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Diversity of trees and their use in cocoa agroforestry systems in Alta Verapaz, Guatemala

Dissertation thesis

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DECLARATION OF AUTHORSHIP

I hereby declare that the content presented in this thesis, titled " Diversity of trees and their use in cocoa agroforestry systems in Alta Verapaz, Guatemala" submitted as a partial fulfillment of the requirements for the Ph.D. degree at the Faculty of Tropical AgriSciences, Czech University of Life Sciences Prague, is entirely my own work, unless explicitly listed in the reference section. Furthermore, I affirm that no part of this work has been submitted for any other degree at this university or any other institution.

Prague, 2024

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Carlos Enrique Villanueva González

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List of Abbreviations

AFS	Agroforestry Systems
B/C	Benefit-Cost Ratio
BA	Basal Area
CAFS	Cocoa Agroforestry Systems
CATIE	Tropical Agricultural Research and Higher Education Center
CONAP	National Council of Protected Areas (Guatemala)
DAPC	Discriminant Analysis of Principal Components
DEN	Relative Density
DOM	Relative Dominance
DBH	Diameter at Breast Height
FAO	Food and Agriculture Organization of the United Nations
FRE	Relative Frequency
FF	Shape Factor
H	Total or Merchantable Height
H'	Shannon Index (H')
HC	Commercial Height
GBIF	Global Biodiversity Information Facility
IARNA	Institute of Agriculture, Natural Resources and Environment (Guatemala)
ICRAF	International Center for Research in Agroforestry
IDES	Institute of Economic and Social Research (Guatemala)
INAB	National Forest Institute (Guatemala)
INE	National Institute of Statistics (Guatemala)
INIAP	National Institute of Agricultural Research (Ecuador)
IRR	Internal Rate of Return
IVI	Importance Value Index
J'	Pielou's Evenness Index
MAGA	Ministry of Agriculture, Livestock and Food (Guatemala)
NPV	Net Present Value
PNUD	United Nations Development Programme
RDOM	Relative Dominance
RFRE	Relative Frequency
S	Species Richness

TH	Rafael Landívar University (Guatemala)
V	Volume
VC	Commercial Volume
VT	Total Volume
χ^2	Pearson's Chi-Square Test

Abstract

Cocoa agroforestry systems (CAFS) are highly valuated for their ability to reconcile agricultural production, biodiversity conservation, and the provision of ecosystem services. In Guatemala, cocoa (*Theobroma cacao* L.) is an important commercial crop, especially in the department of Alta Verapaz, where numerous families depend on CAFS as their primary source of income. A comprehensive assessment of tree diversity in CAFS is essential to understand their contribution to plant biodiversity conservation. Likewise, the analysis of the timber potential of trees associated with cocoa is relevant, since the generation of timber products can provide additional economic incentives for farmers to maintain and conserve a greater diversity of tree species in their agroforestry systems, thus favoring biodiversity conservation and contributing to sustainable rural development in the region. This study aims to identify the diversity and economic potential of CAFS trees of different ages in Alta Verapaz, Guatemala. The methodology in this study included the establishment of 70 temporary sampling plots in selected municipalities, where a floristic inventory was conducted, and densitometric variables were measured. Diversity indices were calculated, and the similarity of species composition between localities was analyzed. Additionally, 20 plots were selected to assess timber potential, and the vertical structure and uses of the trees were characterized. The socioeconomic evaluation was carried out through semi-structured interviews with cocoa producers, and financial indicators such as Net Present Value (NPV), Internal Rate of Return (IRR), and Benefit-Cost Ratio (B/C) were calculated. The results revealed a high diversity of tree species in the evaluated CAFS, with 59 species belonging to 34 families. Diversity varied according to the age of the systems, with 9-12-year-old CAFS presenting the highest diversity. Tree species with the most significant timber/fuelwood potential were identified, highlighting *Swietenia macrophylla* King in Hook., *Cedrela odorata* L., *Protium copal* (Schltdl. & Cham.) Engl., *Cordia alliodora* (Ruiz & Pav.) Oken, and *Gliricidia sepium* (Jacq.) Kunth, which also have a wide range of local uses. The socioeconomic evaluation of two CAFS arrangements, under complex shade, or with *S. macrophylla*, showed differences in their viability, where CAFS with *S. magrophylla* being more profitable according to financial indicators. However, CAFS under complex shade, presented a more significant potential to diversify producers' income. In conclusion, this study highlights the fundamental role of CAFS in biodiversity conservation and sustainable rural development in Alta Verapaz. The results provide a solid foundation for promoting sustainable management practices that foster the productivity and preservation of these systems and for considering the socioeconomic factors that influence their adoption and management. It is recommended that strategies be developed to harness the potential of CAFS for conservation and improvement of local communities' livelihoods in the region.

Keywords: Biodiversity conservation; botanical composition; dendrometric variables; economic sustainability; species diversity; species richness; timber production.

1. Introduction

Cocoa (*Theobroma cacao L.*) is currently a burgeoning crop on a global scale (Palacios Bucheli & Bokelmann 2017; Carvalho et al. 2023). Worldwide, approximately 12 million ha of land is under cocoa production (Niether et al. 2020), representing one of the most important cash crops in humid tropics, especially for smallholder farmers (Tscharntke et al. 2011). Around 70% of the world's cocoa is grown alongside shade trees, as well as annual and perennial crops (Matey et al., 2013). Although full sunlight cocoa production systems have been developed in Africa, Malaysia, Peru, Colombia, and Ecuador (González 2005). Cocoa is usually cultivated by smallholder farmers in tropical regions (Braga et al., 2019) and when agroforestry practices are used, these can mimic structural and functional elements of a natural forest (Mcneely & Schroth, 2006; Vebrova et al., 2014). In Latin America, about 350,000 families practice cocoa farming and at least 1.7 million rely on cocoa production (INIAP 2019). According to Sol-Sánchez et al. (2018), in Latin America, cocoa cultivation has been established under the shade of tree species remaining from the natural forest, which, sometimes, do not represent economic benefits for the producers, rather than an immense ecological value.

Agroforestry (AF) is widely considered an alternative to conventional agriculture that provides greater productive and ecological benefits, such as: functional diversity improvement (Abada Mbolo et al., 2016; Ambele et al., 2023; Navarro et al., 2012); carbon sequestration (Ma et al., 2020; Manaye et al., 2021); food administration, wood, fuel (Pocomucha et al., 2016; Soler et al., 2012: Suarez-Venero et al., 2019) and improved micro-climate (Shah et al., 2021) among others. The structure and composition of traditional AFS is determined by the cultural heritage of the growers and the application of management practices during the production cycle (Chablé-Pascual et al., 2015; Cotta, 2017). Despite CAFS socioeconomic and ecological importance in Guatemala, more knowledge is needed about tree diversity, timber potential, and their contribution to the sustainability of these traditional systems.

In the last decades there has been a constant growth in the number of studies about the potential for biodiversity conservation in shade-grown cacao (Delgado-Vargas et al., 2022; Morán-Villa et al., 2022; Sonwa et al., 2017). The results demonstrate that AFS with a diverse canopy of shade trees have a greater potential for biodiversity conservation as compared to plantations with a simplified shade canopy or monocultures of cocoa (Braga et al., 2019; Méndez et al., 2013; Sánchez Gutierrez et al., 2016).

The socioeconomic and ecological importance of these systems is being recognized by the scientific community around the world. In Mexico, Zequeira-Larios et al. (2021) demonstrated that the management practices employed by smallholder cocoa growers have enabled the conservation function of these AFS, as well as strengthening their own food security and increasing their income through the variety of other products cultivated in these systems. In Uganda, Bukomeko et al. (2019), found that the AFS had the capacity to conserve a high level of biodiversity of tree species that provide important ecological services, while in Ecuador, the complex structure of the CAFS contributes to the preservation of native and endangered species and reduces the degradation of forests and soils (Vera-Velez et al., 2019).

Guatemala is a country with a high percentage of population living in rural areas, of which around 59% live in conditions of poverty (INE, 2018). Two thirds of this population depend on agriculture and silviculture as their main livelihood (Nicli et al., 2019). Notwithstanding, intensive agriculture is one of the main threats to forest resources and the biodiversity that is protected in them, due to the fact that the population has seen the need to replace the forest for various uses and consequently, the satisfaction of basic needs (Pineda 2022). According to Bullock et al. (2020) the total deforested area in Guatemala between 2000 and 2017 was around 854,137 ha of forest. Studies by various national institutions have shown that the main causes of biodiversity loss in Guatemala are non-integrated biodiversity management, unsustainable land use, undervaluation of biodiversity and the goods and services derived from it, poverty, and the structures of conventional agriculture (CONAP 2009 and IARNA, 2012).

CAFS managed by indigenous communities provide multiple advantages associated with land use. They largely contribute to mitigating climate change and biodiversity loss, by preserving a diversity of trees in production designs (Manaye et al., 2021; Mejia-Rueda et al., 2023). Suárez-Venero et al. (2019) and Ramírez-Meneses et al. (2013), affirm that, not having any record of tree diversity and species richness used in the shade canopy for cocoa cultivation limits the development of policies that contribute to the management of CAFS and the valuation of natural resources and conservation of cocoo. The ecological importance and the socio-cultural contribution of these systems established in the rural areas of Guatemala remain little known.

Therefore, the objectives of this study were to characterize the botanical composition and structure of tree vegetation in CAFS of different ages in Alta Verapaz, determine the tree species with significant timber potential and their main local uses, and evaluate the economic viability of these systems by identifying the socioeconomic factors that influence their adoption and management. These objectives will help understand CAFS potential as a strategy for sustainable rural development in the region.

2. Literature review

2.1. Agroforestry: a conceptual review

Agroforestry, a concept that has evolved over the last decades, is a land use system that deliberately integrates trees and shrubs with crops and livestock in the same management unit, seeking ecological, economic, and social benefits (Nair 1993). This practice is based on taking advantage of the positive interactions between tree components and crops or animals, with the objective of optimizing the system's production and sustainability (Bene et al. 1977).

From a historical perspective, traditional communities have practiced agroforestry in different parts of the world to adapt to local environmental conditions and satisfy multiple needs (Somarriba 2012). However, the modern concept of agroforestry emerged in the 1970s as a response to growing concerns about deforestation, land degradation, and food security in developing countries (Lundgren & Raintree 1982).

Since then, agroforestry research has experienced remarkable growth, addressing aspects such as the classification of agroforestry systems (Nair 1993), their design and management (Sol-Sánchez et al. 2018), their role in biodiversity conservation (Zequeira-Larios et al. 2021) and in the provision of ecosystem services (Casanova-Lugo et al. 2016). In addition, the potential of agroforestry to contribute to climate change mitigation and adaptation has been recognized (Mbow et al. 2014), as well as to promote sustainable rural development (Illescas-Alonso et al. 2020).

2.2. Importance and benefits of AF

The growing global concern about environmental issues and climate change during the late 1990s led to the establishment of new international agreements, such as the Kyoto Protocol, and increased attention to ecological functions of land use systems and alternative land uses (Kim et al. 2020). Given the growing demand for versatile and multifunctional agriculture, AFS began to be valued as a promising alternative to monocultures; since these systems provide economic benefits and play a crucial role in soil conservation, water management, carbon sequestration, and biodiversity conservation in fragmented landscapes (Shibu 2009).

Agroforestry is an activity that provides multidisciplinary benefits. On one hand, AFS play a crucial role in species conservation and biodiversity, as highlighted by Esche et al. (2023). These systems, combining trees, shrubs, and crops in the same land unit, create diverse habitats that support a greater variety of flora and fauna. On the other hand, AFS also have high potential for agricultural production, as emphasized by Sol-Sánchez et al. (2018). The integration of woody species and crops can improve soil fertility, reduce erosion, and provide a favourable microclimate, leading to higher yields and greater resilience to climate challenges (Fanish & Sathyapriya 2013).

Furthermore, Braga et al. (2019) highlights the diversity of uses (cultural, economic, and food security) as one of the key benefits of agroforestry practices (**Figure 1**). These systems can produce a variety of products such as food, fodder, timber, firewood, and non-timber forest products, thereby contributing to income diversification and food security in rural communities. Additionally, agroforestry practices may hold significant cultural value for some communities, being part of their traditions and ancestral knowledge (Moreno-Calles et al. 2016).

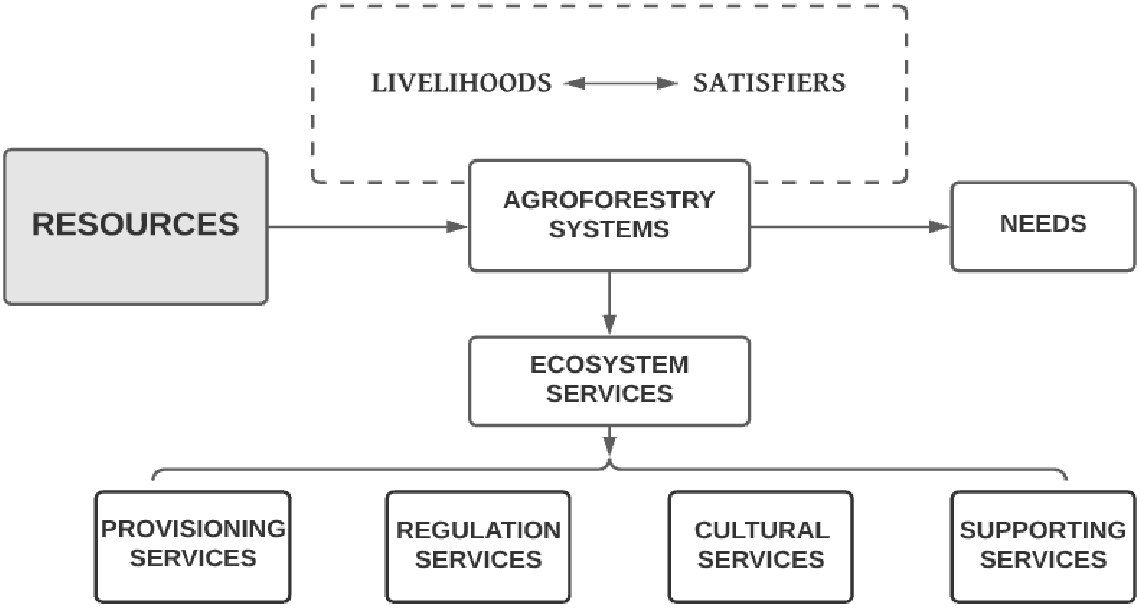

Figure 1. Conceptual framework illustrating the interrelationships among agroforestry systems, resource utilization, livelihoods, and their collective contribution to providing goods and services for human well-being. Adapted from Imbach (2014).

Latin America is known for its rich biodiversity and unique ecosystems. AFS are crucial here, helping to conserve native species and protect the region's natural beauty. Galhena et al. (2013), sustain that the AFS, in the modality of home gardens, integrate multiple crops, and serve several purposes, which include food security and economic advantages. Although, indeed, the AFS do not intervene in the staggered maximization of the economy of the producer families, this activity does contribute directly to the diversification of possible markets to sell the production (Cruz-Aguilar et al., 2016). However, in social conditions of extreme poverty, as is the case of thousands of producer families in Latin America, the products obtained from the AFSs and their benefits become even more relevant (Somarriba et al. 2017).

2.3. Challenges and constraints of agroforestry

Agroforestry has been recognized for its multiple benefits, including biodiversity conservation, improved ecosystem services, and diversification of farmers' incomes (Perry et al. 2016; Solis et al. 2019). However, despite these advantages, AFS also presents certain limitations and negative aspects that must be considered to ensure success and sustainability (Jara-Rojas et al. 2020). One of the main constraints of AFS is the complexity of their management compared to monocultures (Niether et al. 2020).

Combining multiple species with different growth requirements, life cycles, and management needs can make decision-making difficult and increase labor costs (Roy et al. 2015; Peguero et al. 2021). In addition, interactions between components of AFS can be challenging to predict and control, leading to lower resource use efficiency and productivity compared to simplified systems (Villarreyna et al. 2020).

Another significant constraint of AFS is farmers' need for knowledge and experience in their management. Many farmers are accustomed to monocultures and may lack skills to design and manage complex systems (Calle et al. 2009). This lack of knowledge can result in inadequate management of AFS, which in turn can lead to lower productivity and profitability. In addition, lack of access to information, training, and technical assistance can further hinder farmers' adoption and successful management of AFS (Franzel et al. 2001).

Challenges related to land tenure and property rights may also limit the potential of AFS. In many cases, farmers may not have secure access to land or may face restrictions on using trees and other natural resources (Sanchez 1995). Land tenure insecurity may discourage long-term investment in AFS and limit their ability to generate sustainable benefits.

In addition to internal challenges, AFS is susceptible to external factors, such as market variations and government policies. Instability in agricultural commodity prices and the absence of consolidated markets for products derived from AFS can negatively impact their profitability and economic sustainability (Alavalapati et al. 2004). Similarly, government policies prioritizing monocultures or needing to support AFS adequately can hinder their adoption and restrict their contribution to sustainable rural development (Nair 1993).

According to Montagnini & Metzel (2017), continuous effort is required in research and the development of innovative strategies to overcome existing limitations and maximize the potential of AFS. In this way, as Jose (2009) and Waldron et al. (2017) suggested, their contribution to biodiversity conservation and sustainable rural development can be maximized.

2.4. Classification of AFS

Different authors have classified AFS from various perspectives. One of the most used approaches is the classification proposed by Nair (1993) and updated by Mosquera-Losada et al. (2012), who categorize them into three groups:

- agro-silvicultural or silvoarable systems (crops with trees)
- silvopastoral systems (trees with animals and pastures)
- agrosilvopastoral systems (integration of crops, trees, and animals) (**Figure 2**)

Figure 2. Examples of AFS under different management practices. (A) Silvopastoral system in Costa Rica, integrating livestock grazing with the presence of trees. (B) Multistrata AFS in Veracruz, Mexico, combining plantain (*Musa* sp.), coffee (*Coffea* sp.), timber trees, and fruit trees in a vertically stratified arrangement.

Another pertinent approach involves considering the spatial and temporal distribution of system components. In this context Millard (2011), distinguishes between simultaneous systems, where components share the same space and time, and sequential systems, where components alternate in the same space but at different time periods.

For concurrent systems, tropical home gardens are an illustrative example, combining fruit trees, annual crops, and small animals within a single space (Galhena et al. 2013). Similarly, shade trees are maintained concurrently in AFS with perennial crops like coffee or cocoa (**Figure 3**) (Haggar et al. 2015).

Figure 3. Examples of AFS in the Caribbean and Central American regions. (A) Coffee (*Coffea* sp.) AFS in the landscape of Dominican Republic. The system integrates shade trees with coffee plants, creating a multi-strata arrangement that provides ecosystem services and enhances biodiversity. (B) Cocoa (*Theobroma cacao* L.) AFS in Costa Rica.

Sequential systems, on the other hand, exemplify alley cropping, where rows of leguminous trees alternate with annual crops to harness the nutrients the trees fix (Giller et al. 2019). Likewise, improved fallow systems represent another instance where periods of agricultural cultivation alternate with fallow periods, allowing for the growth of woody vegetation to aid in soil recovery (Vieira et al. 2009). This classification, rooted in the spatial and temporal distribution of components, holds significance as it affects the ecological interactions and ecosystem services provided by AFS, which vary based on whether the components coexist simultaneously or alternate over time (Millard 2011).

Torquebiau (2000), proposed a complementary perspective, which was later refined by Somarriba et al. (2014). They classify AFS according to their level of ecological and structural complexity. This classification distinguishes between simple systems (few components and strata), moderately complex systems (more components and strata), and highly complex systems (multiple components and strata that mimic the structure of a natural forest). This classification recognizes the diversity of arrangements and possible combinations in AFS.

A more recent approach is the classification based on ecosystem services and management objectives proposed by Jose (2012) and Wolz et al. (2018). This classification groups AFS according to their primary function, such as food production, forest products, biodiversity conservation, and climate change mitigation. This approach highlights agroforestry systems' multifunctionality and ability to provide various ecosystem services while reflecting the diversity of existing AFS and the need to consider different aspects, such as composition, function, objectives, and complexity, for proper understanding and management (Suarez-Venero et al. 2019).

2.5. Plant diversity in agroforestry systems

2.5.1. Factors contributing to plant diversity

AFS are recognized for their ability to harbor a great diversity of plant species, which is influenced by multiple factors. One key factor is the design management of the system, including practices such as species selection, planting density, and pruning (Esche et al. 2023). Farmers can design and manage AFS to favor a higher diversity of tree, shrub, and herbaceous species, which can improve ecosystem services (Sambuichi et al. 2012; Moreno-Calles et al. 2016).

Local environmental conditions, such as climate, topography, and soil type, are essential in determining plant diversity in AFS (De Stefano & Jacobson 2017). For example, AFS in regions with higher precipitation and lower seasonality tend to harbor a greater plant species richness than those in drier areas or with marked seasonality (Arrazate et al. 2021). Furthermore, the heterogeneity of the surrounding landscape can influence the plant diversity of AFS, as adjacent natural vegetation fragments can act as sources of seeds and vegetative material, as well as habitat for plant species (Mendenhall et al. 2014).

Another factor influencing plant diversity in AFS is land-use history. AFS established in areas previously covered by natural forests tend to exhibit a higher diversity of plant species than those established in areas with a history of intensive agricultural use (Vera-Vélez et al. 2019). Natural forests act as biodiversity reservoirs and sources of reproductive material for the colonization of AFS (Perfecto & Vandermeer 2008).

The interaction between plant and animal components in AFS can also influence plant diversity. For example, seed-dispersing animals, such as birds and mammals, can contribute to the dispersal and establishment of new plant species in the system (Montagnini & Metzel 2017). Additionally, plant-plant interactions, such as facilitation and competition, can shape the structure and composition of the plant community in AFS (Jose et al. 2004).

Lastly, socioeconomic and cultural factors, such as farmers' preferences, traditional knowledge, and market demands, can influence plant diversity in AFS (Ramírez et al. 2020). Farmers may select and manage plant species according to their needs and preferences, which can result in higher or lower species diversity in the system (Morán-Villa et al. 2022).

2.5.2. Role of plant diversity in the resilience of systems

Plant diversity is a crucial component of the sustainability and resilience of AFS (Villarreyna et al. 2020). A higher richness of plant species is associated with a more significant provision of ecosystem services and adaptability to biotic and abiotic disturbances (Shibu 2009). These diverse systems harbor a greater biodiversity of natural enemies of pests, providing resistance and resilience against these biotic stress factors

(Bianchi et al. 2006). Moreover, they promote functional complementarity and facilitation among species, allowing for greater adaptation and recovery from extreme events related to climate change (Gomes et al. 2020).

The role of plant diversity in AFS is fundamental for maintaining soil fertility and nutrient cycling (Fonte et al. 2010). Studies show that AFS, with a higher diversity of tree species, presents a greater accumulation of organic matter and efficiency in nutrient use, contributing to long-term sustainability (Hernández Núñez et al. 2021). Likewise, the presence of different tree species can moderate the effects of climate change, providing shade and regulating the microclimate (Schroth et al. 2016).

These ecosystem services have significant implications for rural communities; increased soil fertility and better pest control can translate into higher yields and lower production costs, improving food security and producer incomes (Niether et al. 2020). Climate change mitigation and adaptation are crucial for the resilience of these agricultural systems and the well-being of the communities that depend on them (Schroth et al. 2016; Rivero-Romero et al. 2016)

In addition to the benefits above, plant diversity in AFS promotes associated biodiversity, including pollinating insects, natural enemies of pests, and other beneficial organisms (Bhagwat et al. 2008). This can improve pollination services and biological pest control, reducing dependence on external inputs (Tscharntke et al. 2011). Furthermore, diverse AFS provide various products such as food, fodder, firewood, timber, and non-timber forest products, reducing farmers' vulnerability to the impacts of climate change and market fluctuations (Méndez et al. 2001; Bezner Kerr et al. 2021).

2.6. Cocoa agroforestry systems (CAFS)

2.6.1. Origin and importance of cocoa cultivation

Cocoa (*Theobroma cacao)* is a species originated in the tropical regions of South America, with its center of genetic diversity in the Amazon basin (Thomas et al. 2012). According to archaeological evidence in southern Mexico and Central America, the domestication and cultivation of cocoa date back to at least 5,300 years ago in Mesoamerica (Powis et al. 2011). However, it is believed that cocoa cultivation had begun even earlier, around 10,000 years ago, in the Amazon basin (Zarrillo et al. 2018).

In Mesoamerican civilizations, such as the Olmecs (1500-400 BC), the Mayans (2000 BC-900 AD), and the Aztecs (1300-1521 AD), cocoa was considered a sacred food; it was used in religious rituals, ceremonies, and as medicine (Powis et al. 2011). Moreover, this product symbolized social status and was used as a currency for exchange (Dillinger et al. 2000). In these civilizations, cocoa was traditionally cultivated in AFS, where cocoa trees were planted alongside other tree species that provided shade and additional products (Moreno-Calles et al. 2016). Cocoa seeds were fermented, dried, and roasted before being ground and mixed with water and spices to create a beverage (McNeil 2009).

From its origin in Mesoamerica and South America, cocoa cultivation spread to other parts of the world through European trade and colonization (Wood & Lass 2001). The Spanish introduced it to Europe in the 16th century, and subsequently, plantations were established in West Africa and Asia (Wessel & Quist-Wessel 2015). This product played a crucial role in the economy and society of Mesoamerican civilizations, being a valuable commodity used as a currency, tribute, and a symbol of social status (Moreno-Calles et al. 2016).

Over time, cocoa cultivation has evolved from traditional multispecies AFS to modern monoculture plantations. This transition has been particularly marked in many cocoa-producing regions, such as West Africa, where there has been a significant increase in full-sun cocoa production (Ruf & Schroth 2004).

In countries such as Côte d'Ivoire and Ghana, which together account for about 60% of world cocoa production (Peprah 2015), full-sun cocoa cultivation has become the norm. This trend has been driven by several factors, such as the increasing global demand for cocoa, the need to increase the productivity and profitability of plantations, and the promotion of monoculture-based technology packages (Beg et al. 2017). However, this shift to full-sun cocoa monoculture has raised concerns about the long-term sustainability of these systems. Cocoa monocultures are more vulnerable to pests and diseases, require more chemical inputs, and can contribute to soil degradation and biodiversity loss (Schroth & Harvey 2007). In contrast, CAFS, which combine cocoa cultivation with shade trees and other crops, offer multiple benefits. These systems can improve soil health, increase biodiversity, provide ecosystem services, and diversify farmers' incomes

(Udawatta et al. 2019). Cocoa remains vital for millions of small farmers and plays a prominent role in the culture and identity of many communities.

