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Modeling of the vertical structure of shade trees in cacao agroforestry systems

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Cacao agrosystems can provide available habitats for wildlife species, due to the structure and diversity of established shade trees in plantations. The objective of this research is to calculate the index of importance and forest value of shade trees used in cacao agrosystems. Field sampling was carried out to collect data on breast height diameter, canopy diameter and canopy height, these variables were used to estimate the importance value index and the forest value index. The trees with the best indexes of importance and forest value are *Erythrina americana* (*IVI* = 62.34 and *FVI* = 50.94), *Bursera simaruba* (*IVI* = 62.53 and *FVI* = 66.99) and *Samanea saman* (*IVI* = 56, 85 and *FVI* = 42.93). The vertical structure of cacao agrosystems is important since it could be used as an input variable to evaluate and predict, through an ecological niche model, the quality of the available habitat for the conservation of wildlife such as birds, reptiles and arboreal mammals.

Keywords: biodiversity conservation, canopy height, Forest value index.

УДК 630

Моделирование вертикальной структуры тенистых деревьев в системах агролесоводства какао

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Агросистемы какао могут обеспечить доступную среду обитания для видов диких животных благодаря структуре и разнообразию укоренившихся тенистых деревьев на плантациях. Целью данного исследования является расчёт индекса важности и лесной ценности тенистых деревьев, используемых в агросистемах выращивания какао. Полевые исследования были проведены для получения данных о диаметре на высоте груди, диаметре и высоте полога. Эти переменные использовались для оценки индекса важности и индекса ценности леса. Деревья с лучшими показателями важности и лесной ценности – *Erythrina americana* (*IVI* = 62,34 и *FVI* = 50,94), *Bursera simaruba* (*IVI* = 62,53 и *FVI* = 66,99) и *Samanea saman* (*IVI* = 56, 85 и *FVI* = 42,93). Вертикальная структура агросистем какао важна, поскольку её можно использовать в качестве входной переменной для оценки и прогнозирования с помощью модели экологической ниши качества доступной среды обитания для сохранения диких животных, таких как птицы, рептилии и древесные млекопитающие.

Ключевые слова: сохранение биоразнообразия, высота полога, индекс ценности леса.

Due to anthropogenic activities in ecosystems, fragmentation, and habitat loss, how the main causes of biodiversity loss at all global, national, and local levels, have modified ecosystem services [1, 2]. Agrosystems (intentional management of shade trees with acrops) have the potential to provide habitats, to conserve wildlife species in highly modified tropical landscapes [3, 4]. Coffee and cacao agrosystems are the best known, and often have a high canopy of various shade tree species [5]. So, these shade trees are very important, and vary widely: 1) polycultural system (multiple species of shade trees planted with forest species), where crop trees are interspersed, with other shade trees planted and cacao, 2) monocultural shade, where the shadow is dominated by one or some tree species, 3) diverse shade systems, where most trees vary from 30 to 40 plant species, in which fruit and timber species are inserted, where The spine, usually are fast-growing nitrogen fixation legumes, include *Erythrina* spp., *Gliricidia sepium*, *Samanea saman*, and *Inga* spp. [6].

In cacao agrosystems (*Theobroma cacao*) worldwide, some shade trees are used that are also present in plantations in Mexico. In Ghana *Persea americana, Citrus senensis, Gliricidia sepium, Persea americana, Ceiba pentandra, Cedrela odorata* and *Spondias mombin* [7–10]. In Brazil *Spondias mombin, Cedrela odorata, Guazuma ulmifolia, Ceiba pentandra* and *Genipa americana* [11, 12]. In Colombia *Spondias mombin, Psidium guajava, Swietenia macrophylla, Cordia alliodora, Annona muricata, Guazuma ulmifolia, Artocarpus altilis, Pouteria caimito, Gliceridia sepium, Persea americana, Musa paradisiaca, Cedrela odorat*a and *Ceiba pentandra* [13–15]. In Bolivia *Cedrela odorata, Spondian mombin* and *Guazuma ulmifolia* [16]. In Cameroon *Ceiba pentandra, Citrus reticulata, C. sinensis, Persea americana, Psidium guajava, Spondias mombin, Manguifera indica* and *Musa paradisiaca* [17, 18]. In Costa Rica *Carica papaya, Castilla elastica, Cedrela odorata, Cocos nucifera, Genipa americana, Gliricida sepium, Leucaena leucocephala, Spondias mombin* and *Samanea saman* [19]. In Nigeria *Citrus sinensis, Manguifera indica, Psidium guajava, Citrus reliculata, Persea americana, Cocos nucifera, Ceiba pentandra* and *Spondias mombin* [20]. In Indonesia *Manguifera indica* and *Swietenia macrophylla* [21, 22]. In Ecuador *Cedrela odorata* [23]. In Peru *Cedrela odorata, Persea americana* and *Swietenia macrophylla* [24].

