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Biodiversity and Carbon Sequestration in Chakra-Type Agroforestry Systems and Humid Tropical Forests of the Ecuadorian Amazon

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Abstract: Currently, there are several studies related to climate change, carbon sequestration, and floristic composition in different scenarios and land uses. In this context, the objective of this research is: (a) to characterize biodiversity based on ecological indicators and diversity indices and (b) to evaluate carbon sequestration in different components of chakra-type agroforestry systems and secondary tropical humid forests of the Ecuadorian Amazon. For this, temporary sampling plots of 1600 m^2 are established on the properties to be investigated. The study found that the structural characteristics and floristic composition vary according to the forest arrangement and the management system. Secondary forests are the most diverse, according to the Shannon (3.49), Simpson (0.96), and Margaleft (9.34) diversity indices, in addition to having the largest carbon stores with 233 (Mg C ha^{-1}), followed by agroforestry systems in association with timber trees (TAFS) and fruit trees (FAFS) with 97.8 and 95.1 (Mg C ha^{-1}) respectively, and cocoa monoculture (CMC) with 90.4 (Mg C ha^{-1}). These results demonstrate the importance of conserving the remnants of tropical forests that still remain, due to the diversity of species, ecosystem services, and the total carbon they contain, as well as the agroforestry systems (AFS), systems analogous to forests, which are gradually becoming important management systems, especially if they are associated with potential species to sequester carbon, such as those documented in this and several other studies that seek solutions to global climate change.

Keywords: diversity; Amazon forest; AFS with cocoa; AGC; BGC

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1. Introduction

Currently, tropical forests constitute 45% of the global forest area according to FAO 2020 [1]. However, in recent times there has been a significant decrease, due to the deforestation and degradation of tropical forests due to the constant change in land use [1,2]. In this sense, the implementation of agroforestry systems and the conservation of the remaining tropical forests emerge as an alternative to mitigate the effects of greenhouse gases (GHGs), and therefore global warming [3–6], for their ability to regulate carbon dioxide (CO_2) and store carbon, as well as influence agreements and decision making on global climate change [7–9].

Carbon sequestration is a process carried out by living organisms, which consists of removing CO_2 from the atmosphere through photosynthesis of the plant cover and storing it in the soil carbon pool mediated by living organisms, mainly plants [10]. Nevertheless, the process of soil carbon storage is based on management practices that improve and increase the amount of carbon stored as soil organic matter (OM). In this sense, the carbon store in tropical forests depends on strongly of the floristic composition, age, diversity, and density of species [11,12], storing more than 50% of the world's terrestrial carbon [13,14], and they are considered important carbon sinks [13,15,16]. Meanwhile, agroforestry systems (AFSs) stand out for the structure and composition of plant species, dependent on biophysical conditions and management [17,18], positioning them as a potential carbon storage alternative [7,9,19]. Furthermore, due to their wide diversification, AFSs are considered sustainable systems that provide social, economic, and environmental benefits [8,20,21], since they contribute to the conservation of biodiversity and food security due to the close interaction between crops, animals, trees, the environment, and humans [2,17]. In this sense, cocoa, being one of the main crops under AFSs in the tropics and requiring little radiation, is able to associate with a variety of forest species that provide shade and have a positive influence on the quality and amount of OM in the soil through the contributions of crop residues, pruning, and leaf litter [18,21] that stimulate edaphic activity and microbial transformations [22].

Without a doubt, the exuberant vegetation of tropical forests provides a high biomass content and diversity of species [11,15] and, when transformed by felling or burning, more than 85% of the carbon stored in biomass is emitted in the form of CO_2 [11,20]. Therefore, the conversion and intensification of agricultural or livestock land is associated with the loss of soil organic carbon (SOC) and the decrease in the carbon store in the biomass of these ecosystems [2,13,23]. In this context, AFSs as systems similar to forests have been positioned in these territories as alternative systems and having productive improvement in association with crops and forest species (i.e., timber or fruit trees) [9,19] as well as being effective carbon sinks in biomass and soil with good design and management of agroforestry practices [18,23].

In AFSs, natural regeneration, perennial crops, as well as in forests, the soil represents the main carbon reserve [24], which is stored in different components and actively circulates between them. The main storage is found in tree biomass and soil [19], the vegetation incorporates atmospheric carbon into the biological carbon cycle, and the soil participates in its recycling and storage, as a result of the contribution of leaf litter, root exudates, microbial activity, stabilization, and leaching processes [7,19]. SOC is a fundamental element for plant development and activity of edaphic organisms, given that it is governed by the balance between the rate of carbon added to the soil (i.e., by plant residues and roots) and organic amendments, as well as carbon losses such as CO_2 [10]. For this reason, it is considered an indicator of the impact of changes in land use and ecosystem services, due to its high susceptibility to changes and management practices [25], mainly in the surface horizon. In normal conditions, it results from the balance between the incorporation of organic material into the soil and the release of carbon as CO_2 [26].

Although there are several studies related to climate change, carbon sequestration, and floristic composition in different scenarios of the Amazon basin, in this work, and for the first time, the effect of managing cocoa monocultures and cocoa agroforestry systems associated with timber and fruit species is analyzed in relation to secondary Amazonian forests, allowing us to quantify and demonstrate the impact of land use change on carbon sequestration in different components and the diversity of species in these systems of the Ecuadorian Amazon. In addition, the importance of maintaining and preserving primary and secondary forests is highlighted as a mitigation measure against global climate change, as well as implementing AFSs as systems similar to forests, which have had favorable results in this and several studies that have been carried out in tropical areas. From this perspective, two objectives are proposed for the development of this research: (a) characterize biodiversity based on ecological indicators and diversity indices and (b) evaluate carbon sequestration in different components (e.g., aboveground biomass, belowground biomass, and soil organic carbon) of cocoa monoculture, chakra-type agroforestry systems, and secondary tropical humid forests in the province of Napo of the Ecuadorian Amazon.

2. Materials and Methods

The research was carried out in the Arosemena Tola and Tena Cantons, located in the province of Napo (Figure 1). The climate in the Amazon region varies between tropical, and humid, with temperatures ranging from 22 °C to 25 °C and with high relative humidity throughout the year. It also presents an average annual rainfall of around 3000 mm. The relief of the region is made up of a series of medium hills that originate from the east-ern Andes, with a predominance of Entisol and Inceptisol order soils [24].