Currently, cocoa maintains its relevance due to its economic importance as a raw material for the chocolate industry and its role in the livelihoods of millions of farmers in developing countries (Franzen & Borgerhoff Mulder 2007). Furthermore, it retains its cultural and symbolic significance in many communities, and its consumption continues to be appreciated worldwide (Orozco Aguilar & Deheuvels 2007). Cocoa's historical and cultural relevance is reflected in the growing demand for original chocolate, highlighting the importance of traditional CAFS and sustainable cultivation practices (Afoakwa 2014).

2.6.2. Characteristics and management of CAFS

CAFS exhibit various characteristics and management practices in the main producing regions around the world. These traditional CAFS have evolved over generations, adapting to local conditions and leveraging farmers' ecological knowledge (Jacobi et al. 2017). In West Africa, for instance, these systems are distinguished by integrating cocoa trees with a wide range of tree species and a less intensive management approach (Asare et al. 2019). The high diversity of tree species in these systems provides shade and protection to the cocoa trees. It contributes to biodiversity conservation and provides various products and ecosystem services (Bisseleua et al. 2009). These traditional systems take advantage of the structure and composition of natural forests, resulting in greater ecological complexity and reduced dependence on external inputs (Sambuichi et al. 2012).

On the other hand, in Latin America, CAFS present a wide range of designs and management practices, from rustic to modern technified systems (Andres et al. 2016; Arrazate et al. 2021, Figure 4). Rustic systems resemble the traditional African systems, with a high diversity of tree species and less intensive management (Biam et al. 2008). However, the technified systems are characterized by more intensive management, lower diversity of associated species, and higher use of external inputs (Jezeer et al. 2017). These techniques and systems aim to optimize cocoa production through regular pruning, pest and disease control, and fertilization (Esche et al. 2023).

Although less common in Latin America compared to West Africa, full-sun cocoa production has gained some interest in countries such as Ecuador, Brazil, and Peru due to its higher short-term yield (Tondoh et al. 2015). In Ecuador, for example, around 30,000 ha of cocoa are estimated to be cultivated under full-sun production systems, representing approximately 10% of the total cocoa production area in the country (Espac 2020). Ecuadorian farmers have adopted this system to increase productivity and profitability, taking advantage of favorable climatic conditions and growing market demand (Pérez-Neira et al. 2020). In Guatemala, most cocoa is grown in AFS, and only a small proportion is grown in full sun. According to a study by Cerda et al. (2014), in Guatemala, about 93% of cocoa plantations are managed under AFS with different shade levels, while only 7% is grown under full sun.

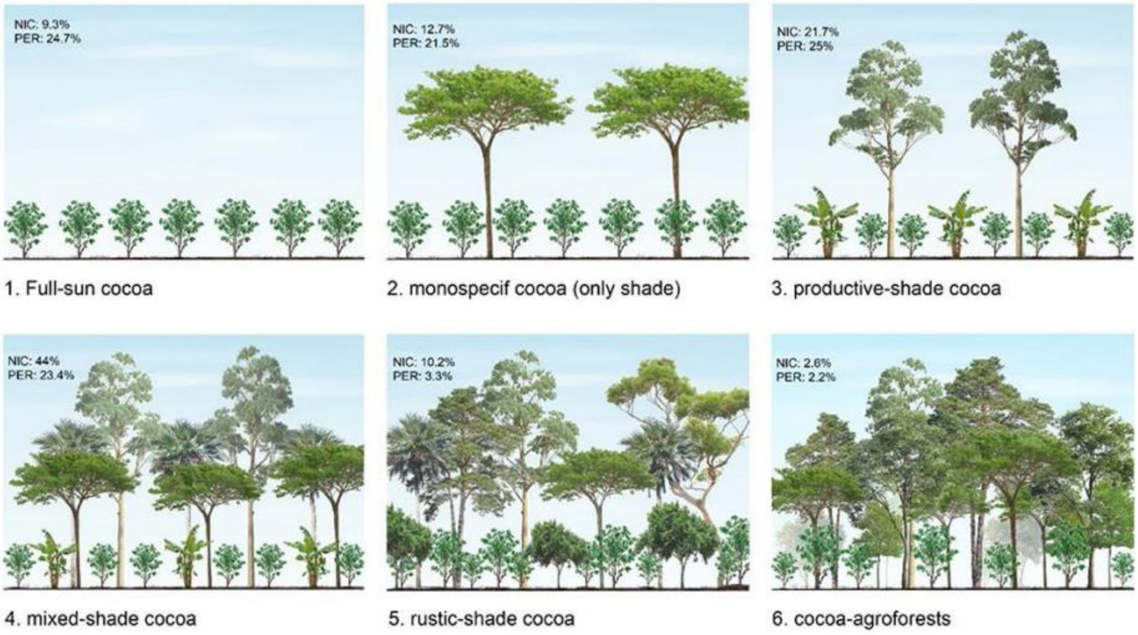

Figure 4. Illustrates the main types of CAFS found in Latin America. These systems are characterized by integrating cocoa cultivation with various tree species, creating a multi-strata structure (Somarriba et al., 2013; Cerda et al., 2014).

Similarly, in Brazil, the state of Bahia has experienced an expansion of full-sun cocoa plantations driven by market demand and the pursuit of higher yields (Schroth et al., 2016). Although traditional CAFS remain predominant in Latin America, some farmers have begun to explore full-sun cocoa production as an alternative to increase short-term income (Jacobi et al. 2017).

However, this production system presents significant challenges regarding long-term sustainability and resilience. Full-sun cocoa monocultures are more vulnerable to pests and diseases, which can result in increased pesticide use and lower product quality (Niether et al. 2020). Furthermore, removing shade and higher exposure to extreme climatic conditions can increase stress on cocoa trees and reduce their longevity (Kaba et al. 2020).

Expanding full-sun cocoa plantations also contributes to deforestation and biodiversity loss in tropical forests (Deheuvels et al. 2014). The resulting fragmentation of ecosystems alters the structure and functionality of natural habitats, negatively affecting pollinator and seed disperser species, which are crucial for cocoa reproduction and the maintenance of genetic diversity (Bennett et al. 2022). The loss of these ecosystem services, along with the decrease in other benefits provided by forests, such as water regulation, soil protection and firewood provision, can exacerbate the impacts of climate change in cocoa-producing regions and compromise the sustainability of this production system (Gockowski & Sonwa 2011).

CAFS structural and functional diversity promotes the provision of essential ecosystem services for sustainable cocoa production (García et al. 2020). Furthermore, the diversification of products obtained in these systems, such as timber, fruits, and other crops, can improve farmers' livelihoods and increase their resilience to market fluctuations, especially for smallholder producers who largely depend on cocoa production for their subsistence (Méndez et al. 2013).

Despite the multiple benefits CAFS offers, farmers who manage them face common challenges, regardless of the region in which they are located. One of the main obstacles is the lack of access to technical assistance and training, which can limit the adoption of sustainable management practices (Notaro et al. 2020; Somarriba et al. 2021).

Without the necessary knowledge and skills to manage these complex systems effectively, farmers may struggle to optimize cocoa production and fully harness the benefits of agroforestry (Cuevas et al. 2021). Furthermore, market pressure to increase yields can lead to management intensification and simplification of the systems (Andres et al. 2016; et al. 2020). This trend towards intensification can undermine the ecological benefits and long-term resilience of CAFS, jeopardizing both the sustainability of production and farmers' livelihoods.

2.6.3. Economic and sociocultural benefits of CAFS

The CAFS demonstrate remarkable complexity and dynamism, making them a viable economic alternative for farmers (Romo-Lozano et al. 2012). From an economic standpoint, the diversity of trees in these systems can diversify farmers' income sources by providing additional products such as timber, fruits, and other crops (Barrezueta Unda & Paz-González 2018). For instance, in some Central American countries, species like laurel *Cordia alliodora* (Ruiz & Pav.) Oken and cedro (*Cedrela odorata* L.) are valued for their high-quality timber, while fruit trees like avocado (*Persea americana* Mill.) and orange (*Citrus sinensis* (L.) Osbeck) offer additional income and contribute to food security (Cerda et al. 2014). This diversification reduces dependence on a single crop and increases farmers' livelihood resilience to market fluctuations (Niether et al. 2020).

In addition, the integration of trees into CAFS can enhance long-term productivity by maintaining soil fertility and regulating microclimate (Arrazate et al. 2021; Morán-Villa et al. 2022). Leguminous species such as erythrina (*Erythrina spp*.) and inga (*Inga spp*.) fix nitrogen in the soil and provide shade, improving conditions for cocoa growth (Tscharntke et al. 2011). Trees in CAFS can also serve as a buffer during difficult times and as a form of savings for rural communities, as they can be utilized in times of economic need or to finance essential investments, such as children's education (Sibelet et al. 2019).

The diversity of trees in CAFS also holds the potential to generate additional income through ecotourism and community-based tourism (Gonçalves et al. 2021). These systems' scenic beauty and rich biodiversity, including bird species, mammals, and reptiles, can attract visitors interested in learning about sustainable cocoa production and local culture (Chaluleu 2020). This diversifies economic opportunities for rural communities and promotes the valorization of their natural and cultural heritage (McNeely & Schroth 2006).

From a sociocultural perspective, the diversity of trees in CAFS plays a crucial role in preserving traditional knowledge and strengthening the cultural identity of communities (Cuevas et al. 2021).

These systems often integrate ancestral agricultural practices with local ecological knowledge, enabling farmers to adapt their practices to the specific conditions of their environment (Ruiz Solsol et al. 2014). For example, farmers in Talamanca, Costa Rica use traditional knowledge to select tree species that provide shade and improve soil fertility, such as laurel (*C. alliodora*) and poró (*Erythrina poeppigiana* (Walp.) O.F. Cook) (Dahlquist et al. 2007). Similarly, in the Chiapas region of Mexico, Mayan farmers use their ancestral knowledge to integrate native tree species into their CAFS, such as chalum (*I. vera* Willd) and ramón (*Brosimum alicastrum* Sw.), which provide shade, fix nitrogen, and produce edible fruits (Salgado-Mora et al. 2007). Another notable example is found in the Bahia region of Brazil, where farmers use traditional knowledge to select tree species that attract pollinators and enhance cocoa production, such as érythryne (*Erythrina fusca* Lour.) and jequitibá (*Cariniana legalis* (Mart.) Kuntze) (Cassano et al. 2016).

Furthermore, CAFS promotes gender equality and women's active participation in natural resource management (Armengot et al. 2016). Women often play a crucial role in the management of these systems, contributing to household food security and income diversification through the collection of non-timber forest products, such as fruits, medicines, and materials for crafts (Bose 2017; Gonçalves et al. 2021).

The inclusion of women in the management of CAFS and the equitable distribution of benefits strengthen social cohesion and empower rural communities (Kiptot & Franzel 2012). This approach has implications for biodiversity conservation by enhancing the capacity to adopt sustainable practices and preserve local ecosystems (Lenjiso et al. 2016; Garavito et al. 2021).

2.7. Botanical composition and diversity of trees in CAFS

In recent years, significant attention has been devoted to researching the botanical composition of CAFS, particularly in Latin American (Ebratt Matute 2022; Morán-Villa et al. 2022). This interest is due to Latin America's economic and ecological importance in global cocoa production, as well as its rich biodiversity and favorable climatic conditions for cultivation (Somarriba et al. 2013). The region harbors a wide variety of CAFS, ranging from traditional systems with high tree species diversity to more intensive plantations. This diversity provides a unique opportunity to study how different management practices influence the botanical composition and biodiversity associated with these systems (Rendón-Sandoval et al. 2020).

CAFS harbor diverse tree species, provide habitat and resources for a wide range of organisms. For example, a study conducted in Ecuador by Jadán et al. (2014) recorded 110 tree species in cocoa plantations belonging to 55 botanical families. This high plant diversity translates into a higher richness of birds, mammals, reptiles, and insects (Stenchly et al. 2012).

Moreover, the tree species associated with cocoa contribute to the improvement of soil quality through nitrogen fixation, nutrient recycling, and the contribution of organic matter (Hernández Núñez et al. 2021). A study in Costa Rica demonstrated that cocoa plantations with a higher diversity of trees had soils with better structure, higher organic carbon content, and higher biological activity than cocoa monocultures (Deheuvels et al. 2012). Likewise, the tree canopy in CAFS regulates the microclimate, reducing temperature, increasing relative humidity, and attenuating solar radiation (Somarriba et al. 2013). This creates a more favorable environment for the development of cocoa and the conservation of associated biodiversity (Suatunce et al. 2003).

In Mexico, Sánchez Gutiérrez et al. (2016) recorded 67 species from 28 botanical families in CAFS, with the most abundant being *Erythrina americana Mill.*, *Diphysa robinioides* Benth. and *Gliricidia sepium* (Jacq.) Kunth. These species are known for their ability to fix atmospheric nitrogen and improve soil fertility, suggesting that Mexican farmers select tree species that provide additional benefits to the cocoa crop.

According to Sol-Sánchez et al. (2018), in Latin America, cocoa cultivation has been established under the shade of tree species remaining from the natural forest, which, sometimes, does not represent an economic value for the producers, but it has a high ecological value. In the last decades there has been a constant growth in the number of studies about the potential for biodiversity conservation in the AFS of shade-grown cocoa (Sonwa et al. 2017; Morán-Villa et al. 2022; Delgado-Vargas & Muñoz Rodríguez 2023). The results demonstrate that CAFS with a diverse canopy of shade trees have a greater potential for biodiversity conservation as compared to plantations with a simplified shade canopy or monocultures of cocoa (Ma et al. 2020; Solarte et al. 2022).

The botanical richness in CAFS is maintained thanks to management practices that promote the conservation of native tree species and natural regeneration. In Mexico, Chablé-Pascual et al. (2015) studied traditional systems over 60 years of age, presenting unique structure and species diversity characteristics. These systems cover areas ranging from 200 to 4,616 m^2 on average and host 330 plant species, including 38 tree species. The authors demonstrated that the management practices used by small-scale cocoa producers have allowed these AFS to fulfill a conservation function, in addition to strengthening the food security of the producers and increasing their income through the diversity of products grown in these systems.

In contrast, cocoa monocultures present significantly lower tree diversity and a simplified vegetation structure; this not only reduces the potential for biodiversity conservation but can also negatively impact soil quality and microclimate regulation (Vaast & Somarriba 2014). For example, in a study conducted in Brazil, Faria et al. (2006), found that cocoa monocultures had a lower abundance and diversity of bird species compared to CAFS.

When comparing the results of different studies in Latin America, variations in the composition of tree species in CAFS can be observed; these differences can be attributed to factors such as climatic conditions, soil type, management practices, and farmers' cultural preferences (Ramírez-Meneses et al. 2013; Abdulai et al. 2018).

For example, while timber species predominate in Colombia (Sambuichi et al. 2012; Suárez Salazar et al. 2018) a greater abundance of nitrogen-fixing species is observed in Mexico (Roa-Romero et al. 2009). In Brazil, Braga et al. (2019) found a high diversity of tree species, but with larger proportion of fruit species, reflecting the importance of non-timber products in Brazilian cocoa plantations.

These variations in the composition of tree species have implications for local agricultural practices. Farmers can adapt their management strategies based on the species present and the benefits they provide. For example, in regions where timber species predominate, farmers can use wood as an additional source of income; in areas with a greater abundance of nitrogen-fixing species, farmers can reduce synthetic fertilizers and take advantage of the natural improvement of soil fertility (Temesgen & Wu 2018).

The studies conducted by Vebrova et al. (2014); Vera-Vélez et al. (2019); Ordoñez & Rangel-Ch (2020); Ngo Bieng et al. (2022) in Colombia, Ecuador, Peru, and Honduras, respectively, have significantly contributed to the knowledge of tree species diversity and richness in CAFS in their countries, laying the foundation for understanding their composition, structure, and role in biodiversity conservation and ecosystem service provision. Their findings have highlighted the importance of CAFS as reservoirs of biological diversity and have provided valuable information for developing sustainable management strategies. However, it is necessary to continue and expand these studies in other cocoa-growing regions to obtain a more comprehensive view of tree diversity in CAFS at regional and global levels, as environmental, sociocultural, and economic conditions can vary significantly between countries and regions, influencing the composition and structure of these AFS.

Studies on tree diversity and its uses in CAFS are critical in countries like Guatemala, where rural poverty is a pressing issue with 59.3% of the rural population living in poverty (INE 2018). In these regions, agriculture may be the only livelihood available to many communities, and the products derived from CAFS, such as cocoa itself, fruits, timber, and other non-timber products, can be essential for their subsistence (Avendaño-Arrazate et al. 2021). Diversifying these systems can help improve the food security and economic resilience of rural households by providing a variety of income sources and reducing dependence on a single crop (Bezner Kerr et al. 2021).

According to Jacobi et al. (2009), the lack of information on the diversity of tree species in CAFS and its relationship with environmental conditions and management practices can limit the ability to develop effective strategies for conservation and sustainable use of these agroecosystems. Furthermore, the lack of knowledge about farmers' perceptions and evaluations of the ecosystem services provided by trees in CAFS can hinder the adoption of sustainable practices (Palacios Bucheli & Bokelmann 2017).

2.8. Cocoa agroforestry systems in Alta Verapaz, Guatemala

Agroforestry in Guatemala has a long history and is closely linked to the traditional land-use practices of indigenous communities, especially the Q'eqchi ethnic group in the Alta Verapaz region. This group has developed and maintained AFS for generations based on their traditional ecological knowledge and a close relationship with nature (Nicli et al.

2019). Indigenous families manage these AFS for subsistence and to generate income, and they form an integral part of households as they are located around dwellings (Ruiz-Solsol et al. 2014). In addition to their role in food security and community livelihoods, traditional Q'eqchi' AFS have proven to be repositories of high tree species diversity, highlighting their value for local biodiversity conservation (Orozco Aguilar & Deheuvels 2007).

Sibelet et al. (2019) investigated the contribution of CAFS to local livelihoods in Guatemala, focusing on firewood provision. The authors highlight that the trees present in AFS constitute a crucial source of firewood for rural communities, reducing pressure on natural forests and generating additional income for families, thus improving their livelihoods.

Despite the recognized environmental and economic benefits CAFS provides, their adoption and establishment in Alta Verapaz face various challenges. One of the main challenges is the limited appreciation of the multiple ecosystem services they provide to the local population and the environment (IARNA 2012). Although CAFS significantly contribute to the provision of these services, the benefits generated are not adequately recognized and compensated, discouraging farmers from maintaining and improving these systems (Schroth et al. 2016). These systems are preserved and implemented traditionally and spontaneously, with virtually no recognition and compensation from the government or other external entities.

Other significant challenges include the advance of the agricultural frontier, driven by the expansion of monocultures and extensive livestock farming, which exerts increasing pressure on CAFS and the remaining forests in the region: this dynamic of land-use change can lead to the fragmentation and degradation of these systems, compromising their capacity to provide ecosystem services and sustain the livelihoods of indigenous communities (Bullock et al. 2020). Moreover, CAFS in Alta Verapaz are vulnerable to pests and diseases, such as moniliasis (*Moniliophthora roreri*) and black pod rot (*Phytophthora palmivora*), which can cause significant losses in cocoa production and quality (Jagoret et al. 2011). Inadequate management of these phytosanitary threats, coupled with a lack of technical assistance and training for farmers, can lead to the abandonment of CAFS and a shift towards less sustainable productive activities.

The sustainability of CAFS in Alta Verapaz depends on ecological and productive factors as well as socioeconomic, political, and institutional aspects. Among the obstacles, land tenure insecurity stands out, which discourages the farmers from long-term investments in AFS (Nicli et al. 2019). Also, the lack of institutional support and public policies that promote and facilitate the implementation of these systems limit the potential of CAFS as a sustainable development strategy for the indigenous communities of Alta Verapaz (Maass 2008).

Despite the importance of CAFS in Alta Verapaz, studies on tree diversity in these systems still need to be conducted. Research focused on the diversity and uses of trees in CAFS is essential to fill this knowledge gap. This type of work contributes to a better understanding of these systems' floristic composition. It lays the foundation for designing management, conservation, and valuation strategies that promote their sustainability and resilience in the local context. Filling this knowledge gap will have practical implications for the management and conservation of CAFS in Alta Verapaz. By understanding the diversity and uses of trees in these systems, we can develop targeted strategies to optimize species selection, promote conservation, develop sustainable harvesting practices, and design incentive programs that reward farmers for adopting sustainable management practices.

Optimizing species selection can maximize the ecological and economic benefits of CAFS, while conservation efforts can maintain critical ecosystem services and support local livelihoods. Sustainable harvesting practices ensure the long-term availability of timber and non-timber forest products, and well-designed incentive programs can encourage the widespread adoption of sustainable management practices.

2.9. Methods for evaluating tree diversity in CAFS

2.9.1. Forest inventories

Forest inventories are the basis for applying other methods, such as the calculation of various diversity indices, the Importance Value Index (IVI), and the evaluation of timber potential. The data collected through these inventories allow for the analysis of the spatial distribution of tree species and their relationship with environmental and management factors, which in turn contribute to a better understanding of the dynamics and functionality of CAFS (Matey et al. 2013).

Consistency in measurements is fundamental to guarantee the quality and comparability of data obtained through forest inventories (Feldpausch et al. 2012). Diameter at breast height (DBH) and total height are key dendrometric variables that should be measured following standardized protocols. DBH is estimated at 1.3 meters above ground level and is an essential indicator of tree size, age, and growth (Ramírez-Argueta et al. 2022). At the same time, total height is measured from the base to the apex of the tree crown and is essential for estimating canopy volume, biomass, and vertical stratification.

In addition to dendrometric measurements, accurate botanical identification of tree species present in CAFS is crucial for assessing the system's diversity and structure (Cámara-Leret et al. 2014). Misidentification can lead to erroneous conclusions about species richness, ecological interactions, and the potential for forest resource utilization (Uowolo et al. 2005). Therefore, it is necessary to have trained personnel and to use taxonomic keys, field guides, and reference herbarium specimens to ensure accurate botanical identification.

Forest inventories also allow for analyzing the spatial distribution of tree species and their relationship with environmental and management factors. The size of the plots used in inventories can vary according to the study and specific objectives, ranging from 400 m^2 plots to circular plots of 1,963 m^2 (Matey et al. 2013; Gómez Cardozo et al. 2018). The appropriate selection of plot size is essential to represent the composition and structure of CAFS accurately and facilitate comparison between different studies.

2.9.2. Diversity indexes

The Shannon Index is widely used and considers species richness and relative abundance (Keylock 2005). This index provides information on the diversity and evenness of tree species in CAFS, allowing comparisons between different systems or strata. On the other hand, Simpson's index (D) focuses on species dominance and measures the probability that two randomly selected individuals belong to the same species (Simpson 1949). This index is more sensitive to changes in dominant species and can help detect disturbances or changes in tree community structure.

The Jaccard index (J) is used to evaluate the similarity or dissimilarity in species composition between different CAFS or strata within the same system (Chao et al. 2005). This index is based on the presence or absence of species and provides information on the degree of overlap in species composition between different study units. On the other hand, the Pielou equity index (J') measures the evenness in the distribution of individuals among the species present, which allows us to evaluate whether species are equally represented in the system or whether some species are dominant over others (Zhang et al. 2018).

These indices will help answer key questions about the diversity and structure of CAFS, such as: What is the relative richness and abundance of tree species in the CAFS studied? Are there dominant species in these systems? How does species composition vary among different CAFS or strata? How evenly are individuals distributed among the species present? Answers to these questions will provide a comprehensive understanding of tree diversity in CAFS and lay the foundation for the development of effective management and conservation strategies.

2.9.3. Importance Value Index (IVI)

In addition to the diversity indices, IVI is another measure used to evaluate the ecological importance of tree species in CAFS. The IVI is calculated from the results of the forest inventory and combines the relative abundance, relative frequency, and relative dominance of each species, providing an integrated measure of its importance in the system (Soler et al. 2012).

According to Rasingam & Parthasarathy (2009), relative abundance refers to the proportion of individuals of a species to the total number of individuals of all species; relative frequency represents the proportion of plots or sampling units in which a species is present, and relative dominance is calculated from the basal area or crown cover of a species over the total basal area or crown cover of all species. This index allows for the identification of crucial tree species and their contribution to the structure and function of the AFS (Vera-Vélez et al. 2019).

The IVI provides valuable information on the ecological importance of each tree species in CAFS, which is fundamental to understanding the dynamics and functionality of these systems (Condit et al. 2000). By identifying key species, the IVI helps guide management and conservation decisions, as these species can play critical roles in maintaining the ecological structure and processes of CAFS (Soler et al. 2012).

2.9.4. Discriminant analysis of principal components (DAPC)

In studies of botanical diversity, structure, and composition of CAFS, it is relevant to perform DAPC to confirm the similarity between the sampled locations (Jombart et al. 2010) This multivariate statistical technique combines principal component analysis (PCA) and discriminant analysis (DA) to identify and describe groups of related trees within the studied population (Legendre & Legendre 2012). By applying DAPC to the diversity data of the sampled trees, the structure and composition of the CAFS can be graphically represented in a two-dimensional space, minimizing intra-population variation and maximizing inter-population variation (Jombart et al. 2010).

Applying the DAPC allows the exploration of patterns and relationships between the different CAFS studied based on their composition and tree structure. This will help answer questions such as: Are there distinct groups of CAFS based on their species diversity and composition? What management variables may be influencing the formation of these groups? How do these groups relate to the functionality and resilience of CAFS in the context of climate change?

2.9.5. Assessment of the timber potential in CAFS

The assessment of timber potential involves the estimation of total and commercial volume and the quality of timber produced by the associated tree species (Somarriba et al. 2014). Dendrometric measurements, obtained through forest inventories, allow for the characterization of trees and forest stands; these measurements include diameter at breast height (DBH), measured at 1.3 meters above ground level, total height, commercial height, crown diameter, basal area, and volume (Ramírez-Argueta et al. 2022).

DBH is used to estimate the tree's volume, biomass, and growth. At the same time, total height is the vertical distance from the base to the tip of the crown, and commercial height is the height at which trees are considered suitable for commercial harvesting or exploitation (Feldpausch et al. 2012). Crown diameter is the measure of the width of the crown, basal area is the cross-sectional area of the trunk at breast height, and volume is the amount of wood or biomass in the tree (Román-Dañobeytia et al. 2014).

