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Timber growth, cacao yields, and financial revenues in a long-term experiment of cacao agroforestry systems in northern Honduras

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Cacao in Honduras is cultivated under traditional shade tree species (Inga sp., Erythrina sp., Gliricidia sp.), fruit and timber species deliberately planted or selected and managed from natural regeneration. Typically, the shade canopy of these cacao plantations is poorly managed resulting in high tree density and heavy shading, thus affecting cacao yield performance overtime. We assessed 12 cacao plots made up of 15–35 useful timber shade trees with varying spacing 6 × 9, 9 × 9, 8 × 10, and 10 × 12 m. Initially, each plot consisted of three shade components plus cacao. Plantain (*Musa x paradisiaca*) and madreado (*Gliricidia sepium*) were used as temporary shade and timber species, were selected as permanent shade. Dasometric data were retrieved to assess growth rates of timber species and cacao yield per plant were recorded to explore the effects of shade cover yield performance and the incidence of main diseases. Specifically, we: a) calculated growth rates and build curves for diameter (DBH), total height (Ht), and commercial volume (Vc) and compared the growing performance with ANOVA and DGC tests; b) run a correlation analysis between shade cover, timber basal area, cocoa yields, and the incidence of monilia and black pod. Statistical differences were found in terms of growth rates among timber species evaluated. Mean annual growth rates were 2.25 cm in DBH, 1 m in Ht, and the standing commercial timber gained was 4.2 $m^3ha^{-1}year^{-1}$. Cocoa yields ranged between 950 and 1,365 kg ha^1year^1 and were negatively affected by both increased tree cover and timber basal area. Cacao yields were reduced up to 25% when tree cover and tree basal area were over 40% and 10 m^2ha^{-1}, respectively. Regardless of timber tree species, no significant effect of tree cover was found on the incidence of cacao diseases. After 22 years, total revenues were determined by the proportion of incomes provided by each component of the agroforestry systems assessed. Five out of 12 timber-based cacao plantations accumulated more than U$95,000 of combined revenues, equivalent to incomes of US$3775 ha^{-1} year^{-1}. Timber-based cacao plantations are a promising alternative for farm diversification in northern Honduras.

KEYWORDS

timber species, shaded cacao, canopy cover, intercropping, revenues, perennial crops

Introduction

Farmers grow cacao under the shade grow cacao under the shade of timber species of good market potential and successful examples of this practice are reported in several tropical countries of Meso and South America (Bentley et al., 2004; Orozco et al., 2008; Almendarez et al., 2013; Jacobi et al., 2014; Vebrova et al., 2014; de Sousa et al., 2016; Notaro et al., 2020). Farmers either plant or retain naturally regenerated trees, provide silvicultural management and eventually harvest timber trees to cover some family needs or to aid farm investments but not always maximize timber yield (Beer et al., 1998; Ryan et al., 2009). This, in fact, is the dominant timber production model among smallholder cacao farmers in Latin America (Mussak and Laarman, 1989; Cerda et al., 2014; Somarriba et al., 2014; Vebrova et al., 2014).

Two scenarios for timber production in cacao plantations have been identified: 1) trees are recruited from the natural regeneration at the site and 2) trees are planted for shade and lumber production at the onset of the cocoa plantation. In the first model, tree recruitment is a continuous process and mortality/harvest occurs during the entire cycle of the cacao plantation; the tree stand is uneven-aged. Naturally regenerated timber species in cacao shade canopies belong to a small group of successfully reproducing, native species. Notable examples include *Cordia alliodora* in Central America (Dubón and Sánchez, 2006; Somarriba et al., 2013), and *Terminalia ivorensis* and *Terminalia superba* in West Africa (Asare, 2005). Uneven-aged timber tree stands used as tree cover require the analysis of the population dynamics of a structured (age and size) tree population. Parameters such as stem diameter frequency distribution, recruitment of new individuals, growth rates, mortality, and harvest rates are evaluated to forecast population size and structure over time (Beer et al., 1998; Somarriba et al., 2013). Under this scenario, timber shade trees occur at low to medium densities, are subject to poor silvicultural management affecting their growing performance and productivity, and are harvested at unsustainable rates thus reducing timber revenues and altering the population dynamic (Suarez and Somarriba, 2002; Calero, 2008; Somarriba et al., 2013).

