implement these strategies and the platforms that promote it. This aspect is also strongly linked to other internal elements of agroecology, such as diversity (0.87), efficiency (0.85), and recycling (0.80).

4.2.2. Agroecological Characterization by Selected typology

Agroforestry involves optimizing the interactions between trees, crops, and animals to enhance biodiversity, increase resilience to climate change, and provide multiple ecological and economic benefits. While agroecology encompasses a broader set of agricultural practices integrating ecological principles into farming systems, agroforestry is closely aligned with many of these principles. As illustrated in Figure 10 significant positive outcomes can be observed, showing the progress of smallholder groups in the agroecological transition with the implementation of agroforestry systems within the reserve.

Figure 10. CAET results for selected typology

The stages of agroecological transition across the groups show varying levels of improvement in the 10 elements of agroecology. Notably, culture and food tradition consistently scored high across all groups, reflecting the strong maintenance of staple crop diversity and culinary traditions among the smallholders.

Significant progress is evident in the elements of efficiency, diversity, synergies, and co-creation and sharing of knowledge. The first three are closely linked to the inherent agricultural practices within agroforestry systems, such as crop diversification, reduced reliance on external inputs, and improved soil management. In contrast, the co-creation and sharing of knowledge are facilitated by external support from NGOs and regional retailers through training and workshops. Notably, groups established without the support of EXPASA scored higher in this element, likely due to their access to a broader range of knowledge sources.

Overall, better scores were observed in established smallholders without EXPASA's support, although groups dependent on the company's external inputs achieved good scores in most agroecological practices but lower scores in knowledge co-creation and sharing.

4.3. Sustainability Performance

4.3.1. Economic and Production Dimension

Productivity

The farm output, which includes the combined production of crops and livestock at the farm level, is measured in terms of value due to the varying units of measurement for different outputs. This aggregated value, calculated by multiplying quantities by their respective prices, allows for a comprehensive assessment of productivity. The following graph illustrates the productivity results as a ratio generated by comparing it with the average value generated by smallholders in Nicaragua, which is US$ 717/ha. To provide a more accurate analysis, the median value was used instead of the average for each group of smallholders. This approach was selected due to the diverse set of crops and activities within the families that incorporate agroforestry in their system, which varies significantly among producers and makes the data highly heterogeneous.

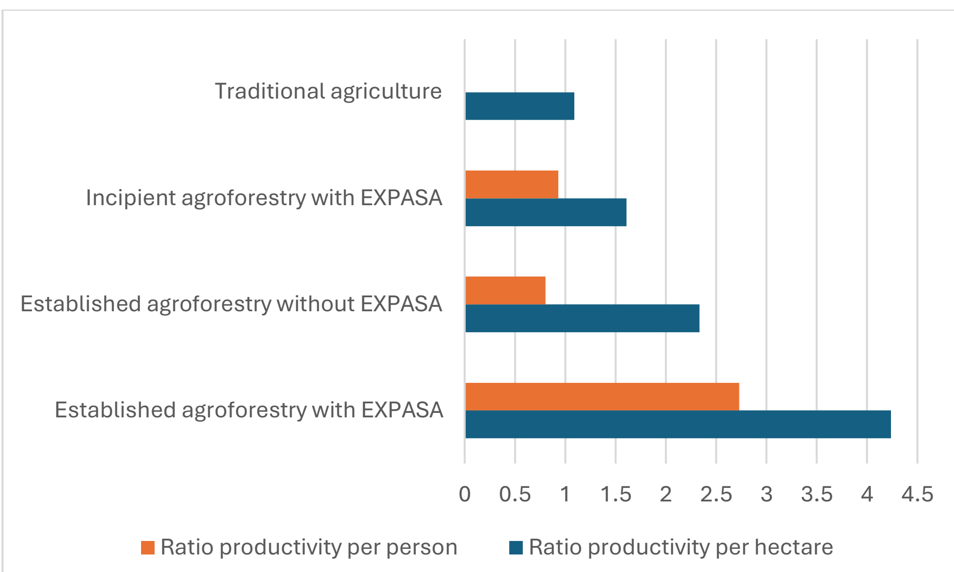


Figure 11 Ratio of productivity per person and productivity per hectare, in the selected typology

The results indicate significantly better productivity in the agroforestry systems established by EXPASA, which is expected since the company ensures good management practices, and the household guarantees the workforce effectively.

Similarly, established agroforestry without EXPASA shows a better score than the other two groups, but it still represents only half the productivity per hectare achieved with the company's support. This disparity is related to better access to high-value markets and the increased efforts and input provided by EXPASA to achieve economically feasible production. Incipient agroforestry systems established with EXPASA also demonstrate better productivity compared to traditional maize and bean agriculture. However, the difference is smaller because the coffee plants are still in development, with higher yields expected only in the following year.

The following graphs illustrate how the yields vary according to the age of the plant. This data is based on information collected from the established agroforestry system in collaboration with EXPASA and company technicians.

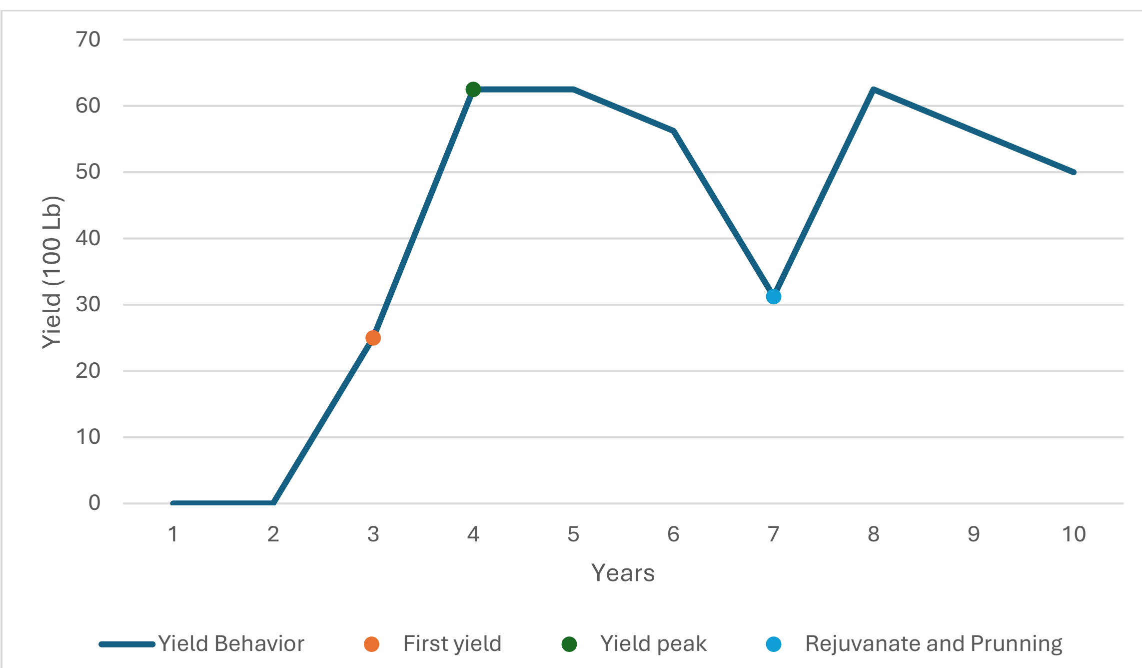


Figure 12. Marsellesa coffee variety yield development through years.