Furthermore, it is essential to consider the additional uses of trees, such as the provision of firewood, fruits, medicines, and other non-timber products (Jagoret et al. 2011). Participatory assessment with farmers can help identify and value these multiple uses of trees in CAFS (Sonwa et al. 2007).

Assessing timber potential in CAFS is crucial for understanding their economic and ecological value and developing sustainable management strategies to optimize timber production and the provision of other ecosystem goods and services. In addition, the assessment of timber potential can help identify key tree species for timber production in CAFS and detect possible synergies between timber production and other management objectives, such as biodiversity conservation or the provision of ecosystem services (Ramírez-Argueta et al. 2022). This information is fundamental for developing adaptive management strategies that seek to optimize the multiple benefits of CAFS in the context of climate change.

2.10 Estimated economic indicators

Cost-benefit analysis: Cost-benefit analysis is a tool used to evaluate the economic profitability of CAFS. This method involves identifying and quantifying all costs and benefits associated with the system over a given period (Barrezueta Unda & Paz-González 2018). Costs may include the establishment and maintenance of the system, labor, inputs, and harvesting, while benefits can be derived from the sale of cocoa, timber, fruits, and other products, as well as from the ecosystem services provided by the system (Cuevas-Reyes et al. 2020).

Cost-benefit analysis allows for the calculation of financial indicators such as net present value (NPV), internal rate of return (IRR), and benefit-cost ratio (B/C) to evaluate the economic viability of the AFS (Current et al. 1995).

The discount rate (DR) is a crucial element in project evaluation, as it represents the minimum required profitability to recover the investment, cover costs, and generate benefits (Armengot 2016). Given that each project carries a different risk, the discount rate may vary according to the specific characteristics of each investment. Its relevance lies in its ability to assess and compare the financial viability of different investment alternatives. In the context of Guatemala, it is recommended to use a discount rate of 12% to evaluate forestry and agroforestry projects (Reiche & Romero, 1999), which reflects the opportunity cost of capital and the risks associated with this type of investment in the country.

Net Present Value (NPV) is an indicator that measures the present value of the projected net benefits of a CAFS over its helpful life, discounted at a rate that reflects the opportunity cost of capital. A positive NPV indicates that the investment will generate profits over the required return, making it economically viable. Conversely, a negative NPV suggests that the costs exceed the expected benefits (Žižlavský 2014).

The Internal Rate of Return (IRR) represents the discount rate that equates the present value of future revenues to the present value of the CAFS costs. It is the compound annual rate of return that the project will pay on the initial investment. If the CAFS exceeds the opportunity cost of capital, the project is considered financially acceptable (Osborne 2010).

The Benefit/Cost (B/C) ratio is a crucial indicator that assesses the economic viability of a project by comparing the present value of its projected benefits to the present value of its estimated implementation and maintenance costs. In the context of CAFS, a B/C ratio greater than one indicates that the anticipated benefits outweigh the associated costs, rendering the project economically profitable and attractive to stakeholders. Moreover, a higher B/C ratio suggests a more favorable return on investment, implying that the project generates more benefits than costs (Cuevas-Reyes et al. 2020).This metric is essential for decision-makers, as it helps them prioritize projects that offer the greatest economic returns while considering the long-term sustainability and resilience of the AFS in the face of climate change.

Cost-benefit analysis is a valuable tool for evaluating the economic viability of CAFS and guiding investment and management decisions (Vojinovic et al. 2016). The cost-benefit analysis will allow the financial profitability of the CAFS studied to be evaluated, considering both the costs of establishment and management and the benefits derived from producing cocoa, timber, and other ecosystem goods, and services. This will help to answer questions such as: Are the CAFS economically viable? What are the main factors that influence their profitability? What management strategies could improve the profitability and sustainability of these systems?.

3. Problem statement

Guatemala faces significant challenges in conserving its natural resources, including the lack of valuation of biodiversity, threats from monoculture and livestock expansion, and the vulnerability of production systems to pests and diseases (CONAP 2009; Ruiz-Chután et al. 2024). In this context, CAFS in Alta Verapaz emerge as a promising alternative to reconciling agricultural production with trees biodiversity conservation and the provision of ecosystem services. CAFS, managed mainly by Q'eqchi indigenous communities, are home to many tree species that provide shade for cocoa and diverse products and services (Orozco Aguilar & Deheuvels 2007).

These systems are fundamental for biodiversity conservation, rural families' economic development, and resilience in the face of the threats. However, our knowledge about their tree diversity, timber potential, and financial viability still needs to be improved. To promote sustainable management and conservation of CAFS in Alta Verapaz, an assessment covering three key aspects is necessary. First, a detailed characterization of the diversity of tree species present will allow the identification of those species that contribute to biodiversity conservation and the provision of ecosystem services. Secondly, an analysis of the timber potential of the identified trees will help determine their possible contribution to generating additional income for farmers, thus encouraging the conservation of a greater diversity of tree species in these systems. Finally, an economic evaluation that considers factors such as profitability will provide valuable information on the viability of CAFS and their ability to contribute to the economic development of the rural communities that depend on them.

This work seeks to highlight the fundamental role of CAFS in the region and promote its valuation as a key tool for sustainable development and conservation of natural resources in Guatemala.

4. Objectives and Hypotheses

The study aimed to evaluate the tree diversity, timber potential, and socioeconomic viability of CAFS in the Alta Verapaz of Guatemala to determine their contribution to biodiversity conservation, timber product generation, and sustainable rural development.

Specific objectives

i. To characterize the diversity, composition, and structure of tree vegetation in CAFS of different ages in Alta Verapaz, Guatemala.

ii. To identify the tree species with the greatest timber potential and their main local uses in CAFS in Alta Verapaz, Guatemala.

iii. To analyze the economic viability of two models of CAFS in Alta Verapaz through financial indicators and determine their capacity to promote sustainable rural development.

Hypotheses

i. Tree species diversity in CAFS in Alta Verapaz, Guatemala, varies according to socioeconomic factors and management of the system by local indigenous communities.

ii. There are dominant tree species with the significant timber potential in CAFS of varying ages in Alta Verapaz, Guatemala, that can serve for various local purposes.

iii. Cocoa agroforestry systems evaluated in Alta Verapaz will present positive indicators of economic viability that could increase their socioeconomic impact among rural communities.

5. Methodology

5.1. Study area

The study was conducted in four municipalities of the Alta Verapaz department: Lanquín, Cahabón, Cobán, and Panzós **(Figure 5).** These municipalities were selected to capture the ecological variability of the region's CAFS, as they account for a significant portion of the department's cocoa production. Alta Verapaz is a crucial contributor to Guatemala's cocoa sector, responsible for 31% of the country's cocoa output (Ministerio de Agricultura Ganadería y Alimentación 2016).

Alta Verapaz has a territorial surface of 8,686 km^2, equivalent to 8% of the national territory. The climate is characterized by annual precipitation rates of approximately 2,500 mm, and an average annual temperature between 24 and 28.1 °C. The average altitude of the department is 1,316 m asl, although the topography is varied, with mountains and peaks that exceed 2,000 m asl and lowlands with heights of only 50 m asl (IDES 2012).

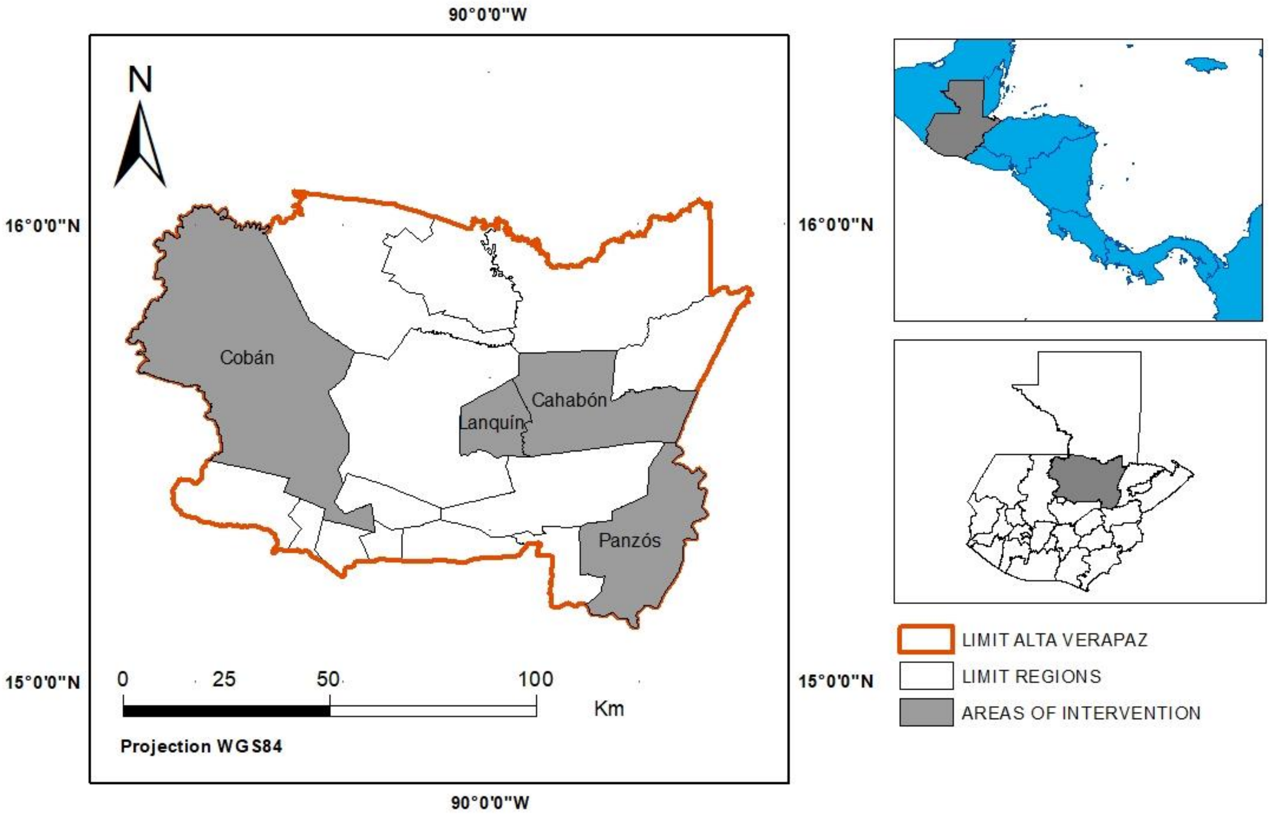

Figure 5. Location of the study area within the department of Alta Verapaz, Guatemala.

Alta Verapaz is a predominantly rural department, with 79% of its population residing outside cities (INE 2018). Indigenous communities, mainly the Q'eqchi' and Poqomchi', constitute 93% of the total inhabitants (PNUD 2016). The region's economy is primarily based on agriculture, with cardamom (*Elettaria cardamomum* (L.) Maton), coffee (*Coffea arabica* L.), cocoa (*Theobroma cacao*), maize (*Zea mays* L.), being the most prominent crops (MAGA 2016). In particular, the Q'eqchi communities are dedicated to cocoa production in AFS (Villatoro-Sánchez et al., 2019). Poverty is a significant problem in Alta Verapaz, with 83% of the population living in poverty and 53% in extreme poverty (PNUD 2016). The livelihoods of the local population depend mainly on subsistence agriculture and the sale of agricultural products in local markets (IDES 2012). In addition, the collection of non-timber forest products, such as xate (*Chamadorea* spp) and allspice (*Pimenta dioica* (L.) Merr.), contributes to the income of many households (Nicli et al., 2019).

Forest cover in Alta Verapaz has decreased significantly in recent decades due to agricultural expansion, illegal logging, and firewood extraction; between 2016 and 2020, the deforestation rate in the department was 12,402 hectares per year, representing an annual loss of 1.35% of forest cover (INAB, 2021). AFS, including shaded cocoa plantations, play an important role in biodiversity conservation and the maintenance of local livelihoods in the region.

5.2. Assessment of tree diversity

5.2.1. Study sites and data collection

To evaluate tree diversity and the structure of CAFS in the region, 70 temporary sample plots were established in the four selected municipalities. In each of the municipalities of Lanquín, Cahabón, and Panzós, 18 sampling plots were delimited, while 16 plots were established in Cobán **(Table 1).**

Table 1. Biophysical and demographic characteristics of selected municipalities in Alta Verapaz.

Site	Elevation (masl)	Average Temperature (°C)	Annual Precipitation (mm)	Forest Cover (%)	Population	Area of the municipalities km²	Population Density (people/km²)	Overall Poverty (%)
Lanquín	200 - 600	21 - 27	2,000 - 3,000	65	30,261	208	145	78
Cahabón	200 - 600	22 - 28	2,500 - 3,500	55	69,349	900	77	92
Panzós	100 - 600	24 - 30	2,000 - 3,000	40	84,484	730	115	85
Cobán	182 - 1,600	15 - 25	1,500 - 2,500	70	212,421	2,269	100	65

The sampling plots were established following a non-probabilistic stratified sampling design, considering specific criteria to ensure the sample's representativeness (Maza et al. 2016). The selection criteria included: (i) accessibility of the plots, (ii) availability of the farmers to participate in the study, (iii) age of the CAFS, covering different stages of development, (iv) type of management applied in the systems, and (v) area under cocoa cultivation. Including CAFS of different ages allowed for an analysis of how tree diversity and system structure change over time, providing valuable insights into the dynamics of these AFS and how management practices such as shade management, soil fertility, and biodiversity, influence their composition and structure as they mature.

Each sampling unit consisted of a rectangular plot of 2,500 m², with dimensions of 50 m × 50 m, following the methodology proposed by Vebrova et al. (2014) and Gómez-Cardozo et al. (2018) for evaluating agroforestry systems. This sampling area is considered adequate to capture the variability of tree diversity and CAFS structure at the plot scale (Abou Rajab et al. 2016). The 70 sampling plots covered a total area of 175,000 m².

The inventory of tree species in the CAFS was developed following the method of Navarro-Garza et al. (2012). In each sampling unit, the diameter at breast height (DBH) ≥ 5 cm and height of each tree were measured, and all individuals were identified to species level. Tree height and DBH were measured with a clinometer and a diameter tape, respectively.

Species identity was confirmed by the Herbarium of the Natural Sciences Laboratory of the Universidad Rafael Landívar, supported by resources such as *Flora of Guatemala* (Standley and Steyermark, 1946), Tropicos nomenclature database *(www.tropicos.org);* the online database from the *Global Biodiversity Information Facility* (www.gbif.org); and in the *Guide for the Identification of Common Trees in Guatemala* (Guerra-Centeno et al. 2016). In addition, the shade trees inventoried were categorized according to their height in low (1 to 8 m), medium (9 to 24 m) and high (25 to 35 m) strata (Suarez-Venero et al. 2019).

5.2.2. Diversity indexes and analysis of floristic composition

Several ecological indices were calculated to evaluate the floristic diversity and composition of the CAFS. The specific richness index (*S*) was used to determine the number of species in the evaluated systems. Tree diversity was determined based on species abundances and evenness according to Shannon, Pielou, and Simpson indices for the identified trees, following by Jadán-Maza et al. (2016) suggestions.

These analyses were performed with the Vegan package (Oksanen et al., 2022) using R v. 4.0.3 (R CoreTeam, 2022). In addition, IVI was calculated using the abundance, frequency, and relative dominance of each species found in the CAFS (**Table 2**). Similarity with regards to the composition species between localities was analyzed using Jaccard's method, and a visualization was generated using hierarchical cluster analysis.

Table 2. Equations to calculate IVI, diversity, evenness and dominance of species in cocoa agroforestry systems in Alta Verapaz, Guatemala.

Equation	Description
Absolute density (A_{den}) and relative density (R_{den})	
$A_{den} = \frac{N_i}{S}$ $R_{den} = \left(\frac{A_{den}}{\sum j = 1 A_{den}}\right) * 100$	A_{den} = Absolute density R_{den} = Relative density per species N_i = number of individuals of species i S = sampling area (ha) ∑j=1A$_{den}$ = The sum of all the absolute densities of the species in the study area Source: Curtis & Mcintosh (1951)
Absolute dominance (A_{dom}) and relative dominance (R_{dom})	
$A_{dom} = \frac{B_a}{S}$ $R_{dom} = \left(\frac{A_{dom}}{\sum j = 1 A_{dom}}\right) * 100$	A_{dom} = Absolute dominance R_{dom} = relative dominance of species i respecting the total dominance B_a = basal area of species i S = sampling area (ha) ∑j=1A$_{dom}$ = The sum of all the absolute densities of the species in the study area Source: Curtis & Mcintosh (1951)

Table 2. Equations to calculate IVI, diversity, evenness and dominance of species in cocoa agroforestry systems in Alta Verapaz, Guatemala.

Equation	Definitions
Absolute frequency (A_{fre}) and relative frequency (R_{fre})	
$A_{fre} = \frac{P_i}{NS}$ $R_{fre} = \left(\frac{A_{fre}}{\sum j = 1 A_{fre}}\right) * 100$	A_{fre} = absolute frequency R_{fre} = relative frequency of species i respecting the total frequency P_i= area number in where the species i is present NS = total number of sampling areas $\sum j=1 A_{fre}$ = The sum of all the absolute frequency of the species in the study area Source: Curtis & Mcintosh (1951)
Importance value index (IVI)	
$IVI = \frac{Rden + Rdom + Rfre}{3}$	IVI = importance value index $Rden$ = relative density per species respecting the total density $Rdom$ = relative dominance of species I respecting the total dominance $Rfre$ = relative frequency of the species I respecting the total frequency Source: Curtis & Mcintosh (1951)
Shannon Index	
$H' = -\sum p_i ln p_i$	H' = Shannon Index p_i = relative abundance ln = natural logarithm
Simpson's Index	
$D = \frac{\sum n(n-1)}{N(N-1)}$	D = Simpson's dominance index n = total organisms of a given species N = total organisms of all the especies 1 = number is used to calculate the unique combinations of pairs of individuals of a species
Pielou's Evenness Index	
$Pielou = \frac{H'}{ln(S)}$	$Pielou$ = Pielou's Evenness Index (J') H' = Shannon Index (S) = Species count
Jaccard Similarity Index	
$Jaccard = \frac{c}{(a+b-c)}$	$Jaccard$ = Jaccard Similarity Inndex a = species unique to sample 1 b = species unique to sample 2 c = species present in both samples

5.2.3. Statistical analysis

A discriminant analysis of principal components (DAPC) was performed to confirm similarity among localities using the Adegenet package in R v. 4.2.0 (Jombart et al. 2010). In addition, CAFS were grouped according to age of establishment. Diversity was estimated from the number of species and abundances with Shannon, Pielou, and Simpson indices using the Vegan package (Oksanen et al., 2022). Alpha diversity variables were compared between ages using analysis of variance (ANOVA) to determine if there were significant differences in diversity according to CAFS age.

5.2.4. Assessment of the productive potential of CAFS timber trees

5.2.5. Plot selection criteria

To evaluate the timber and firewood production potential in the CAFS, 20 sample plots were selected from the 70 plots previously assessed in the diversity analysis. The selection criteria prioritized species composition, focusing on plots that contained timber species with high economic value in the local market and species suitable for firewood production.

The considered factors were the presence of tree species with a minimum DBH of 30 cm for commercial timber and a DBH of 5 to 10 cm for firewood production were considered, recognizing that trees with diameters above these thresholds have more significant potential for the respective uses.

In addition, priority was given to plots with a volume of commercial timber greater than 15 m^3/ha and a volume of firewood larger than 10 m^3/ha, as these values indicate relevant productivity levels. These criteria allowed focusing the analysis on CAFS that harbor trees with outstanding dendrometric characteristics and a composition of valuable species for both timber and fuelwood production, thus ensuring that representative data were obtained for systems with a high potential for both purposes.

5.2.6. Dendrometric variables measurements

The main dendrometric variables of all woody specimens were measured in each sampling unit, including total height (th), commercial height (hc) and DBH $\geq$ 5 cm. The formulas recommended by Sánchez Gutiérrez et al. (2016) were applied as follows to calculate basal area (BA), commercial volume (VC), and total volume (VT):

$$BA = \pi * (DBH/2)^{\wedge 2}$$

Total volume and commercial volume (VT, VC, m^3) were calculated using the following equation:

$$V=BA \times ff \times H$$

where: ff= shape factor (0.70) and H= total or merchantable height. Total height and DBH were measured using a clinometer and diametric tape.

5.2.7. Characterization of the vertical structure and uses

The method proposed by Somarriba (2004) based on the forest inventory results, was used to stratify the shade canopy. The trees were classified into three strata: 1) the lowest stratum (indicated by trees and their seedlings/saplings 1-8 m tall), 2) the middle stratum (indicated by trees 9-24 m in height), and 3) the tallest stratum (indicated by emergent trees 25-35 m in height). To estimate timber production, the DBH variable was classified into different diameter categories: firewood (5-10 cm), poles (10-15 cm), thin boards (15-30 cm) and thick boards (>30 cm) (Sánchez Gutiérrez et al. 2016).

5.2.8. Data analysis

To visualize the contribution of each tree species to the dendrometric variables, we generated bar charts using the ggplot2 statistical package (Wickham, 2016). The frequency of the species was analyzed using a statistical cross-tabulation approach to determine the frequency distribution of species across the different age categories of each population where the CAFS were located. To assess the relationship between the variables included in the crosstabulation, Pearson's Chi-square test ($\chi 2$) was used. These analyses were conducted using the ggstatsplot package implemented in R (Patil 2021).

5.3. Socioeconomic assessments of two CAFS models

5.3.1. Sampling

The study was carried out over 18 months, from August 2021 to October 2022. To select participants, deterministic sampling was used. This technique allowed cocoa farmers to be selected according to predefined criteria that fit the research objectives (Martínez Reina et al. 2022). In this case, a representative sample of 154 cocoa producers belonging to the Maya-q'eqchi ethnic group was identified, considering factors such as the time availability of the participants, the application of agroforestry practices in their productive systems, and the surface of the areas cultivated with cocoa. These selection criteria were established to obtain a sample that adequately reflects the characteristics and variability of cocoa producers in the study region.

The sample size was then calculated according to the two CAFS models selected: (i) cocoa under complex shade (various tree species) and (ii) cocoa associated with predominantly caoba trees (*Swietenia macrophylla* King in Hook.). Thus, a sample size of 92 farmers was established for the first model and 62 farmers for the second. The producers in each system were selected randomly. This proportional stratified sampling approach ensured that both agroforestry systems were adequately represented in the sample, allowing for unbiased comparative analyses.

5.3.2. Description of selected CAFS

Cocoa under complex shade: This system is characterized by the association of cocoa with various tree species that provide shade to the crop. Producers who manage this system have production areas ranging from 0.10 to 2 ha. The floristic composition of the shade species is varied, contributing to productive diversification and the generation of ecosystem services. This system estimates an average density of 400 to 600 cocoa trees ha^{-1} and about 200 forest trees of different species ha^{-1}. Dry cocoa yields in this system range between 200 and 250 kg ha^{-1}, depending on agronomic management and soil and climatic conditions.

Cocoa with caoba trees: In this arrangement, cocoa is mainly associated with caoba trees (*S. macrophylla*), a high economic value timber species. The producers that implement this system have production areas greater than 2 ha. The density of cocoa trees in this system ranges between 900 and 1,111 plants per ha, while the density of caoba trees varies between 80 and 100 individuals ha^{-1}. This system's average dry cocoa bean yield is between 400 and 500 kg ha^{-1}.

5.3.3. Data collection through interviews

Data was collected through face-to-face interviews with the producers selected in the sample. A structured questionnaire was applied that included questions on the socioeconomic characteristics of the production units, production costs, income obtained from the sale of cocoa and other products, and the contribution of the CAFS to the family economy (**Appendix 6**).

The interviews were carried out in the producers' plots, allowing direct on-site observations of the agroforestry systems and complementing the information collected. The interviews with cocoa producers were conducted in the q'eqchi language, and local interpreters collaborated to facilitate communication with the producers.

5.3.4. Data analysis

Financial indicators, including the Internal Rate of Return (IRR), Net Present Value (NPV), and Benefit-Cost Ratio (B/C), were calculated using the methodology developed by Ferrere et al. (2020) and Cruz-Aguilar et al. (2016). In determining these indicators, the equations detailed below were applied:

$$\boldsymbol{IRR} = \sum_{t=0}^{n} \frac{CF_t}{(1+r)^t}$$

The IRR represents the profitability of the system and is the discount rate that makes the NPV equal to zero (0), where CFt represents cash flows in period *t*, *r* is the IRR to be calculated, *t* is the period, and *n* is the last period in which cash flows were generated.

$$\boldsymbol{NPV} = C_0 + \frac{C_1}{(1+r)^1} + \frac{C_2}{(1+r)^2} + \cdots + \frac{C_n}{(1+r)n}$$

The NPV represents the sum of discounted cash flows for the established cycle, where C0 represents the initial investment, C1…Cn means the net cash flows, r is the discount rate (12% and 25%) , and n denotes the years considered in the evaluation.

$$\boldsymbol{B/C} = \frac{BN}{CI}$$

A comprehensive analysis of income and expenses was conducted to assess the financial situation of the two CAFS. This analysis covered the activities necessary to establish the procedures and planned maintenance activities over 25 years, from year 0 to year 24. The results are based on the current and contextual costs in the rural area of the Alta Verapaz department. To determine the investment cost of the CAFS, a detailed breakdown of fixed and variable expenses was carried out during the establishment process. An ex-post analysis recommended by Romo-Lozano et al. (2012) was used, considering the costs of establishment of the CAFS. It is important to note that the evaluated systems' average age of 12 years was considered when calculating this indicator.

A sensitivity analysis was conducted to evaluate the impact of crucial parameter variations on the CAFS-assessed profitability. First, the most influential factors on costs and revenues were identified. The analysis used the current values of these parameters in the study area as a baseline. Subsequently, each parameter was varied, applying increases and decreases of ±50% over its original value, keeping all other factors constant. The economic indicators were recalculated for each modified scenario: NPV and B/C ratio. This procedure made it possible to identify the most sensitive parameters, i.e., those whose variations caused the most significant changes in the projected profitability of each type of CAFS.

In addition, two DRs, 12%, and 25%, were considered to evaluate the sensitivity of the economic indicators to different profitability scenarios. The 12% DR represents the social opportunity cost of capital in the Guatemalan economy, allowing the project's viability to be evaluated from a social perspective (Cerda 2022). On the other hand, the 25% DR reflects the market interest rate at which small producers can access credit, given their limited collateral and capital assets (Lojka et al. 2007).