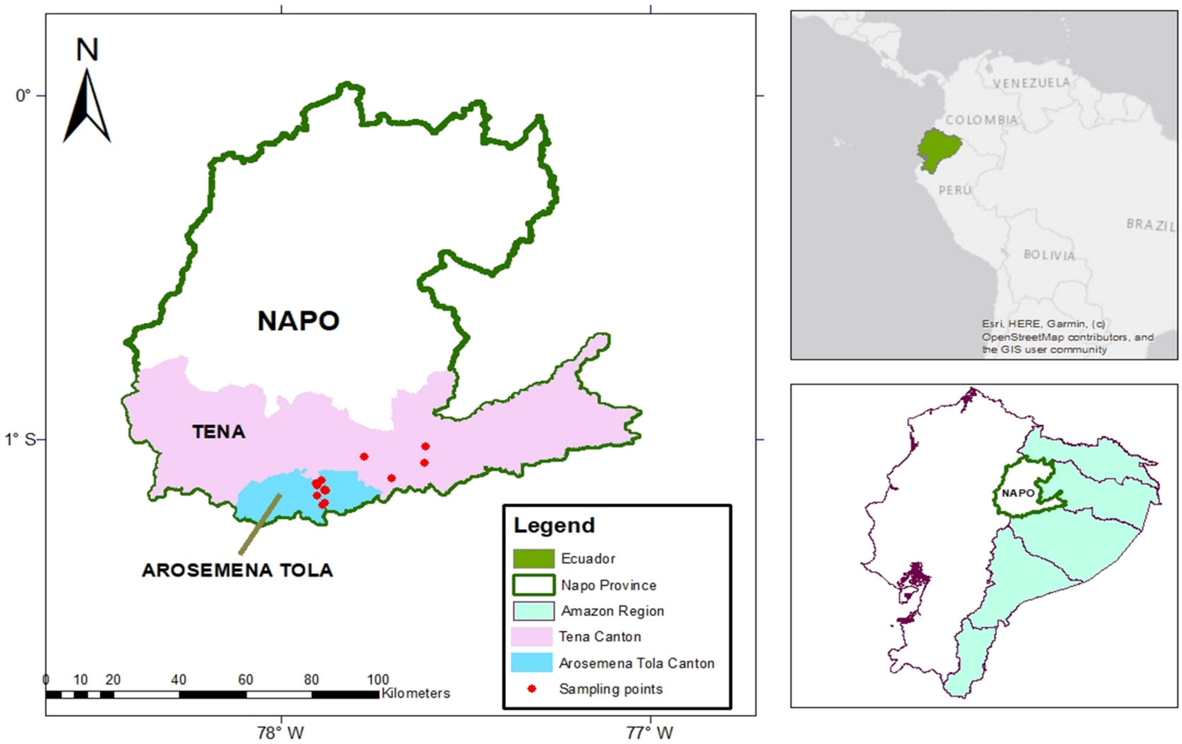

Figure 1. Sampling area location map.

2.1. Selected Land Uses

In the Ecuadorian Amazon, due to the characteristics of the region, different kinds of land uses have been developed, such as associations of crops, monocultures, forage, and forestry or agroforestry systems, which are adapted according to the needs of production. This research covers 13 sampling sites: 3 cocoa monocultures (CMC), 7 chakra-type agroforestry systems with cocoa in association of timber forest species (TAFS) and fruit forest species (FAFS), and 3 secondary forests. Table 1 shows a brief description of the land uses under study.

Table 1. Description of the types of land uses selected for the study.

Types of Land Uses	Description
Chakra-type agroforestry system (AFS)	These arise as an alternative for management and production that is friendly to the ecosystem, since they resemble the succession of a natural forest [27–29], and generally adaptation in the tropics is very high [19]. In the Amazon of Ecuador, this type of management has been traditionally and culturally practiced directly and indirectly, with the implementation of the so-called Amazon chakras, part of the cultural identity of the populations that inhabit the Amazon, and little by little it has been established as a diversified farming model in association with cocoa, coffee, and timber species, among others, and may vary according to the purpose, type of soil, and management practices in relation to geographical location [4,28], since it provides food, medicinal, construction, habitat, and nutrient cycling resources and contributes to carbon storage [27,30,31]. Therefore, it captures atmospheric CO_2 and promotes the conservation of biodiversity [22,32].

Table 1. *Cont.*

Types of Land Uses	Description
Chakra	As traditional production systems similar to agrarian management of the forest on a family scale and an alternative to industrial and intensive crops, these systems or polycultures called chakra arise, which have been traditionally developed by Amazonian populations for the purposes of family subsistence. The chakras or diversified production systems are associated with different kind of crops, like: yucca, banana, naranjilla, coffee, cocoa, etc., as well as fruit trees (e.g., *Inga edulis*, *Citrus sinensis*, *Terminalia oblonga*, *Citrus aurantiifolia*, *Bactris gasipaes*, etc.), timber trees (e.g., *Cordia alliodora*, *Piptocoma discolor*, *Schefflera morototoni*, *Persea americana*, etc.), and fauna species in a natural state, without neglecting the variety of medicinal plants. The ideology of these communities is to maintain a balance between chakra and nature, without altering the forest, the life that inhabits that space, or the soil, the main support of life.
Cocoa monoculture (CMC)	Considered as a production system devoid of tree species, dependent on the use of agrochemicals, fertilizers, and amendments. From an economic point of view, it can be considered a very efficient production system, but in the long term, it can become a threat to the remaining natural resource that still remains. Faced with this scenario, and the interest in maintaining tropical forests and conserving their biodiversity, alternatives should be chosen that involve economic, social, cultural, and ecological interests, promoting the conversion and implementation of nature-friendly management systems such as forestry, agroforestry, or silvopastoral [2].
Forest	Land covered with exuberant natural vegetation, home to a great biodiversity of tree plant species (e.g., *Otoba glycycarpa*, *Inga* sp., *Cecropia sciadophylla*, *Apeiba membranacea*, *Mabea standleyi*, *Protium sagotianum*, *Iriartea deltoidea*, *Chimarrhis glabriflora*, *Sterculia colombiana*, *Virola flexuosa*, *Annona papilionella*, etc.), with a high carbon storage potential in plant biomass that contributes to a notable reduction of greenhouse gases [5]. In addition to being recognized for maintaining a balance between all elements, it is highly efficient and at the same time has the capacity to withstand changes [2,5].

2.2. Field Sampling

The experimental design followed systematic sampling, which included: 4 treatments, 4 sampling or measurement points, and a depth factor. During the data collection and sampling phase, the necessary measures were taken to achieve true and representative information.

The size of the sampling sites was 1600 m^2 (40 m × 40 m plots), where systematic sampling was carried out, establishing four 10 m × 10 m subplots with five sampling points each to determine the bulk density and the storage of organic carbon in the soil (Figure 2).

