Diversity and productive potential of timber trees in cocoa agroforestry systems in Alta Verapaz, Guatemala

Diversidad y potencial productivo de árboles maderables en sistemas agroforestales de cacao en Alta Verapaz, Guatemala

Diversidade e potencial produtivo de árvores madeireiras em sistemas agroflorestais de cacau em Alta Verapaz, Guatemala

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Abstract

Timber production in agroforestry systems can improve environmental and economic sustainability, especially for families living in rural areas. Despite its importance in Guatemala, little is known about the potential of wood and its contribution to the sustainability of traditional agroforestry systems. This study aims to analyze the timber resources in cocoa agroforestry systems (CAFS) of different ages, evaluating variables such as floristic composition, species diversity, and the potential to obtain timber from the species present in the evaluated CAFS. Twenty temporary sampling plots of 2,500 m^2 were established, and dendrometric variables were measured in all plots. Species occurrence was statistically analyzed by cross-tabulation and Pearson's Chi-square test (χ^2) to determine species' frequency distribution among the evaluated CAFS ages. Eight hundred twenty-seven trees of 38 species belonging to 19 families were identified. The most represented species in the age range of the evaluated CAFS were *Gliricidia sepium* (35.07 %), *Swietenia macrophylla* (19.11 %), and *Inga sapindoides* (7.62 %). The total shade trees occupied a basal area of 33.29 m^2, and a total volume of 352.35 m^3 was recorded, of which 148.9 m^3 were for commercial use. The most frequent uses of the wood were firewood (38.21 %), thin plank (30.23 %), and poles (22.85 %), while the use of thick plank was the least common (8.71 %). The CAFS in the studied area are characterized by a wide diversity of shade tree species. These results provide a solid basis for promoting sustainable practices that foster the productivity and preservation of these systems, thus contributing to the sustainability and well-being of farmers.

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Resumen

La producción de madera en sistemas agroforestales puede mejorar la sostenibilidad ambiental y económica, especialmente para las familias que viven en zonas rurales. Este estudio tuvo como objetivo analizar los recursos maderables en SAF de cacao de diferentes edades, evaluando variables como la composición florística, la diversidad de especies y el potencial de obtención de madera de las especies presentes en los SAF evaluados. Se establecieron 20 parcelas temporales de muestreo con un tamaño de 2.500 m^2 y en todas ellas se midieron variables dendrométricas. La presencia de especies se analizó estadísticamente mediante tabulación cruzada y la prueba Chi-cuadrado de Pearson (χ^2) para determinar la distribución de frecuencia de las especies entre las edades de SAF evaluadas. Se determinaron taxonómicamente 827 árboles de 38 especies pertenecientes a 19 familias. Las especies más representadas en el rango de edad de los SAF evaluados fueron *Gliricidia sepium* (35,07 %), *Swietenia macrophylla* (19,11 %) e *Inga sapindoides* (7,62 %). Los árboles de sombra total ocuparon un área basal de 33,29 m^2, y se registró un volumen total de 352,35 m^3, de los cuales 148,9 m^3 fueron de uso comercial. Los usos más frecuentes de la madera fueron leña (38,21 %), tabla delgada (30,23 %) y postes (22,85 %), mientras que el uso de tabla gruesa fue el menos común (8,71 %). Estos resultados proporcionan una base sólida para promover prácticas sostenibles que fomenten la productividad y la preservación de estos sistemas, contribuyendo así a la sostenibilidad y el bienestar de los agricultores.

Palabras clave: diversidad de árboles; producción de madera; variables dendrométricas.