Incipient agroforestry coffee systems established by EXPASA are currently in their third year. As a result, they have only produced a small yield this year. Up to this point, their incomes have primarily come from other crops, small stores, employment, and revenue from fruit trees and plantains used as shading plants. Established agroforestry systems working with EXPASA have already begun pruning and rejuvenating the coffee trees, which has resulted in lower yields compared to previous years. However, the impact on yields also depends on how the smallholder chooses to rejuvenate their plantation. While there are various methods, the most common practice among smallholders is a stratified approach, which helps avoid a sudden drop in income.

A small note should be made on the maintenance of this coffee variety established by EXPASA, which is currently assuming the costs of its upkeep. Most of the interviewees expressed that without the program's support, it would be challenging for them to maintain the crop, as the variety they are using is quite demanding. They are hesitant to take the risk of investing heavily in it without guaranteed results. While smallholders who have been working with EXPASA for seven years have developed a better understanding of the importance of proper cultivation management, there remains a reluctance to fully embrace this coffee variety.

Income and added value

System profitability is a crucial measure that influences many decisions and drives agricultural policies. The method of assessment captures whether the income level earned by the producer is reasonable, considering the factors of production and assets employed. The following graph presents the results of income and added value for the systems under study.

Figure 13. Income and added value ratio compared to national statistics for selected typology

It's important to note that these results are presented as ratios rather than currency values, providing a contextual perspective against the traditional income for Nicaraguan smallholders, which is $1291 USD with an added value corresponding to 15.3% of the income.

Similarly to productivity, the income and added value ratio have increased significantly in the group of established agroforestry systems working with EXPASA. This improvement is attributed to better access to higher-paying markets through the company, which has established buyers willing to pay a premium for coffee produced sustainably by smallholders. In comparison, established agroforestry systems not affiliated with EXPASA also demonstrate better income than traditional agricultural practices. This advantage is due to the diversity of products in their crop portfolio and the higher prices paid for coffee compared to traditional crops. It is not surprising that producers in the group of incipient agroforestry systems associated with EXPASA are not yet experiencing significant incomes. In fact, their income levels are slightly lower than those from traditional maize and bean agriculture, as the coffee plants are still in their early phenological stages and have not yet yielded significant harvests.

4.3.2. Environmental and Health Dimension

Agrobiodiversity and Soil Management

The conservation of agricultural biodiversity is essential to meeting the challenges of climate change, improving nutrition and health, and transforming production systems to be more sustainable and equitable. The next figure shows average scores obtained in each of elements of agrobiodiversity analyzed with the tool.

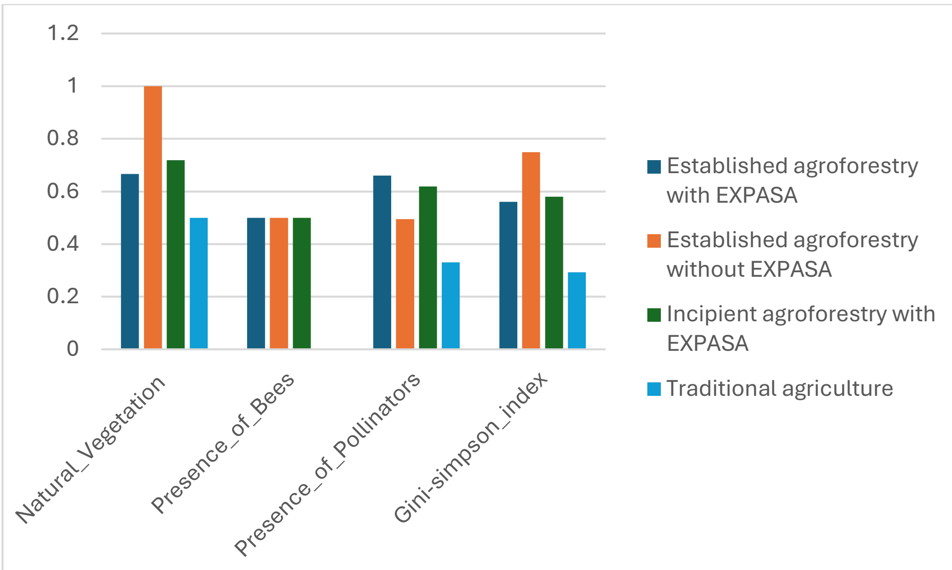


Figure 14. Agrobiodiversity scores by selected typology

Farms that have adopted coffee agroforestry systems within their crops exhibit better biodiversity on their land. This is influenced not only by the variety of crops integrated within the agroforestry system but also by an increased presence of pollinators and bees.

It is relevant to notice that within the coffee agroforestry system, often associated with Musaceae, a diverse of small crops are cultivated including cassava (*Manihot esculenta*), species from the gender *Xanthosoma*, winter squash (*Cucurbita* spp.) and other staple crops that enhance the food diversity of the smallholders.

Similarly, soil serves as the foundation for agricultural productivity and ecosystem health. Therefore, maintaining the quantity and quality of organic matter in agricultural soils is crucial for achieving sustainability in agriculture. In Figure 15, the score for the elements that were analyzed for soil health are displayed, reflecting the results for the four groups of smallholders.

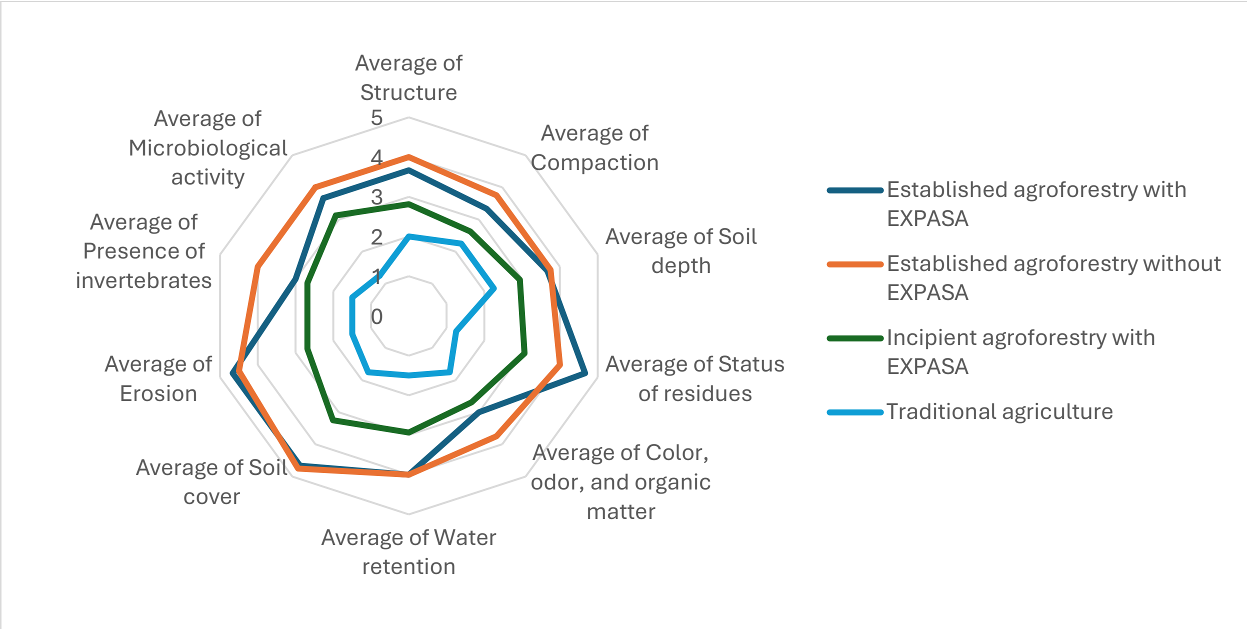


Figure 15. Performances on each element of soil health evaluated, by selected typology.