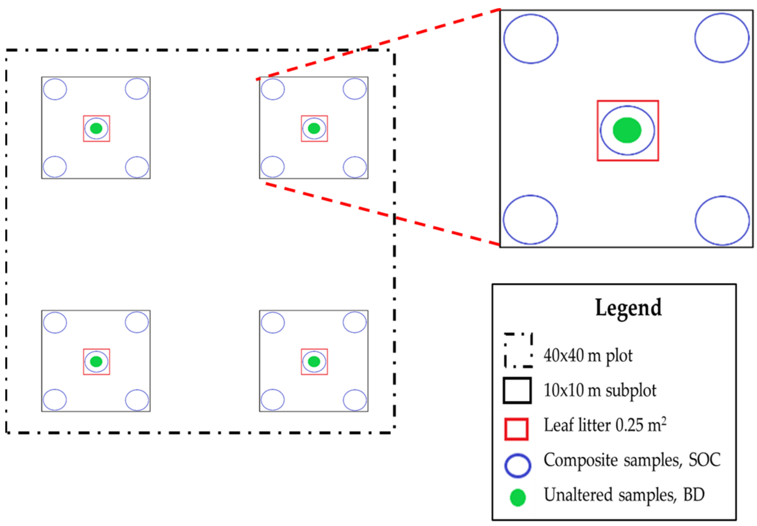

Figure 2. Scheme of the soil sampling process.

In each experimental plot, and for each subplot, sampling to determine the SOC was carried out at two depths (0–10 and 10–30 cm), for which 5 soil subsamples were taken within the subplot, represented by blue circles (Figure 2), and were homogenized to obtain the composite sample for each depth (13 plots × 4 subplots × 2 depths). The bulk density was determined by the cylinder method, taking a sample of undisturbed soil in the center of each subplot with the help of metal cylinders of 5 cm × 5 cm (length and diameter) at two sampling intervals, from 0 to 10 cm and 10 to 30 cm deep, marked with a green circle (Figure 2).

In the center of each subplot, with the help of a 0.25 m^2 quadrant, the material corresponding to dead plant remains (leaf litter) was collected to calculate the biomass of litter and thus estimate the carbon storage in this component (red box, Figure 2). At the same time, a record of forest species was collected to estimate the aboveground biomass and carbon storage in the 40 m × 40 m plot, in which the diameter at breast height (DBH) ≥ 10 cm was measured and a taxonomic identification of the species was carried out to determine the diversity, abundance, and importance of the identified species.

2.3. Floristic Composition

After the forest record, the characterization of species made it possible to define the composition and floristic diversity present in the sampled plots, as well as the different ecological parameters and equations used [14,33] (Table 2):

Table 2. Summary of ecological parameters and allometric equations used.

Parameter	Equation	References	
Basal area (Ba)	$\mathrm{Ba} = 0.7854 \times (\mathrm{DBH})^2$	[14,34]	(1)
Relative density (RD)	$\mathrm{RD} = \frac{\#\mathrm{ind.spp}}{\mathrm{sampling\ surface}} \times 100$	[14]	(2)
Relative dominance (RDom)	$\mathrm{RDom} = \frac{\mathrm{Ba\ spp}}{\mathrm{Total\ Ba}} \times 100$	[14]	(3)
Importance value index (IVI)	$\mathrm{IVI} = \mathrm{RD} + \mathrm{RDom}$	[14,35]	(4)
Biomass importance value (BIV)	$\mathrm{BIV} = \mathrm{Ba} + \mathrm{RD} + \mathrm{AGB}$	[36]	(5)
Simpson index (S)	$\mathrm{S} = \frac{\sum \mathrm{n\ (n-1)}}{\mathrm{N\ (N-1)}}$	[30,35]	(6)
Margalef index (D)	$\mathrm{D} = \frac{\#\mathrm{total\ spp}-1}{\mathrm{Ln\ N}}$	[14,33,37,38]	(7)
Shannon–Wiener index (H')	$\mathrm{H}' = -\sum(\mathrm{pi} \times (\log 2\ \mathrm{pi}))$ $\mathrm{pi} = \mathrm{ni}/\mathrm{N}$	[38]	(8)

n: total number of individuals of a species; N: total number of individuals of all species; pi: relative abundance; ni: number of individuals of a species.

2.4. Estimation of Carbon Sequestration

For this study, the total stored carbon (TSC) resulted from the sum of the following components: aboveground carbon (AGC), belowground root carbon (BGCr), litter biomass carbon (LBC), and soil organic carbon (SOC) [39]. However, this equation can be made up of more or fewer components according to the criteria and interest of the researchers [24,30,40,41].

$$\mathrm{TSC\ (Mg\ C\ ha^{-1})} = \mathrm{AGC} + \mathrm{BGCr} + \mathrm{LBC} + \mathrm{SOC} \tag{9}$$

where TSC: total stored carbon in Mg C ha^{-1}; and the Mg CO_2 ha^{-1} results from the product between the Mg C ha^{-1} and 3.67 which corresponds to the molecular weight of CO_2.

To estimate the aboveground biomass of the trees, the allometric equation proposed by [14,42] was used. For this, the plot is established where the inventory of floristic composition will be carried out, registering every individual ≥10 cm DBH. The allometric equation applies to all measurements of trees in tropical forests [30,36,42], thus estimating the carbon storage of AGB.

$$\begin{aligned}\mathrm{AGB} = (\rho \times \exp\,(-1.499 + (2.148 \times \ln(\mathrm{DBH})) + (0.207 \times \ln(\mathrm{DBH})^2) \\ - (0.0281 \times \ln(\mathrm{DBH})^3) \times 0.001\end{aligned} \tag{10}$$

where ρ corresponds to the density of the wood (g cm^{-3}) and DBH is the diameter measured at chest height, or 1.3 m above the ground.

The aboveground biomass of cocoa is estimated from the equation used by GIZ, in a study carried out in the territories of the Kichwa People of Rukullacta [43].

$$AGBCo = 1.0408\ e^{0.0736 \times d30} \tag{11}$$

AGBCo: aboveground biomass of cocoa; d30: diameter measured 30 cm from the ground.

The Mg C ha^{-1} of AGB and AGBCo are obtained and multiplied by 0.5, which is the carbon fraction (CF), proposed as a measure by the Intergovernmental Panel on Climate Change (IPCC) [24].

The biomass below the ground, provided by the roots, is obtained from the equation developed by [44], which was proposed by the IPCC in 2003 [24] and widely used by authors interested in knowing the biomass provided by the roots [24,30,39].

$$BGBr = \exp(-1.0587 + 0.8836 \times \ln AGB) \tag{12}$$

where BGBr: belowground biomass of roots and AGB: aboveground biomass. The Mg C ha^{-1} of BGCr is obtained by multiplying by 0.5 CF, according to the IPCC [24].

Litter carbon (LC) was obtained after drying the material collected with the help of the 0.25 m^2 quadrant [30], described above, at 105 °C for 24 h, obtaining dry matter (DM) per hectare and at the same time estimating the carbon storage in leaf litter, according to the following equation:

$$LC = DM \times CF \times 10000 \tag{13}$$

where LC: litter carbon in Mg C ha^{-1}, DM: dry matter in Mg, and CF: IPCC carbon fraction, which is 0.5.

The soil organic carbon (SOC) is obtained from the following equation [3,24,39–41].

$$SOC = BD \times (TOC/100) \times D \times 10000 \tag{14}$$

where SOC: in Mg C ha^{-1}; BD: bulk density in Mg m^{-3}; TOC: total organic carbon of soil %; and D corresponds to the depth in meters.