6. Results

6.1. Tree diversity, structure, and composition in CAFS in Alta Verapaz, Guatemala

6.1.1. Tree species composition

In all CAFS sampling plots (n=70), we identified 2,519 individual trees belonging to 59 species and 34 families (**Appendix 1**). **Table 3** presents the density of trees (per plot and ha), number of families, and species per hectare in the four study municipalities' cacao agroforestry systems (CAFS). The results show differences in the composition of the CAFS among the municipalities, with Cahabón presenting the highest tree density (180 trees ha^{-1}) and species richness (8 species ha^{-1}). In comparison, Cobán registers the lowest values in these parameters (102 trees ha^{-1} and four species ha^{-1}).

Table 3. The density of trees, families, and species per hectare in CAFS in Alta Verapaz, Guatemala.

Location	Trees/plot	Trees ha^{-1}	Families ha^{-1}	Species ha^{-1}
Cahabón	45	180	4	8
Cobán	25	102	3	4
Lanquín	30	120	4	6
Panzón	38	153	4	6

The tree species from Fabaceae (50.69%), Meliaceae (16.11%), Burseraceae (6,58 %) and Lauraceae (3.45%) families were the most dominant. As these four families represent 76.83% of the total number of tree individuals, the remaining 23.17% of the total inventory belonged to 30 families. The dominant tree species with the highestnumber of individuals from all sample sites were *G. sepium* (1,117 individuals), *S. macrophylla* (260), *C. odorata* (154), *Protium copal* (Schltdl. & Cham.) Engl. (165), and *C. alliodora* (94); representing 71.05% of all inventoried trees.

6.1.2. Vegetation structure, vertical and horizontal stratification

The cocoa plantations were found to be between 3 and 30 years of age. The mean height of inventoried trees in the CAFS was 10.9 m, ranging from 2 m to 32 m **(Figure 6a).** 55.9% of the total trees had a height less than 16 m. The average DBH was 18.2 cm, varying from 3 to 90 cm. 58.79% of the trees recorded in the CAFS are concentrated in the second diametric class (10-20 cm) **(Figure 6b)**.

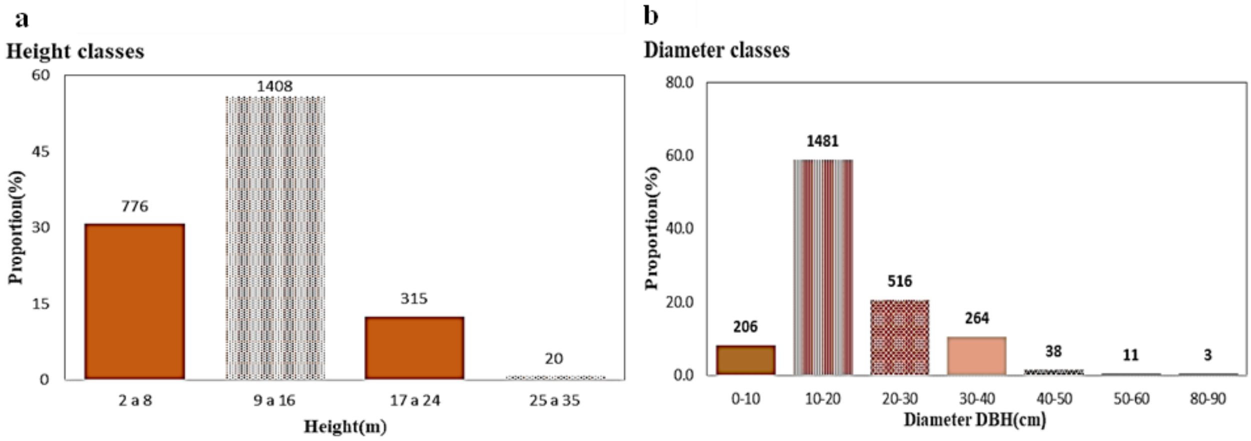

Figure 6. Analysis of the principal biometric variables. a) Classification of strata corresponding to the height of the shade-trees inventoried in the CAFS of Alta Verapaz, Guatemala and, b) Classification of the diameters of the same shade-trees.

The tree density varied from 122 to 185 trees ha^{-1} which correspond to 8 and 25 years old systems respectively (**Table 4**). Shade-tree species in cocoa parcels are propagated by means of reforestation or species enrichment methods, in addition to natural regeneration. Reforestation involves actively planting selected tree species in plots, considering their compatibility with cocoa, their potential to provide additional products and services, and their adaptation to local conditions. On the other hand, species enrichment focuses on diversifying the species composition of the system, incorporating new tree species that can complement or improve the ecological and productive functions of existing trees in the CAFS. The total number of inventoried shade trees (2,519 individuals) occupied a total basal area of 80.49 m^2 (8.05 m^2 ha^{-1}). The low stratum (2-8 m), encompassed 30 % of the individuals, while the middle stratum (9-24 m) had 69 % of the total inventoried trees, dominated by timber species and cultural value trees.

The highest strata (25-35 m), concentrated 1% of individuals and was represented by timber species of commercial value in the local context, such as *S. macrophylla* and *C. odorata*. The undergrowth was dominated by essential agricultural species for subsistence (*Capsicum annuum* L, *Carludovica palmata* Ruiz & Pav., *Chamaidorea tepejilote* Liebm., *Manihot esculenta* Crantz, among others).

Table 4. Dendrological variables and number of families and species registered in CAFS, Alta Verapaz, Guatemala.

Cocoa AFS		Average height (m)	Basal area (m^2ha^{-1})	Tree density (Trees ha^{-1})	Number of Taxa	
Age	**#**				**Families**	**Species**
5	6	9.78	5.27	175	14	20
8	15	11.51	4.66	122	18	26
12	15	10.06	4.00	158	19	32
15	20	9.98	2.67	126	23	35
20	4	10.06	3.37	150	13	20
25	6	14.28	9.99	185	16	29
30	4	13.70	6.73	132	13	20

#= number of systems

6.1.3. The dominant tree species

The species exhibiting the highest Importance Value Index (IVI) in the study include *G. sepium* (49.2%), *S. macrophylla* (15.1%), *C. odorata* (11.6%), *P. copal* (9.2%), and *C. alliodora* (8.99%). *G. sepium* and *S. macrophylla* were registered in all evaluated locations. *P. copal* is present in the CAFS within the municipalities of Lanquín and Cahabón, while *C. alliodora* is present in Cobán, Cahabón and Panzós. **Table 5** shows the ten species with the highest Importance Value Index of tree species in CAFS in Alta Verapaz, Guatemala. Nicli et al. (2019), states that these species are of high importance in Alta Verapaz for the balance of nutrients in ecosystems, such is the case of *G. sepium*, a forest species which provides nutrients in the form of abundant biomass to the benefit of the agroforestry systems (Avendaño-Arzate et al., 2021). In addition, trees in these systems are valued primarily for their timber potential and for the opportunities they offer to diversify household incomes and livelihoods.

Table 5. Quantitative analysis for the Importance Value Index (IVI) of the most common tree species in cocoa agroforestry systems in Alta Verapaz, Guatemala.

Species	Family	Ab	Sites	RA	RD	RDOM	IVI
Gliricidia sepium (Jacq.) Kunth.	Fabaceae	1117	4	3.6	44.2	1.4	49.2
Swietenia macrophylla King in Hook.	Meliaceae	260	4	3.6	10.3	1.2	15.1
Cedrela odorata L.	Meliaceae	154	4	3.6	6.1	2.0	11.6
Protium copal (Schltdl. & Cham.) Engl.	Burseraceae	165	2	1.8	6.5	0.9	9.2
Cordia alliodora (Ruiz & Pav.) Oken	Boraginaceae	94	3	2.7	3.7	2.6	9.0
Vatairea lundellii (Standl.) Killip	Fabaceae	5	2	1.8	0.2	6.7	8.7
Inga sapindoides Willd.	Fabaceae	98	4	3.6	3.9	1.2	8.6
Sterculia apetala (Jacq.) H.Karst.	Malvaceae	1	1	0.9	0.1	7.0	8.0
Vochysia guatemalensis Donn.Sm.	Vochysiaceae	40	3	2.7	1.6	3.5	7.7
Terminalia amazonia (J.F.Gmel.) Exell	Combretaceae	2	1	0.9	0.1	6.7	7.7
Other Species		583		74.8	23.3	66.8	181
$\sum$	=	**2519**		**100**	**100**	**100**	**300**

Ab= abundance, RA= Relative Abundance (%), RD= Relative Density (%), RDOM= relative dominance, IVI= Importance Value Index

6.1.4. The tree species richness and diversity

The tree species richness in the CAFS within Alta Verapaz was between 4 and 64 species ha^{-1}. The specific richness across the municipalities was determined between 11 and 39 species per plot. Cahabón showed the greatest species richness; Lanquín and Panzós were equivalent in number of species (31), while Cobán exhibited the lowest species record.

According to Shannon's Index, the CAFS evaluated in the municipality of Panzós were the ones that registered the greatest diversity with respect to the relative abundance of the species (H´=2.17), followed by the municipalities of Cahabón (H´=2.13) and Lanquín (H´=2.11), the CAFS of the municipality of Cobán presented the lowest diversity (H´=1.56) **(Table 6**).

In contrast, the Pielou index revealed that Cobán is the site with the highest value of evenness (J'=0.65), since the different species occur with relatively similar abundance. According to this same index, Cahabón shows lower species evenness (J'= 0.58) as the species registered greater variability in abundance between the plots (*G. sepium*) (**Table 6**). Simpson's dominance index (D) indicates that there is a greater degree of species dominance in the municipality of Lanquín (D=0.77), followed by Panzós, Cahabón and Cobán (D=0.75, 0.72, and 0.69 respectively) **(Table 6**).

Table 6. Comparison of the diversity across municipalities: Species richness Shannon Index, Simpson Index and Pielou Evenness Index for CAFS in the four municipalities of Cahabón, Cobán, Lanquín and Panzós in Alta Verapaz, Guatemala.

Site	Species richness	Shannon (H')	Simpson (D)	Pielou (J')
Cahabon	39	2.130	0.729	0.581
Lanquín	31	2.112	0.769	0.615
Cobán	11	1.563	0.696	0.652
Panzós	31	2.167	0.756	0.631

The seventy CAFS were classified into seven groups based on the age of the cocoa trees. Applying the Shannon Index, the AFS between 9-12 years of age showed the greatest diversity of tree species (H´ = 1.99), followed by those between 6-8 years (H´ =1.80) and 13-15 years (H´ = 1,62), while the AFS of 16+ years exhibited the lowest

Shannon Index **(Figure 7a).** According to the Pielou Index (J´) of the age groups, the 6-8 year old AFS revealed greater homogeneity in number of individuals by species (J’=0.76), while the 26-30 year AFS exhibited the least evenness (J’ 0.21) (**Figure 7b**). This is due to a predominance of commercially valued timber species in the older AFS while younger AFS are composed of species used mainly for firewood or construction timber. A comparison of species richness of the CAFSs by age groups did not show significant difference (P> 0.05) with either the Shannon, Pielou or Simpson indices.

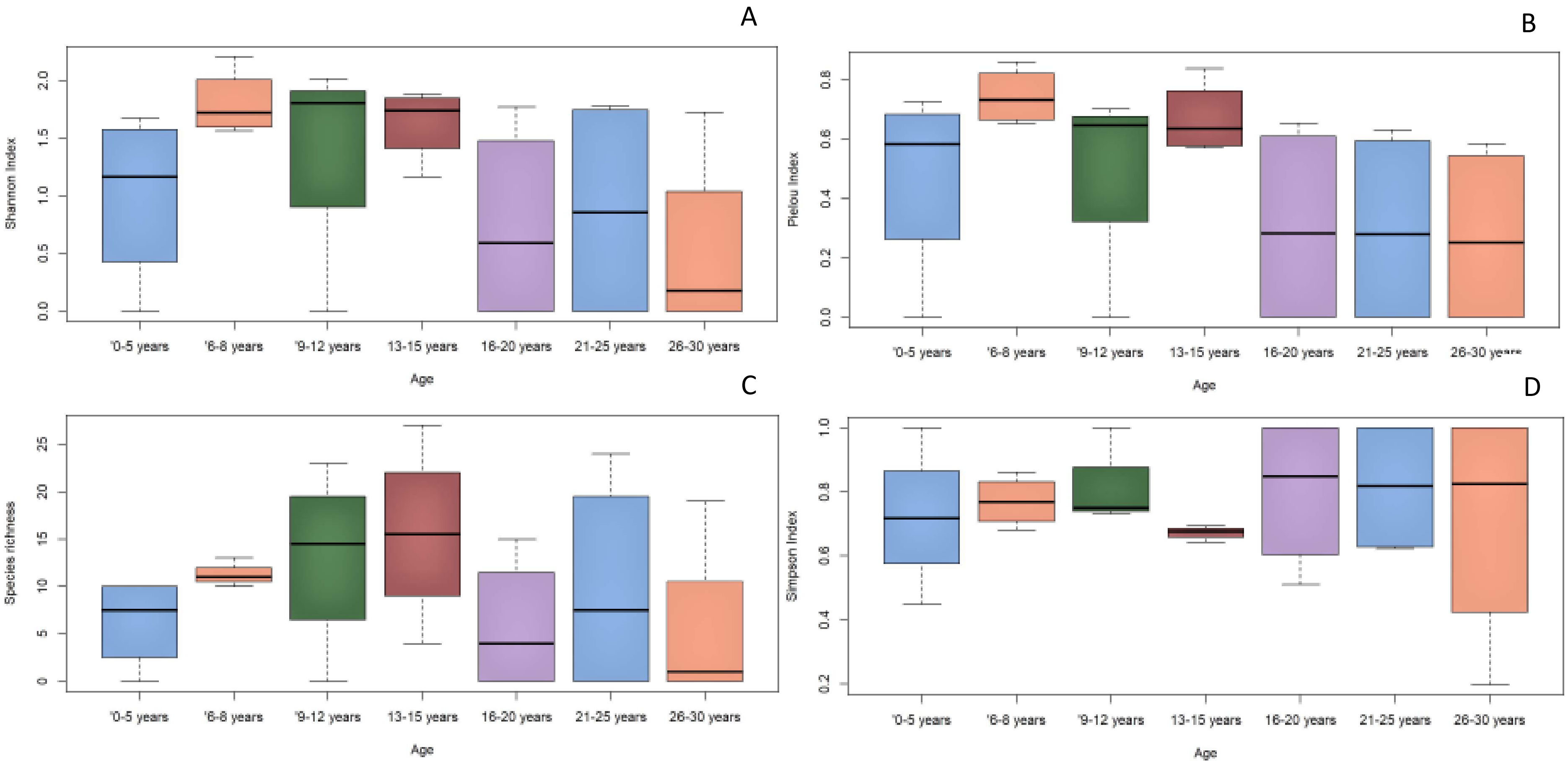

Figure 7. Relationship between the age of the CAFS in the department of Alta Verapaz with species equity (a,b), age with species richness (c) and species dominance (d). A comparison of species richness of the CAFS by age groups did not show significant difference (P> 0.05) with either the Shannon, Pielou or Simpson indices, which demonstrates sustainability in terms of the rational use of tree species across time.

6.1.5. Similarity Indices

The Jaccard similarity index for the CAFS in the municipalities of Cahabón, Panzós and Lanquín indicates that these tend to be highly similar in species composition (0.57, 0.62 and 0.68) respectively; However, the most direct similarity is between the municipalities of Panzós and Cahabón sharing a total of 21 species across the sites (**Figure 8**). The CAFS in Cobán presented the greatest dissimilarity in terms of species (0.83) as compared to the AFS evaluated in the other three localities (**Figure 8**).

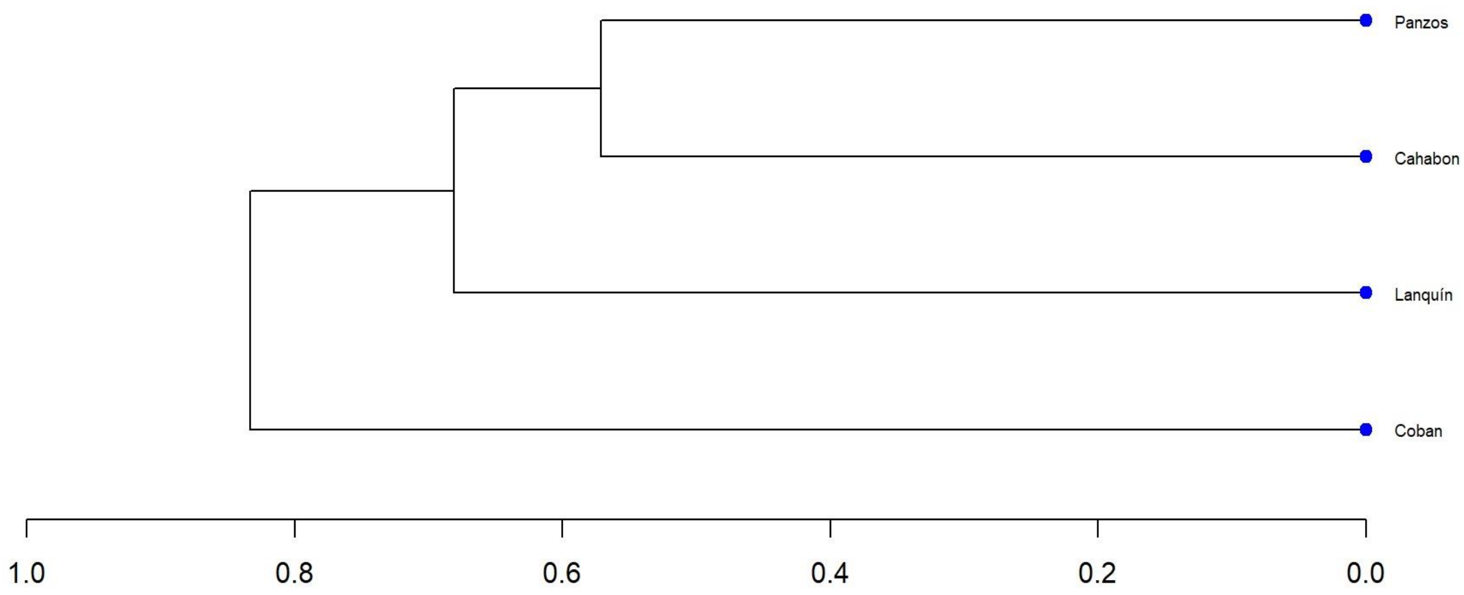

Figure 8. Tree diagram of Jaccard's similarity index in relation to the presence of shade tree species identified in municipalities of Alta Verapaz.

The DAPC analysis revealed that some CAFS in Cahabón, Panzós, and Cobán had a similar composition to the structure and floristic diversity recorded in Lanquín **(Figure 9A and Figure 9B)**. This analysis shows the assignment and probability of membership of each CAFS to the groups defined by the municipalities based on species composition.

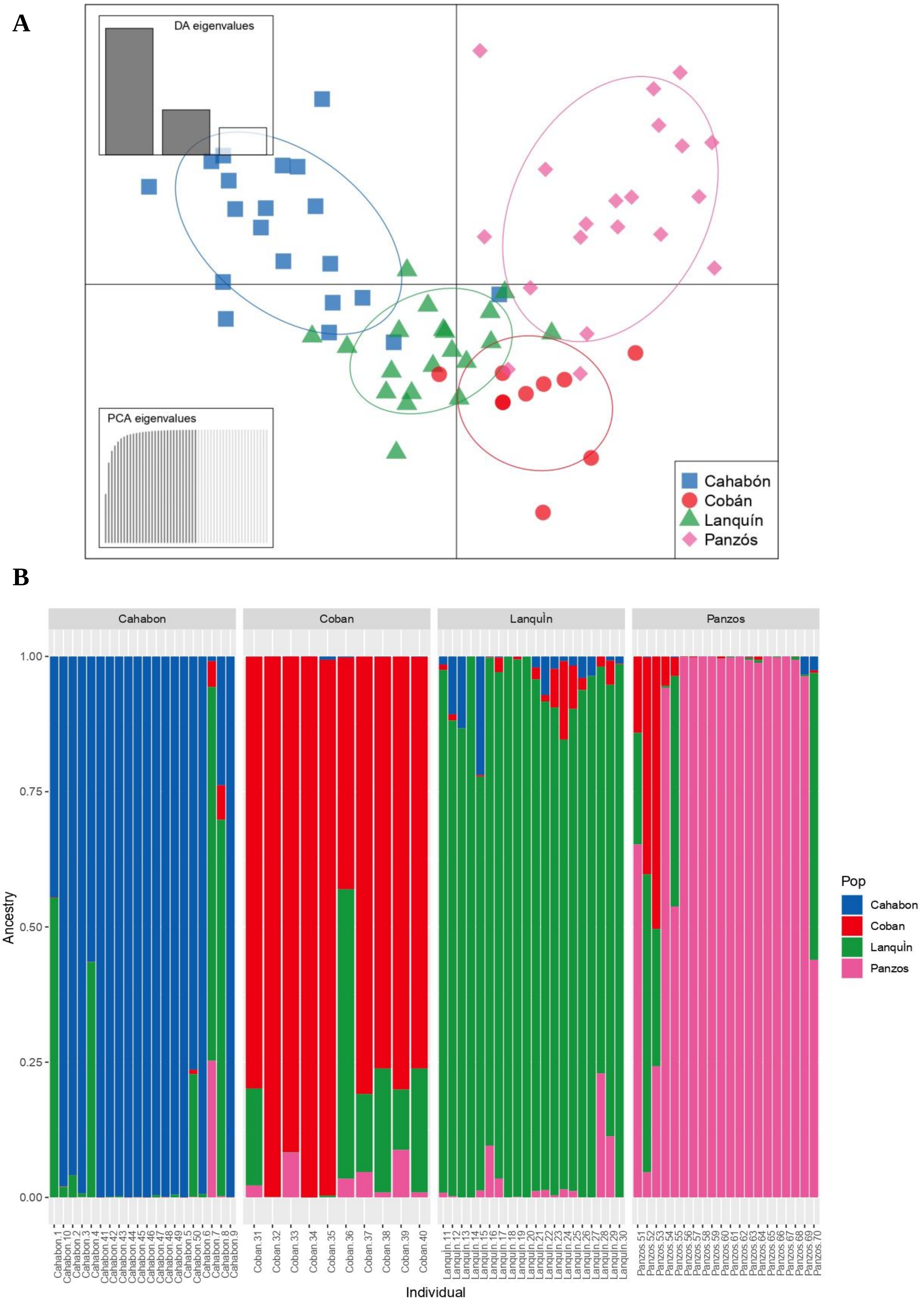

Figure 9. A) Scatterplot based on a DAPC; B) assignment and membership probability of individual agroforestry systems based on species composition.

6.2. Productive potential of timber trees in CAFS in Alta Verapaz, Guatemala

6.2.1. Tree diversity and composition

In total, 877 forest trees corresponding to 38 species belonging to 19 botanical families were found grown for timber and firewood production within 20 sampled CAFS plots (**Appendix 3**). The behavior of the specific richness is determined between 11 and 25 species per municipality, with the municipality of Panzós being the area with the highest richness. At the same time, Cobán has the lowest species record.

In the other municipalities, a more traditional management approach prevails. On average, a density of 165.4 trees ha^{-1} was found, varying from 36 to 364 trees ha^{-1} (**Table 7**). The Fabaceae and Meliaceae were the most represented families, accounting for 45.7% and 25.6% of the total number of species, respectively. G. *sepium* (290; 35.1%), S. *macrophylla* (158; 19.1%), *I. sapindoides* Will. (63; 7.6%), *C. odorata* (54; 6.5%), and *C. alliodora* (42; 5.1%) were the most abundant species.

Table 7. Average value of dendrological variables and number of families and species registered in CAFS, Alta Verapaz, Guatemala.

CAFS		Height	BA	Density	Number of Taxa	
Age	**#**	(m)	$(m^2 ha^{-1})$	$(Trees\ ha^{-1})$	**Families**	**Species**
3	2	11.36	9.5	202	7	10
4	1	11.12	7.9	364	3	3
7	3	12.78	3.7	117	11	13
8	2	13.56	6.5	128	7	9
10	1	12.17	13.5	212	5	6
11	2	10.95	5.1	126	7	10
12	3	10.22	5.8	208	13	22
13	1	8.58	2.2	72	3	4
14	1	11.06	3.2	124	6	8
20	1	14.23	3.2	60	3	4
25	3	14.43	10.5	196	14	23

#= number of systems, BA= basal area

6.2.2. Frequency of trees by CAFS-age

According to dominant species of CAFS tree component, we can distinguish four types: (i) CAFS in Cahabón, where *G. sepium* and *S. macrophylla* area the predominant species; (ii) CAFS in Cobán, characterized by the presence of *S. macrophylla* and *I. sapindoides*; (iii) CAFS in Lanquín, where *G. sepium* and *P. copal* are the dominant species; and (iv) CAFS in Panzós, where *G. sepium* and *C. odorota* prevail. A pattern of species occurrence by age was observed in all zones, suggesting that species are not distributed indistinctly from the age of the CAFS in each locality ($p<0.05$) **(Figure 10).**

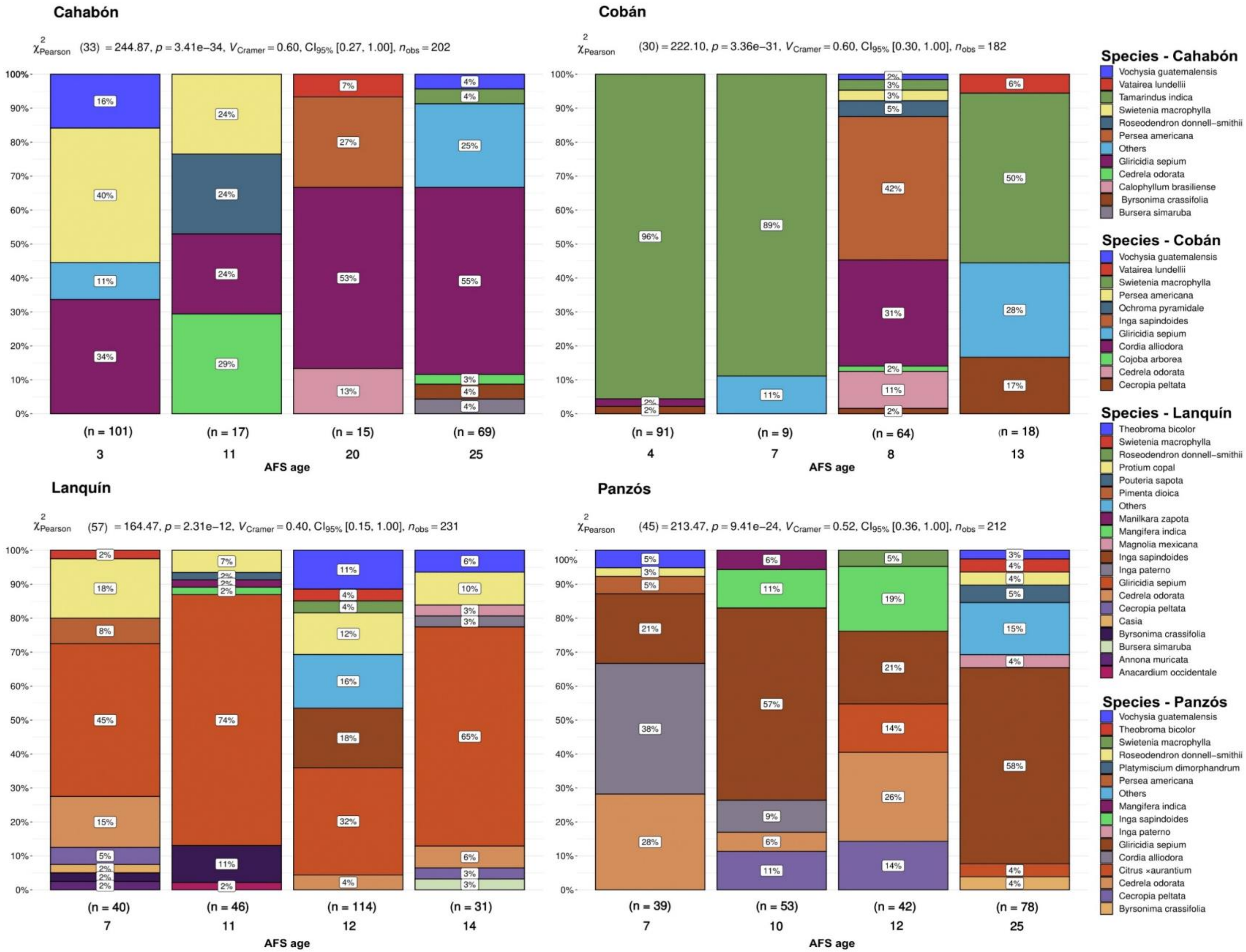

Figure 10. Frequency description and Chi-square test of species distribution by the age of cocoa agroforestry systems among the study localities.