Resumo

A produção de madeira em sistemas agroflorestais promove a sustentabilidade ambiental e econômica, especialmente em ambientes rurais. Na Guatemala, a importância dos recursos madeireiros em sistemas agroflorestais tradicionais aindanãofoi plenamente reconhecida. Este estudo concentra-se em analisar os recursos madeireiros em sistemas agroflorestais de cacau (CAFS) de diferentes idades, avaliando variáveis como a composição florística, a diversidade de espécies e o potencial de obtenção de madeira. Foram estabelecidas 20 parcelas de amostragem temporárias de 2.500 m^2, on de foram registradas variáveis dendrométricas. A análiseestatística, que incluiu o teste de Qui-quadrado de Pearson (χ^2), identificou 827 árvores de 38 espécies pertencentes a 19 famílias. As espécies predominantes nos CAFS avaliados foram *Gliricidia sepium* (35,07 %), *Swietenia macrophylla* (19,11 %) e *Inga sapindoides* (7,62 %). As árvores de sombra ocuparam uma área basal de 33,29 m^2, comum volume total de 352,35 m^3, incluindo 148,9 m^3 destinados ao uso comercial. A madeira foi principalmente utilizada como lenha (38,21 %), tábuas finas (30,23 %) e postes (22,85 %), en quanto tábuas grossas foram menos comuns (8,71 %). Os CAFS naregião se destacam pela ampla diversidade de espécies de árvores de sombra. Esses resultados apoiam a adoção de práticas sustentáveis que beneficiam agricultores e o meio ambiente, contribuido assim para a sustentabilidade e o bem-estar em áreas rurais**.**

Palavras-chave: diversidade de árvores; produção de madeira; variáveis dendrométricas

Introduction

Currently, agroforestry presents multiple opportunities to improve ecosystem services to people and communities and, at the same time, decrease pressure on the environment (Braga *et al*., 2019; Manaye *et al*., 2021). Integrating woody and non-woody species, such as fruit, is commonly employed by smallholders to diversify land use in agroforestry systems (AFS) (Mercedes and Rangel-Ch., 2020). Trees play a fundamental role in agroforestry production and farmers' livelihoods in Latin América, as they provide a wide range of ecosystem services, which are essential for maintaining the health and productivity of agricultural and forestry systems and improving the resilience and adaptation of rural communities to the impacts of climate change (Morán-Villa *et al*., 2022; Ramos-Prado *et al*., 2023).

In Mesoamérica, about 85 % of cocoa production is grown in association with shade trees and annual and perennial plants (Matey *et al*., 2013). In México, for example, 46 tree species have been recorded in traditional cocoa-agroforestry systems (CAFS) (Roa-Mero *et al*., 2009). Furthermore, in Costa Rica, Colombia, and Perú, studies of floristic diversity and structure in CAFS have revealed the presence of 56, 61, and 33 species, respectively (Suatune *et al*., 2003; Vebrova *et al*., 2014).

In these systems, trees are highly valued for their timber potential and the opportunities they provide to diversify household income and livelihoods. For example, in the *Kichwa* indigenous community of Ecuador, in the CAFS called *Chakras*, *Cordia alliodora* (Ruiz & Pav.) Oken and *Cedrela odorata* L. were identified as the species with the highest timber potential (22 $m^3.ha^{-1}$) (Jadán *et al*., 2015), while, in Cardenas, México, the species *Erythrina poeppigiana* (Walp.) O.F. Cook (64.4 $m^3.ha^{-1}$), *E. americana* Mill. (40.3 $m^3.ha^{-1}$), and *C. odorata* (15.5 $m^3.ha^{-1}$) recorded the highest values (Sánchez *et al*., 2016). Timber production is experiencing an increase among small producers in indigenous communities around the world (Morán-Villa *et al*., 2022; Tapia-Vera *et al*., 2021).

According to Bullock *et al*. (2020) the total deforested area in Guatemala between 2,000 and 2,017 was around 854,137 ha of forest. Deforestation has reduced species richness and diversity, as well as the timber supply in the country. Agroforestry is considered an effective strategy in several regions of Guatemala to address various socioeconomic and environmental phenomena, including deforestation (Braga *et al*., 2019). However, little is known in Guatemala about the timber potential and its contribution to the sustainability of traditional CAFS. This study aims to examine the timber resource in CAFS of different ages and evaluate variables such as floristic composition, species richness, and timber productive potential of woody species present in the CAFS located in four municipalities of the department of Alta Verapaz, Guatemala.