The variety of trees established as shade in cacao plantations, are valuable spaces for wildlife conservation, providing habitat for insects, birds, amphibians, reptiles, and mammals [25–28]. Cacao is one of the main crops that can be associated with a great diversity of trees used as shade [29]. Globally, the most commonly used shade trees in cacao plantations are *Spondias mombis*, *Cedrela odorata*, *Persea americana*, *Mangifera indica,* and *Citrus sinensis* [10, 19, 20, 30, 31]. In Tabasco, the most common shade trees in cacao trees are *Guazuma ulmifolia*, *Ceiba pentandra*, *Erythrina americana* and *Samanea saman* [32–35]; where mammals such as the howler monkey (*Alouatta palliata*) endangered species (Sernapam NOM-059), has adapted, using these agrosystems as a refuge. In addition, the red list of the International Union for the Conservation of Nature (IUCN) considers *A. palliata mexicana* as critically endangered.

The objective of this research is to calculate the index of importance and forest value of the shade trees frequently used in cacao agrosystems, as available habitats for the conservation of wildlife species.

Objects and Methods

Characterization of the study area. The study was carried out in six different cacao agrosystems (Fig. 1, see color insert I). In the state of "Tabasco", Mexico. In this investigation, three different cacao agrosystems were selected as study sites.

Sampling procedure. For the sampling of the vegetation structure in the cacao agrosystems, the 3 study sites were used (Table 1), in which 10 plots of 25 × 10 m were selected in each, each plot had an area of 250 m^2, taking into account what is suggested by [36], for a total of 30 Temporary Sample Plot (*TSP*), where

Table 1

Sites used in this study

Study sites	Location	Coordinates, m (UTM, WGS84)		Area	Source
		X	Y		
SA 1	Aldama	461830	2017193	21.08 ha	[32]
SA 2	Carlos Greene	454416	2016030	49.59 ha	[37]
SA 3	Zapotal	471172	2023367	57.82 ha	[38]

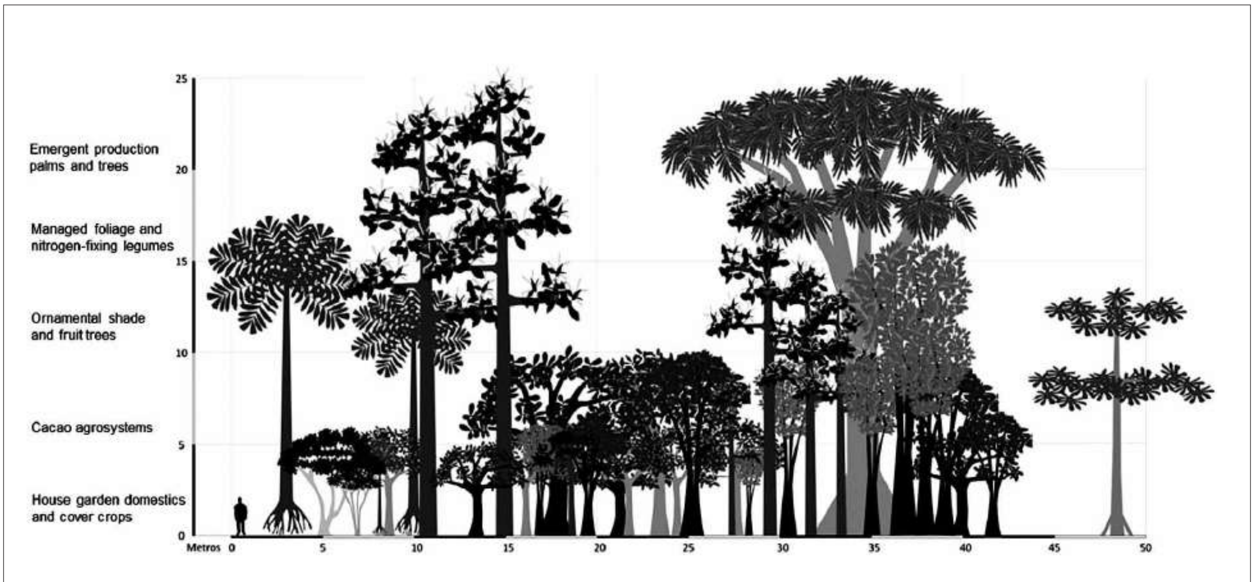

Fig. 2. Vertical structure of the cacao agroecosystem with shade trees [13]