A general improvement can be seen with the transition to agroforestry coffee within the groups for soil health. This enhancement is related to the diverse set of soil management benefits that agroforestry introduces into the farming system, including stabilization of soil structure, improved water-holding capacity, and permanent soil cover, among others. Conversely, traditional grain monoculture with intensive practices and pesticide use negatively impacts soil health, resulting in poor scores. Established agroforestry without EXPASA got better scores overall, specifically in presence of invertebrates and the category color, odor and organic matter. During the interviews less use of inputs from the farmers that do not work with the company could be noted.

It is remarkable to notice the important improvement with scores between the incipient agroforestry and the smallholders how continue with traditional cultivation of maize and beans, the next figure shows the typical aspect of the soil observed during the farm visits.

Figure 16. Typical aspect of soil: a) Soil used for cultivation of maize and beans, b) Coffee agroforestry system in early stage.

Use of pesticides

Smallholders in the region typically grow maize and beans even if only as staple crops, including those working with EXPASA within an agroforestry system. They employ a very similar approach: for one manzana, they use 1.5 liters of glyphosate (and in some cases 2,4-D or Flumioxazin), 1.5 liters of Paraquat, and 86 kg of urea as fertilizer. In instances where they have fruit trees, cocoa, or small coffee plantations, they sometimes use Myrex, currently banned by the Stockholm Convention, as an insecticide for ants. Table 7 shows the inputs they usually use in their traditional crops, and the World Health Organization (WHO) classification of pesticides by hazard

Table 7 List of inputs used in traditional agriculture

INPUTS	WHO CLASSIFICATION	USE

GLYPHOSATE	Unlikely	Herbicide
PARAQUAT	Class II and restricted	Herbicide
2, 4-D	Class II	Herbicide
MYREX	Class Ia	Insecticide
FLUMIOXAZIN	Class III	Herbicide
UREA	N/A	Fertilizer

The coffee plantations established by EXPASA follow a standardized crop management approach. Even though they still use some non-organic products and apply glyphosate once a year as an herbicide, they conduct four mowings annually to minimize herbicide use. The smallholders who carry out these activities are equipped with the necessary personal protective equipment (PPE). Additionally, EXPASA collects the empty containers for proper disposal through the manufacturers. Foliar protection and fertilization are done four times a year as a preventive measure. The products used are detailed in Table 8.

Established coffee agroforestry system that works without the intervention of EXPASA doesn't use chemical inputs.

Table 8 List of inputs used in coffee agroforestry with EXPASA

INPUT	WHO CLASSIFICATION	USE
FOLIAR MULTIMINERAL FERTILIZER	Organic	Plant Nutrition
FULVIC ACID ENRICHED FERTILIZER	Organic	Plant Nutrition
FOLIAR OF ZINC + BORO	N/A	Plant Nutrition
GLYPHOSATE	Unlikely	Herbicide
AZOXYSTROBIN	Class III	Fungicide

The use of pesticides is analyzed through the tool, classifying the results into three categories: Desirable, Acceptable, and Unsustainable (Figure 17).

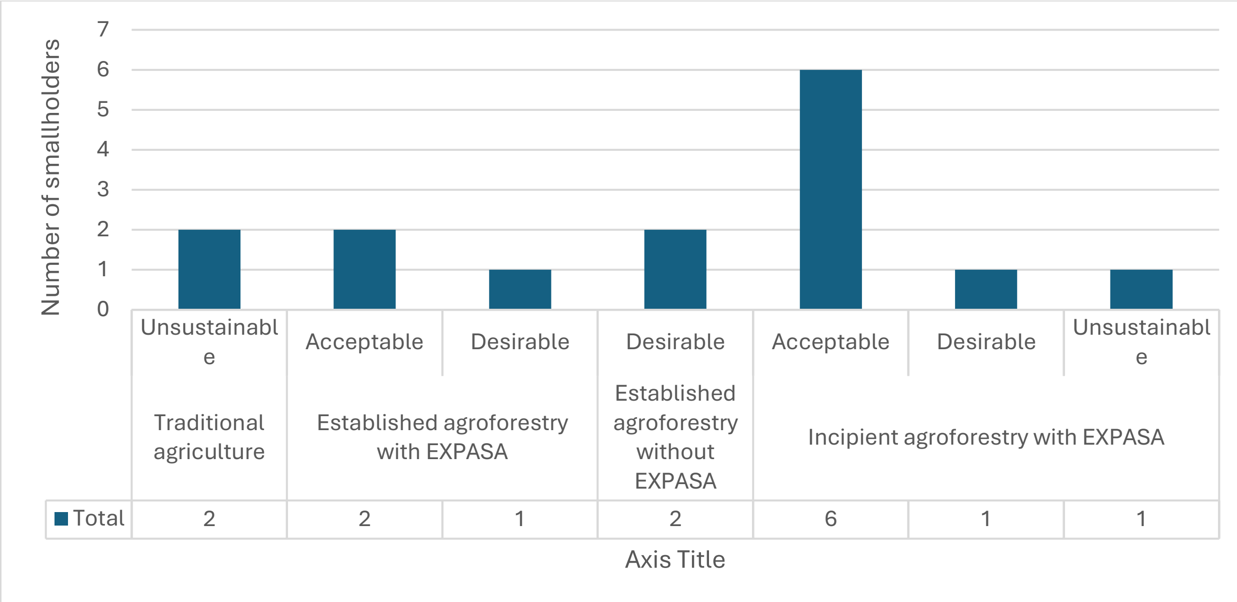


Figure 17. Scores on exposure to pesticides for the selected typology

The two smallholders representing traditional grain agriculture in the area generally do not use any protective equipment while applying pesticides. They are unaware of the consequences, do not manage waste properly, and apply products classified as IA and II according to the WHO classification leading them to be classified as unsustainable.

A general improvement is observed with the agroforestry system, where the use of agrochemicals is limited to small amounts. Through various workshops, better education was provided related to the use of pesticides and the management of empty containers. However, one was classified as unsustainable because, even though the company provides inputs not prohibited by international conventions, the smallholder is applying Mirex, which is banned, to control ants on his parcel. Three producers achieved the desirable classification because they either do not use any pesticides, employing other integrated pest management techniques, or they use small amounts of pesticides that are not highly dangerous, with at least four mitigation techniques, and prioritize organic inputs and physical management techniques.

4.3.3. Social Dimension

Women's empowerment

The Women's Empowerment in Agriculture Index (WEAI) is measured in TAPE by evaluating four empowerment indicators: i) decision-making on agricultural production, ii) access to resources, iii) control over income generated by production and leadership, and iv) workload (Mottet et al., 2020). In Figure 18, a general improvement in the WEAI can be seen within the coffee agroforestry systems.