6.2.3. Tree basal area reflecting particular species and system age

The results were classified according to the municipality, the age of the CAFS, and the basal area (BA) variable for each trees species inventoried. A total of 827 shade trees were recorded, occupying a BA of 33.29 m^2. The mean BA was 6.65 m^2 ha^{-1}, ranging from 0.62 to 13.57 m^2 ha^{-1}. The highest BA value (13.57 m^2 ha^{-1}) has been determined for a 10-year-old CAFS, while a 13-year-old CAFS presented the lowest BA value (2.23 m^2 ha^{-1} (Appendix 4).

The species *G. sepium*, *S. macrophylla*, *C. odorata*, and *C. alliodora* represented 71% of the recorded BA **(Figure 11A).** The locality with the highest BA was Panzós, with a value of 10.99 m^2 ha^{-1}, while Lanquín presented the lowest BA with 4.02 m^2 ha^{-1} **(Figure 11B).** In the three and 4-year-old CAFS, *S. macrophylla* was the dominant species in the BA with a density average of 254 trees ha^{-1}, while in the 10, 11, 12, 14, and 25-year-old systems, *G. sepium* prevailed with 172 trees ha^{-1} **(Figure 12).**

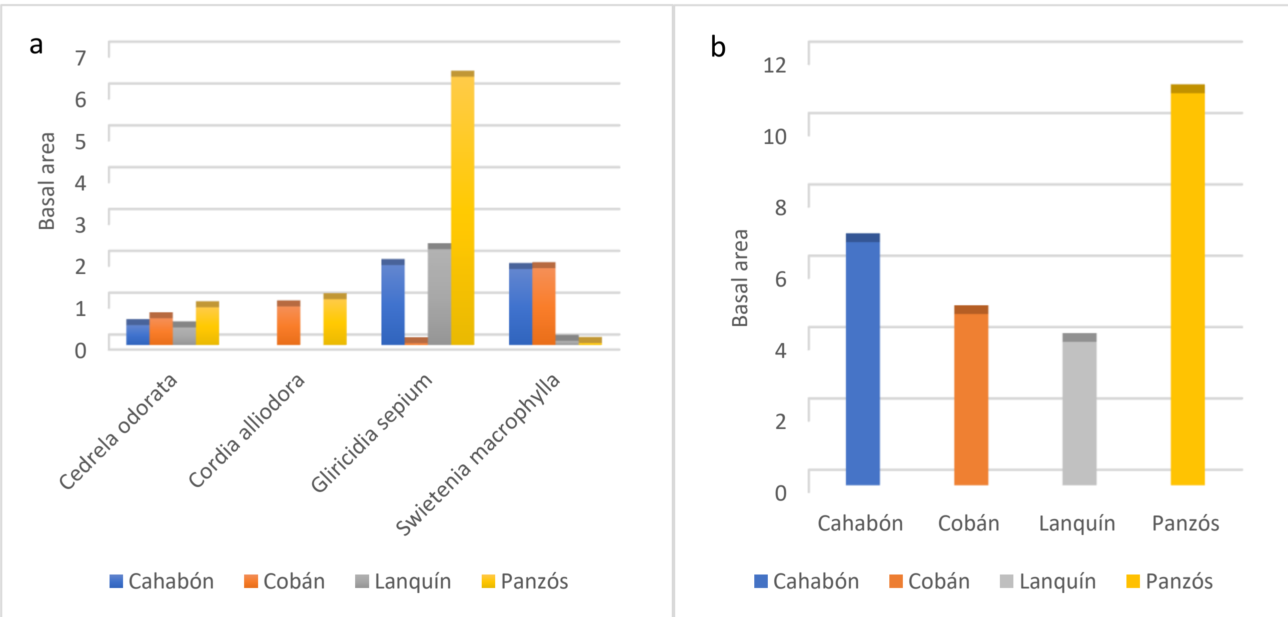

Figure 11. A) Basal area (m^2/ha^{-1}) of tree species by municipality and B) Tree species dominance by municipality (BA/ha^{-1}).

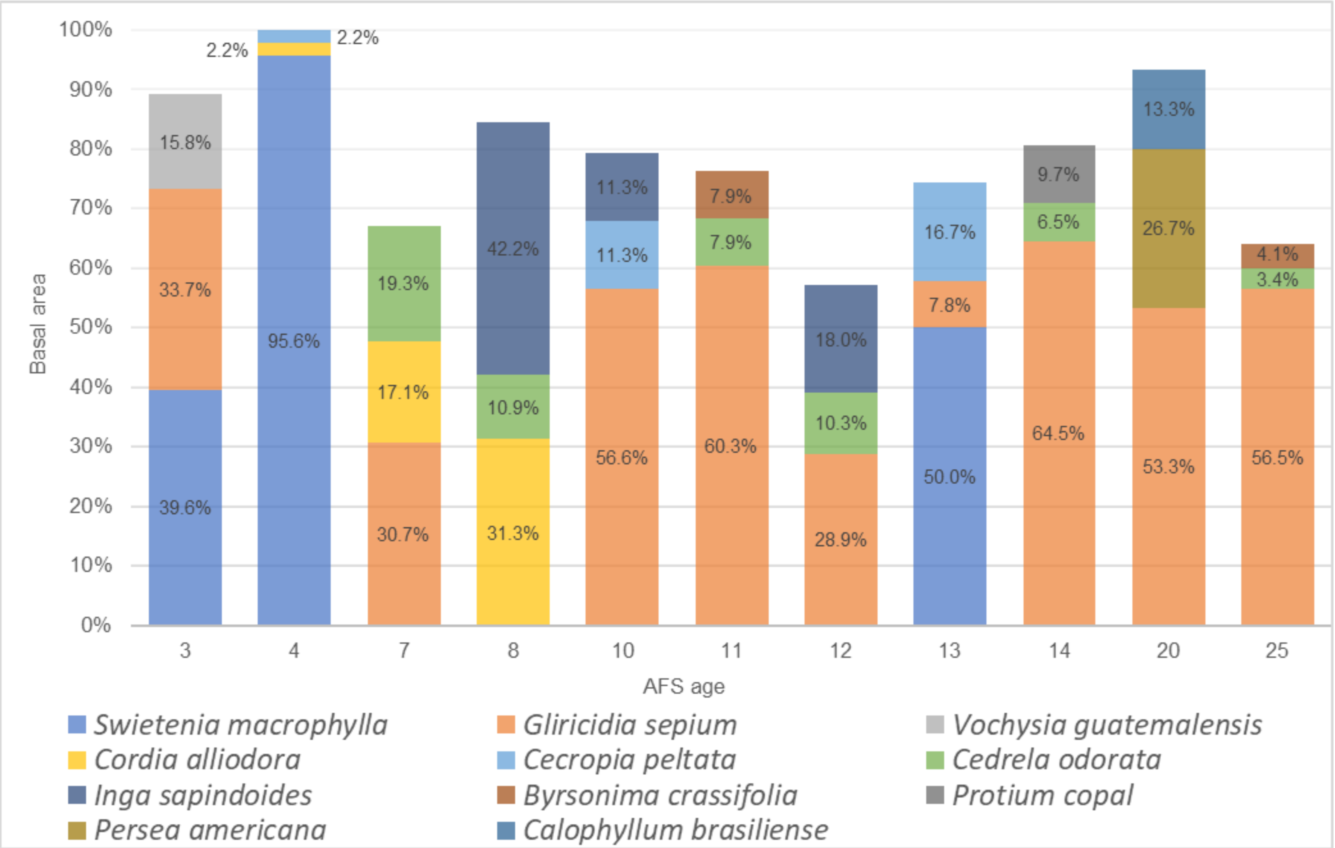

Figure 12. Relative Basal area of the three most dominant tree species in different age groups of evaluated agroforestry systems, Alta Verapaz.

6.2.4. Total and commercial volume of timber

The total volume of timber recorded in the whole sample was 352.3 m^3, with a mean of 70.4 m^3 ha^{-1}, varying from 4.9 m^3 ha^{-1} to 171.4 m^3 ha^{-1}. As for the commercial volume, 148.9 m^3 was reached in the total area, with an average of 29.7 m^3 ha^{-1}, ranging from 2.9 m^3 ha^{-1} to 73.1 m^3 ha^{-1} (Table 8).

Table 8. Estimating total and commercial timber volume in CAFS of Alta Verapaz, Guatemala.

Location	Total Volume m^3	Volume m^3 /ha^{-1}	Total commercial volume m^3	Commercial volume m^3/ha^{-1}
Cahabón	86.75	69.40	41.34	33.07
Lanquín	37.62	30.10	12.03	9.62
Cobán	60.66	48.52	33.82	27.06
Panzós	167.31	133.84	61.69	49.35
Total	352.34	$\bar{x}$= 70.46	148.90	$\bar{x}$= 29.78

The five species that stand out in the present study, in terms of total volume per species and localities, are *G. sepium* (25.1 m^3 ha^{-1}), *S. macrophylla* (9.4 m^3 ha^{-1}), *C. odorata* (8.2 m^3 ha^{-1}), *C. alliodora* (7.1 m^3 ha^{-1}) and *Vochysia guatemalensis* Donn. Sm. (5.3 m^3 ha^{-1}), followed by *M. indica* (2.4 m^3 ha^{-1}), *I. sapindoides* (2.3 m^3 ha^{-1}), *P. americana* (1.6 m^3 ha^{-1}), and *Vatairea lundellii* (Standl) (1.4 m^3 ha^{-1}). The remaining 29 species presented values < 1 m^3 ha^{-1}.

The 25- and 13-year-old CAFS reported the highest and lowest values, with 133.3 m^3 ha^{-1} and 18.4 m^3 ha^{-1}, respectively (**Appendix 2**). The same analysis by locality showed that Panzós had the highest total volume with 133.8 m^3 ha^{-1}, while Lanquín had the lowest value with 30.1 m^3 ha^{-1}.

The results of our study indicate that the most relevant species for commercial timber production are *S. macrophylla* (5.6 m^3 ha^{-1}), *C. odorata* (5.1 m^3 ha^{-1}), *G. sepium* (5.1 m^3 ha^{-1}), *C. alliodora* (4.3 m^3 ha^{-1}) and *V. guatemalensis* (3.2 m^3 ha^{-1}). In contrast, the remaining 33 species presented values of commercial timber volume <1 m^3 ha^{-1}, suggesting their potential for commercial timber production is much lower than the five species mentioned. The 3-year- old CAFS (46.6 m^3 ha^{-1}) and 14-year-old (8.0 m^3 ha^{-1}) presented the maximum and minimum values, respectively **(Figure 13**). This difference is because the 3-year-old CAFS harbored timber species of high commercial value with outstanding DBH and height. The locality that reported the highest commercial timber volume was Panzós, with 49.3 m^3 ha^{-1}, and the lowest was Lanquín, with 9.6 m^3 ha^{-1}.

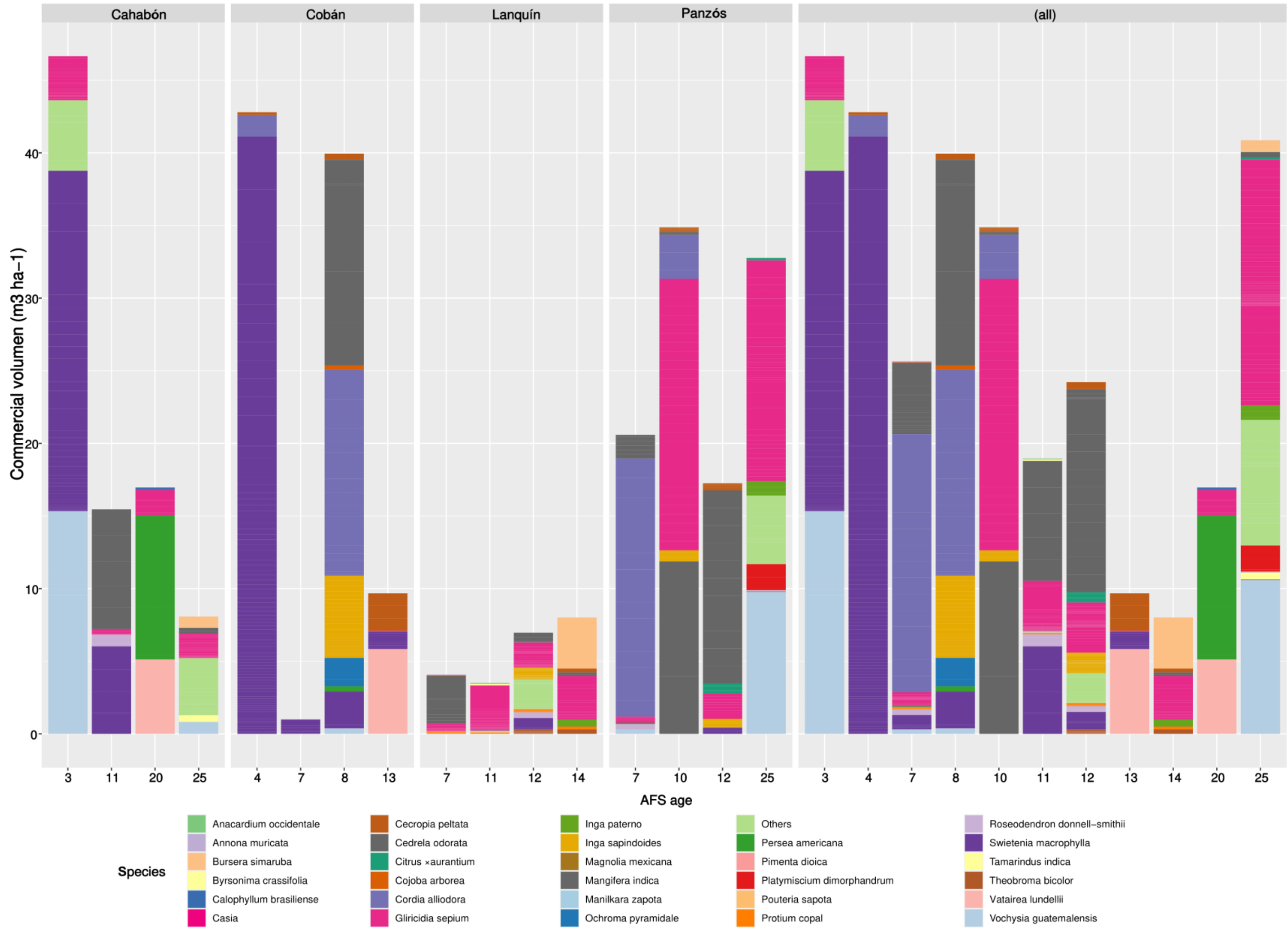

Figure 13. Distribution of commercial timber volume of each tree species by age of the CAFS between study locations.

6.2.5. Description of vegetation structure

The tree inventory confirmed the presence of three main strata in the study area; the lowest stratum, representing 19.3% of the total number of recorded trees, with an account of 160 individuals, the most representative species being *G. sepium*, *I. sapindoides*, and *P. copal*. The middle stratum, with a total of 648 individuals, represented 78.3% of the total, and two dominant species were identified, *G. sepium* and *S. macrophylla*. On the other hand, the high stratum, represented by 19 individuals and concentrating only 2.3% of the total, had *C. alliodora* as the dominant species. The average total height of the trees was 11.9 m, with a variability ranging from 2 m for *G. sepium* to 27 m for *V. guatemalensis*.

Table 9. Description of the vegetation structure estimated in analyzing the timber potential CAFS in Alta Verapaz, Guatemala.

Strata	Individual	Percentage
Lowest stratum (1-8 m),	160	19.3 %
Middle stratum (9-24 m),	648	78.3 %
High stratum (25-35 m)	19	2.3 %

6.2.6. Potential use of the trees as a function of DBH

The statistical analysis of DBH revealed that the average diameter of trees associated with CAFS in Alta Verapaz is 20.2 cm, ranging from 5 cm to 90 cm. The distribution of individuals showed that the most common diameter interval was between 5 cm and 15 cm, with a total of 316 individuals, while the lowest frequency of individuals was observed in the diameter interval ≥35 cm, with a total of 72 individuals. Upon analyzing the results, it is evident that the primary use of trees associated with CAFS in Alta Verapaz is obtaining firewood, accounting for 38.1% of the cases.

According to interviews, farmers in the region use these trees as a source of fuel. Additionally, significant use of the trees was observed for obtaining thin boards at 30.2% and posts at 22.8%. These materials are used to construct rural houses, especially for making roofs, walls, and fences to restrict properties and agricultural areas. Furthermore, they produce furniture such as tables, chairs, and beds. On the other hand, the least frequent use was obtaining thick boards, representing only 8.71% of the cases.

6.3. Economic assessments of two CAFS types

6.3.1. Investment and operating costs

Investment costs for establishing CAFS differ according to the specific type of the system that is being implemented (**Table 10**), with the initial investment for CAFS under complex shade being lower than for CAFS with caoba due to factors such as the cost of planting materials, land preparation, and establishment of the shade tree component.

Projected 24-year operating costs also vary (**Table 10**), being lower for CAFS under complex shade, influenced by the intensity of management required, the cost of inputs, and the efficiency of the production system. In terms of labor, calculated considering the time invested in CAFS management over 25 years, the number of people involved, and the corresponding costs in the rural context of the study area (**Table 10**), CAFS under complex shade requires a higher number of labor and associated costs compared to CAFS with caoba, attributed to the complexity of the shade tree component and the management practices involved.

Table 10. Investment, operation, and labor costs for cocoa agroforestry systems under complex shade and with caoba for 25 years.

	CAFS – complex shade	CAFS – caoba
Investment costs	$2,200	$2,700
Operating costs	$4,745	$8,282
Labor	$15,204	$10,866
Total costs	$19,949	$19,148
Labor days	2,534	1,440

Despite the differences in investment and operation costs, 82% of the interviewed producers expressed a strong interest in conserving disease-resistant, climate-tolerant, and highly productive tree species. Furthermore, 70% of the producers recognized multiple benefits from species diversification in the CAFs. These benefits include economic aspects, such as the inclusion of species with high commercial value in local markets, and ecological elements, such as the reduction of pests and diseases, which contribute to the sustainable productivity of cocoa.

6.3.2. Revenues and profits

Given the various benefits of CAFS, estimated income was projected for year 12. The CAFS under complex shade had an estimated income of \$1,218 ha^{-1} per year, while the CAFS with Caoba generated an annual income of \$1,540 $ha^{-1.}$ The main income-generating components in the CAFS under complex shade are cocoa, banana, corn, citrus, resins, firewood, and timber, while in the CAFS with caoba, the main income generators are cocoa, banana, and timber **(Figure 14).**

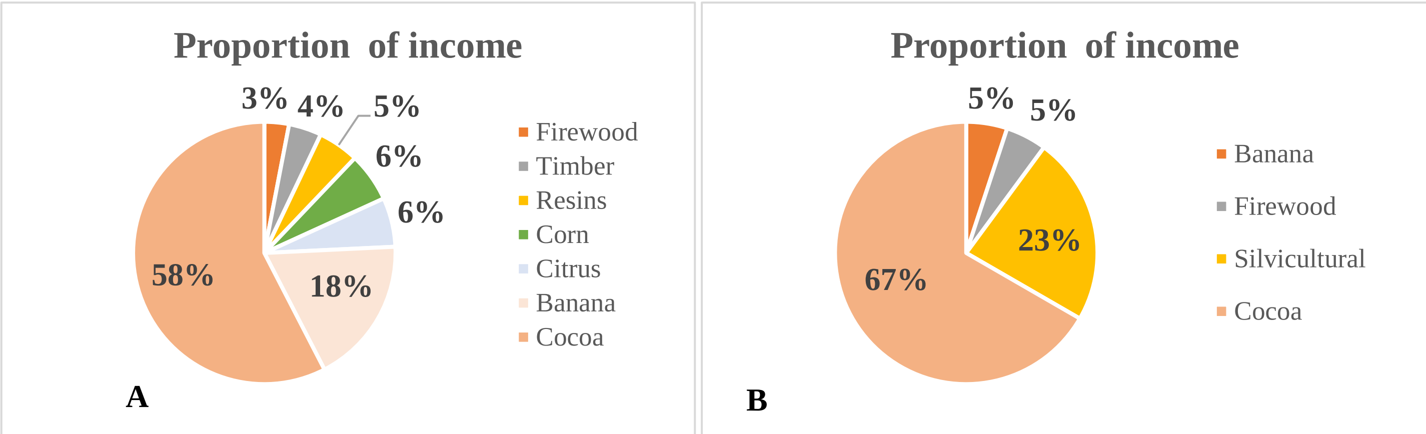

Figure 14. Percentage distribution of income generated by different products in two CAFS under different shade conditions: (A) the income distribution for a CAFS under complex shade, where cocoa is grown together with diverse species that provide shade and additional products. (B) the income distribution for a CAFS with caoba, where cocoa is grown together with high-value timber species.

6.3.3. Profitability of CAFS

Table 11 presents the financial indicators of NPV and B/C for two CAFS in Alta Verapaz, Guatemala: CAFS with complex shade and CAFS with caoba. These indicators were calculated using two different DR, 12% and 25%, in order to compare the systems' profitability under various economic scenarios.

The results showed that both CAFS present a positive NPV under the two discount rates applied, indicating that they are economically viable throughout the analysis period.

However, the CAFS with caoba exhibits a higher NPV than the CAFS with complex shade, under both DR, suggesting a higher profitability in terms of present value.

Considering B/C, both CAFS show values greater than 1, implying that the benefits generated exceed the costs incurred. For both DR evaluated, the CAFS with complex shade had a lower B/C ratio than the CAFS with caoba, indicating a lower efficiency in generating benefits per unit of cost.

Table 11. Net Present Value (NPV) and Benefit-Cost Ratio (B/C) for cocoa agroforestry systems with complex shade and Caoba under two discount rates (DR) in Alta Verapaz, Guatemala.

	CAFS-complex shade		**CAFS-caoba**	
	DR 12%	*DR 25%*	*DR 12%*	*DR 25%*
NPV	$ 1,178	$ 370	$ 1,763	$ 478
B/C	1.23	1.13	1.33	1.25

IRR varied according to the type of CAFS and the discount rate applied, which allows for a comparison of the profitability of each system under different economic scenarios. These results benefit decision-making regarding implementing and managing CAFS in the region. IRR was estimated at 26% for the CAFS under complex shade and 34% for the CAFS with caoba. These values were calculated considering a 25-year time horizon.

6.4. Sensitivity analysis

6.4.1. Sensitivity analysis for CAFS under complex shade

With a discount rate of 12%, the NPV of the CAFS under complex shade is $1,178 in the base scenario. If cash flows increase by 50%, the NPV increases to $1,767, while if they decrease by 50%, the NPV decreases to $589. This indicates that the project is sensitive to changes in cash flows and that its profitability is significantly affected in the pessimistic scenario. At a 25% discount rate, the NPV of the CAFS under complex shade is $370 in the base scenario. A 50% increase in cash flows results in an NPV of $555, while a 50% decrease generates an NPV of $185 (**Table 12**). Although the project is less profitable at a higher discount rate, it is still viable in the baseline and optimistic scenario, but its profitability is compromised in the pessimistic scenario.

The B/C ratio is 1.23 and 1.13 in the baseline scenario, with 12% and 25% discount rates, respectively. In the optimistic scenario, the B/C ratio increases to 1.85 and 1.70, indicating higher profitability. However, in the pessimistic scenario, the B/C ratio decreases to 0.62 and 0.57, suggesting that the project would not be profitable under these adverse conditions (**Table 12**).

Table 12. Sensitivity analysis of the Net Present Value (NPV) and Benefit-Cost Ratio (B/C) for the CAFS under complex shade, considering variations of ±50% in cash flows and discount rates of 12% and 25%.

12% discount rate			
Indicator	**Base scenario**	**Scenario +50%**	**Scenario -50%**
NPV	$1,178	$1,767	$589
B/C	1.23	1.85	0.62
25% discount rate			
NPV	$370	$555	$185
B/C	1.13	1.70	0.57

6.4.2. Sensitivity analysis for CAFS with caoba

With a discount rate of 12%, the NPV of the caoba CAFS is $1,763 in the base scenario. If cash flows increase by 50%, the NPV increases to $2,645; if they decrease by 50%, the NPV decreases to $882 (**Table 13**). This indicates that the systems with cocoa and Caoba are sensitive to changes in cash flows and, although they remain profitable in the pessimistic scenario, the profitability is significantly affected. At a 25% discount rate, the NPV of CAFS with caoba is $487 in the base scenario. A 50% increase in cash flows results in an NPV of $730, while a 50% decrease generates an NPV of $243 (**Table 13**). Although the systems are less profitable at a higher discount rate, they are still viable in the baseline and optimistic scenario. However, the profitability is compromised in the pessimistic scenario, as the NPV is significantly reduced.