the diameter at breast height (*DBH*), total height and crown diameter (all individuals with $DBH \geq 1.3$ m) were recorded.

Characterization of the vertical structure. The cacao agrosystems are integrated polycultivation plots where all major plant types are represented in layers and tiers from the open sun to the closed shade (Fig. 2).

Dasometric variables. The trees were taxonomically identified and geo-referenced with GPS. The dasometric variables recorded were the diameter at breast height (*DHB* 1.3 m) and crown diameter, measured with a tape measure, and total height (*Ht*) with a clinometer [39].

Diameter at breast height (*DBH*). Once the plots were established, a direct determination of the diameter at breast height (*DBH*) of all the trees present in each of the TSPs was carried out, making a single reading per tree, where $DBH = C/\varpi$.

Determination of canopy height. Due to the practical difficulties in measuring canopy heights directly, through an indirect method, was used by a clinometer to measure the angles of the tree base (θ), the canopy (ρ) and the horizontal distance (*hd*), using the following basic trigonometric formula: $Ht = hd(\tan\rho + \tan\theta)$.

Determination of crown diameter (*CD*). For the determination of the crown diameter present in each *TSP*, the projection of these was measured in two directions, mainly North-South and East-West, taking as reference the projection of the ends of the same on the ground $CD = (cd1+cd2)/2$ [68].

Basal Area Calculation. With the measurements data, a database was generated, with which the calculation of the Basal Area (*BA*), cross-sectional area of the tree, measured at 1.30 m height was determined and calculated by the following formula: $BA = 0.7854 \cdot DBH^2$, where *BA* = *Basal area* in m^2 and *DBH* = *diameter at breast height* in m^2.

Importance Value Index. The importance value index (*IVI*) defines which of the species present contribute to the character and structure of an ecosystem, which is obtained from the study of structural variables such as abundance, dominance, coverage, and frequency [40]. It was calculated as follows: *IVI* = *Relative dominance* + *Relative density* + *Relative frequency*.

The dominance (biomass estimator: basal area, coverage) relative was obtained as follows: *Relative dominance* = (*Absolute dominance per each tree*)/(*Absolute dominance of all trees*) · 100,

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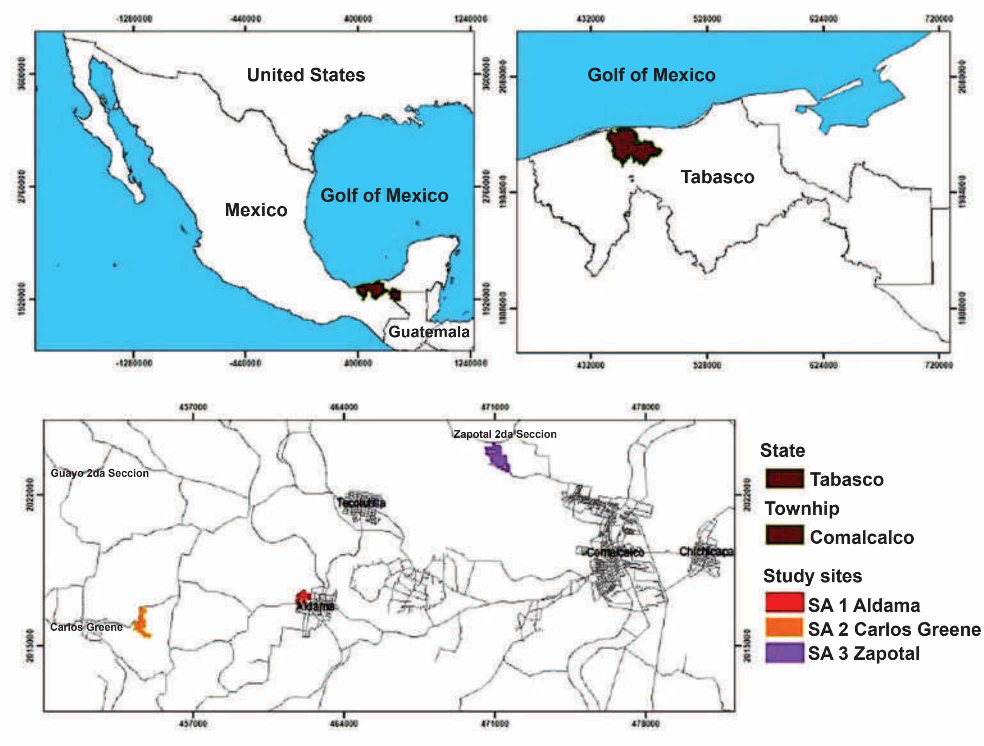