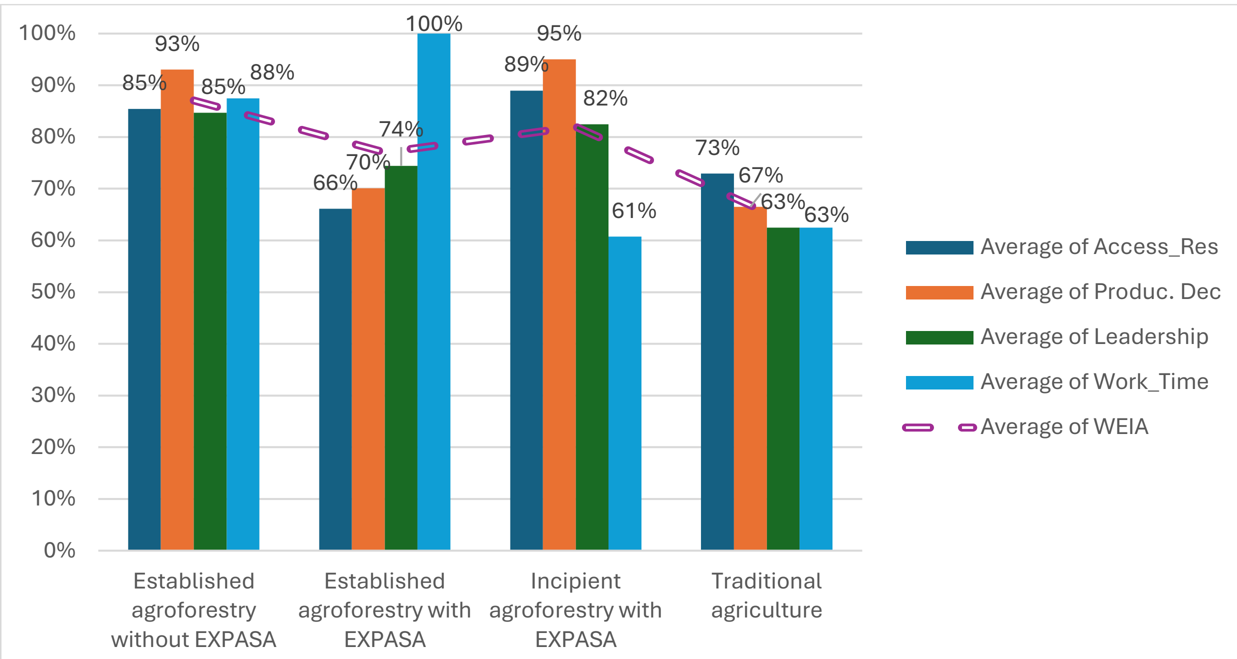


Figure 18. Women's Empowerment in Agriculture Index (WEAI) and its indicators, on selected typology

Access to resources it is enhanced with the possibility that women have to request credits, and that they usually share the ownership of the house and the production system with their husbands however they usually do not have the legal document of ownership on their names. Decisions regarding the production system are usually made by men in traditional agriculture, however since the smallholders with agroforestry system have gone through many trainings and workshop for developing women's capacity in the field and giving empowerment to women either with or without EXPASA, better scores were achieved. This also applies to leadership, because with this empowerment they have more power when making decisions about what to do with the revenue.

Differences can be seen with the work time between incipient agroforestry and traditional agriculture, with the established agroforestry system. This is because established agroforestry has more income, and it is possible to lower the hours with external work. Incipient agroforestry still needs some time for getting good yields, and with that more income.

It is interesting to see a drop in the average of WEAI scores when comparisons are made between established agroforestry with EXPASA and incipient agroforestry, and this is mainly related on the way the sample is made, with the first group mention, there are no women owners however in the second group 50% of the smallholders interviewed are women. This could also be on the way the interventions where made, observations can be made that in the second phase of the project and with the intervention of the GIZ, more women were included as beneficiaries of the project.

Youth employment

The results presented in Figure 19 show the average scores related to Youth Employment Opportunities. These scores represent the average obtained in different indicators related to the number of young people aged 15-24 who are working in the farm system, those who want to migrate, and those who have already migrated.

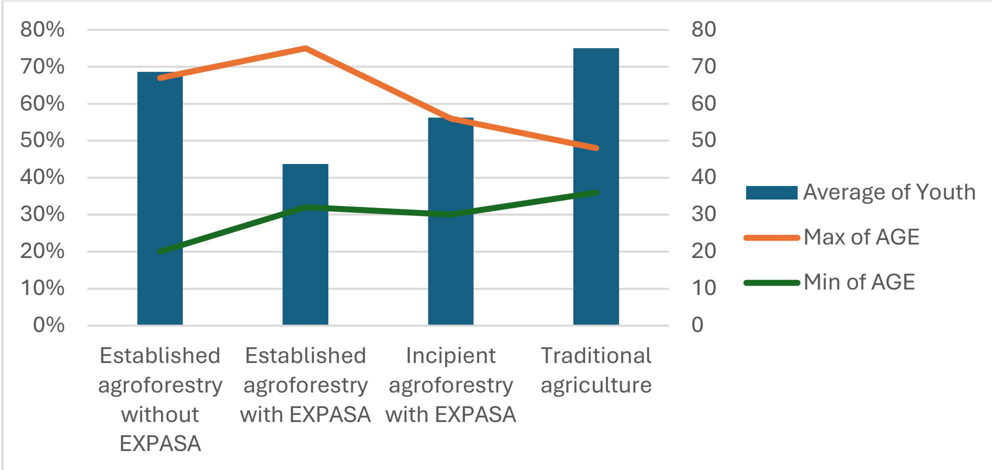


Figure 19. Average score for youth employment compared to minimum and maximum age, based on selected typology.

It is important to note that the region has lost a significant part of its workforce in recent years because of migration. Since 2018, due to political instability in the country, more than 800,000 people have migrated, mainly to the United States and Costa Rica.

The sample being studied mainly consists of individuals older than 24, but usually not older than 65. These individuals are often the landowners and do not have children in the 15-24 age group. Most young people do not have the chance to stay on farms because these farms are very small. Without land of their own to work on, many young people prefer to migrate for several months or years and then return to start new projects if they are still interested in farming, which is often the case. Some of the interviewees travel back and forth to Costa Rica to find other sources of income beyond farming and to save more money for investing in their properties.

Generally, the interviewees stated that individuals who own land and have an ongoing project are more likely to stay in the community. For these smallholders with agroforestry systems, even though the income is generally increase, the land is too small to support both the current owners and future generations at the same time during the transition period.

From the data, a relation can be seen as the age of the smallholder increases, it is more likely that their children are old enough to migrate, and in most cases, they take the opportunity to do so.

4.3.4. Nutrition Dimension

Figure 20 reflects food consumption related to household access to a variety of foods, which is crucial for addressing imbalances in our food systems and moving towards a zero-hunger world.

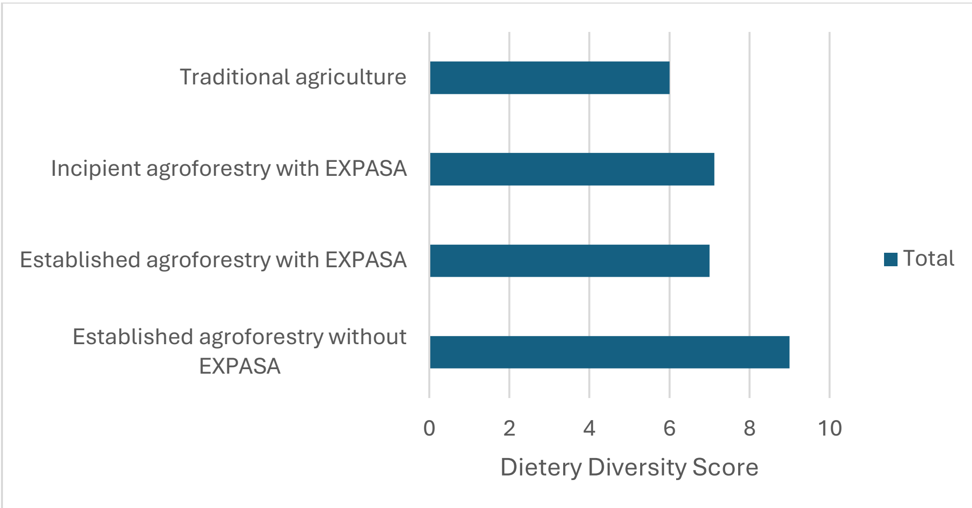


Figure 20. Average of food groups consumed in the last 24 hours for the selected typology.