Material and methods

Study area

The study was carried out in CAFS located in the municipalities of Cahabón, Cobán, Lanquín, and Panzós in the department of Alta Verapaz (15° 29' N, 90° 20' W). The climatic zone in the study area corresponds to the very humid subtropical (warm) forest (bmh-S (c)) (Holdridge, 2000). The temperature varies slightly over the year (from 24 to 28.1 °C) with an annual average of 25.6 °C. The average annual precipitation is estimated at 2,199 mm, varying from 1,426 to 4,071 mm.

Study plot and sampling procedure

Five sampling plots were delineated in each of the four selected municipalities, each with dimensions of 50 x 50 meters (2,500 m²). This approach resulted in 20 plots distributed across the entire study area, covering a total sampling area of 50,000 m². A non-probabilistic selection method of study units was used, considering specific selection criteria such as time availability of producers, age of the CAFSs, management, and crop area (Maza *et al*., 2016). The CAFS in the age range of 3 to 25 years were evaluated, with a predominance of plots (11) in the age range of 7 to 12 years.

Floristic composition and dendrometric variables

The main dendrometric variables of all woody specimens were measured in each sampling unit, including total height (*th*), commercial height (*hc*) and diameter at breast height (*DBH*) ≥5 cm. The formulas recommended by Sánchez *et al*. (2016) were applied as follows to calculate basal area (*BA*), commercial volume (*VC*), and total volume (*VT*): $BA = 0.7854 \times DBH^2$, where 0.7854 represents the constant. Total volume and merchantable volume (VT, VC, m³) were calculated using the following equation: $V=BA \times ff \times H$, where: *ff*= shape factor (0.70) and *H*= total or merchantable height.

Botanists and local producers assisted in taxonomic determination of the scientific and common names of the species in the field. For this purpose, duplicates of each identified species were collected corresponding to botanical specimens. Utilized various resources to verify the species' identity, including the Flora of Guatemala (Standley and Steyermark, 1946), the Tropics nomenclature database (www.tropicos.org, 2023) and GBIF.org (www.gbif.org, 2023).

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 *et al*., 2016).

Data analysis

To analyze the contribution of each species to the different quantitative measures, we utilized the ggplot2 statistical package to generate a bar chart (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 CAFSs were located. To assess the relationship between the variables included in the cross-tabulation, Pearson's Chi-square test (χ^2) was used. These analyses were conducted using the ggstatsplot package implemented in R (Patil, 2021).

Results and discussion

Floristic diversity and composition

Eight hundred twenty-seven tree individuals corresponding to 38 species belonging to 19 botanical families were found cultivated within all sampled CAFS plots. 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. This difference originates from the prioritization by the producers of Cobán in managing trees of high commercial value in their agroforestry designs.

In terms of species diversity, the CAFS of Alta Verapaz are similar to other cocoa-growing areas of the Mesoamerican region (Salvador-Morales *et al*., 2020; Suárez-Venero *et al*., 2019). However, studies carried out in Colombia by Jadán *et al*. (2015) and in Ecuador by Mercedes and Ranchel-Ch (2020), suggest that traditional CAFS managed by smallholders have an even greater diversity at species and family levels, with records of up to 110 species and 68 families, and 61 species and 26 families, respectively.

Compared to the results of our study, there are other cocoa-growing regions with higher richness and diversity of species; this could be because, in the Amazon, cocoa plantations 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. Additionally, some trees already existing in the place at the time of the establishment of the CAFS were conserved (Somarriba, 2004). Despite this difference, these 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 (Neither *et al*., 2020).

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 *Protium copal* (Schltdl. & Cham.) Engl. 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 1).

In Mesoamérica, various studies have identified the potential of certain tree species cultivated in diverse AFS 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*., 2015). In the context of agroforestry arrangements in Alta Verapaz, the frequency of species (figure 1), 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. According to Nicli *et al*. (2019) report, the 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 agroforestry systems.