Fig. 1. Cacao agrosystems used as study sites

Table 2

Tree species are found in three cacao agrosystems in Comalcalco, Tabasco

Family	Scientific name	Height (m)	Agrosystems		
			SA 1	SA 2	SA 3
Anacardiaceae	*Mangifera indica*	10–30	X		
	Spondias mombin	10–30	X	X	X
	S. purpurea	3–8	X		
Annonaceae	*Annona muricata*	3–8	X		
	A. reticulata	6–8			X
Bignoniaceae	*Tabebuia rosea*	10–30	X	X	X
Burseraceae	*Bursera simaruba*	20–35		X	
Fabaceae	*Erythrina americana*	10–30	X	X	
	Inga jinicuil	12–15		X	X
	Gliricidia sepium	12–20	X		
	Tamarindus indica	10–30		X	X
	Samanea saman	25–50		X	X
	Leucaena leucocephala	3–6			X
Lauraceae	*Cinnamomum zeylanicum*	10–15		X	
	Persea schiedeana	8–25	X		
	Persea americana	10–20		X	X
Malpighiaceae	*Byrsonima crassifolia*	3–7			X
Malvaceae	*Ceiba pentandra*	20–70	X		X
	Guazuma ulmifolia	8–15		X	
Meliaceae	*Cedrela odorata*	10–35	X	X	X
	Swietenia macrophylla	35–50			X
Moraceae	*Artocarpus altilis*	12–21	X		
	Castilla el stica	20–25			X
Myrtaceae	*Pimenta dioica*	6–8	X		
	Psidium guajava	3–10			X
	Syzygium jambos	10–16		X	
Rutaceae	*Citrus latifolia*	3–6			X
	C. sinensis	9–10	X		
	C. nobilis	2–6		X	
	C. aurantium	3–5			X
Sapindaceae	*Talisia olivaeformis*	15–20			X
	Nephelium lappaceum	12–20	X		
Sapotaceae	*Chrysophyllum cainito*	10–25		X	
	Manilkara sapota	25–30		X	
	Pouteria sapota	15–45	X		X
Oxalidaceae	*Averrhoa carambola*	3–5		X	
Bixaceae	*Bixa orellana*	2–5	X		
Boraginaceae	*Cordia alliodora*	7–25		X	
Caricaceae	*Carica papaya*	2–8			X
Musaceae	*Musa paradisiaca*	1–3		X	
Muntingiaceae	*Muntingia calabura*	3–8		X	
Rubiaceae	*Genipa americana*	15–25	X		

Table 3

Tree species with the highest importance value (*IVI*) and forest value indices in the three cacao-based agrosystems

Species	*IVI*		Species	*FVI*
SA 1			SA 1	
Erythrina americana	62.34		*Erythrina americana*	50.94
Cedrela odorata	46.64		*Ceiba pentandra*	49.06
Tabebuia rosea	39.03		*Mangifera indica*	41.30
Mangifera indica	25.32		*Artocarpus altilis*	35.22
Artocarpus altilis	22.91		*Spondias mombin*	28.12
Twelve remaining species	103.76		Twelve remaining species	95.36
SA 2			SA 2	
Bursera simaruba	62.53		*Bursera simaruba*	66.99
Cedrela odorata	50.86		*Samanea saman*	49.19
Samanea saman	36.92		*Spondias mombin*	37.89
Tabebuia rosea	36.25		*Cedrela odorata*	24.92
Inga jinicuil	26.39		*Tabebuia rosea*	21.40
Fourteen remaining species	87.05		Fourteen remaining species	99.61
SA 3			SA 3	
Samanea saman	56.85		*Samanea saman*	42.93
Tabebuia rosea	56.02		*Ceiba pentandra*	36.98
Ceiba pentandra	31.31		*Pouteria sapota*	35.78
Spondias mombin	30.76		*Tabebuia rosea*	33.45
Cedrela odorata	23.86		*Persea americana*	29.54
Fifteen remaining species	101.20		Fifteen remaining species	121.32