According to the criteria established for analyzing dietary diversity, the results show that three of the groups fall into the desirable category, while the smallholders within traditional agriculture fall into the acceptable category. Hence, it can be generally assumed that food diversity is good among the sample. A considerable increase in scores can be seen in the established agroforestry systems without EXPASA, which could be linked to better incomes and a greater diversity of economic activities on these farms.

For a more detailed analysis, a frequency table is presented for each of the 10 food groups, within the selected typology of farms

Table 9. Percentage of groups of food eaten in the last 24 hours, for the selected typology.

Classification	Grains/ Tubers/Starchy veg.	Legum.	Nuts/seed	Dairy prod.	Meat /fish	Eggs	Green veg.	Yellow fruits/ veg	Other veg.	Other Fruits
Established agroforestry without EXPASA	100%	100%	0%	100%	100%	100%	100%	100%	100%	100%
Established agroforestry with EXPASA	100%	100%	0%	100%	33%	100%	67%	100%	100%	0%
Incipient agroforestry with EXPASA	100%	100%	25%	88%	50%	88%	25%	88%	100%	50%
Traditional agriculture	100%	100%	0%	50%	50%	50%	50%	100%	50%	50%

Perfect scores were achieved in the categories of grains/tubers/starchy vegetables and legumes, as all smallholders consume rice, beans, and maize tortillas daily. This is the traditional dish of Nicaraguan families, and smallholders usually ensure, through their own production, that they have at least these foods available. Nuts and seeds are not commonly consumed by the sample, as these are not typically grown in the area. Dairy products are more common, especially in households with higher incomes. The same applies to meat and fish, which are not frequently eaten, though an increased rate can be observed in the agroforestry coffee groups, who have higher incomes. Eggs are the main source of protein; however, some smallholders do not consume them daily because they either do not have chickens or prefer to sell the eggs to generate additional income.

4.3.5. Governance and Land Tenure Dimension

Sustainable agriculture and resilient food systems rely on governance structures that ensure fair access to resources. Equitable access to land and natural resources is essential for social justice, gender equality, and encouraging long-term investments. The following table represents the level of land tenure according to the methodology followed, disaggregated by gender.

Table 10. Land tenure disaggregated by gender for the selected typology

Land Tenure	Women Score	Men Score
Established agroforestry with EXPASA	**3**	**3**
Acceptable	2	1
Desirable	1	2
Established agroforestry without EXPASA	**2**	**2**
Acceptable	2	1
Desirable	0	1
Traditional agriculture	**2**	**2**
Acceptable	2	0
Desirable	0	2
Incipient agroforestry with EXPASA	**7**	**6**
Acceptable	3	4
Desirable	4	3
Grand Total	**14**	**13**

Even though all interviewed smallholders have either acceptable or desirable levels of land tenure, the results reflect that, in most cases, women have less secure access to land. Only five women are in the desirable category of land tenure, meaning they have legal documents in their names. Most of these women inherited their land from their parents and are now part of the agroforestry coffee project promoted by EXPASA. It is important to note that this situation is not common in the area; these women were specifically selected for the project to ensure diversity.

Typically, men hold the contracts in their names. Although women have a secure perception of land tenure and are legally able to inherit land to their children, hence, they fit within the acceptable category of Land Tenure.

5. DISCUSSION

Agroforestry is seen as a viable approach to mitigating the environmental impact of conventional agriculture while simultaneously improving food security and livelihoods for smallholder farmers (Duffy et al., 2021; Quandt et al., 2023; Ulya et al., 2023; Zamora & Udawatta, 2016). However, the implementation of agroforestry has its challenges. Issues such as the high initial costs of transition, dependency on external inputs and expertise, and the need for market access and supportive policies can limit its adoption and effectiveness(Beuchelt & Zeller, 2011; Caviedes Rubio et al., 2023; Snider et al., 2017; Valkila, 2009).

In the context of Latin America, and specifically Nicaragua, agroforestry systems have been promoted to achieve sustainable livelihoods based on a key agricultural sector(Bacon et al., 2014; Bro et al., 2019; Judith Vanegas, 2021) . While these systems have shown significant potential in enhancing ecological and economic outcomes, they also reveal critical dependencies on external actors, such as private companies and NGOs, for the provision of resources, knowledge, and market access. These dependencies raise important questions about the long-term viability and autonomy of smallholders who adopt agroforestry practices. Thus, it is crucial to explore how these systems can contribute to sustainable agricultural development within local context in a way that is both inclusive and resilient.

5.1. Barriers and Accessibility of Agroforestry Systems for Smallholders

Agroforestry coffee cultivation, within the group of smallholders analyzed, offers better profitability compared to traditional crops like maize and beans, which have become increasingly unsustainable due to low yields and climate variability. Especially when these systems are so dependent on the weather conditions, since there is no irrigation within the zone (MARENA, 2021). However, it is relevant to notice that the cultivation practices currently observed for maize and beans within the CKNR have deviated substantially from traditional methods. These practices have increasingly been shaped by conventional agricultural techniques, driven by the necessity to achieve higher yields in order to stay competitive in markets where prices are consistently low. This shift towards high-input farming practices has significantly altered the landscape of agriculture in the region. As a consequence, much of the traditional knowledge that once guided milpa cultivation has been marginalized or displaced altogether (Fonteyne S et al., 2023).

On the other hand, this transition is made attractive by the potential for higher and more stable income, driven by premium prices for sustainably produced coffee and income diversification through timber and fruit production (Carpente et al., 2020). However, the initial investment required, estimated at around 2100 USD per hectare (Penot et al., 2017), represents a significant financial barrier for smallholders, many of whom are already operating at or below subsistence levels. To this, it sums up the long maturation period of coffee plants, during which farmers must rely on less profitable intercrops, further straining their finances.

Even though private sector projects like MATRICE provide financial support through structured repayment plans and profit-sharing models to mitigate some of the financial risks associated with establishing agroforestry systems, these initiatives come with trade-offs and are not easily scalable to all smallholders. Apart from these projects that provide the full "technological package" to smallholders, there is generally a low willingness to transition to agroforestry systems. This hesitation is largely due to the perceived high risk associated with taking on debt, as their vision is always set on guaranteeing their food safety first before thinking on what products to sell. The relative stability of traditional crops, despite their lower profitability, is often viewed as less risky compared to the uncertainties involved in adopting new agroforestry practices as it also guarantees the day-to-day food. Similar barriers were identified by Haryono et al. (2023) including the lack of an effective financing scheme that hold the smallholders in making the transition to a more profitable crops that are grown in agroforestry system.