Tree basal area reflecting particular species and CAFS age

The results were classified according to the municipality, the age of establishment of the CAFS evaluated, and the BA variable for each trees species inventoried. A total of 827 shade trees were recorded, occupying a BA of 33.29 m². 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 10-year-old CAFS, while a 13-year-old CAFS presented the lowest BA value (2.23 $m^2.ha^{-1}$).

The dominance of *G. sepium*, *S. macrophylla*, *C. odorata*, and *C. alliodora*, representing 71% of the basal area, highlights significant patterns in CAFS configuration. This observation suggests the influence of local adaptability, the ability to thrive in agroforestry

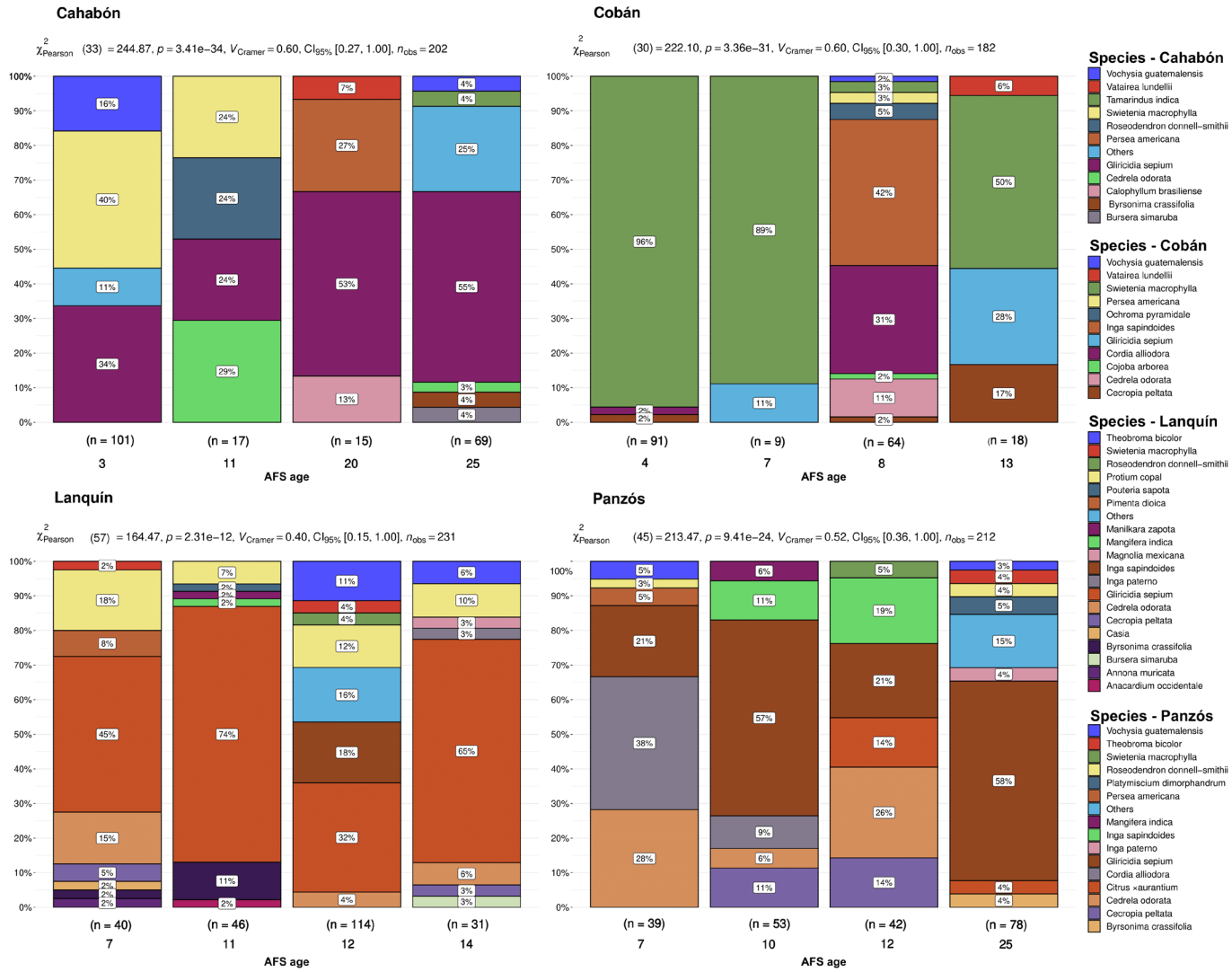

Figure 1. Frequency description and Chi-square test of species distribution by the age of cocoa agroforestry systems among the study localities.