Table 4

Density, height, basal area, and cover of shade trees in cacao agrosystems

Indicators	Camerún	Indonesia	Mexico	Ghana	Ecuador	Costa Rica
Canopy coverage (%)	87.8±7.4	78.7±0.4	72.75±5.74	51.6±3.67	72±27	66.0±18.1
Tree species (no.)	11.0±0.0	20.8±7.8	11.93±0.94	10.8±1.27	17±5	15.8±5.8
Tree density (tree/ha)	51.3±12.0	77.5±21.1	45.75±3.89	49.0±9.7	54.6±33.2	61.0±22.1
Tree height (m)	55.5±3.3	11.56±0.49 9.47±0.26	11.28±0.69	15.1±0.74	12.1±1.0	21.1±3.6
Basal area (m^2/ha)	48.7±14.6	56.7±9.10	34.1±2.86	42.8±2.5	37.7±5.1	25.5±7.4
Source	[5, 17, 42]	[43–46]	[47, 48]	[7, 8, 49]	[23, 50]	[51–53]

where: *Absolute dominance* = (*Basal area of a tree*)/(*Sampled area*).

The basal area (*BA*) was obtained with the following equation:

$$BA = \frac{\pi}{4} DBH^2.$$

The relative density is calculated as follows:

Absolute density = (*Number of individuals in a tree*)/(*Sampled area*)

Relative density = (*Absolute density per each tree*)/(*Absolute density of all trees*) · 100,

where: The relative frequency is calculated as follows:

Relative density = (*Absolute density per each tree*)/(*Absolute density of all trees*) · 100,

where: *Absolute frecuency* = (*Number of frames in which each tree is presented*)/(*Total number of sampled frames*).

Forest Value Index. The forest value index (*FVI*) proposed by [41], which is made up of the relative values of the diameter, height, and coverage of the species in the area. It was calculated as follows: *FVI* = *Relative diameter* + *Relative height* + *Relative cover*.

The relative diameter was obtained by the equation:

Relative diameter = (*Absolute diameter per each tree*)/(*Absolute diameter of all trees*) · 100,

where: *Absolute diameter* = (*Diameter of a tree*)/(*Sampled area*).

The relative height was obtained by the equation:

Relative height = (*Absolute height per each tree*)/(*Absolute height of all trees*) · 100,

where: *Absolute height* = (*Height of a tree*)/(*Sampled area*).

The relative coverage was obtained through the equation:

Relative coverage = (*Absolute coverage per each tree*)/(*Absolute coverage of all trees*) · 100,

where: *Absolute coverage* = (*Coverage of a tree*)/(*Sampled area*).

Results

Field sampling. The family with the highest presence of species was Fabaceae with four species. The Malvaceae and Sapotaceae families presented three species each, while the Anacardiaceae, Bignoniaceae, Lauraceae, Meliaceae, Moraceae, and Rutaceae families each, had two species (Table 2).

Ecological importance value index. The tree species with the highest structural values in each agrosystem were the same in both indices, *Erythrina americana* (*IVI* = 62.34 and *FVI* = 50.94), *Bursera simaruba* (*IVI* = 62.53 and *FVI* = 66.99), and *Inga jinicuil* (*IVI* = 56.85 and *FVI* = 42.93) (Table 3).

Review of structural characteristics in shade tree vegetation in cacao agrosystems. A literature review of the structural characteristics of shade tree vegetation in cacao agrosystems was carried out worldwide (Table 4).

Discussion

Due to the fragmentation and loss of habitat, species such as insects, amphibians, reptiles, birds and mammals have needed to take refuge in cacao and coffee agrosystems [25, 32, 54], in no way can these types of available habitats be compared with rainforests, which due to their biotic and abiotic processes would be the ideal habitats for many species. However, in the case of some endangered species, agrosystems are the only habitat available, because, due to their diversity of trees and different strata in their canopies, they have the potential to provide habitats for the conservation of species of wildlife [3, 4]. The different strata in cacao plantations, allow obtaining various benefits and natural services such as water collection and purification, soil conservation, crop pollination, carbon sequestration, organic waste decomposition, species conservation, ultraviolet rays protection, partial stabilization of the climate, and the aesthetic beauty of natural environments [55]. Therefore, economic incentives or payment for environmental services could be provided to small producers, so that they conserve and improve the tree cover of their cacao plantations [56].