Social and cultural factors also play a crucial role. Many smallholders lack the necessary knowledge and technical skills to manage complex agroforestry systems, which require understanding of tree-crop interactions, pest and disease management, and soil health improvement. Traditional reliance on external inputs further complicates the adoption of more sustainable practices. While organizations like ADDAC and GIZ provide essential training and capacity-building, the depth and reach of these programs need expansion to ensure that all smallholders can effectively manage agroforestry systems. Additionally, there is a cultural reluctance to adopt new practices, coming from a history of dependency on external projects and risk aversion. These findings align with the results of Kouassi et al. (2021) where limited access to education and information resources was identified as a significant barrier, and there was a tendency among farmers to rely on traditional methods due to the perceived risks and uncertainties associated with new practices. Encouraging a shift towards a more proactive mindset, investing in local leadership, and promoting success stories are crucial for overcoming these cultural barriers

However, this conservatism should not be interpreted simply as resistance to change, but rather as an expression of a worldview that values stability, continuity, and the preservation of a way of life that has been central to their identity and survival (Armando Bartra & Arisbel Leyva, 2012).

From an environmental and sustainability perspective, agroforestry systems offer increased resilience to climate change compared to monocultures (Gidey et al., 2020). These systems enhance biodiversity, improve soil health, and conserve water through better moisture retention. The integration of shade trees, such as timber species and fruit trees, not only supports coffee growth but also helps mitigate the impacts of changing weather patterns (Gomes et al., 2020) . Smallholders in the CKNR are noticing the benefits of agroforestry in reducing these climate-related effects. However, despite these advantages, the barriers previously mentioned, such as financial constraints and limited knowledge, continue to deter smallholders from independently initiating the switch to agroforestry without external support.

The environmental benefits of agroforestry, including carbon sequestration and habitat provision, align with global sustainability goals have the potential to attract additional funding from international organizations (Quandt et al., 2023) . Educating smallholders on these benefits and how they can translate into economic gains through sustainable certification schemes is crucial for promoting wider adoption of agroforestry practices.

Institutionally, the lack of government support is a significant barrier. Without policies or incentives for adopting sustainable practices, smallholders often lack the necessary backing to make such a significant shift. As stated by Ulya et al. (2023) government support in the form of subsidies, technical assistance, and market development is crucial. Integrating agroforestry into national agricultural policies could provide a framework for scaling these practices and ensuring sustainable management.

Moreover, migration patterns, especially among the youth, have led to labor shortages across rural areas and the entire country, increasing labor costs and reducing the available workforce necessary for the labor-intensive initial stages of agroforestry system establishment. Mulyoutami et al. (2020), point out that income diversification, which significantly supports households, reduced availability of male labor has also empowered women to assume greater roles, increasing their workload while enhancing their involvement in agroforestry practices. In the case of the smallholders of CKNR, similar patterns can be seen with men seasonally migrating to United States or Costa Rica, for having additional incomes (Judith Vanegas, 2021), increasing the load on women that need to step into the production system while continuing with the household activities.

5.2. Enhancing Sustainability through Agroforestry Practices

Although agroforestry is not strictly agroecology, it incorporates various elements that align with it as the results reflect - such as increased biodiversity, enhanced synergies within farming systems, and a strong culture of knowledge exchange. These aspects collectively contribute to more resilient agricultural systems, capable of better adaptation of climatic and economic challenges while also indicating improved soil health and reduced dependence on external inputs like synthetic fertilizers and pesticides. This is aligned with Zamora & Udawatta (2016) results, indicating that agroforestry improves soil quality by increasing organic matter and enhancing soil microbial activity, which supports better water retention and reduces erosion, while also providing shade and habitat for various species, thereby fostering biodiversity

The CKNR region shows that community-based learning and management practices have been incorporated, which further enhance agroecological principles by fostering a sustainable and participatory approach to farming. Similar to the Participatory Action Research PAR approach (Guzmán Luna et al., 2022), these practices involve farmers in decision-making processes, enabling them to share knowledge and experiences. This participatory method aligns with agroecological elements, leading to better outcomes despite challenges in scaling these practices and overcoming financial barriers.

The shift towards agroforestry has significantly improved productivity and income stability for smallholders. The integration of diverse crops within agroforestry systems not only enhance the resilience of these systems to market and climatic shocks but also increases profitability (Oviedo-Celis & Castro-Escobar, 2021; Jena et al., 2017). The higher market value of sustainably produced coffee, coupled with the diversified income from annual crops fruit trees, and in the long-term timber, offers a more stable and higher income compared to traditional maize and bean cultivation. The interviewed stakeholders are conscious of how economic diversification is critical for the smallholders who are currently facing bad prices in the local market for their products and low yields because of climate variations.

Market access can also be a constraint on the economic side, as having an agroforestry system does not automatically guarantee access to higher-paying markets. Alliances must be formed, and smallholders must organize to find these specialty markets, which offer better prices and, consequently, more motivation for producers to manage their plantations properly. (Bro et al., 2019) have shown that cooperative membership significantly improves market access to niche markets offering premium prices for sustainably produced coffee. These cooperatives facilitate connections with higher-value markets and provide essential support, such as credit and technical assistance, which collectively enhance the profitability and economic stability of smallholders. Capacity building on leadership within the smallholders should be the focus in order for establishing more horizontal organization, instead of depending on external actors. (Ramos-Pérez et al., 2016)

In addition, it's important to recognize that the initial costs of transitioning to agroforestry systems, such as purchasing seedlings and building the necessary infrastructure, can be prohibitive for many smallholders. In addition, starting a coffee system from scratch will result in minimal to no income during the early phenological stages of the plant, requiring alternative sources of income for the first four years. However, Bro et al. (2019) note that cooperatives play a crucial role in mitigating these financial barriers. By providing access to credit and financial support, cooperatives help smallholders overcome the high initial investment required to adopt sustainable practices. This support is essential to enable smallholders to make the transition without incurring prohibitive financial risks. In addition, cooperatives provide technical assistance and training, further reducing the challenges associated with this transition and promoting the adoption of sustainable agricultural practices.

The environmental and health benefits of transitioning to agroforestry coffee systems in the CKNR region are also significant. One of the main advantages is the enhancement of biodiversity. Agroforestry systems integrate a variety of crops and tree species, which not only diversify the agricultural landscape but also provide habitats for numerous organisms, including beneficial insects and pollinators (M. A. Altieri & Toledo, 2011). This biodiversity is crucial for maintaining ecological balance and resilience against pests and diseases, reducing the need for chemical pesticides.

Improved soil health is another critical benefit observed in agroforestry systems. The inclusion of various tree species in these systems contributes to better soil structure, increased organic matter, and improved water retention. These factors collectively enhance soil fertility and reduce erosion. Similarly to M. A. Altieri & Toledo (2011) findings, the presence of shade trees in the smallholders of the CKNR, such as timber and fruit tree, also moderates soil temperature and protects crops from extreme weather conditions.

In Colombia Caviedes Rubio et al., (2023) found to enhance habitat diversity and support various wildlife, thus increasing biodiversity. Additionally, certified farms, like some of the ones interviewed under Rainforest Alliance, often implement best management practices such as organic fertilization and erosion control, which improve soil structure, fertility, and health.