environments, and potential economic value (Sol-Sánchez *et al*., 2018). Although these findings raise questions about the dynamics and interactions of these species, further research is needed to fully understand their ecological and socio-economic relevance in the studied AFS.

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}. It is essential to highlight that the 10-year-old CAFS stood out by exhibiting the highest BA value, reaching 13.57 m^2.ha^{-1}. The presence of trees with outstanding dendrometric characteristics, such as *V. guatemalensis* and *C. alliodora*, could be a crucial component contributing to this prominent BA value.

In contrast, the 13-year-old AFS presented the lowest BA value, with only 2.23 m^2.ha^{-1}. This disparity could be attributed to several factors, with silvicultural management being crucial, where appropriate practices such as selective pruning, tree density regulation, and specific treatments can significantly influence tree growth and development (Sambuichi *et al*., 2012). These factors have been mentioned in previous studies as possible causes of the variability in the values of BA in AFSs (Haggar *et al*., 2015; Suárez-Venero *et al*., 2019; Tapia-Vera *et al*., 2021).

Total and commercial volume of timber

A total volume of timber 352.3 m^3 was recorded in the whole sample, consisting of 5 ha 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} per plot, ranging from 2.9 m^3.ha^{-1} to 73.1 m^3.ha^{-1}. These findings align with the documented patterns observed in the literature concerning agroforestry systems (CAFS) within tropical regions of the Americas (Jadán *et al*., 2015). Nevertheless, it is crucial to note that the timber potential in these systems may vary depending on specific factors in each region, such as climatic conditions and management practices (Esche *et al*., 2023). This underscores the importance of considering the particular context when interpreting these results.

The results of this 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}). Other studies have also reported that producers prefer these species due to their wood potential and high economic value (Ebratt-Matute, 2022). *G. sepium* stood out in all municipalities for its versatility in providing ecosystem services to the local population (Burgos *et al*., 2016). In contrast, the

remaining 33 species presented figures <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 2). This difference is because the 3-year-old CAFS harbored timber species of high commercial value with outstanding *DBH* and *H*. The locality that reported the highest commercial volume was Panzós, with 49.3 $m^3.ha^{-1}$, and the lowest was Lanquín, with 9.6 $m^3.ha^{-1}$ (figure 2). In the Panzós case, producers preferred to preserve some remaining trees from the secondary forest within the CAFS. 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; Villanueva-González *et al*., 2023).

Vegetation structure and potential use of the trees as a function of *DBH*

The tree inventory confirmed the presence of three main strata in the study area, as shown. The lowest stratum (1-8 m), 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*. These results confirm the presence of short-cycle species in this canopy, which is attributed to enrichment practices and management of natural regeneration. The middle stratum (9-24 m), 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 (25-35 m), 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*. The statistical analysis of the *DBH* variable 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 highest concentration was found in the diameter interval ≥5 cm and <15 cm, with a total of 316 individuals, while the lowest concentration 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 (Nicli *et al*., 2019). 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