In the second model, planted, timber stands used as shade in cacao plantations trees are harvested (clear cut) at rotation age, hopefully coinciding with a renovation of the cacao stand. Because all timber trees are planted at the same time, the tree stand is even aged. As trees grow and develop their crowns the shade level increases until a maximum threshold level is reached; cacao yields are depressed, when tree stand density passes this threshold. Differential silvicultural management including tree thinning and pruning keeps stand density above a minimum threshold below in which timber yield per hectare is insignificant. The rate of thinning (trees ha^{-1} removed each year) over the life cycle of the cocoa plantation is determined by the initial planting density, crown growth rate, crown closure, and leaf fall patterns of the timber trees (Somarriba and Beer, 2011; Blaser-Hart et al., 2021).

Research institutions have also established and assessed several cacao timber-based agroforestry systems including both native and exotic species in Costa Rica, Panama, Colombia, Bolivia, Venezuela, Nicaragua, and Peru (Somarriba et al., 2001; Salgado-Mora et al., 2007; Dubón and Sánchez, 2011; Dumont et al., 2014; Niether et al., 2018; Salazar-Diaz and Tixier, 2019; Wartenberg et al., 2019). Nevertheless, these experimental plots have recorded data on timber growth and cacao yield for short to medium terms and reported mixed results. For instance, Jaimez et al. (2013) in Merida state, Venezuela registered promising survival and growth rates of both timber trees (*Cordia thaisiana, Cedrela odorata, Swietenia macrophylla,* and *Tabebuia rosea*) and cacao plants during the early stages. A 10-year trial in lowland Costa Rican and Panama (Somarriba and Beer, 2011) reported favorable growth rates and similar cacao yields under leguminous (*Erythrina poeppigiana, Gliricidia sepium,* and *Inga edulis*) and timber shade trees (*Cordia alliodora, Tabebuia rosea,* and *Terminalia ivorensis*). In Alto Beni, Bolivia, a medium-term trial (12–15 years) mixing timber species (*Schizolobium parahyba, S. amazonicum, C. ochroxylum, Amburana cearensis,* and *Swietenia macrophylla*) and fruit trees reported satisfactory growth curves, suitable harvestable lumber potential and promising cacao yields (Jacobi et al., 2014; Schneider et al., 2016). A short-term trial in Santander, Colombia (Carrillo et al., 2012; Agudelo, 2020) has reported acceptable results but consistent data on tree growth, tree cover, and the detrimental effect on cacao yields in the long term are still pending.

Several actors including development projects, cooperation agencies, and government-led initiatives are promoting timber shade trees as a potential saving account for cacao farmers, which could eventually counterbalance financial losses caused by fluctuating market prices, yield reduction due to pest and diseases outbreaks or any other unexpected family need (Ryan et al., 2009; Cerda et al., 2014; Somarriba and López, 2018). Despite all the on-farm benefits derived from timber-based agroforestry systems, cacao cultivation projects that advise the use of native timber trees for shade have often fallen short of expectations (Tscharntke et al., 2011, 2015; Sonwa et al., 2014). In general terms, studies that assessed timber-based agroforestry performance provide either tree growth rates only at early stages or do not assess tree growing performance and cacao yields long enough to support farmers' decision-making on the correct tree-crop combination that offers the best tree cover levels and sustainably produce commercial timber without affecting cacao productivity overtime. Other tree features such as tree height, crown size, shape and the shading factor for proposed timber species are key to better design and manage profitable cacao agroforestry systems and ultimately to foster the promotion and scaling up of a wide list of native timber shade trees in perennial crops (Tscharntke et al., 2011). In this research, we evaluated growth rates of 12 timber species and cacao yields over 22 years to explore the effects of tree cover on yield performance and to elucidate the potential effect on the incidence of the main cacao pod diseases. The following questions were addressed in this study: 1) What is the evolution of cacao yields over time, 2) Are cacao yields similar under the shade canopy of different timber species, 3) Are there significant effects of tree cover and tree basal area on cacao productivity? 4) Are tree cover levels significantly affecting the incidences of cacao pod diseases? and 5) Do the potential revenues from standing volume lead to higher total system revenues compared to accumulated income from cacao beans?