TOC was determined by the Walkley–Black wet digestion method [45]; BD by the cylinder method, in which the samples are weighed and dried at 105 °C for 24 h [7,46,47]. The determination of this parameter allows chemical and biological variables to be expressed in terms of surface area (kg ha^{-1} or Mg ha^{-1}) [48].

2.5. Data Analysis

The data analysis was carried out using SPSS IBM trial version 25 software. The composition and floristic diversity were found using allometric equations in Excel databases. A one-way ANOVA was applied, followed by a post hoc *Tukey test* ($p \leq 0.05$), to detect significant differences ($p < 0.05$) between land uses in relation to ecological parameters, indices, and carbon sequestration in different components. Prior to the ANOVA, an exploratory data set analysis was carried out using descriptive statistics, and normality was tested with the *Shapiro–Wilk test.*

3. Results

3.1. Floristic Composition

The floristic composition for each type of land use (TLU) varies according to management, as evidenced in Figure 3, where a total of 289 individuals are distributed in 82 species and 34 botanical families for the forest, for the agroforestry systems with fruit species (FAFS) and with timber species (TAFS), the number of individuals is 87 and 83, respectively, while the monoculture cocoa system (CMC) presents a total of 13 individuals, distributed in 7 species and families. These results allow us to understand the importance of conserving tropical forests due to the diversity of flora they have; however, it is evident that chakra-type agroforestry systems, despite being made up of some crops, also have a considerable number of species and forest families in comparison with the monocultures recorded in the present study.

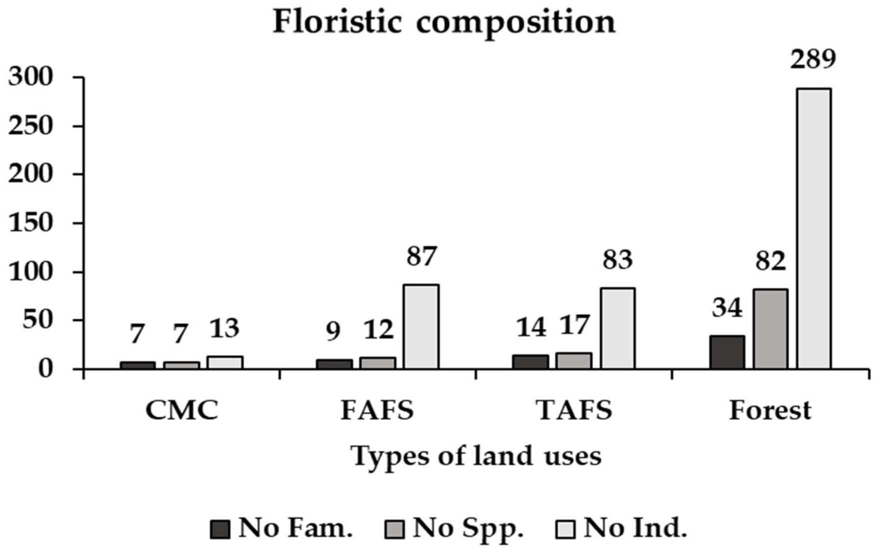

Figure 3. Floristic composition in the study systems. CMC: cocoa monoculture; FAFS: fruit agroforestry system; TAFS: timber agroforestry system.

3.2. Importance Value Index (IVI)

The species with the highest ecological weight for each type of land use under study are shown in Table 3. Thus, for CMC, the taxon that represents the highest IVI is *Cordia alliodora* with 32.5%, followed by *Bactris gasipaes* with 20.0%. Regarding FAFS, the highest IVI is 40.9% for *Inga edulis*, with 21.4% for *Cordia alliodora*. Meanwhile, in TAFS the highest IVIs are represented by *Cordia alliodora* and *Piptocoma discolor* with 27.8% and 26.7%, respectively. In the forest, the greatest ecological weight is supported by *Otoba glycycarpa* with 8.7%, followed by *Inga* sp., *Cecropia sciadophylla*, and *Apeiba membranacea* with 4.5% each, resulting in a subtotal of 39.9% for the ten most representative species in terms of IVI, while 60.1% is made up of the remaining 71 species registered in the forest.

Table 3. Importance Value Index (IVI).

Family	Species	N° ind.	RD %	RDom %	IVI %
Cocoa monoculture (CMC)					
Boraginaceae	*Cordia alliodora*	4	30.8	34.2	32.5
Arecaceae	*Bactris gasipaes*	3	23.1	17.0	20.0
Lauraceae	*Persea americana*	2	15.4	14.1	14.7
Urticaceae	*Pourouma cecropiifolia*	1	7.69	12.5	10.1
Malvaceae	*Ceiba samauma*	1	7.69	11.2	9.46
Subtotal		11	84.6	89.0	86.8
Fruit agroforestry system (FAFS)					
Fabaceae	*Inga edulis*	40	46.0	35.8	40.9
Boraginaceae	*Cordia alliodora*	13	14.9	27.8	21.3
Rutaceae	*Citrus sinensis*	13	14.9	8.03	11.5
Rutaceae	*Citrus aurantiifolia*	9	10.3	4.86	7.60
Meliaceae	*Cedrela odorata*	3	3.45	5.62	4.54
Subtotal		78	89.7	82.0	85.9

Table 3. *Cont.*

Family	Species	N° ind.	RD %	RDom %	IVI %
	Timber agroforestry system (TAFS)				
Boraginaceae	*Cordia alliodora*	21	25.3	30.2	27.8
Asteraceae	*Piptocoma discolor*	26	31.3	22.0	26.7
Fabaceae	*Inga edulis*	6	7.23	7.85	7.54
Araliaceae	*Schefflera morototoni*	3	3.61	9.00	6.31
Arecaceae	*Bactris gasipaes*	6	7.23	4.39	5.81
Subtotal		62	74.7	73.5	74.1
	Forest				
Myristicaceae	*Otoba glycycarpa*	24	8.30	9.11	8.71
Fabaceae	*Inga* sp.	9	3.11	5.91	4.51
Urticaceae	*Cecropia sciadophylla*	8	2.77	6.20	4.48
Malvaceae	*Apeiba membranacea*	8	2.77	6.18	4.47
Euphorbiaceae	*Mabea standleyi*	9	3.11	5.41	4.26
Burseraceae	*Protium sagotianum*	10	3.46	3.31	3.38
Arecaceae	*Iriartea deltoidea*	11	3.81	1.98	2.89
Rubiaceae	*Chimarrhis glabriflora*	8	2.77	2.76	2.76
Malvaceae	*Sterculia colombiana*	6	2.08	2.31	2.19
Myristicaceae	*Virola flexuosa*	7	2.42	1.95	2.18
Subtotal		100	34.6	45.1	39.9
Rest of species (71)		189	65.4	54.9	60.1

N° ind.: number of individuals; RD: relative density; RDom: relative dominance.