In the CAFS with caoba, the B/C ratio is 1.33 and 1.25 in the base scenario, with 12% and 25% discount rates, respectively. In the optimistic scenario, the B/C ratio increases to 2 and 1.88, indicating higher profitability. However, in the pessimistic scenario, the B/C ratio decreases to 0.67 and 0.63, suggesting that the systems would not be profitable under these unfavorable conditions, as the costs would exceed the benefits (**Table 13**).

Table 13. Sensitivity analysis of the Net Present Value (NPV) and Benefit-Cost Ratio (B/C) for the CAFS whit caoba, considering variations of ±50% in cash flows and discount rates of 12% and 25%.

12% discount rate			
Indicator	**Base scenario**	**Scenario +50%**	**Scenario -50%**
NPV	$1,763	$2,644	$882
B/C	1.33	2	0.67
25% discount rate			
NPV	$487	$730	$244
B/C	1.25	1.88	0.63

7. Discussion

7.1. Tree diversity, structure, and composition in CAFS in Alta Verapaz, Guatemala

The results of this study demonstrate that CAFS in the department of Alta Verapaz, Guatemala, harbor a high diversity of tree species, thus contributing to biodiversity conservation in the region. These findings are in line with previous studies conducted in other countries where the role of CAFS in wildlife conservation has been recognized (Abada Mbolo et al. 2016; Blaser et al. 2018).

The main hypothesis in this research established that the CAFS of Alta Verapaz harbor a high diversity of tree species and this diversity varies according to the age of the systems and the management practices adopted by the producers. The results support this hypothesis since 59 species belonging to 34 families were identified in the evaluated CAFS. Although species diversity and composition differences were observed between systems of different ages and locations, these were not statistically significant according to the analysis of variance ($p > 0.05$).

The results showed that CAFS of 9-12 years had the highest diversity according to Shannon's Index (H'=1.99), while those of 26-30 years had the lowest diversity (H'=0.34). This pattern may be due to growers enriching the agroforestry systems during the first years with a variety of timber species which are then harvested at around 16 years of growth, which manifests as a decrease in tree species richness as well as diversity indices. Previous studies have suggested that CAFS can maintain higher diversity than conventional farming systems (Suatunce et al. 2003; Deheuvels et al. 2012), but further research is needed in Alta Verapaz to confirm whether this is the case in the region.

These findings have significant implications for biodiversity conservation and ecosystem services in the region, as even mature agroforestry systems can play a crucial role in preserving native species, maintaining wildlife habitats, functioning as biological corridors, providing alternative habitats for wildlife, facilitating species adaptation to modified landscapes, and maintaining essential services for human well-being (Córdova-Ávalos et al. 2001). In addition, species diversity in CAFS can provide farmers with opportunities to diversify their sources of income, thereby increasing their economic resilience (Rahman et al. 2023).

However, the decline in diversity in older CAFS underscores the need to develop long-term management strategies to maintain adequate levels of diversity throughout the life cycle of the systems. This may involve promoting natural regeneration, species enrichment, system renewal and rehabilitation, and selective pruning rather than complete clear-cutting of mature trees (Octavia et al. 2022). These strategies can help ensure that CAFS continue to provide ecological and socioeconomic benefits to Alta Verapaz communities over the long term.

Regarding differences by location, CAFS in the municipality of Panzós showed the highest diversity (H'=2.17), followed by Cahabón (H'=2.13) and Lanquín (H'=2.11), while Cobán showed the lowest diversity (H'=1.56). This may be due to differences in management practices, production objectives, and agroecological conditions between sites. In the case of Cobán, the lower diversity of tree species in CAFS could be related to a more intensive cocoa-oriented approach, where farmers prioritize establishing systems with fewer shade tree species to maximize cocoa yields. In addition, in Cobán, CAFS are more often established on previously deforested or degraded land, rather than under thinned forest canopy, implying that farmers start from a base of lower tree diversity when establishing their systems, reflected in the observed diversity indices.

Jaccard's index showed that the CAFS in Cahabón, Panzós, and Lanquín have moderate to high similarity in species composition (0.57, 0.62, and 0.68, respectively), with the highest similarity between Panzós and Cahabón, sharing 21 species. These results imply that these sites adhere to traditional management practices that promote natural regeneration, thus aiding in the conservation of native species. On the other hand, the DAPC revealed that some CAFS in Cahabón, Panzós, and Cobán have a similar composition to the floristic structure and diversity recorded in Lanquín.

This indicates that the Lanquín CAFS model, characterized by a more agroecological approach, is beginning to be implemented in other cocoa-producing areas. The agroecological approach implemented in the Lanquín CAFS is based on fundamental principles, such as species diversification, taking advantage of ecological processes, minimizing external inputs, and integrating traditional knowledge (Altieri et al. 2015). Lanquín's CAFS has more tree and crop species and cocoa. This diversity creates a more complex and varied system, which helps to have more biodiversity and a better functioning ecosystem. In addition, natural processes such as nutrient recycling, natural pest and disease control, and soil moisture retention are better utilized in Lanquin's CAFS. This is achieved by using cover crops, adding organic matter to the soil, and encouraging positive interactions between plant species.

The similarity in species composition between some CAFS in Cahabón, Panzós, and Cobán with the Lanquín systems suggests that farmers in these areas are adopting similar agroecological practices, such as conservation of native species, species enrichment, and management of natural regeneration. This could be due to a growing recognition of the potential of agroecological systems to reconcile cocoa production with biodiversity conservation and the provision of ecosystem services (Vaast & Somarriba 2014). In addition, the adoption of agroecological practices could be influenced by the growing demand in international markets for cocoa produced in a sustainable and biodiversity-friendly manner (Rueda et al. 2015).

The analysis of the IVI of tree species in the CAFS of Alta Verapaz provides crucial information on their ecological role and contribution to these systems' structure and function. Species with the highest IVI, such as *G. sepium* (49.2%), *S. macrophylla* (15.1%), *C. odorata* (11.6%), *P. copal* (9.2%) and *C. alliodora* (8.99%), play fundamental roles in maintaining the productivity, sustainability and economic resilience of CAFS in the region. *G. sepium*, a nitrogen fixing legume stands out for its ability to improve soil fertility and provide adequate shade for cocoa (Casanova-Lugo et al. 2016), while *S. macrophylla* and *C. odorata*, species of high timber value, offer farmers an additional source of long-term income (Ramírez-Argueta et al. 2022). On the other hand, *P. copal* and *C. alliodora,* species native to the region, reflect local farmers' appreciation for the conservation of native biodiversity and the use of local resources. *P. copal* is valued for its aromatic resin, used in traditional medicine and religious ceremonies (Merali et al. 2018), while *C. alliodora* is appreciated for its high-quality timber, which is often used in construction and carpentry (Somarriba et al. 2014).

Species IVI may vary among regions and agroforestry systems, depending on local agroecological conditions and farmer preferences (Salvador-Morales et al. 2020; Zequeira-Larios et al. 2021). These findings can guide farmers and decision-makers in selecting priority species for the conservation and sustainable management of CAFS, thus contributing to preserving biodiversity and the well-being of local communities (Jacobi et al. 2009; Rivero-Romero et al. 2016).

The findings of this study are consistent with the results of previous research that has evaluated species diversity in CAFS in different parts of the world. For example, studies conducted in Nicaragua, Mexico and Costa Rica have reported species richness similar to that found in the CAFS of Alta Verapaz (Suatunce et al. 2003; Matey et al. 2013a; Sánchez Gutiérrez et al. 2016b). Research on CAFS in West Africa, such as Ghana and Cameroon, has also highlighted their importance for conserving tree biodiversity (Sonwa et al. 2017; Asare et al. 2019). However, this study makes new contributions to knowledge by providing detailed information on tree species diversity and composition in CAFS in a region where previous knowledge was limited. In addition, the focus on the relationship between system age and tree species diversity provides new insights into the temporal dynamics of these systems and their potential for biodiversity conservation over time.

One of the main strengths of this study is the focus on a specific region (Alta Verapaz) and the detailed analysis of tree species diversity and composition in CAFS. This fact allows a deeper understanding of the contribution of these systems to biodiversity conservation in the local context. In addition, assessing the relationship between CAFS age and tree species diversity provides valuable information on the temporal dynamics of these systems. Farmers' management practices influence these changes in diversity over time (Sambuichi et al. 2012). For example, farmers may intentionally plant a greater variety of tree species in young CAFS to improve the structure and function of the system (Goñas et al. 2022). As CAFS age, farmers may selectively harvest some tree species for timber and non-timber products, which may decrease diversity in older systems.

However, it is essential to recognize some limitations of the study. The assessment focused only on tree species diversity without considering other components of biodiversity, such as herbaceous plants, the fauna associated with CAFS, and others. Future studies could address biodiversity in these systems more comprehensively, including other relevant taxonomic groups.

In practical terms, the results suggest that CAFS managed by Q'eqchi's indigenous communities plays a crucial role in biodiversity conservation in the region. Furthermore, the findings can support the development of conservation policies and strategies that recognize and support the role of CAFS in biodiversity protection.

This study raises new lines of research for future work; one promising line would be to evaluate the relationship between tree species diversity in CAFS and the provision of specific ecosystem services, such as microclimate regulation, carbon sequestration, and soil health conservation. This would provide a deeper understanding of the ecological role of these systems. In addition, conducting comparative studies between CAFS and other land use systems, such as natural forests and monocultures, would allow an assessment of their relative effectiveness in biodiversity conservation. This information would be valuable in guiding landscape management decisions and conservation priorities.

7.2. Productive potential of timber trees in CAFS in Alta Verapaz, Guatemala

The results of this study reveal the diversity of tree species with timber potential in CAFS in Alta Verapaz, Guatemala, and support the hypothesis that these species, in addition to their timber value, have a wide range of local uses that contribute to the generation of forest products and the socioeconomic development of the communities that depend on CAFS.

Compared to the results of our study, there are other cocoa-growing regions with higher richness and diversity of species, e.g. in the Amazon; this could be because cocoa plantations in the Amazonian region are established in areas of cleared forests, while in Alta Verapaz, most of the shade trees in the CAFS were intentionally planted after clearing the forests (Somarriba 2004). Despite this difference, the present results are valuable for the conservation of biodiversity since they indicate that the management of CAFS by small producers can foster a greater diversity of species and families compared to other cultivation systems (Sol-Sánchez et al. 2018; Niether et al. 2020).

These findings are significant since biodiversity is essential for the maintenance of healthy ecosystems and for the provision of ecosystem services that are critical to human well-being, such as pollination (Barrios et al. 2018), pest control (Delgado-Vargas & Muñoz Rodríguez 2023) and firewood supply (Sibelet et al. 2019).

In Mesoamerica, various studies have identified the potential of certain tree species cultivated in diverse CAFS designs to produce wood; these studies have also highlighted the possibility of selling this wood in local markets as a source of income for farmers (de Sousa et al. 2016). In the context of agroforestry arrangements in Alta Verapaz, the frequency of species, such as *G. sepium, S. macrophylla*, *I. sapindoides, P. copal*, and *C. odorota*, can have substantial economic implications for local communities that depend on agricultural production. A concrete example is found in the municipalities of Lanquín and Cahabón, where the sale of resins extracted from *P. copal* trees generates complementary income for family sustenance during most of the year.

In the case of Cobán, the producers manage the *S. macrophylla* and *C. odorota* trees, before final harvesting, by pruning and thinning, obtaining economic resources simultaneously. These examples illustrate how the presence and abundance of certain species in AFS can provide additional economic opportunities for local communities. Therefore, it is essential to carefully consider species selection in agroforestry designs to promote resilience and long-term sustainability. During interviews with cocoa producers in Alta Verapaz, their interest in preserving tree species in these designs that are disease-resistant, climate-tolerant, and highly productive was evident, particularly regarding the supply of firewood and timber to meet their basic needs. Therefore, it is essential to take into account economic, ecological, and social aspects when selecting and managing species in these agroforestry arrangements (Núñez et al. 2021).

Wood production in the CAFS of Alta Verapaz is crucial because many people in rural Guatemala depend on firewood for cooking and other household needs (Pineda 2022). In addition to covering these basic needs, timber production in these systems can generate additional income for farmers and their families, especially in communities where paid employment opportunities are limited (Sibelet et al. 2019). Well-designed AFS can provide a significant volume of wood and by-products when correctly managed. This management may involve pruning practices, careful species selection, and crop rotation, which contribute to increasing soil productivity (Niether et al. 2018).

The richness of tree species recorded in this study represents a distinctive CAFS trait in the Alta Verapaz department. This finding provides a valuable perspective on the potential of the tree component in CAFS to offer a wide range of ecosystem services for the population (Bukomeko et al. 2019). One of the key indicators to understand the relevance of shade trees in the evaluated CAFS is the total basal area recorded, which reached 33.3 m^2. It is essential to highlight that the 10-year-old CAFS stood out by exhibiting the highest basal area value, reaching 13.57 m^2 ha^{-1} (Appendix 5), suggesting that this specific system has effectively promoted the growth and development of shade trees. In contrast, in Lanquín, the 13-year-old AFS presented the lowest basal area value, with only 2.23 m^2 ha^{-1} (Appendix 5). This disparity could be attributed to several factors, among which silvicultural management and the diversity and density of recorded trees stand out. These factors have been mentioned in previous studies as possible causes of the variability in the values of BA in AFS (Navarro-Garza et al. 2012; Haggar et al. 2015).

In the Panzós region, producers preferred to preserve some remaining trees from the secondary forest within the CAFS. This decision positively affected the reported total wood volume, with species such as *V. guatemalensis* and *C. alliodora* standing out. On the other hand, it was found that the timber potential in Lanquín differs from that of the evaluated CAFS in other municipalities. This is due to the farmers' preference for fast-growing trees with less canopy coverage, which, in turn, have the capacity to provide shade and improve soil fertility (Matey et al., 2013). Among the most prominent species in this preference are *G. sepium, P. copal*, *I. sapindoides*, and *Theobroma bicolor* Bonpl., which are used both for firewood production and other essential products for the subsistence of the local population. According to Nicli et al., (2019), the versatility, and multiple benefits these species offer to agricultural communities have been crucial for their adoption, leading to the recognition of their importance in the department's management and conservation of AFS.

Our results indicate that wood's potential for producing thick planks is lower than that recorded by other authors (Sánchez Gutiérrez et al. 2016) who report that up to 27% of the total volume is used for this purpose. The fact that most of the trees associated with the CAFS are used for producing firewood, thin boards, and poles suggests that, although wood provides some income, its value in the local market is relatively low, and it is not considered a critical source of income for the producers. Nonetheless, this production does strengthen the rural livelihoods of the families, providing additional resources and improving their overall well-being.

In addition, the low frequency of use of wood to produce thick planks indicates a low demand for this type of wood in the area, which limits business opportunities for producers. To increase the diversity of timber trees and ensure usable volumes in the future in those CAFS with low commercial yields, it is essential to improve agroforestry designs and apply silvicultural planning tools (Esche et al. 2023).

A key strategy is to prioritize the combination of trees intended for subsistence and those of commercial value, aiming to enhance forest production and the satisfaction of basic family needs (Méndez et al. 2013; Maza et al. 2016; Villareyna et al. 2020). However, it is essential to highlight that the lack of economic valuation of timber in the local market does not necessarily imply that wood has no value in ecosystem services (Sol-Sánchez et al. 2018). Trees in AFS provide a series of benefits, such as carbon sequestration (Ibrahim et al. 2007), climate regulation (Peralta-Rivero 2022), soil conservation, and biodiversity conservation (Vebrova et al. 2014; López-Baez et al. 2015), which can have a positive impact on the sustainability of the production system. In addition, there are opportunities to explore other markets, such as crafts, and access to certification programs and sustainable markets; by maintaining a diversity of trees, small producers can meet certification criteria for sustainable practices, giving them access to programs and markets that value responsible and environmentally friendly production. Therefore, it is vital to consider the immediate economic value of timber and its importance in terms of ecosystem services and possible alternative market opportunities.

From a theoretical perspective, the results contribute to the knowledge of tree species' multifunctional role in CAFS by providing timber products, non-timber products, and ecosystem services (Sol-Sánchez et al., 2018; Niether et al., 2020). In addition, the study highlights the importance of various local uses of species to understand their contribution to the socioeconomic development of communities.

The results have important implications for the management and conservation of CAFS in Alta Verapaz. Identifying key species with timber potential and multiple local uses can guide species selection and management strategies, promoting the resilience and sustainability of these systems. In addition, the study highlights the role of CAFS in providing ecosystem services and supporting the livelihoods of rural communities (Barrios et al., 2018; Sibelet et al., 2019).

This study opens new avenues for future research, such as the evaluation of the economic viability and value chain of products derived from CAFS, the in-depth exploration of traditional knowledge and practices associated with the management and use of tree species, and the development of participatory approaches that empower local communities in the sustainable management of these systems. Interesting findings, such as the preference of producers in Panzós for conserving remnant trees from secondary forests within CAFS or the importance of fast-growing species and lower canopy cover in Lanquín, highlight the effectiveness of integrating native species in CAFS to improve their timber potential and contribute to the conservation of local biodiversity (Delgado-Vargas et al., 2022), as well as the multifunctionality of tree species and the need to consider the multiple benefits they provide when designing and managing these systems.

7.3. Economic assessments of two CAFS arrangements

The results of this study reveal that CAFS under complex shade and with caoba trees in Alta Verapaz present differences in their socioeconomic viability. The evaluation of investment, operation and labor costs, as well as the income and profits generated by these systems, confirm that factors such as cocoa yields, sales prices, production costs and the generation of additional income influence their profitability and potential to contribute to sustainable rural development in the region (Espinosa-García et al. 2015).

CAFS under complex shade requires a lower initial investment than CAFS with caoba due to factors such as the cost of planting materials, land preparation, and establishment of the shade tree component. In addition, projected 24-year operating costs also vary, being lower for CAFS under complex shade, influenced by the intensity of management required, the cost of inputs, and the efficiency of the production system.

In terms of labor, CAFS under complex shade require higher labor and associated costs than CAFS with caoba, which is attributed to the complexity of the shade tree component and the management practices involved. These results have important implications for producer decision-making and the planning of rural development strategies that promote the adoption and sustainable management of CAFS in the region (Armengot et al. 2020).

These implications can be analyzed from different perspectives.

First, the higher number of labor days and associated labor costs in complex shade CAFS can influence total production costs. Producers should consider these additional costs when evaluating the profitability of their systems and making decisions about adopting or maintaining this type of agroforestry arrangement (Jezeer et al. 2017). These findings can guide producer decision-making and the formulation of rural development policies and programs that encourage the adoption and sustainable management of CAFS in Alta Verapaz and other regions with similar conditions (Trinidad et al. 2016).

On the other hand, the increased demand for labor in complex shade CAFS can be seen as an opportunity for employment generation in rural communities. These systems can contribute to job creation and improved livelihoods for families dependent on agriculture (Cerda et al. 2014). In addition, the complexity of managing CAFS under complex shade may require further training and technical assistance for producers (Dahlquist et al. 2007).

This implies the need to develop extension and training programs that provide producers with the knowledge and skills to manage these systems efficiently. Rural development strategy planners should consider including these training and technical assistance components in their CAFS adoption support programs (Orozco Aguilar et al. 2015). Finally, the distribution of labor-related tasks and benefits in CAFS may also affect gender equity (Kiptot & Franzel 2012). It is essential to consider how employment opportunities and income generated by these systems are distributed between men and women.

The results of this study are consistent with previous research that has evaluated the economic viability of cocoa agroforestry systems in different parts of the world. Studies in Ghana (Obiri et al. 2007), Costa Rica (Somarriba et al. 2013), and Ecuador (Tapia-Vera et al. 2021) have shown that CAFS can be economically profitable and contribute to sustainable rural development, depending on factors such as cocoa yields, selling prices, production costs and the generation of additional income from other products in the system.

Identifying the factors that influence the profitability of these systems can help producers optimize their management practices and improve the economic viability of their systems (Gockowski et al. 2013). In addition, the study highlights the importance of considering income diversification in CAFS through the production of other products such as bananas, maize, citrus, resins, and timber, which can contribute to the economic resilience of producers and the long-term sustainability of the systems (Jagoret et al. 2011).

An interesting result of this study is that, although caoba CAFS are more profitable in terms of NPV and IRR, complex shade CAFS have a greater potential to generate diversified income from a variety of products in addition to cocoa. This suggests that income diversification can effectively improve farmers' economic resilience and reduce their dependence on a single crop (Gama-Rodrigues et al. 2021).

Another unexpected result is that, although CAFS with caoba require a higher initial investment, long-term operating costs are higher in CAFS under complex shade. This could be due to the greater complexity of management needed for these systems, which implies a more intensive use of labor and other resources. This finding highlights the importance of considering investment costs and long-term operating costs when evaluating the economic viability of different CAFS arrangements (Kouassi et al. 2023).

Sensitivity analysis showed that both complex shade CAFS and caoba CAFS were sensitive to changes in cash flows. In the optimistic scenario, with a 50% increase in cash flows, NPV and B/C ratio improved for both systems, indicating higher profitability. In the pessimistic scenario, with a 50% decrease in cash flows, NPV decreased but remained positive for both systems. However, the B/C ratio was less than 1 in this scenario, suggesting that the systems would not be profitable under these adverse conditions, as the costs would exceed the benefits. These results are consistent with the findings of Gockowski et al. (2013), who found that the financial indicators of CAFS were more sensitive to changes in revenues than to changes in costs.

This finding highlights the importance of considering different economic scenarios when assessing the viability of CAFS. Sensitivity analysis provides valuable information for decision-makers by showing how financial indicators may be affected by changes in key variables, allowing for better planning and risk management (Espinosa-García et al. 2015).

This study opens new outlooks for future research on the socioeconomic viability of CAFS and their potential to contribute to sustainable in Alta Verapaz. One line of research would be to evaluate the impact of different management practices, such as pruning, fertilization, and pest and disease control, on these systems' profitability and long-term sustainability (Esche et al. 2023). Another relevant area of research would be the analysis of the value chain of cocoa and other products generated in CAFS to identify opportunities to improve these chains' efficiency, equity, and sustainability.

8. Conclusion

This research aimed to evaluate the tree diversity, timber potential, and socioeconomic viability of cacao agroforestry systems in Alta Verapaz, Guatemala, to determine their contribution to biodiversity conservation, timber product generation, and sustainable rural development.

The first specific objective sought to characterize the botanical composition and structure of tree vegetation in CAFS of different ages. The results revealed a high diversity of tree species identified in the evaluated systems. In addition, diversity was found to vary according to the age of the CAFS. These findings provide valuable information on diversity dynamics in these systems and lay the foundation for developing management practices promoting biodiversity conservation.

The second objective was determining the tree species with the greatest timber potential and their local uses. The results identified certain species as having the most significant timber potential and a wide range of local uses. These findings highlight the role of CAFS in generating forest products and the livelihoods of the local communities that depend on them.

The third objective evaluated the economic viability of CAFS and the socioeconomic factors that influence their adoption and management. The results showed differences in socioeconomic viability among CAFS under different arrangements. These findings significantly guide producers in making informed decisions on the most suitable CAFS arrangement according to their objectives and needs. Likewise, this information is valuable for designing rural development programs that promote adoption and sustainable management of CAFS arrangements that best fit local communities' socioeconomic and environmental contexts.

In a broader context, the results have implications for biodiversity conservation and sustainable development in tropical regions. CAFS can contribute to mitigating the impacts of climate change, regulating ecosystem services, and providing livelihoods for rural communities. The findings of this study may be relevant and applicable in other tropical regions where CAFS is a common agricultural practice. The information generated provides valuable knowledge to guide the sustainable management of these systems and formulate public policies that promote their adoption and strengthening, recognizing their contribution to environmental conservation and rural development.

9. Application and practical implications of the research findings

Sustainable management of CAFS: The results of this study can guide professionals and producers who manage CAFS in prioritizing the conservation of native and ecologically and economically important tree species. These species identified in the study contribute significantly to biodiversity, provision of ecosystem services, and income diversification. In addition, the findings suggest implementing sustainable management practices throughout the life cycle of CAFS, including promoting natural regeneration, enrichment with native species, selective pruning, and planning the renewal of systems rather than the complete felling of mature trees. The results also highlight the importance of considering the integration of high-value commercial timber species, along with multipurpose species, to diversify income and improve the economic resilience of producers.

Strengthening rural development policies and programs: The results of this study call on those responsible for rural development policies and programs to integrate these findings in formulating strategies to promote the adoption and sustainable management of CAFS. One concrete action derived from this research is the implementation of a National Training Program on Integrated CAFS Management aimed at cocoa farmers and agricultural extensionists. This program, based on the evidence generated by this study, should address critical issues such as the selection and management of native and economically important tree species, sustainable silvicultural practices, harvesting of timber and non-timber products, biological pest control, and access to differentiated markets for CAFS products.

Future research and expanding knowledge: The results of this study lay the foundation for future research to deepen the understanding of CAFS and their role in biodiversity conservation and ecosystem service provision. It is recommended that studies on CAFS diversity be expanded, including more comprehensive assessments of associated biodiversity, and the relationship between tree species diversity and the provision of specific ecosystem services be analyzed in detail. In addition, it is suggested that long-term studies be designed to monitor the dynamics of CAFS diversity and structure throughout their life cycle and to develop predictive models to guide the management and renewal of these systems. Finally, the findings of this work highlight the importance of exploring strategies for the economic valuation of the ecosystem services provided by CAFS to support policies and compensation mechanisms that promote their conservation and sustainable management.

Practical considerations and limitations: It is essential to recognize that implementing these recommendations may face practical challenges, such as a lack of financial and technical resources, limitations in knowledge transfer, and resistance to change by some producers. Therefore, it will be crucial to develop participatory approaches involving local communities and producers in planning and implementing sustainable management strategies. In addition, this study focused on a specific region so that the results may have limitations in their applicability to other areas with different environmental, social, and cultural conditions. It is recommended that similar studies be conducted in other regions to validate and adapt the recommendations according to local circumstances.