Methodology

Description of study site

The study was conducted at the experimental site called "CEDEC-JAS" operated by Fundacion Hondureña de Investigación Agricola (FHIA) since 1986. The site is located at la Masica, in the department of Atlántida Honduras (15°38'43" N, 87°06'46" W; Bertoli, 2017). According to Köppen-Geiger, the regional climate is classified as an equatorial monsoon (Kottek et al., 2006) at an altitude of 25 m. The annual mean temperature varies between 22°C and 35°C and the monthly precipitation ranges between 100 mm in April and May and close to 500 mm in October–December (Gramlich et al., 2018) (Table 1). From 1989–2019, the annual mean temperature was 25.6°C, and the annual rainfall was 2,938.1 mm. The soil of the experimental area is alluvial with a sandy loam texture, strongly acidic (pH 5.3), low fertility associated with low levels of available nitrogen, phosphorous, and potassium, organic matter (2.67%), and high iron content (López et al., 2021).

Description of the cacao timber-based agroforestry systems

On several tree plantations and agroforestry systems, covering a total area of 43 ha, many different cacao varieties are grown (3 × 3 m) in combination with 35 timber shade species (see the distribution map of experimental plots in Appendix 1). International cacao clones/cultivars (IMC-67, UF-613, UF-667, UF-650, ICS-1, ICS-6, ICS-39, ICS-60, ICS-95, TSH-565, CAP-34, EET-62, EET-162, EET-400) were grafted onto rootstocks and planted in parallel rows with one cultivar per row. All cacao plants within each experimental plot were selected to register cacao yields and pests and diseases data overtime. There was no irrigation system in place, and no pesticides were used. Only mineral fertilizer was applied annually in three equal doses during June, August, and October. A total of 12 once per plant of ammonium nitrate (N15-P15-K15), and 53 g of N, 30 g de P (P_2O_5), and 72 g of K (K_2O) of potassium chloride per plant were applied. Lime amendments were also applied yearly at a single dose of 0.5 t ha^{-1}year^{-1}. For more details on dosage and chemical composition of fertilizers used, see López et al. (2021). Cultural practices were promoted to control the main cacao pod diseases (black pod and frosty pod). Diseased pods were removed every 14 days and placed below cacao litter or buried outside the experimental plot. Cacao pruning was done twice a year during the first 5 years and annually onward. Weed control was given three times a year during the first 5 years and twice a year afterward. All experimental plots were managed in the same way.

Based on market potential, the top 12 timber species were chosen to monitor tree growth rates, cacao productivity, and incidences of cacao diseases for over 22 years. Selected species were marapolán (*Guarea grandifolia*), Granadillo rojo (*Dalbergia glomerata*), Barba de jolote (*Cojoba arborea*), Hormigo (*Plathymiscium dimorphandrum*), San Juan guayapeño (*Tabebuia donnell-smithii*), San Juan areno (*Ilex tectonica*), Santa María (*Calophyllum brasiliense*), Rosita (*Hyeronima alchorneoides*), Cincho (*Lonchocarpus* sp.), Jigua (*Nectandra* sp.), Huesito (*Macrohasseltia macroterantha*), and y Caoba del atlántico (*Swietenia macrophylla*) (Figure 1). Timber-based cacao agroforestry systems evaluated consisted of 1,400–4,200 m^2 containing 15–35 useful trees planted at regular distances according to crown size to avoid overlapping (6 × 9, 9 × 9, 8 × 10, 9 × 10, and 10 × 12 m). Soil and environmental conditions were similar across the experimental site, so no replicates of experimental plots were in place. The overall goal of the Cacao and Agroforestry program at FHIA is to test and monitor a wide range of timber, fruit, and leguminous species suitable for cacao farming in northern Honduras, emphasizing native/nontraditional tree species (Sanchez and Dudon, 2016; Fundacion Hondurena de Investigacion Agricola (FHIA), 2022).

FIGURE 1
Top 12 timber shade species intercropped with cacao and assessed in the experimental site "CEDEC-JAS", La Masica, Atlántida, Honduras.