3.3. Diversity Index

Specific richness corresponds to the number of species identified for each TLU (Figure 3), while biodiversity is considered as an indicator of the state of ecological systems, estimated through different ecological diversity indices [49], as in this study (Table 4). Significant differences are evident in all cases ($p \leq 0.05$) and, according to Margalef or specific richness index, the forest is positioned as high in diversity with respect to CMC, FAFS, and TAFS, which maintain a medium level. The Simpson index, or dominance index, follows the same pattern of behavior as Margalef, highlighting the forest as high in dominance and the other TLUs as having a medium level, while the Shannon diversity index, based on equity, positions the forest as high in diversity unlike CMC, FAFS, and TAFS which are low in diversity.

Table 4. Diversity index.

Index	CMC	FAFS	TAFS	Forest	Significance
Shannon H′	0.977 ^{b} (±0.389)	0.873 ^{b} (±0.424)	1.39 ^{b} (±0.482)	3.49 ^{a} (±0.122)	***
Simpson S	0.577 ^{ab} (±0.176)	0.423 ^{b} (±0.230)	0.655 ^{ab} (±0.141)	0.960 ^{a} (±0.000)	**
Margalef D	1.34 ^{b} (±0.577)	1.24 ^{b} (±0.397)	1.79 ^{b} (±0.804)	9.34 ^{a} (±1.16)	***
Ba ha^{-1}	0.793 ^{c} (±0.177)	5.18 ^{b} (±0.613)	4.06 ^{bc} (±1.39)	27.1 ^{a} (±2.47)	***
AGB ha^{-1}	5.34 ^{c} (±1.29)	42.9 ^{b} (±4.25)	30.7 ^{bc} (±10.5)	245 ^{a} (±22.1)	***

Superscript letters denote significant differences according to the ANOVA test, at a level of $p \leq 0.05$. Values ± in parentheses are standard deviations from the mean. Significance levels: **, *** are 95% and 99%. CMC: cocoa monoculture; FAFS: fruit agroforestry system; TAFS: timber agroforestry system; Ba: basal area per hectare; AGB: aboveground biomass per hectare.

Furthermore, in Table 4, the means are presented in terms of the basal area (Ba) and the aboveground biomass (AGB), which express marked significant differences in the forest with respect to the management systems.

Taking into account that these indices are used as indicators of diversity in different scenarios, each one refers specifically to certain variables of wealth, dominance, and equity, and regardless of the index used in the present study, there is clear evidence of the effect of change of land use in terms of species diversity in management systems with respect to the forest.

3.4. Biomass Importance Value (BIV)

In tropical ecosystems, the biomass that is housed above ground contributes significantly to carbon sequestration, as evidenced in Table 5. The species with the highest BIV, and those that contribute the greatest AGB, therefore sequester more carbon, such as: *Cordia alliodora* and *Persea Americana* with 38.1%, and 16.7%, respectively (CMC); *Inga edulis* and *Cordia alliodora* with 30.8% and 27.7%, respectively (FAFS); *Cordia alliodora* and *Piptocoma discolor* with 30.4% and 17.0% (TAFS); *Cecropia sciadophylla* and *Otoba glycycarpa* with 8.55% and 7.46%, respectively (forest).

Table 5. Biomass importance value (BIV).

Family	Species	RD %	Ba %	AGB %	BIV %
Cocoa monoculture (CMC)					
Boraginaceae	*Cordia alliodora*	30.8	34.2	38.1	34.4
Arecaceae	*Bactris gasipaes*	23.1	17.0	12.8	17.6
Lauraceae	*Persea americana*	15.4	14.1	16.7	15.4
Malvaceae	*Ceiba samauma*	7.69	11.3	14.4	11.1
Urticaceae	*Pourouma cecropiifolia*	7.69	12.5	10.1	10.1
Subtotal		84.6	89.0	92.2	88.6
Fruit agroforestry system (FAFS)					
Fabaceae	*Inga edulis*	46.0	35.8	30.9	37.5
Boraginaceae	*Cordia alliodora*	14.9	27.8	27.6	23.4
Rutaceae	*Citrus sinensis*	14.9	8.03	7.56	10.2
Combretaceae	*Terminalia oblonga*	1.15	6.87	12.5	6.85
Rutaceae	*Citrus aurantiifolia*	10.3	4.86	4.28	6.49
Subtotal		87.4	83.3	82.9	84.5
Timber agroforestry system (TAFS)					
Boraginaceae	*Cordia alliodora*	25.3	30.2	30.4	28.6
Asteraceae	*Piptocoma discolor*	31.3	22.0	17.0	23.5
Fabaceae	*Inga edulis*	7.23	7.85	8.34	7.80
Araliaceae	*Schefflera morototoni*	3.61	9.00	9.66	7.42
Lauraceae	*Persea americana*	4.82	4.69	5.27	4.93
Subtotal		72.3	73.8	70.7	72.3
Forest					
Myristicaceae	*Otoba glycycarpa*	8.30	9.11	7.46	8.29
Urticaceae	*Cecropia sciadophylla*	2.77	6.20	8.55	5.84
Fabaceae	*Inga* sp.	3.11	5.91	6.41	5.15
Euphorbiaceae	*Mabea standleyi*	3.11	5.41	6.90	5.14
Malvaceae	*Apeiba membranácea*	2.77	6.18	4.73	4.56
Burseraceae	*Protium sagotianum*	3.46	3.31	3.51	3.43
Rubiaceae	*Chimarrhis glabriflora*	2.77	2.76	4.02	3.18
Annonaceae	*Annona papilionella*	1.38	2.65	2.88	2.30
Arecaceae	*Iriartea deltoidea*	3.81	1.98	0.90	2.23
Malvaceae	*Sterculia colombiana*	2.08	2.31	1.99	2.13
Subtotal		33.6	45.8	47.4	42.2

RD: relative density; Ba: basal area; AGB: aboveground biomass.

The species with the highest BIV are: *Cordia alliodora* (CMC), with 34.4%; *Inga edulis* (FAFS), with 37.5%; *Cordia alliodora* (TAFS), with 28.6%; and *Otoba glycycarpa* (forest), with 8.29%. Furthermore, it is evident that the five species with the highest BIV for CMC, FAFS, and TAFS contribute 92.2%, 82.8%, and 70.7%, respectively, of the total AGB, while in the forest the ten species with the highest BIV represent 47.4% of total AGB.

3.5. Total Stored Carbon

The TSC, in the different types of land uses and components (biomass, litter, roots, and soil), is shown in the Table 6, showing an important difference of TSC in the forest (233 Mg C ha^{-1}) with respect to CMC, FAFS, and TAFS. The carbon contribution of the TAGC and BGCr components is significantly higher in the forest at 115 Mg C ha^{-1} and 40.7 Mg C ha^{-1}, respectively, than in other land uses. The carbon storage in litter and soil did not show significant differences between the selected land uses (Table 6). Furthermore, also in Table 6, the total equivalent CO_2 stored in each land use and for each component is represented in Mg CO_2 ha^{-1}. Important significant differences are shown when comparing the total CO_2 equivalent stored in the forest with each kind of land use. The total CO_2 equivalent stored in FAFS and TAFS is higher than in CMC.