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11. Appendices

List of the appendices

Appendix 1: Quantitative analysis for the Importance Value Index (IVI) of the most common tree species in cocoa agroforestry systems in Alta Verapaz, Guatemala.

Species	Family	Ab	Sites	RA	RD	RDOM	IVI
Gliricidia sepium (Jacq.) Kunth.	Fabaceae	1117	4	3.6	44.2	1.4	49.2
Swietenia macrophylla King in Hook.	Meliaceae	260	4	3.6	10.3	1.2	15.1
Cedrela odorata L.	Meliaceae	154	4	3.6	6.1	2.0	11.6
Protium copal (Schltdl. & Cham.) Engl.	Burseraceae	165	2	1.8	6.5	0.9	9.2
Cordia alliodora (Ruiz & Pav.) Oken	Boraginaceae	94	3	2.7	3.7	2.6	9.0
Vatairea lundellii (Standl.) Killip	Fabaceae	5	2	1.8	0.2	6.7	8.7
Inga sapindoides Willd.	Fabaceae	98	4	3.6	3.9	1.2	8.6
Sterculia apetala (Jacq.) H.Karst.	Malvaceae	1	1	0.9	0.0	7.0	8.0
Vochysia guatemalensis Donn.Sm.	Vochysiaceae	40	3	2.7	1.6	3.5	7.7
Terminalia amazonia (J.F.Gmel.) Exell	Combretaceae	2	1	0.9	0.1	6.7	7.7
Dalbergia stevensonii Standl.	Fabaceae	1	1	0.9	0.0	6.5	7.4
Mangifera indica L.	Anacardiaceae	44	3	2.7	1.7	3.0	7.4
Persea americana Mill.	Lauraceae	41	4	3.6	1.6	2.2	7.4
Roseodendron donnell-smithii (Rose) Miranda	Bignoniaceae	73	3	2.7	2.9	1.4	7.0
Pouteria sapota (Jacq.) H.E.Moore & Stearn	Sapotaceae	51	3	2.7	2.0	1.5	6.2
Ochroma pyramidale (Cav. ex Lam.) Urb.	Malvaceae	9	2	1.8	0.4	4.0	6.1
Cecropia peltata L.	Urticaceae	25	4	3.6	1.0	1.1	5.7
Bursera simaruba Sarg.	Burseraceae	10	3	2.7	0.4	2.3	5.4
Brosimum alicastrum Sw.	Moraceae	5	2	1.8	0.2	3.4	5.4
Platymiscium dimorphandrum Donn.Sm.	Fabaceae	17	1	0.9	0.7	3.8	5.3

Species	Family	Ab	Sites	RA	RD	RDOM	IVI
Persea schiedeana Nees	Lauraceae	12	3	2.7	0.5	1.9	5.0
Manilkara zapota (L.) P.Royen	Sapotaceae	9	2	1.8	0.4	2.9	5.0
Hevea brasiliensis (Willd. Ex A.Juss.) Müll.Arg.	Euphorbiaceae	48	1	0.9	1.9	2.0	4.8
Inga paterno Harms	Fabaceae	22	3	2.7	0.9	1.2	4.8
Byrsonima crassifolia Kunth	Malpighiaceae	28	3	2.7	1.1	0.6	4.4
Quercus L.	Fagaceae	3	1	0.9	0.1	3.1	4.1
Cojoba arborea (L.) Britton & Rose	Fabaceae	18	3	2.7	0.7	0.5	3.8
Artocarpus altilis (Parkinson) Fosberg	Moraceae	8	2	1.8	0.3	1.7	3.8
Tamarindus indica L.	Fabaceae	3	1	0.9	0.1	2.8	3.8
Pinus caribaea Morelet	Pinaceae	17	2	1.8	0.7	1.3	3.8
Citrus aurantium L.	Rutaceae	21	2	1.8	0.8	1.0	3.6
Acrocomia aculeata (Jacq.) Lodd. ex R.Keith	Arecaceae	2	1	0.9	0.1	2.4	3.4
Theobroma bicolor Bonpl.	Malvaceae	23	2	1.8	0.9	0.5	3.2
Zanthoxylum riedelianum Engl.	Rutaceae	3	1	0.9	0.1	2.1	3.1
Calophyllum brasiliense Cambess.	Calophyllaceae	14	2	1.8	0.6	0.6	3.0
Pimenta dioica (L.) Merr.	Myrtaceae	16	2	1.8	0.6	0.5	2.9
Psidium guajava L.	Myrtaceae	6	2	1.8	0.2	0.7	2.7
Anacardium occidentale L.	Anacardiaceae	1	1	0.9	0.0	1.6	2.5
Erythrina berteroana Urb.	Fabaceae	5	2	1.8	0.2	0.5	2.5
Enterolobium cyclocarpum (Jacq.) Griseb.	Fabaceae	4	2	1.8	0.2	0.4	2.4
Trema micranthum (L.) Blume	Cannabaceae	1	1	0.9	0.0	1.3	2.2
Crescentia alata Kunth	Bignoniaceae	2	1	0.9	0.1	0.9	1.8
Spondias purpurea L.	Anacardiaceae	1	1	0.9	0.0	0.7	1.7
Annona muricata L.	Annonaceae	2	1	0.9	0.1	0.7	1.7
Cinnamomum verum J.Presl	Lauraceae	12	1	0.9	0.5	0.3	1.7

Species	Family	Ab	Sites	RA	RD	RDOM	IVI
Simira salvadorensis (Standl.) Steyerm.	Rubiaceae	7	1	0.9	0.3	0.5	1.7
Nephelium lappaceum L.	Sapindaceae	6	1	0.9	0.2	0.5	1.6
Tabebuia rosea (Bertol.) DC.	Bignoniaceae	1	1	0.9	0.0	0.6	1.5
Perymenium grande Hemsl.	Asteraceae	1	1	0.9	0.0	0.6	1.5
Annona squamosa L.	Annonaceae	2	1	0.9	0.1	0.5	1.5
Leptolobium panamense (Benth.) Sch.Rodr. & A.M.G.Azevedo	Fabaceae	1	1	0.9	0.0	0.5	1.4
Casia L.	Fabaceae	1	1	0.9	0.0	0.4	1.4
Magnolia mexicana DC.	Magnoliaceae	1	1	0.9	0.0	0.4	1.4
Schizolobium parahyba (Vell.) S.F.Blake	Fabaceae	2	1	0.9	0.1	0.1	1.1
Malus domestica (Suckow) Borkh.	Rosaceae	3	1	0.9	0.1	0.1	1.1
Toxicodendron striatum Kuntz e	Anacardiaceae	1	1	0.9	0.0	0.1	1.1
Citrus aurantiifolia (Christm.) Swingle	Rutaceae	2	1	0.9	0.1	0.1	1.0
∑	=			**100**	**100**	**100**	**300**

Ab= abundance, RA=Relative Abundance (%), RD= Relative Density (%), RDOM= relative dominance, IVI= Importance Value Index

Appendix 2. Total volume was recorded in cocoa agroforestry systems of different ages in Alta Verapaz, Guatemala.

CAFS year-old	Volumen m3 /ha-1
3	91.12624127
4	71.51925893
7	46.60388494
8	73.84095803
10	131.1750021
11	44.29809252
12	53.19959386
13	18.4866227
14	27.81894261
20	42.399272
25	133.3572422

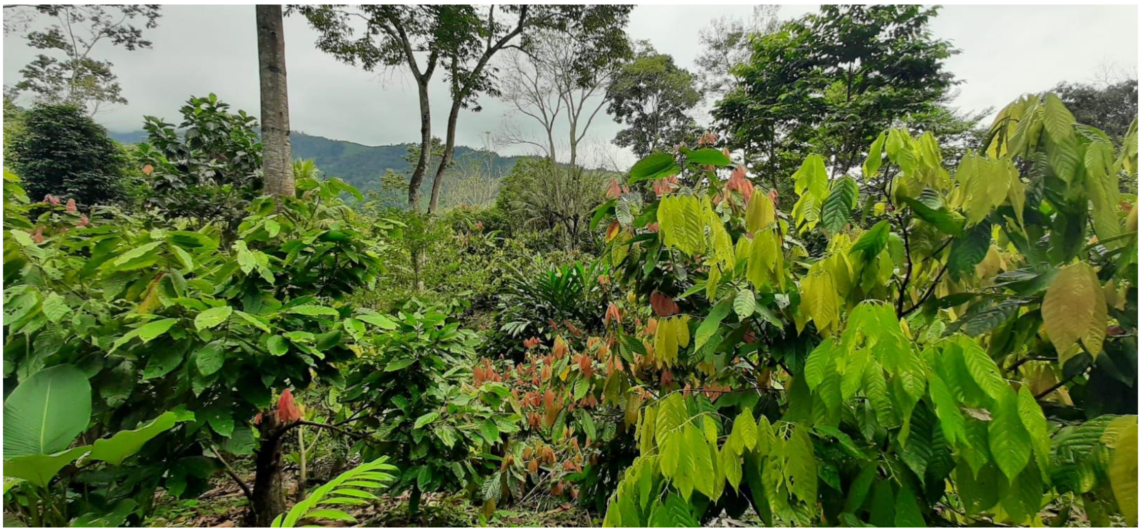
Appendix 3. List of tree species and their abundance associated with cacao (*Theobroma cacao* L.) agroforestry systems in Alta Verapaz, Guatemala.

Family	**Species**	**Common name**	**Abundance**	**Site**
Fabaceae	*Gliricidia sepium* (Jacq.) Kunth.	Madre cacao	290	4
Meliaceae	*Swietenia macrophylla* G.King	Caoba	158	4
Fabaceae	*Inga sapindoides* Willd.	Cuje	63	4
Meliaceae	*Cedrela odorata* L.	Cedro	54	4
Cordiaceae	*Cordia alliodora* (Ruiz & Pav.) Oken	Laurel	42	2
Burseraceae	*Protium copal* (Schltdl. & Cham.) Engl.	Copal Pom	27	2
Vochysiaceae	*Vochysia guatemalensis* Donn.Sm.	San Juan	24	3
Urticaceae	*Cecropia peltata* L.	Guarumo	23	4
Malvaceae	*Theobroma bicolor* Humb. & Bonpl.	Pataxte	18	2
Lauraceae	*Persea americana* Mill.	Aguacate	13	3
Bignoniaceae	*Roseodendron donnell-smithii* (Rose) Miranda	Palo Blanco	13	3
Malpighiaceae	*Byrsonima crassifolia* (L.) Kunth	Nance	12	3
Anacardiaceae	*Mangifera indica* L.	Mango	10	3
Rutaceae	*Citrus ×aurantium* L.	Naranja	9	1
Sapotaceae	*Pouteria sapota* (Jacq.) H.E.Moore & Stearn	Zapote	9	3
Fabaceae	*Inga paterno* Harms	Paterna	7	3
Burseraceae	*Bursera simaruba* (L.) Sarg.	Palo de Jiote	5	2
Calophyllaceae	*Calophyllum brasiliense* Cambess.	Santa María	4	1
Sapotaceae	*Manilkara zapota* (L.) P.Royen	Zapotón	4	2
Malvaceae	*Ochroma pyramidale* (Cav.) Urb.	Palo Balsa	4	2

Family	**Species**	**Common name**	**Abundance**	**Site**
Lauraceae	*Persea schiedeana* Nees	Coyou	4	2
Myrtaceae	*Pimenta dioica* (L.) Merr.	Pimienta gorda	4	1
Fabaceae	*Platymiscium dimorphandrum* Donn.Sm.	Hormigo	4	1
Fabaceae	*Vatairea lundellii* (Standl.) Killip	Medallo	4	2
Fabaceae	*Cojoba arborea* (L.) Britton & Rose	Cola de Coche	3	3
Pinaceae	*Pinus caribaea* Morelet	Pino Blanco	3	2
Fabaceae	*Tamarindus indica* L.	Tamarindo	3	1
Annonaceae	*Annona muricata* L.	Guanabana	2	1
Annonaceae	*Annona squamosa* L.	Anona	2	1
Anacardiaceae	*Anacardium occidentale* L.	Jocote de marañon	1	1
Moraceae	*Artocarpus altilis* (Parkinson) Fosberg	Mazapan	1	1
Fabaceae	*Cassia grandis* L.f.	Mucut	1	1
Fabaceae	*Dalbergia stevensonii* Standl.	Rosul	1	1
Fabaceae	*Enterolobium cyclocarpum* (Jacq.) Griseb.	Puntero	1	1
Fabaceae	*Leptolobium panamense* (Benth.) Sch.Rodr. & A.M.G.Azevedo	Chichipate	1	1
Magnoliaceae	*Magnolia mexicana* DC.	Palo de peña	1	1
Anacardiaceae	*Spondias purpurea* L.	Jocote de mico	1	1
Bignoniaceae	*Tabebuia rosea* (Bertol.) DC.	Matilisguate	1	1

Appendix 4. Cocoa agroforestry systems and their importance in the livelihoods of Q'eqchí families, Department of Alta Verapaz, Guatemala.

Traditional cocoa agroforestry systems in Alta Verapaz Guatemala



Structure and diversity of species in cocoa agroforestry systems, Alta Verapaz, Guatemala

Focus groups with the participation of cocoa producers in Alta Verapaz, Guatemala

Methodological process with the participation of cocoa producers in Alta Verapaz, Guatemala

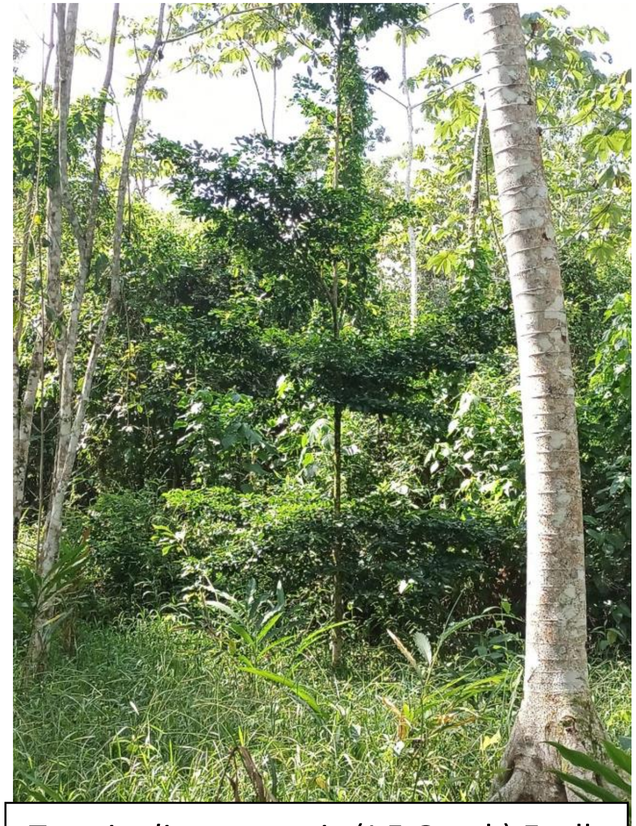
Study on the diversity in cocoa agroforestry systems and the participation of cocoa producers

Application of interviews with cocoa producers in Alta Verapaz, Guatemala

Cocoa production and livelihoods in rural Alta Verapaz, Guatemala

Integrated work between researchers, community leaders, and cocoa producers in Alta Verapaz, Guatemala

Tree diversity in cacao agroforestry systems, Alta Verapaz, Guatemala



Terminalia amazonia (J.F.Gmel.) Exell

Inga sapindoides Wild

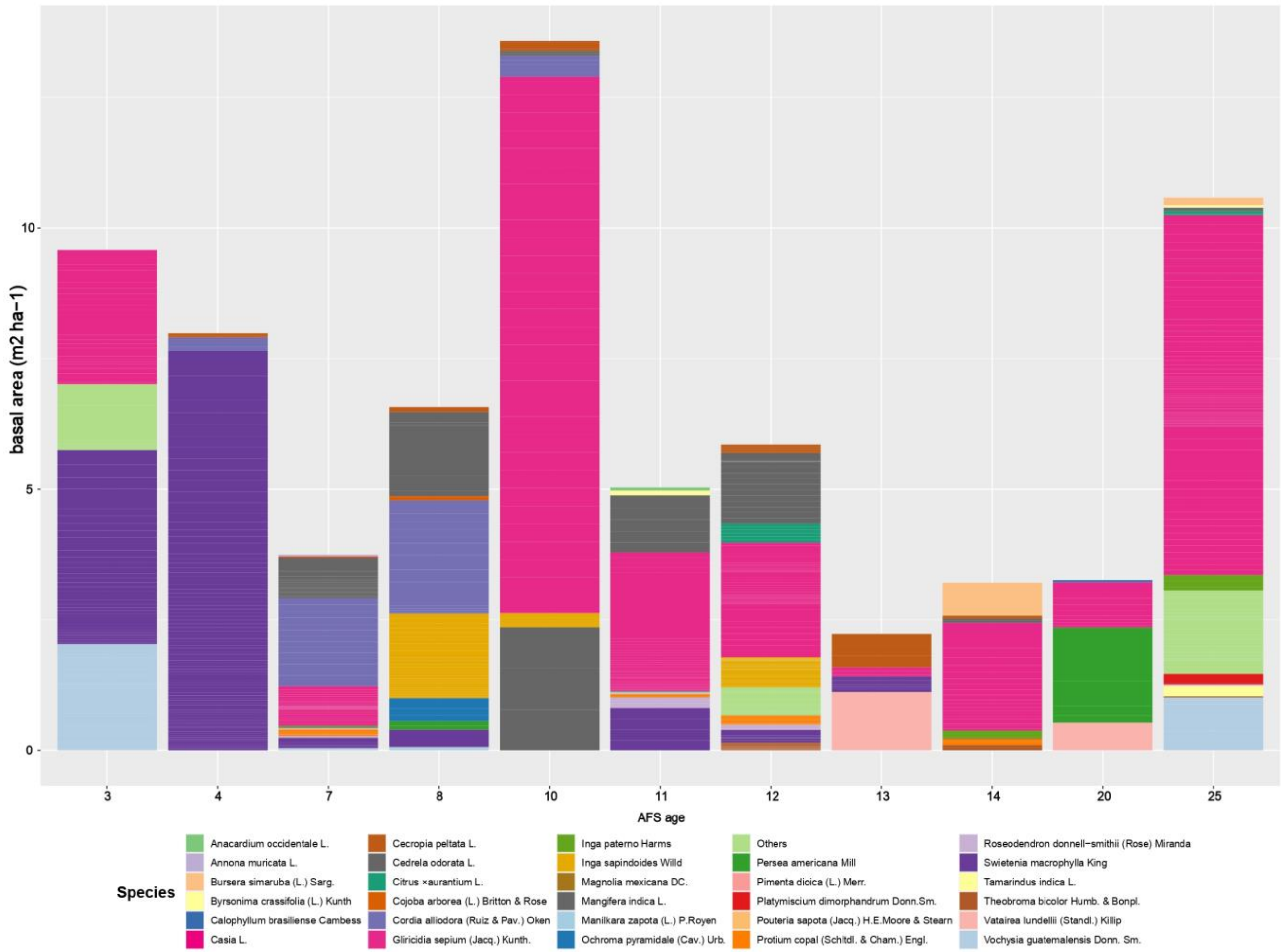
Manilkara zapota (L.) P.Royen

Manilkara zapota (L.) P.Royen

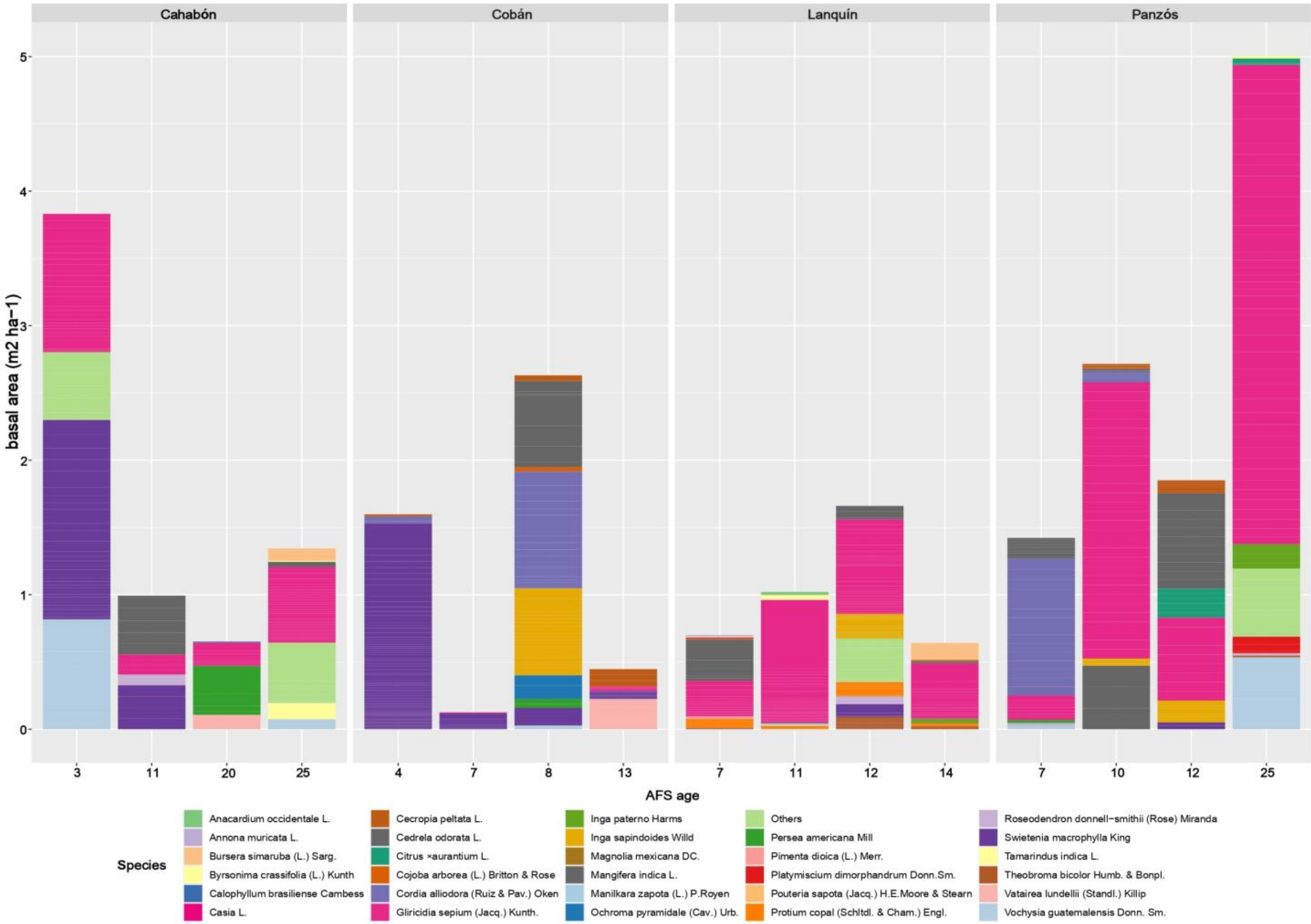
Artocarpus altilis (Parkinson) Fosberg

Simira salvadorensis (Standl.) Steyerm

Appendix 5. Dendrometric estimations, CAFS, Alta Verapaz.



Distribution of the basal area of each species by the age of the CAFS studied in the localities of Alta Verapaz, Guatemala.



Distribution of the basal area (BA) in the CAFS studied in the localities of Cahabón, Cobán, Lanquín, and Panzós, Alta Verapaz, Guatemala

Appendix 6: Shade Diagnosis in Cocoa Agroforestry Systems

1. DIAGNOSIS OF THE AGROFORESTRY SYSTEM (AFS)

Socioeconomic diagnosis (of the family's objectives and resources)

The guiding questions for this diagnosis are:

1) What products do you currently get and what products would you like to get from the AFS? Please also indicate the priority

They can be: cocoa, coffee, banana, plantain, orange, lemon, avocado, timber, firewood, construction materials, medicinal plants, etc.

2) How many people in the family work in your AFS and how much time do they spend on it, and how many people do you or could you hire per year to work in the AFS?

Specific answers should be noted for the number of people working and their estimated time commitment.

3) What type of AFS does your AFS belong to?

Some figures will be shown and the producer should say which type it belongs to and the technician should verify the answer.

In a practice, you can use: FORM 1.

Diagnosis of the site (soil, altitude, topography, climate).

This consists of a general tour of the AFS, preferably with the farmer, to note the main characteristics of the site and the climate by observation.

During the tour, make a drawing of the shape of the FFS and its surroundings, which will be useful for the agroforestry diagnosis.

The guiding questions for this diagnostic are:

1) At what altitude above sea level is the AFS located?

2) How much is the area of your established AFS or how much will be the area of the new AFS?

Write in the data in tasks

3) How old is the AFS?

4) What percentage of the area is on flat, medium slope, and steep slope?

5) Which months of the year are cloudy/rainy, and which months are dry?

6) Are there strong winds that reach the AFS and cause problems? In which months of the year?

7) Is there large adjacent vegetation on the banks that gives much or moderate shade to the AFS? Reflect this on the AFS sketch.

In a practical exercise use FORM 2 for the AFS sketch; FORM 3 for data entry.

Agroforestry Diagnosis (shade, species and phenology)

This consists of making a sketch of the AFS in broad outline, and recording important data on the shade cover, the species of plants/palms/trees present and the products/services they provide, and the phenology of the crop on the site.

The guiding activities or questions for this diagnostic are:

1) On the AFS sketch (FORM 2), roughly indicate which locations (patches) are heavily, moderately, or lightly shaded; patches with a concentration of a specific type of tree, sloping locations; vegetation or land uses abutting the AFS; major rivers, ditches, or trails that cross the AFS.

2) Identify plants/palms/trees for each type of species; group the number of trees per species that are of similar sizes; take estimated data on total height, crown width and occlusion of a tree for each group you made; for each species note the products/services they provide.

4) What is the distance between rows and between plants used for planting? Ask the farmer and verify

5) What percentage of the AFS is growing, starting production or already in full production?

6) In which months: the highest flowering, the highest presence of young fruits, the beginning of ripening?

7) What are the months when harvest, peak harvest, and late harvest begin?

In a practice run use FORM 4.

FORM 1.