Initially, each timber-based cacao agroforestry systems were intercropped with transitory shade including plantain (*Musa x paradisiaca*) at 3 × 3 m and madreado (*Gliricidia sepium*) at 6 × 6 m. The former accompanied the cacao during the first 3 years and the latter stayed in the plot for up to 10 years. Several goods and products were harvested from each timber-based agroforestry system at different periods, plantain corms and bundles were picked annually for 2 years, during the 3rd-year plantains were thinned (50%) and all bundles were collected and sold. From years 2 to 10, *G. sepium* trees were pruned annually and 3–4 stakes per stem were harvested and used as new planting material (Figure 2). Cacao yields were recorded from year eight and onward, once the crop started the full production phase (Ryan et al., 2009; Dubón and Sánchez, 2016). Planting distance, number of useful trees, and final densities of each component within shaded cacao plots are presented in Table 1. All goods and products collected from the experimental plots were sold locally at farm gate prices. Measurements done, instruments used, and the frequency and evaluation period for each cacao timber-based agroforestry system are listed in Table 2. Tree cover and shading factors of sampled trees were estimated using a mobile App named HabitApp, which reliability and operational advantages have been tested in shaded coffee plantations in Colombia (Farfán et al., 2016).

Silvicultural management and shade regulation

Each timber species was managed differentially (frequency, intensity, and timing of thinning and pruning regimes) to satisfy the shade requirement of the cacao and timber stands growth. In general terms, pruning was applied to the lower 1/3 tree crown and following standard guidelines. The overall goal of tree management was to create a microenvironment unfavorable to frosty pod and black pod and to satisfy the light regime needed by fully stocked (1,111 trees/ha) clonal cacao stands with good crop husbandry (Beer et al., 1998; Somarriba and Beer, 2011). Shade levels were adjusted (frequency of pruning and/or thinning events) both annually (to compensate for increasing self-shading as the cacao trees grow older and bigger) and monthly (to cope with local phenological and agronomic rhythms). Formative pruning (elimination of lower/broken branches) was given to all timber species from year one until year 12. Most timber species were thinned systematically (*I. tectonica*, *T. donnell-smithii*, *P. dimorphandrum*, *Lonchocarpus* sp., *H. alchornoides*, *C. megalantha*, and *M. macroterantha*) seeking spatially homogeneous canopy cover, while few timber species were thinned selectively based on field

FIGURE 2
Harvestable good and products (plantain corms + bundles, madreado steaks, cacao beans and timber lumber) from the 12 timber-based cacao agroforestry systems in the experimental site "CEDEC-JAS", La Masica, Atlántida, Honduras.

observations (*D. glomerata, S. macrophylla, G. grandifolia, C. brasiliense,* and *C. arborea*), removing diseased or slow-growing trees and providing the growing space of the future harvest trees. The two systematic thinning events were conducted in year five and eight applying 50 and 25% intensity, respectively.

Data analysis

Based on field data collected, an agronomic and economic summary (quantity + gross economic value) of good and products from each cacao timber-based agroforestry system were done. In addition, dasometric data were retrieved to evaluate the growing performance (tree diameter and height) of timber species and to explore the potential effects on cacao yield and the dynamics of the main cacao diseases namely frosty pod and black pod. The set of statistical analysis was the following: first, tree growth rates were used to build growth curves and to calculate mean annual increment (MAI) for diameter (DBH) (total height (Ht) and commercial volume (Cv). Second, ANOVA and DGC tests ($p < 0.05$) were run to identify statistical differences among timber growth rates. Because of the lack of true replicates, the information of each timber shade tree was considered in order to calculate an error term to perform the ANOVA (Suárez Salazar et al., 2018, 2021). Moreover, the distance between shade trees was wide enough to consider independent growing conditions. Third, Pearson correlation analysis between tree cover (%), basal area of timber trees (m^2 ha^{-1}), cacao yields (kg ha^{-1} $year^{-1}$), and the incidence (%) of frosty pods and black pods was run to explore meaningful associations across cacao plots. Fourth, the so-called competitive allocation model of basal area of the cacao plantation prosed by Somarriba et al. (2018) was tested for all timber-based agroforestry systems to elucidate whether basal area of shade trees might influence recorded yields overtime. The proposed model is given next:

$$P = \Sigma[K + D\,(T{+}F{+}L{+}O)] \leq 40m^2\ ha^{-1} \qquad (1)$$

where P is the total basal area of the cacao plantation, K denotes total basal area of cacao plants, D represents the total basal area of all shade canopy trees including T = timber, F = fruits, L= leguminous tress, and O = other shade trees. The model suggests the following allowable thresholds: K = up to 30 m^2 ha^{-1} and D = up to 10 m^2 ha^{-1}.