Table 6. Means of carbon sequestration in the different components analyzed.

Units	Components	Types of Land Uses				Significance
		CMC	FAFS	TAFS	Forest	
Mg C ha^{-1}	AGC	2.51 ^{c} (±0.61)	20.2 ^{b} (±2.00)	14.4 ^{bc} (±4.93)	115 ^{a} (±10.4)	***
	AGCC$_o$	3.49 ^{a} (±1.30)	3.10 ^{a} (±1.14)	3.49 ^{a} (±0.62)	---	n/s
	TAGC	6.00 ^{c} (±1.83)	23.3 ^{b} (±3.09)	17.9 ^{bc} (±5.16)	115 ^{a} (±10.4)	***
	BGC$_r$	1.02 ^{c} (±0.22)	7.79 ^{b} (±0.65)	5.65 ^{bc} (±1.92)	40.7 ^{a} (±3.15)	***
	LC	7.33 ^{a} (±3.15)	6.37 ^{a} (±2.30)	10.1 ^{a} (±3.95)	12.8 ^{a} (±2.37)	n/s
	SOC$_{10cm}$	30.0 ^{a} (±5.61)	24.6 ^{a} (±7.10)	26.3 ^{a} (±8.72)	32.6 ^{a} (±1.89)	n/s
	SOC$_{30cm}$	46.0 ^{a} (±1.90)	33.1 ^{a} (±5.64)	37.8 ^{a} (±14.2)	32.3 ^{a} (±5.32)	n/s
	TSC	**90.4 ^{b} (±4.23)**	**95.1 ^{b} (±15.2)**	**97.8 ^{b} (±16.2)**	**233 ^{a} (±7.68)**	***
Mg CO_2 ha^{-1}	AGC	9.20 ^{c} (±2.23)	73.9 ^{b} (±7.32)	53.0 ^{bc} (±18.1)	421 ^{a} (±38.1)	
	AGCC$_o$	12.8 ^{a} (±4.78)	11.4 ^{a} (±4.17)	12.8 ^{a} (±2.28)	---	
	TAGC	22.0 ^{c} (±6.73)	85.3 ^{b} (±11.3)	65.8 ^{bc} (±18.9)	421 ^{a} (±38.1)	
	BGC$_r$	3.75 ^{c} (±0.82)	28.6 ^{b} (±2.39)	20.7 ^{bc} (±7.05)	149 ^{a} (±11.5)	
	LC	26.9 ^{a} (±11.6)	23.4 ^{a} (±8.44)	37.0 ^{a} (±14.5)	46.9 ^{a} (±8.69)	
	SOC$_{10cm}$	110 ^{a} (±20.6)	90.1 ^{a} (±26.0)	96.3 ^{a} (±32.0)	119 ^{a} (±6.92)	
	SOC$_{30cm}$	169 ^{a} (±6.98)	121 ^{a} (±20.7)	139 ^{a} (±52.2)	119 ^{a} (±19.5)	
	CO_{2eq} total	**331 ^{b} (±15.5)**	**349 ^{b} (±55.9)**	**358 ^{b} (±59.5)**	**856 ^{a} (±28.2)**	

Results in the same row marked with different letters indicate significant differences according to the ANOVA test, at a level of $p \leq 0.05$. Values ± in parentheses are standard deviations from the mean. Significance levels: *** is 99%. CMC: cocoa monoculture; FAFS: agroforestry system with fruit trees; TAFS: agroforestry system with timber trees; AGC: aboveground carbon; AGCCo: aboveground carbon cocoa; TAGC: total aboveground carbon (AGC + AGCCo); BGCr: belowground carbon roots; LC: litter carbon; SOC$_{10cm}$: soil organic carbon at 10 cm depth; SOC$_{30cm}$: soil organic carbon at 30 cm depth; TSC: total stored carbon; CO_2eq total: total CO_2 equivalent.

The total stored carbon of the above- and belowground components for each type of land use in the forest is statistically very significantly greater with respect to the others (Table 6). Furthermore, it can be seen that the soils of the Amazon forests represent 27.8% of the TSC, which indicates that the contribution of AGC when quantifying carbon sequestration is representative in tropical forests. However, the soil carbon storage of CMC, FAFS, and TAFS represents 84.1, 65.5, and 60.6%, respectively, of the TSC, as evident in Figure 4. Nevertheless, the carbon stored in forest roots is very significant with respect to the others, which is mainly due to the exuberant floristic composition.