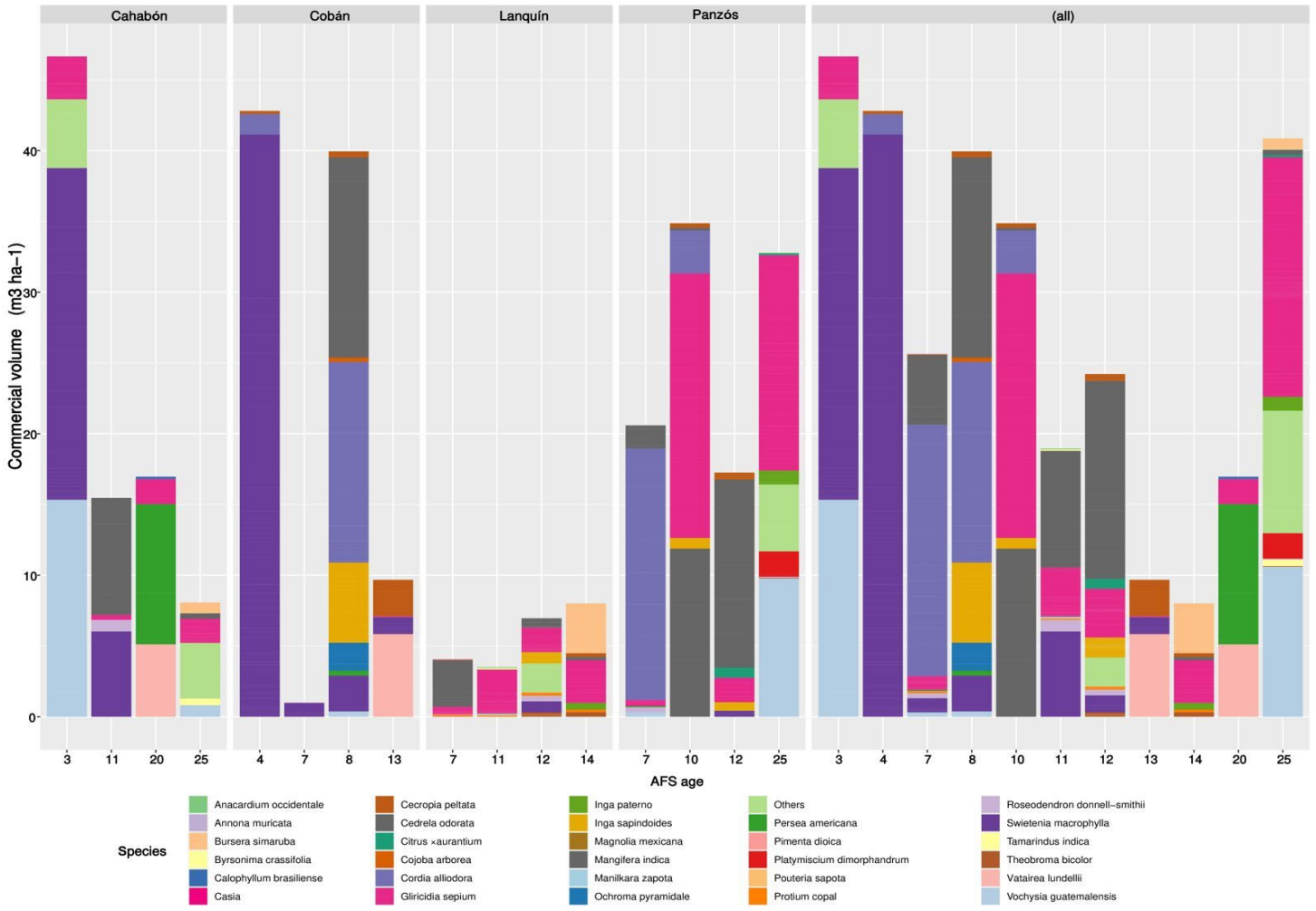

Figure 2. Distribution of the volume of each species by age of the CAFS between study locations.

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. 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).

Conclusions

The results of this study provide essential insight into the richness and productive potential of timber trees in CAFS in Alta Verapaz, Guatemala. These findings have practical applications by providing valuable information to improve crop diversification strategies and promote more effective agroforestry practices. Among these practices, implementing specific sustainable management techniques, such as selective pruning, regulation of tree density to optimize growth, and selection of critical species, stand out. CAFS emerged as a viable strategy for timber production, offering economic and environmental benefits that support local development and improve the quality of life of the communities involved.

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