SOCIOECONOMIC DIAGNOSIS

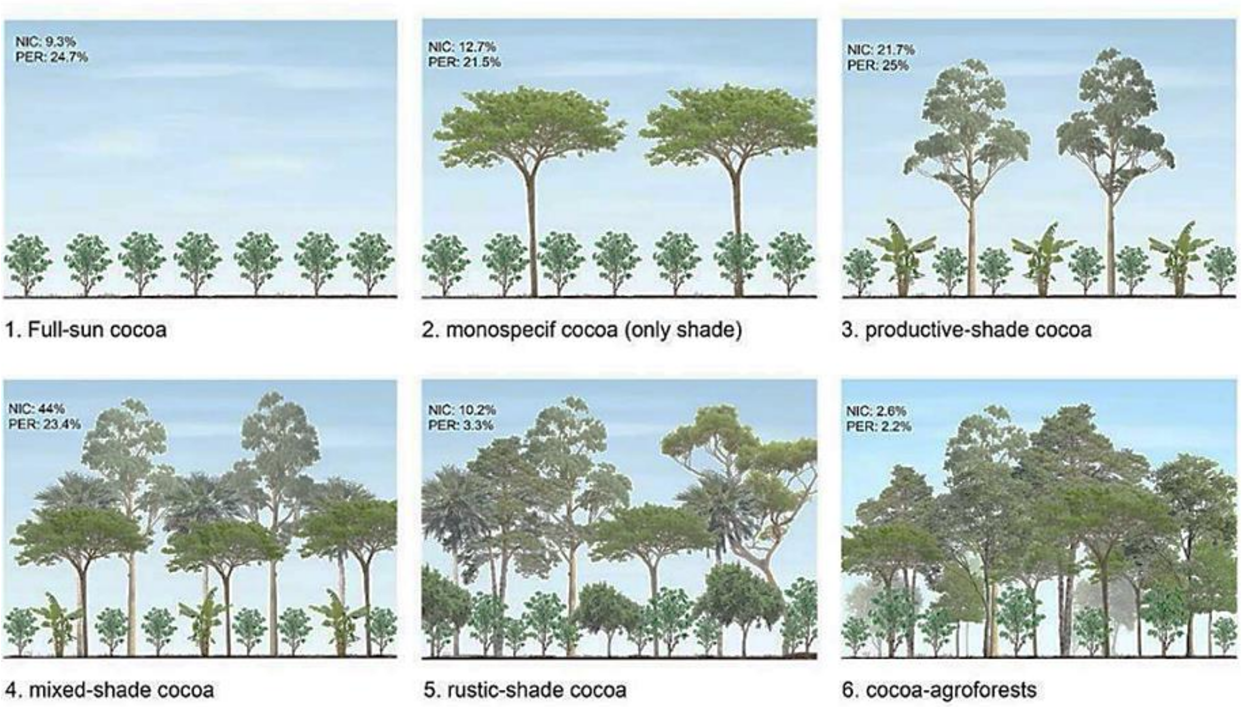
Owner's name: _________________________ Community: __________________ Date: ____________

AFS products (mark with an X)			
	Currently obtains	Would like to obtain	Priority
Cocoa			
Banana			
Banana			
Lemon			
Orange			
Avocado			
Sapote			
Wood			
Firewood			
Materials			
Medicine			

AFS Services (mark with an X)		
	Would like to improve	Priority
Soil moisture maintenance		
Fertility improvement		
Pest and disease regulation		

People working in the AFS		
	Number	**% of time spent**
Persons in the family working in the AFS <30 years old		
Persons in the family working in the AFS 30-45 years old		
Persons in the family working in the AFS > 45 years of age		
Persons currently employed		
Persons who could be hired in the future		

Circle the type of AFS that the producer has (a)



FORM 2.

DIAGNOSTIC SKETCH

Owner's Name: ________________________ Community: __________________ Date: ___

During the site assessment (walk-through): note adjacent land uses, names of neighbors on each side, adjacent vegetation that can provide important shade to the AFS, direction of slopes, identify if there are places that flood or have better/worse soil.

For the agroforestry diagnosis: note/draw the patches with no shade, little or a lot of shade, reflect if in any place there are groupings of species of the same type, and any other situation that is important to consider for future improvements.

Croquis

(Also draw references such as roads, rivers or houses).

FORM 3.

SITE ASSESSMENT

Owner's name: ________________________ Community: _________________ Date: ___________

____

Altitude of the AFS: ______ meters above sea level

Area of the AFS: _______ tareas

Age of the AFS: _______ years

____

Percentage of land at each slope level:

Flat: ____% Medium slope: ____% Steep slope: ____%

____

Slope Orientation (mark with an X)

North: ___ South: ___ East: ___ West: ___

North East: ___ North West: ____ South East: ___ South West: ___

____

Soil fertility (mark with an X)

Poor: _____ Fair: _____ Good: _____ Very good: _____

Rainy/cloudy months and dry months (mark with an X)

Months	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Rainy/cloudy												
Dry												

There are strong winds that cause problems to the AFS (mark with an X): YES: ___

NO: ___

If YES, mark with an X

Months	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC

Rainy/cloudy												

FORM 4.

AGROFORESTRY DIAGNOSIS

Owner's name: ________________________ Community: __________________ Date: ____________

Characteristics of shade species in the canopy

Species	**No. of similar individuals**	**Total height (m)**	**Crown width (m)**	**Cup occlusion (%)**	**Product**	**Service**

Percentage of plants per variety in the AFS:

Clones ____% Hybrids (from seed)____%

Planting distances of cocoa plants:

Row spacing: ______ m Plant spacing: ______ m

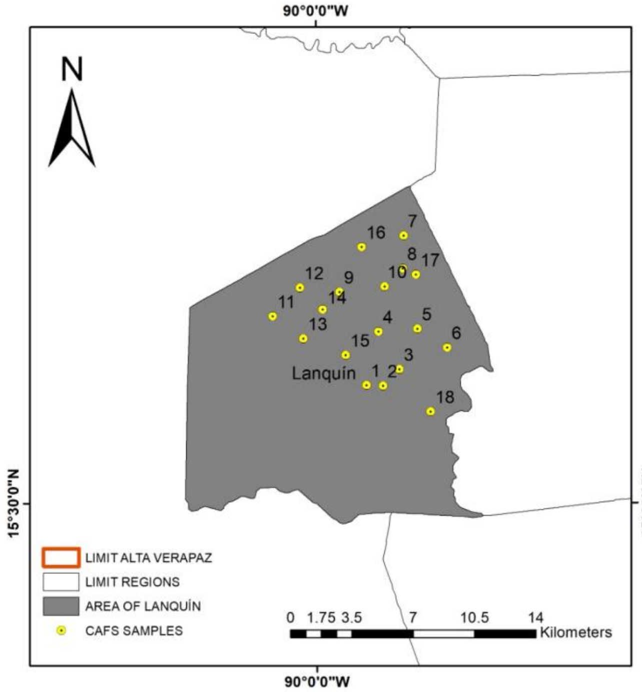
Percentage of the AFS that is in (Mark with an X):

Growth: ____ Start of production: ____ Full production: ____

AFS phenology and harvesting during the year

Months	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**	**OCT**	**NOV**	**DEC**
Vegetative growth												
Increased flowering												
Increased presence of young fruits												
Beginning of harvest												
Harvest peak												
End of harvest												

Appendix 7. Location of temporary sample plots in CAFS, Alta Verapaz, Guatemala



PLOT	LAT	LONG	PLOT	LAT	LONG
1	15° 33' 39.00	89° 58' 25.00	11	15° 35' 47.24	90° 1' 24.148
2	15° 33' 37.70	89° 57' 52.80	12	15° 36' 40.08	90° 0' 32.057
3	15° 34' 8.540	89° 57' 21.90	13	15° 35' 5.794	90° 0' 25.619
4	15° 35' 18.37	89° 58' 1.692	14	15° 35' 59.94	89° 59' 48.18
5	15° 35' 23.35	89° 56' 47.06	15	15° 34' 34.61	89° 59' 4.423
6	15° 34' 48.34	89° 55' 49.87	16	15° 37' 55.99	89° 58' 33.26
7	15° 38' 16.46	89° 57' 13.25	17	15° 37' 4.088	89° 56' 49.46
8	15° 37' 15.77	89° 57' 14.74	18	15° 32' 49.61	89° 56' 22.16
9	15° 36' 32.15	89° 59' 16.12			
10	15° 36' 42.28	89° 57' 49.48			

15°30'0"N

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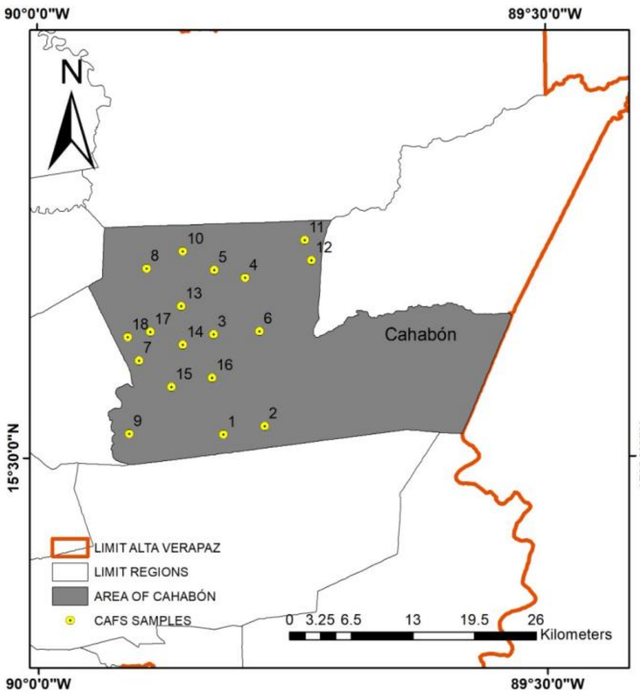
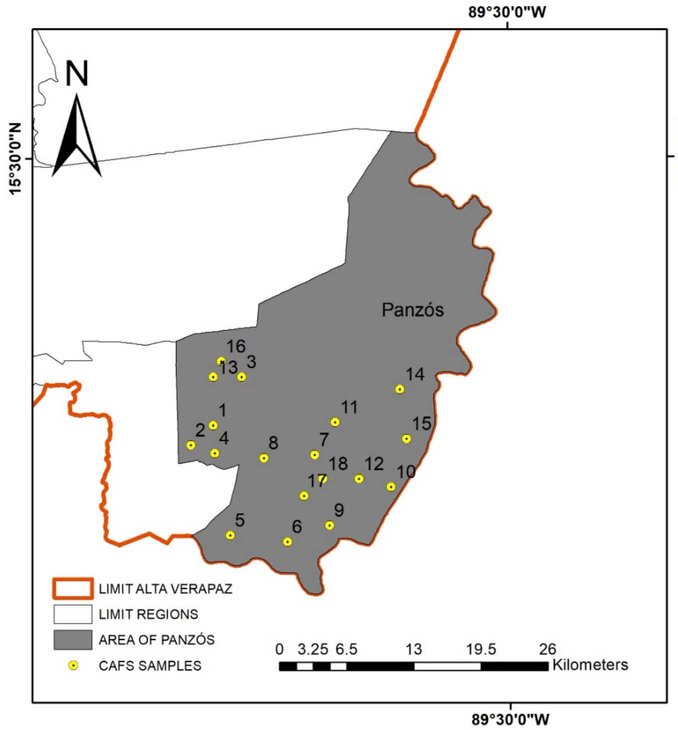
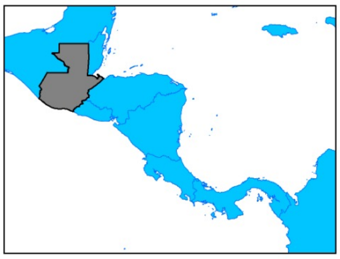


PLOT	LAT	LONG	PLOT	LAT	LONG
1	15° 31' 18.59	89° 49' 5.180	11	15° 42' 23.98	89° 44' 15.02
2	15° 31' 46.54	89° 46' 38.57	12	15° 41' 14.16	89° 43' 51.29
3	15° 37' 2.206	89° 49' 38.69	13	15° 38' 38.10	89° 51' 32.99
4	15° 40' 15.55	89° 47' 46.09	14	15° 36' 26.37	89° 51' 28.07
5	15° 40' 41.72	89° 49' 35.31	15	15° 34' 1.858	89° 52' 8.488
6	15° 37' 12.02	89° 46' 56.09	16	15° 34' 32.42	89° 49' 44.51
7	15° 35' 32.57	89° 54' 2.797	17	15° 37' 10.60	89° 53' 22.53
8	15° 40' 47.59	89° 53' 35.22	18	15° 36' 52.74	89° 54' 42.54
9	15° 31' 22.14	89° 54' 38.15			
10	15° 41' 46.63	89° 51' 27.07			

15°30'0"N

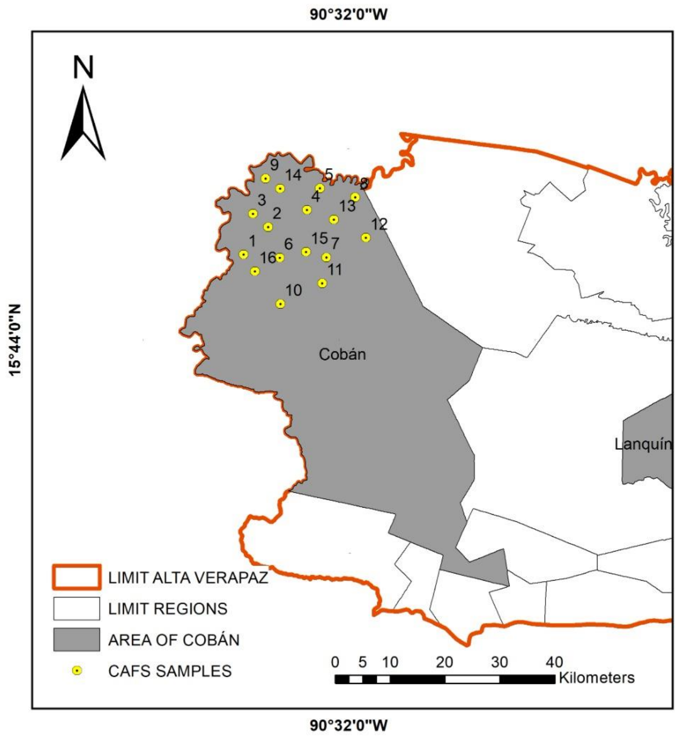
Fakulta tropického zemědělství

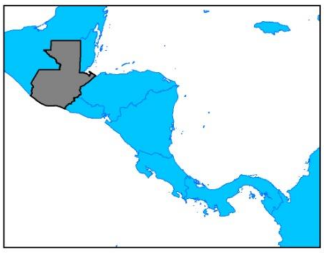




PLOT	LAT	LONG	PLOT	LAT	LONG
1	15° 15' 58.03	89° 46' 1.936	11	15° 16' 6.976	89° 39' 25.48
2	15° 14' 56.28	89° 47' 13.97	12	15° 13' 8.478	89° 38' 9.055
3	15° 18' 30.10	89° 44' 28.26	13	15° 18' 30.42	89° 46' 1.406
4	15° 14' 30.20	89° 45' 56.92	14	15° 17' 49.46	89° 35' 54.86
5	15° 10' 11.76	89° 45' 7.286	15	15° 15' 14.41	89° 35' 34.24
6	15° 9' 50.464	89° 42' 1.213	16	15° 19' 19.40	89° 45' 34.62
7	15° 14' 23.91	89° 40' 32.39	17	15° 12' 14.90	89° 41' 7.475
8	15° 14' 14.17	89° 43' 17.36	18	15° 13' 8.919	89° 40' 6.089
9	15° 10' 41.62	89° 39' 45.39			
10	15° 12' 42.24	89° 36' 25.43			

Fakulta tropického zemědělství





PLOT	LAT	LONG	PLOT	LAT	LONG
1	15° 52' 31.1	90° 42' 45.3	11	15° 49' 40.0	90° 34' 45.5
2	15° 55' 13.9	90° 40' 16.0	12	15° 54' 10.5	90° 30' 17.3
3	15° 56' 31.3	90° 41' 49.5	13	15° 55' 58.6	90° 33' 32.9
4	15° 56' 54.8	90° 36' 18.5	14	15° 59' 1.77	90° 39' 3.54
5	15° 59' 4.01	90° 34' 58.5	15	15° 52' 45.1	90° 36' 22.8
6	15° 52' 10.6	90° 39' 3.85	16	15° 50' 50.0	90° 41' 37.3
7	15° 52' 13.3	90° 34' 18.3			
8	15° 58' 9.82	90° 31' 22.2			
9	16° 0' 0.630	90° 40' 32.3			
10	15° 47' 36.8	90° 39' 0.98			

Fakulta tropického zemědělství

Appendix 8: Currirulum Vitae

Name: Carlos Enrique Villanueva González
Address: 12th 1-71 16 001, Alta Verapaz, Guatemala
Phone number: +502 47527607
Email: villanueva@ftz.zcu.cz; krevilla01@gmail.com

EDUCATION

PhD. Czech University of Life Sciences, Prague (CZU), Faculty of Tropical AgriSciences (FTA) Study Programme: Agriculture in Tropics and Subtropics

Thesis title: Diversity of trees and their use in cocoa agroforestry systems in Alta Verapaz, Guatemala.

2018 – present

Mgrt. Tropical Agricultural Research and Higher Education Center (CATIE)

Study programme: Biodiversity conservation

Thesis title: Home gardens and their relationship with traditional agricultural knowledge, food security, and conservation of agrobiodiversity in Guatemala.

2013-2014

BSc. Universidad Rafael Landívar (URL), Facultad de Ciencias Ambientales y Agrícolas

Study programme: Ingeniería forestal con énfasis en silvicultura y manejo de bosques

Thesis title: Evaluation of the socioeconomic impacts of the implementation of the forestry incentives Program for Small Holders with Forestry or Agroforestry Vocation in Baja Verapaz, Guatemala.

2003-2010

RESEARCH PROJECTS

Title: **Comprehensive Project for Strengthening Productivity, Management of Agroforestry Systems, and Commercialization in Cacao Growers' Associations of Guatemala**

Donor: Consortium of the Association for the Integral Development of Northern Guatemala (ADINOR) and Inter-American Institute for Cooperation on Agriculture, Regional Consortium for Agricultural Research (CRIA-IICA).

Implementation period: 2024-present

Principal investigator: Carlos Enrique Villanueva González

Responsabilities: project management, component evaluation and report writing, data analysis

Title: **Economic study of agroforestry plantations within the forest incentives program for the restoration of degraded lands, Cobán, Alta Verapaz (PROBOSQUE)**

Donor: National Forest Institute (INAB-Guatemala) and Universidad Rafael Landivar (URL)

Implementation period: 2022-2023

Principal investigator: Carlos Enrique Villanueva González

Responsabilities: data analysis, manuscript preparation, and dissemination of results

Title: **Sustainability assessment of traditional cacao systems in Alta Verapaz, Guatemala**

Donor: Maya Technological Institute of Higher Education (ITMES). Inter-American Institute for Cooperation on Agriculture, Regional Consortium for Agricultural Research (CRIA-IICA).

Implementation period: 2022-2023

Principal investigator: Carlos Enrique Villanueva González

Responsabilities: project management, component evaluation and report writing, data analysis.

Title: **Social and biodiversity study for the Chimelb project, Guatemala.**

Donor: Terra Global Capital LLC-ADINOR Consortium.

Implementation period: 2023.

Principal investigator: Carlos Enrique Villanueva González

Responsabilities: project management, biodiversity assessment, report writing

Title: **Socioeconomic study of the primary transformation of cacao beans in the Polochic Valley, Guatemala**

Donor: Maya Technological Institute of Higher Education (ITMES). Inter-American Institute for Cooperation on Agriculture, Regional Consortium for Agricultural Research (CRIA-IICA).

Implementation period: 2017

Principal investigator: Carlos Enrique Villanueva González

Responsabilities: transformation process evaluation, data analysis, and report writing

Title: **Socioeconomic study of the primary transformation of cacao (*Theobroma cacao* L.) beans in the Sub region Lachuá ecoregion, Alta Verapaz, Guatemala**

Donor: Universidad Rafael Landívar (URL). Inter-American Institute for Cooperation on Agriculture, Regional Consortium for Agricultural Research (CRIA-IICA).

Implementation period: 2018

Principal investigator: Carlos Enrique Villanueva González

Responsabilities: transformation process evaluation, data analysis, and report writing

Title: **Socioeconomic study of the primary transformation of cacao (*Theobroma cacao* L.) beans in the Sub region Lanquin and Cahabon ecoregion, Alta Verapaz, Guatemala**

Donor: Universidad Rafael Landívar (URL). Inter-American Institute for Cooperation on Agriculture, Regional Consortium for Agricultural Research (CRIA-IICA).

Implementation period: 2017

Principal investigator: Carlos Enrique Villanueva González

Responsabilities: transformation process evaluation, data analysis, and report writing

WORK EXPERIENCE

Inter-American Institute for Cooperation on Agriculture IICA-Guatemala, Regional Consortium for Agricultural Research (CRIA)	2016-present

Position: Principal investigator

Association for the Integral Development of Northern Guatemala (ADINOR)	2016- present

Position: Regional director

Universidad Rafael Landívar, Facultad de Ciencias Ambientales y Agrícolas	2015- present

Position: Professor

Department of Forest Research of Guatemala, National Forest Institute (INAB)	2023-present

Position: research associate

International Analog Forestry Network (IAFN)	2024-present

Position: National Representative

Mayan Technological Institute of Higher Education (ITMES)	2018-2022

Position: Professor and scientific researcher

SCIENTIFIC PUBLICATIONS

Villanueva-González CE, Ruiz-Chután J, Polesny Z, Kalousova M, Villanueva C, Lojka B. 2024. Diversity and productive potential of timber trees in cocoa agroforestry systems in Alta Verapaz, Guatemala. Revista de la Facultad de Agronomía, Universidad del Zulia **41**:e244108. DOI:10.47280/RevFacAgron(LUZ).v41.n1.08

Villanueva-González CE, Kalousova M, Ruiz-Chután JA, Moya Fernandez RW, Villanueva C, Lojka B. 2023. Botanical diversity, structure and composition in cocoa agroforest systems in Alta Verapaz, Guatemala. Scientia Agropecuaria **14**:223–234. DOI:10.17268/sci.agropecu.2023.020

Ruiz-Chután JA, Kalousová M, Maňourová A, Degu HD, Berdúo-Sandoval JE, ***Villanueva-González CE***, Lojka B. 2023. Core collection formation in Guatemalan wild avocado germplasm with phenotypic and SSR data. Agronomy **13**:2385. https://doi.org/10.3390/agronomy13092385

Pérez-Olmos KN, Aguilar-Rivera N, ***Villanueva-González CE***. 2023. Potentials and challenges of sustainable agritourism in Fortín, Veracruz, Mexico. Pages 147–163 Handbook on Tourism and Conservation. Edward Elgar Publishing.

Ruiz-Chután JA, Berdúo-Sandoval JE, Maňourová A, Kalousová M, ***Villanueva-González CE***, Fernández E, Žiarovská J, Sánchez-Pérez A, Lojka B. 2023. Variability analysis of wild Guatemalan avocado germplasm based on agro-morphological traits. Tropical and Subtropical Agroecosystems 26. https://doi.org/10.56369/tsaes.4663

Villanueva-Gonzáles CE, Lojka B, Archila Cardona CE. 2022. Agroforestería para la conservación de la biodiversidad en América Latina: una revisión sistemática. Eutopia :1–25.

Chavarría Ramírez CA, ***Villanueva-González CE***, Pérez - Olmos KN. 2022. Análisis de la estructura y diversidad arbórea en sistemas agroforestales de cacao en Jolom-ijix II, Alta Verapaz, Guatemala. Revista Ingeniería y Ciencia 2:1–12.

Ruiz-Chután, J.A., Maňourová, A., Degu H. D., Berdúo-Sandoval, J.E, Kalousová, M., Barrios S., ***Villanueva-González, C.E***., Herrera, M., Lojka, Bohdan. Assessing the genetic diversity of endangered species using molecular markers: The case of Dalbergia stevensonii in Guatemala, Submitted for consideration in Bosque (May 2023)

Villanueva-González CE, Pérez-Olmos KN, Sabino-Mollinedo, M, Lojka B. Exploring Agroforestry and Food Security in Latin America: A Systematic Review. Submitted for consideration in Journal Environment Development and Sustainability (October 2022).

SCIENTIFIC CONFERENCES

Villanueva-González*, *CE., Ruiz-Chután, J.A., Kalousová, M., Villanueva, C., A. Lojka, B. (2023). Analysis of the diversity and timber potential in cocoa agroforestry systems in Alta Verapaz, Guatemala. Tropentag: Competing pathways for equitable food systems transformation: trade-offs and synergies.

Villanueva-González*, *CE., Ruiz-Chután, J.A., Kalousová, M., Villanueva, C., A. Lojka, B. (2023). Tree diversity and its cultural use in productive systems in Alta Verapaz. LXV, Annual Meeting the Central American Cooperative Program for the Improvement of Crops and Animals (PCCMCA): Biofortification of crops and climate adaptation for Food and Nutritional Security.

***Villanueva-González*, *CE*.,** Chavarría-Ramirez, CA. (2023). Tree diversity and structure in cocoa agroforestry systems in Jolomijiix II, Alta Verapaz. VII Scientific week, Rafael Landivar University, Guatemala. University, Science and Social Transformation: research and education in the face of the global and local Central American reality.

Villanueva-González*, *CE., Ruiz-Chután, J.A., Kalousová, M., Villanueva, C., A. Lojka, B. (2023). Study on the diversity and productive potential of wood in agroforestry systems in Guatemala: Climate change, territoriality, and environmental management. VI Research and Postgraduate Meeting, Central America and the Caribbean-Nicaragua.

Ruiz-Chután, J.A., Kalousová, M., Berdúo-Sandoval, J.E, ***Villanueva-González, CE***., Sánchez-Pérez, A. Lojka, B. (2023). Uncovering the genetic diversity of hemileia vastatrix in three coffee-producing areas in Guatemala and its implications for resistance of coffee varieties. Tropentag: Competing pathways for equitable food systems transformation: trade-offs and synergies.

Ruiz-Chután, J.A., Berdúo-Sandoval, J.E., Montes, L., Kalousová, M., Lojka, B., ***Villanueva-González, CE*.**, Sánchez-Pérez, A. (2021). Genetic diversity and population structure of *Moniliophthora roreri* in cocoa producing areas in

Guatemala. Tropentag: Towards shifting paradigms in agriculture for a healthy and sustainable future.

Villanueva-González, CE., Lojka, B., Archila, C. E & Ruiz-Chutan, J. A. (2020) Diversity of tree and their use in cocoa agroforestry systems in Alta Verapaz, Guatemala. Tropentag: Food and nutrition security and its resilience to global crises.