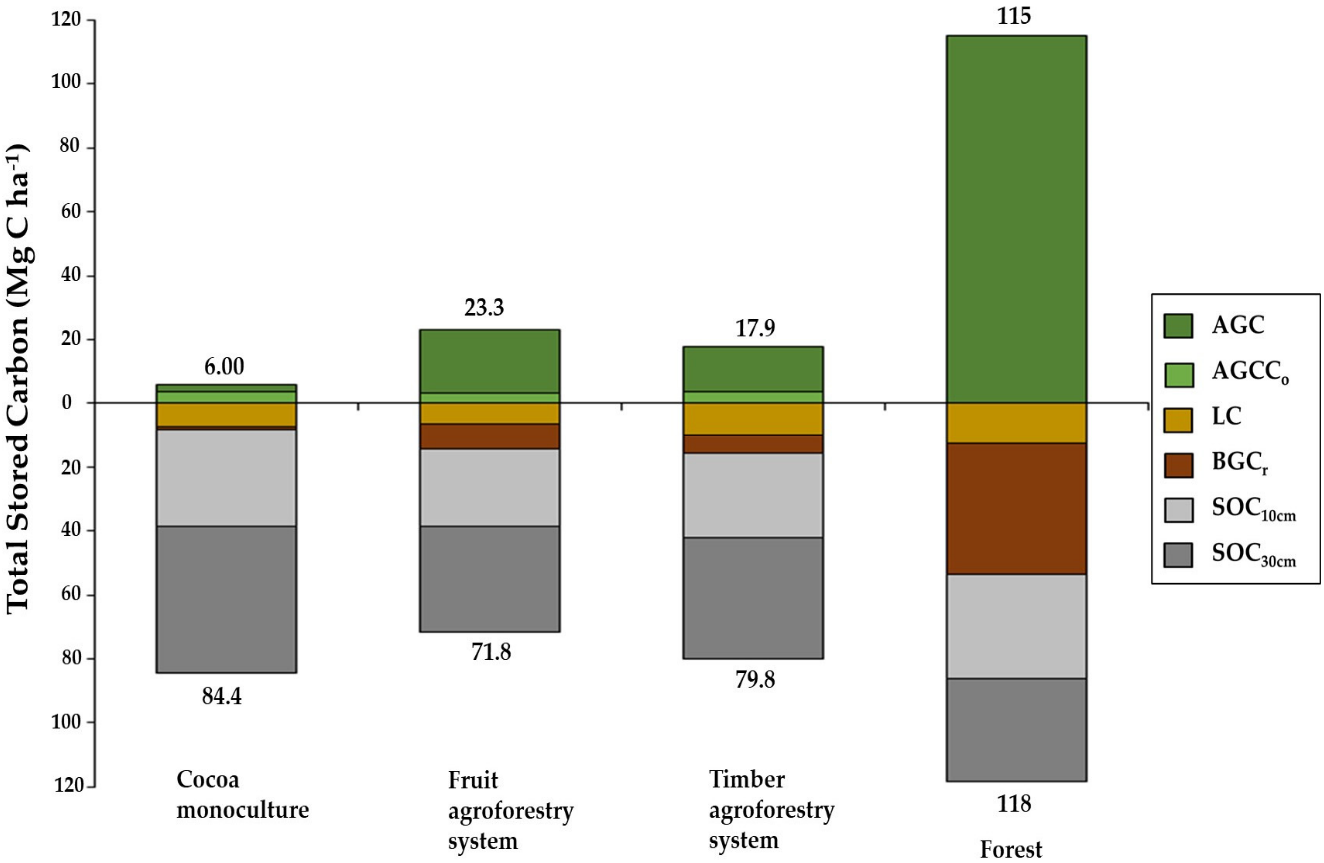

Figure 4. Representation of total stored carbon in the components of each type of land use. Dark green represents aboveground carbon (AGC); light green corresponds to aboveground carbon of cocoa (AGCCo); light brown is litter carbon (LC); brown represents belowground carbon of roots (BGCr); light gray and dark gray correspond to soil organic carbon at 10 and 30 cm depths, respectively.

4. Discussion

4.1. Floristic Composition

The richness, density, and floristic composition are important characteristics to take into account for a correct description and interpretation of the stand or sampling plot [38], Thus, what was found in this study corresponds to what has been described for tropical ecosystems, with *Cordia alliodora* standing out, with *Inga edulis*, *Piptocoma discolor*, and *Otoba glycycarpa*, as the most representative of the management systems and the forest (Table 3), which are distinctive elements of Amazonian ecosystems [12,15]. As reported in forest formations at different altitudinal levels in Napo, *Otoba glycycarpa*, *Cecropia sciadophylla*, and *Inga* sp. Are among the species with the greatest potential to store biomass [36]. Studies carried out in Colombian forests (tropical humid forest) report Fabaceae, Myristicaceae, Malvaceae, and Burseraceae as the most important families [50]. These families are also representative of the forests recorded in this study. Furthermore, these findings provide valuable information on the representative taxa of this Amazonian area.

In AFSs associated with coffee in from Colombia, *Cordia alliodora* and *Inga edulis* are reported as the species with the highest IVI, followed by *Citrus sinensis* [32]. In AFSs under shade in Peru, several of the species identified in the management systems in this study are also reported [17], species that in agroforestry management systems maximize wood production and sequestration of atmospheric CO_2 when avoiding increased deforestation [6]. The species with greatest ecological importance in the forest according to the IVI have also been recorded in other tropical contexts, with some of these species considered common in the Amazon region [15].

As for diversity, it encompasses several interpretations, with the simplest version focusing on the diversity of species [38], thus managing to categorize, according to the Margalef index, the forest as high in species diversity, as reported [14] for the evergreen montane forest of the Sumaco Biosphere Reserve. The estimate of the Shannon diversity index positions the management systems as low in species diversity with respect to the forest (high diversity), which is common to Amazonian ecosystems and similar to what was reported by [14]. However, studies on AFSs with coffee report very low values for this index [17]. According to the Simpson index, AFSs and CMC represent a medium level, while the forest represents a high dominance of species, a characteristic behavior of tropical forests in the Amazon region, due to the exuberant vegetation they have. In tropical humid forests of Colombia, the same pattern of behavior is reported for the Margalef (ranges from 7.3 to 9.7), Shannon (from 3.2 to 3.6), and Simpson indices (from 0.95 to 0.97) [50], just like what was reported in a tropical forest of Brazil, according to the Shannon index (3.57) [51]. As expected, the findings of the diversity indices are representative and this demonstrates the importance and richness of the Amazonian secondary forests, which will be increased if they are taken care of.

4.2. Stored Biomass Carbon

Changes in land use in the Amazon have generated the need to look for mitigation alternatives and amendments in this scenario. Therefore, the estimation of aerial biomass in tropical ecosystems is crucial to quantify the storage of carbon [14], showing that the total AGC recorded in the forest is similar to what was found in the Amazon forests of Colombia [11] and what was recorded in the evergreen Amazonian forests in the montane foothills of the high zone of Ecuador [12]. On the contrary, the contribution of biomass in the AFS is similar to what was found by the Los Laureles Natural Laboratory of Nicaragua in AFSs associated with fruit and timber species such as *Inga edulis*, *Citrus aurantifolia*, *Cordia alliodora*, and *Bactris gasipaes*, among others [9], and to what was found in AFSs under conventional and organic management, with behavior that depends on the type of association, with fruit or timber species managed in the system, while AGCCo is similar to what was registered in CMC in Bolivia [22].

The BIV (Table 5) indicator of potential species in carbon storage and structure in tropical forests shows species that represent great commercial value for wood and firewood (*Cordia alliodora*), are a source of food (*Inga edulis*), provide shade, incorporate nutrients, and store carbon in the soil [32,34,52]. In addition, it establishes with scientific bases the species with the greatest ecological value and capacity to store carbon [12,15,22,36]. Similar species are reported from an evergreen montane forest, in the Ecuadorian Amazon [36], while, for evergreen montane forests, *Ficus cuatrecasana* and *Ficus* sp. are the species with the highest BIV [14]. These findings provide important information for research on enhancing carbon storage through vegetation.