In terms of health, the reduced reliance on synthetic fertilizers and pesticides in agroforestry systems has direct and indirect benefits. Farmers and local communities are less exposed to harmful chemicals, which reduces health risks associated with chemical use, such as respiratory issues and skin irritations(Valkila, 2009). The adoption of organic and integrated pest management practices also contributes to healthier food products that are grown within the system, which is particularly important for local consumption

However, it is important to note that while agroforestry systems reduce the need for chemical inputs, some smallholders still use these products, particularly for crops like maize and beans that are grown alongside coffee in different parcels as a staple crop. This continued use of chemicals can pose health risks and potentially minimize the environmental benefits of agroforestry. Therefore, ongoing education and support for smallholders are necessary to fully transition to more sustainable practices. In this sense, results reported by Wienhold & Goulao (2023) could be promising as they consider that he knowledge and skills gained from implementing agroforestry practices in coffee production can be transferred to other crops. Training programs that focus on sustainable practices can equip farmers with the techniques needed to enhance the productivity and sustainability of various crops. This could happen in the near future where sustainable practices are also extended to other crops owned by the smallholders.

The transition to agroforestry coffee systems in the CKNR region has a significant impact on the social dimension, particularly in areas such as community cohesion, gender equity, and youth engagement. One of the key social benefits is the improvement of community cohesion through collective learning and shared agricultural practices. The implementation of agroforestry in this area has been accompany with different supports from NGOs, cooperatives and private sector, which often involves collaborative efforts, including knowledge exchange workshops and group training sessions, which help build stronger community ties. These activities disseminate vital agricultural knowledge and foster a sense of solidarity among smallholders, promoting a more inclusive and supportive farming community Guzmán Luna et al. (2022).

Wienhold & Goulao (2023) highlighted how social networks are strengthen trough collective learning platforms which helps build resilience within farming communities. These networks enable farmers to collectively address challenges such as climate change, market fluctuations, and pest outbreaks. The cooperative efforts facilitated by these platforms ensure that farmers are better equipped to handle adversities, thereby enhancing the overall sustainability of their agricultural practices. However, these collective learning platforms were placed by external actors and continued to be dependent on the presence of this actors for the platform to continue working.

Gender equity is another aspect positively impacted by the adoption of agroforestry systems. The involvement of women in agroforestry projects, as seen in the CKNR region, has led to increased opportunities for women in decision-making roles and greater access to resources. Programs that focus on training and empowering women contribute to their economic independence and enhance their participation in agricultural activities.

A similar intervention with an emphasis on the empowerment of women in coffee agroforestry system (Simelton E et al., 2021) have also reflect an improvement on decision making power over agricultural and household finances, shifts in household dynamics with men becoming more supportive of shared responsibilities, and enhanced negotiation skills.

This empowerment is crucial for achieving gender equity within the community and ensuring that women have a voice in the management and development of their farms. However, challenges remain, particularly regarding land tenure security for women, which can limit their full participation and benefits from agroforestry systems.

Youth engagement is also influenced by the shift to agroforestry. The introduction of more diverse and potentially profitable farming practices can provide viable alternatives to migration, which has been a significant issue in the region. By creating more attractive and sustainable livelihoods, agroforestry can help keep young people in rural areas. However, the success of this initiative depends on the support in education and creating training opportunities directed at the younger generation.

Del Castillo (2024) explores how access to high-value markets for sustainably produced coffee provides better income opportunities for smallholder farmers. Therefore, this economic stability and potential for higher earnings can reduce the incentive for youth to migrate in search of better livelihoods. As well these projects often include programs that integrate young farmers into the coffee value chain with vocational training, leadership development, and business opportunities.

Although these developments are positive, the social dimension of agroforestry adoption still faces challenges. The dependency on external support and the lack of consistent local leadership can hold back the long-term sustainability of these social benefits. Chazovachii et al. (2021) explain how the contract farming or outgrowers scheme often creates a lack of autonomy on the smallholders for making independent decisions about their farming practices. The contracting companies typically dictate what crops to grow, how to grow them, and where to sell them. In this way, farmers become reliant on the contracting companies for inputs, technical support, and market access, limiting farmers' control over their agricultural practices.

There is also the need for a broader cultural shift towards adopting sustainable practices, which may require overcoming deep-seated traditional practices. Additionally, the integration of agroforestry systems must be inclusive of all community members, ensuring that marginalized groups, including those with less access to land and resources, are not left behind. Adams et al. (2019) highlighted how contract farming schemes tend to selectively include farmers who are seen as more reliable or influential, which can exacerbate social inequalities. Poorer community members might be excluded or dispossessed in these types of projects, leading to increased social stratification.

The nutrition dimension has also been positively impacted by the transition to agroforestry coffee systems in the CKNR, improving the dietary diversity and food security of smallholder households. Agroforestry systems incorporate a wide variety of crops, including fruits, vegetables, and staple foods, which contribute to a more balanced and nutritious diet. Besides, most smallholders still allocate a parcel for growing maize and beans, which other studies of the region emphasize as essential. These studies (Bacon et al., 2014; Guzmán Luna et al., 2022)highlight the need for a balanced approach that includes staple crops like maize and beans, vital for household consumption, and can be complemented with coffee farming as a cash crop.

It is especially important for the household nutrition that agroforestry systems also include fruit trees, plantains, and bananas, as this increases the availability of diverse foods, which is crucial in rural areas where access to a variety of nutritious food sources can be limited. This was specially highlighted by Carpente (2020) as the smallholders in the CKNR region highly value fruit trees in their coffee plots for both income and household consumption, with fruit donations being a significant tradition. Besides, having multiple food sources within the same farming system also reduces dependence on external markets

Furthermore, the increased income from agroforestry systems allows households to purchase additional food items, making it possible for them to diversify their diets (Duffy et al., 2021). The economic benefits of agroforestry enable smallholders to invest in a broader range of foods, including protein-rich foods like meat, eggs, and dairy products, which may not be produced on the farm. This increased purchasing power helps to improve the overall nutritional quality of meals.

However, the transition to agroforestry systems also presents certain challenges in the nutrition dimension. The initial focus on establishing coffee and other long-term crops can temporarily limit the availability of diverse foods, particularly in the early years of transition when the system is not yet fully productive. Additionally, traditional dietary practices and preferences may influence the extent to which the benefits of dietary diversity are realized.

Special attention should be paid to the reduction of land for staple crops production in favor of prioritizing coffee production. Guzmán Luna et al. (2022) discusses that despite diversification efforts, more than 50% of coffee-producing households experience periods of food scarcity each year. This issue is partly due to the heavy reliance on coffee as the primary income source, which can lead to reduced cultivation of staple crops necessary for household consumption.

Organizations like EXPASA and ADDAC have played a key role as drivers in supporting land tenure security for smallholders. Participation in projects facilitated by these organizations often requires smallholders to have legal land status, which has encouraged many to complete the necessary legal processes with local governments to gain formal recognition of their land rights. This legal recognition not only fosters a greater willingness to invest in agroforestry systems but also enhances access to financial resources, as secure land can be used as collateral.

However, challenges remain in ensuring equitable access to land and resources. Women often face barriers to securing land tenure, which can limit their ability to fully participate in agroforestry initiatives. Although some progress has been made in improving women's access to land and resources, significant gender disparities in land ownership and tenure security persist. Addressing these issues is essential for ensuring that all community members can benefit from agroforestry practices.

In the MATRICE project from EXPASA, female producers were intentionally included, even though there are not many women landowners in the area. This initiative was made to allocate resources on women for becoming leaders in their system as a beneficiaries of the agroforestry projects

5.3. Dependency Dynamics and Implications of External Support

The prevailing socioeconomic conditions and inherent risk aversion prevent them from independently transitioning to coffee agroforestry systems. These changes are only feasible when external stakeholders, such as companies or NGOs, intervene and mitigate initial risks while securing access to high-paying markets. Specifically, interventions by EXPASA have been instrumental in allocating international resources for cooperation, building capacity, and establishing coffee plantations—serving as a critical starting point for smallholders. This outgrowers scheme or contract farming is well known of its benefits of providing the essential support to smallholders including inputs, technical support, and access to stable better paying market (Brüntrup et al., 2018).