The vertical stratification of vegetation contributes to the plant-animal interaction, population dynamics, and the evolution of the life history of animals that depend on plants for food [57, 58]. In addition, abiotic and biotic factors influence structural aspects such as canopy height and geographic distribution of species, which is important for maintaining different strata and abundance of trees [59]. Vertical stratification in rainforests and cacao agrosystems is very important because of their composition, structure, and diversity since their different strata are favorable to support the conservation of wildlife species [29]. As for the vertical stratification of the forest, it is classified into five levels: emerging layer, canopy, undergrowth, and soil layer [60, 61]. While the vertical stratification of cacao agrosystems is classified as high, medium, low, and floor [62].

Some of the trees found in these study sites are fruit trees such as *Citrus sinensis*, *Mangifera indica*, *Annona muricata*, and *Persea americana* [9, 17], while others are forestries such as *Tabebuia rosae* and *T. guayacan*. In addition, species such as *Cedrela odorata* and *Swietenia macrophylla*, which according to the IUCN category are considered vulnerable species. Shadow trees in cacao should be promoted as a way of conserving wildlife species [25], as it provides biological corridors for the movement and shelter of animals such as insects, birds, and mammals [9, 17]. Currently, diversification in agrosystems is a strategy that allows producers to compensate for economic losses caused by price fluctuations and low coffee and cacao production [63]. These types of strategies have focused on product diversification with basic crops, vegetables, fruit, timber, ornamental, and even animals [64]. Diversification can increase the overall production of the system, the rational incorporation of shade trees and the biodiversity associated with the system offers the possibility of improving the provision of ecosystem services without reducing coffee production [65].

In this research, the species *Erythrina americana* obtained an *IVI* value of 62.34, similar to other studies where the species had an *IVI* of 59.18 [33], 68.22 [66] and 78.5 [67]; the *Tabebuia rosea* species obtained an *IVI* of 36.25 similar to other studies where it had 35.30 [67] and 26.80 [33]; the *Maguifera indica* species obtained an *IVI* of 25.32 comparable with other *IVI* of 18.00 [67], 31.70 [33] and 31.41 [66]; the species *Cedrela odorata* obtained an *IVI* of 23.86 similar to the *IVI* of 25.40 [33], 21.28 [66] and 26.50 [67]; the *Inga jinicuil* species obtained an *IVI* 26.39 very close to 26.84 [66] and 22.79 [33].

The presence of arboreal fauna at different levels of stratification is highly correlated with the structure of the diversity of trees. Therefore, they are crucial elements in the richness of biodiversity. Since currently in our study site, cacao agrosystems are the only thing that is available as a habitat for wildlife, and it is what most resembles a jungle due to its vertical stratification. House garden domestics and cover crops where you can find especially insects, spiders, and some mammals such as anteaters, wild boars, tapirs, and jaguars, where also a large amount of litter falls to the ground and is rapidly degraded by termites, worms, and fungi. Ornamental shade and fruit trees where we can find snakes and some birds. Managed foliage and nitrogen-fixing legumes birds (toucan), mammals (monkeys), reptiles, and amphibians. Emergent production palms and trees birds such as the scarlet macaw and other types of species.

Conclusion

Dasometric variables of the shade trees used in the cacao agrosystems were measured in the field and obtained the information necessary to determine the height of the canopy, crown diameter, and diameter of breast height to obtain the index of importance and forest value, these attributes are important as it could be taken as an input variable or parameter to predict available habitats through an ecological niche model and assess the quality of their habitat, including birds and arboreal primates. Cacao plantations due to shade trees can become key refuge areas for various species such as insects, amphibians, reptiles, birds, and mammals, especially when compared to more intensive agricultural practices. It is recommended to use LiDAR technology as a tool to measure parameters related to the vertical stratification of shade trees used in cacao agrosystems, in addition to quantifying the relationships between species and habitats, which is beneficial as a support for conservation, in the persistence of populations at local scales.

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