Regarding the TAGC, considerable significant differences are reflected between land uses (Table 6), with the forest with 115 Mg C ha^{-1}, which differs from the rest of the uses by the exuberant vegetal composition of the forest ecosystems in the Amazon. Similar reports are recorded for young secondary forests of Colombia, with 112 Mg C ha^{-1} [53]. What was found in this study exceeds the reports from a montane foothill forest (99.7 Mg C ha^{-1}) and a low montane forest (21.8 Mg C ha^{-1}) in the province of Zamora Chinchipe [15] and what was found in a tropical secondary forest in Indonesia (74.1 Mg C ha^{-1}) [54], as well as what was reported in diverse forests of the Eastern Plains in Colombia, with 61.8 Mg C ha^{-1} [55], behavior that is explained by the structure and composition of forest species in these remnants of the Napo Amazonian forests and partly by the altitude at which they are located. On the contrary, the TAGC values of our study are lower than those reported in primary Amazonian tropical forests, with minimal human intervention in Caquetá, Colombia and the Eastern Plains of Colombia [11,20], respectively, as well as what was reported for low-intervention montane forests in the province of Napo [36]. However, the TAGC recorded for FAFS and TAFS (Table 6) exceeds the records in the AFS with cocoa (14.0 Mg C ha^{-1}) from tropical rainy areas in Colombia [18], but it is lower than what was found in tropical ecosystems of Peru (65.61 Mg C ha^{-1}), due to the higher density of associated species for commercial use and sustenance [2]. The TAGC in CMC (Table 6) is higher than that reported in cocoa monocultures in Nicaragua [9]. But it is still very low compared to what was found in FAFS and TAFS, which allows us to infer that the storage of AGC in any type of AFS depends on the management, crop age, diversity, and density of tree species [2,20,34], unlike a monoculture that is limited to certain species. This means that the greater the diversity of species, the greater the carbon store [9,52]. Furthermore, several studies affirm that the transition from monocultures to AFSs has a great potential to store carbon, which improves with the age and density of tree species [34,52], such as silvopastoral systems (SPSs) in the arid region of Colombia with 7.15 Mg C ha^{-1} [1] and other studies in Colombian territory (31 Mg C ha^{-1}) [56]. In this context, it is confirmed that SPSs and AFSs are important management and improvement alternatives to counteract the expansion of the agricultural frontier and therefore minimize GHG emissions that lead to global warming.

Nonetheless, the biomass in the roots represents a considerable carbon store [52], which depends on the density of plant species (AGB), the age of the vegetation cover (forests and regeneration), and mainly the management system (AFS and SPS). The carbon stored by the roots of the forest exceeds that reported for secondary forests in Colombia (33 Mg C ha^{-1}) [53], possibly because these are regenerating forests no older than 20 years, in contrast to the present study that covers mature secondary forests. Meanwhile, root carbon in FAFS and TAFS corresponds to what was reported by [24], and [57] reports similar values for monocultures and AFSs.

4.3. Carbon Stored in the Soil

Several studies affirm that soil is the component that contributes the most to carbon storage [17,26]. Thus, the TSC below the ground of the selected management systems (CMC, FAFS, and TAFS) is between 67 and 92% of the total (Table 6), agreeing with what was cited for tropical forests [13] and with what was found in AFSs of the tropical zone of Peru, while the forest represents 33%, similar to the reports in forests of Zamora [15] and tropical forest of Indonesia [54]. The findings confirm that soils are important carbon stores, which depend mainly on the nutritious plant cover that the Amazon forests have. This is also the case in AFSs, which depend on the plant association and to a lesser extent on crop amendments.

Several works show that the conversion of forests to agricultural land, in many cases, significantly decreases OM reserves and therefore the storage of carbon in the soil, in addition to the essential nutrients for vegetation [13,25]. In this study, no significant differences are evident in terms of carbon storage in litter and soil, but there is a small difference between forest and other uses in terms of litter storage in the surface horizon (Table 6), behavior similar to that found in native forests of southern Brazil [29]. An opposite effect is observed for the depth of 10–30 cm (Table 6), as reported by other authors [24], on edaphic carbon storage in forests of the Ecuadorian Amazon, although with differences in terms of litter values. However, the carbon store in the surface soil in cocoa monocultures and AFS in Brazil reports values higher than what was found in this study and increases with depth [29], just like what was found in the first centimeters of the soil in AFSs in Peru [17]. AFSs with coffee, associated with timber species in organic and conventional management, report 27 and 25.5 Mg C ha^{-1} (0–10 cm), respectively [4], similar to what was found in the surface horizon of this study. But from 10 to 30 cm deep, the behavioral pattern of organic management of the study carried out by the Tropical Agricultural Research and Higher Education Center (CATIE) in Costa Rica is observed [4], since FAFS and TAFS in this study have an organic management, in association with plant species from the area. It should be emphasized that TSC depends strongly on the management in the AFS, the associated plant species (timber or fruit), and mainly the age, just as for forest regeneration.

The soil is an important player in SOC storage, nutrient cycling, and aggregates [25], just like the litter. In the present study, carbon storage in litter (Table 6) is greater than reported for secondary montane forests of Napo and Pastaza [3,13,15] and what was reported in the tropics of Colombia [20]. In relation to the AFS, the carbon store provided by litter (Figure 4) is double that found in AFSs with coffee under shade in Peru [17]. Nevertheless, the TSC in the forest (Table 6) corresponds to what was reported for a montane forest in the Ecuadorian Amazon [15], while it differs from what was found in Colombian forests [20] and with what was reported by [24] for forests in Napo. This behavior is because the present study quantifies the carbon storage in several components, and when talking about total stored carbon, comparisons are not possible due to the difference in components in the cited research. Several studies support the aforementioned results since, recently, it has been shown in different contexts that the implementation of agroforestry systems provides countless environmental, cultural, productive, economic, and social benefits, which give greater emphasis to the implementation and replication of these environmentally friendly systems, especially when it comes to Amazonian contexts.

Therefore, in this study, it has been shown that tropical forests are the best carbon stores in relation to other vegetation covers in terms of biomass, availability of litter, nutrients, and more, agreeing with what was mentioned by [15]. Agroforestry systems, in this case in association with cocoa, differ notably from monocultures due to the forestry component, even more so if they are associated with timber and fruit species in the area. The forestry component, in addition to the multiple benefits it brings to the soil and the environment, provides a social and economic benefit for farmers [20]. These results demonstrate the importance of promoting the implementation of agroforestry in Amazonian contexts, which are governed by intensive cultivation and livestock practices.

5. Conclusions

The composition and structural characteristics for each type of land use vary according to the management and type of forest association. However, it is evident that chakra-type agroforestry systems, despite being made up of some crops, also host a considerable number of forest species and families compared to monocultures. The results show the importance of conserving tropical forests due to the diversity of flora they have. In this sense, this work contributes basic information on the diversity, composition, and structure of trees and shrubs for the adequate management of the main identified species. The value index based on density, abundance, and biomass is a good indicator to recognize potential species in carbon capture and therefore in biomass production.

The species with the greatest potential in carbon storage and structure varied depending on land use, being CMC and TAFS (*Cordia alliodora*), FAFS (*Inga edulis*), and forest (*Otoba glycycarpa*). These species represent great commercial value, provide food, incorporate nutrients, and store carbon in the soil, in addition to providing a scientific basis for the species with the greatest ecological value and capacity for sequestration carbon. In general terms, these findings contribute to increasing knowledge about carbon sequestration throughout the different types of ecosystems that occur on Earth. Furthermore, the contribution of a few species to the maintenance of the level of AGB/carbon stocks suggests that a future intensification of selective deforestation, biased towards high-carbon trees, could lead to carbon depletion of Amazonian forests. This is essential to consider when making decisions in terms of deforestation and reforestation programs.

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