However, the trend towards a total vertical integration in the coffee market, driven by centralized companies like ECOM through EXPASA, creates a significant dependency on these development projects. These projects are often designed to fit the economic models of the sponsoring company, rather than being centered on the needs and goals of the smallholders. Similar studies (Adams et al., 2019; Brüntrup et al., 2018; Chazovachii et al., 2021; Haryono et al., 2023) have also concluded that the outgrowers schemes make a dependency relationship between the smallholder and the contract company for inputs, technical support, and market access, limiting their autonomy and decision-making capacity. This dependency can also result in exploitative practices and unfavorable terms for smallholders.

This dependency raises concerns about the continuity of these systems if external support were to cease. While the benefits of the project are evident across all dimensions of sustainability, the sovereignty of smallholders in decision-making is compromised, as they often heavily rely on the resources and directives provided by the company, even though they are not obligated to continue within this framework.

Notably, smallholders who began participating in the project in 2017 have demonstrated increased leadership and a willingness to continue the practices introduced by the company, indicating some positive development in independence and decision-making. However, the prospect of more horizontal integration, such as forming cooperatives, seems unlikely in the near future. The interviewees expressed a reliance on the platforms and infrastructure already established by the company, which limits their autonomy.

While these trade-offs should not overshadow the significant benefits these projects have brought—such as improved sustainability practices and knowledge acquisition—they highlight the need for better internal governance structures. Building these skills from within, potentially with support from government structures, is crucial to reduce dependency on the private sector, whose primary goal is profitability (Brüntrup et al., 2018; Mulyoutami et al., 2020; Ulya et al., 2023; Wienhold & Goulao, 2023). Even if these projects do not continue indefinitely, the introduction of agroforestry systems in an area previously dominated by harmful practices represents a meaningful shift towards more sustainable agriculture.

5.4. Limitations of the study

The TAPE tool has proven to be a valuable instrument in assessing the sustainability of agroforestry coffee cultivation, particularly due to its adaptability to various contexts and crop types(Lucantoni et al., 2022). The selected indicators of the tool offer a comprehensive framework for evaluating different dimensions of sustainability, such as environmental, economic, and social factors. This allows for a thorough analysis without being overly exhaustive, making it practical for both researchers and practitioners (Darmaun et al., 2023). Additionally, TAPE effectively represents the gains in sustainability associated with the transition to agroforestry coffee systems, showcasing improvements in biodiversity, soil health, and economic resilience.

However, the tool does have limitations. One major constraint is its lack of consideration for the dependencies that often arise during the transition to agroforestry, such as the reliance on external inputs, knowledge, and market access provided by companies or NGOs. These dependencies can impact the long-term sustainability and autonomy of smallholders but are not adequately captured by TAPE.

Additionally, due to time and resource constraints, the study did not focus on a statistically representative sample, making it difficult to generalize the findings. This limitation is particularly evident in the assessment of indicators such as youth employment and migration, where the results do not fully reflect the structural challenges faced by the community and Nicaragua as a whole.

Another important limitation relates to the cultivation practices of maize and beans in the reserve area. The influence of conventional agriculture, driven by the need to achieve high yields to compete with low market prices, has led to a reliance on high input use and has displaced much of the traditional knowledge associated with milpa cultivation. This shift has not only affected the diversity of crops grown for self-consumption but also undermined traditional soil management practices, which are crucial for maintaining long-term agricultural sustainability. As such, while TAPE provides valuable insights into the sustainability of agroforestry systems, these broader contextual factors must also be considered to gain a complete understanding of the results of the comparison made with traditional agriculture.

6. CONCLUSION

The CKNR is a protected natural area where diverse initiatives have been developed to enhance the sustainability of productive systems. These initiatives include a shift towards agroforestry systems. Agroforestry has been documented to be more resilient to environmental changes, offering potential benefits in terms of biodiversity, soil health, and economic stability. The transitions in RNCK involve integrating coffee cultivation with diverse tree species, which could make the agricultural systems more resilient to climate variability and market fluctuations.

The transition to agroforestry coffee systems in the CKNR region presents a promising pathway for enhancing the sustainability of smallholder farming compared to traditional agricultural practices. Agroforestry systems significantly improve the environmental dimension by enhancing biodiversity and soil health. Economically, these systems offer greater income stability and diversification, particularly through the production of high-value coffee and additional crops. Socially, the initiatives that promote agroforestry also foster community cohesion, gender equity, and youth engagement, contributing to stronger and more resilient rural communities. However, this transition has challenges.

Access to agroforestry practices remains a significant limitation for smallholder farmers in the CKNR region. The high initial costs of transitioning to agroforestry, including the purchase of seedlings, infrastructure development, and the long period before coffee plants become productive, make it difficult for many smallholders to adopt these practices without external support. The financial burden is further exacerbated by the lack of effective financing schemes tailored to the needs of smallholders, who often operate at or below subsistence levels. Additionally, the complexity of managing agroforestry systems, which require specialized knowledge of tree-crop interactions, pest and disease management, and soil health improvement, is a significant barrier. Many smallholders lack the necessary training and technical skills to implement these systems effectively, and while external actors provide essential support, the reach and depth of these programs need to be significantly expanded to meet the needs of all smallholders.

Moreover, the dependency on external actors for resources, knowledge, and market access raises critical concerns about the long-term sustainability of agroforestry practices. Smallholders' reliance on a private company for the essential inputs and support required to establish and maintain agroforestry systems limits their autonomy and decision-making capacity. This dependency creates a vulnerability that could undermine the resilience of these systems if external support diminishes or disappears.

To address these challenges, future public policies should focus on developing strategies to enhance smallholders' access to affordable financing, improve the reach of technical training programs, and promote local leadership and governance structures that can support sustainable agroforestry practices independently of external actors. By addressing these limitations, smallholders can be better equipped to adopt and sustain agroforestry practices, ensuring their long-term environmental, economic, and social benefits.

The TAPE tool proved to be a significant instrument for assessing the sustainability of agroforestry coffee cultivation, offering a comprehensive framework to evaluate environmental, economic, and social dimensions. Its adaptability to different contexts and crop types makes it practical for both researchers and practitioners. Effectively showcasing improvements in biodiversity, soil health, and economic resilience associated with the transition to agroforestry systems. However, TAPE has significant limitations, notably its lack of consideration for the dependencies that smallholders develop on external inputs, knowledge, and market access provided by companies or NGOs during the transition. These dependencies can impact the long-term sustainability and autonomy of smallholders but are not fully captured by the tool.

The cultivation practices observed for maize and beans in the CKNR, no longer reflect traditional methods. Instead, they have been significantly influenced by conventional agriculture, where the drive for higher yields to remain competitive in low-price markets has led to a reliance on high-input farming. This shift has resulted in the displacement of much of the traditional knowledge associated with milpa cultivation, further limiting the extent to which these findings can be applied across different contexts within the sector. Additionally, the findings of this study may not be fully generalizable to the entire sector, as the specific segment analyzed may not represent the broader range of practices and experiences in the region. Future studies should conduct a comparison between traditional milpa systems and agroforestry practices within the global value chain. By evaluating traditional milpa cultivation, which relies on indigenous knowledge and low-input practices, against the more commercialized agroforestry systems, researchers could provide insights into the strengths and weaknesses of both approaches.

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