Fifth, the potential gross revenues from goods and products delivered by each timber-based agroforestry system were used to calculate both annual net incomes and accumulated incomes. Finally, using a set of financial variables (annual incomes from madreado (stakes), plantain (corms + bundles) and

TABLE 1 Planting arrangements and densities of measured timber-based agroforestry systems in the "CEDEC-JAS" experimental site at La Masica, Atlántida, Honduras.

Species	Distance (m)	Number of trees	Useful study area (m^2)	Extrapolation to hectare (# stems/ha)			
				Cacao	Plantain	*Gliricidia*	Timber
M. macroterantha	6 × 9	30	1,620	1,037	1,037	259	185
I. tectonica	9 × 9	30	2,430	1,111	1,111	278	123
Nectandra sp.	9 × 9	24	1,944	1,049	1,049	262	123
T. donnell-smithii	8 × 12	15	1,440	1,097	1,097	274	104
C. brasiliense	9 × 9	30	2,430	988	988	247	123
C. arborea	9 × 10	30	2,700	944	944	236	111
Lonchocarpus sp.	9 × 9	25	2,025	1,185	1,185	296	123
P. dimorphandrum	9 × 9	30	2,430	938	938	235	123
G. grandifolia	9 × 9	30	2,430	1,111	1,111	278	123
H. alchorneoides	10 × 12	36	4,320	1,056	1,056	264	83
D. glomerata	9 × 10	30	2,700	1,007	1,007	252	111
S. macrophylla + *C. megalantha*	10 × 12	35	4,200	1,114	1,114	279	83 + 83
Average		29	2,556	1,053	1,053	263	118

harvested timber, cacao yields (kg ha^{-1} $year^{-1}$), and total maintenance costs per hectare (expressed in U$ at the annual average exchange rate), a principal component analysis (PCA) was performed. The biplot constructed by PCA analysis that considered the ordination of the set of financial variables from 12 cacao timber-based agroforestry systems was used to elucidate the contribution of each component (cacao, plantain, stakes of *G. sepium,* and standing timber) to revenues of farmers overtime. All statistical analyses were run using InfoStat (Di Rienzo et al., 2019).

Results

Tree attributes, form factor, crown features, and cacao pod index

Timber trees displayed different attributes and crown features that affected both timber productivity and the level of shade they provide to understory cacao plants. Mean values of commercial high/total height ratio, form factor, and wood density were 0.44, 0.79, and 0.57, respectively (Table 3). In addition, crown area and shading factors varied widely among species. Crown area per tree ranged from 33 to 83 m^2 and shading factors were in the range of 43−86%. All these tree attributes and crown features are key to correctly select the planting arrangements and to better forecast the level of shade within the plot. Although cacao yields were derived from a similar pool of cacao clones, pod index differed among sampled plots and varied between 14.4 and 20.5. Pod index below 20 is considered a proxy of good agronomic performance of cacao clones.

Tree growth rates: Diameter and total height

Significant differences were found in terms of tree diameter (cm) and total height (m) among species evaluated. According to national forestry regulations, all timber species reached the minimum harvesting diameter (25 cm) at 13–15 years. ANOVA ($p < 0.05$) (Figures 3, 4) and DGC test classified timber species growth rates in four categories: 1) very fast-growing species namely *Tabebuia donnell-smithii* and *Nectandra* spp. with mean annual increment (MAI) values in diameter and total height of 3.0 cm and 1.9 m, respectively; 2) fast-growing species which included *Cojoba arborea*, *Hyeronima alchornoides,* and *Ilex tectonica* with recorded MAI values of 2.25 in diameter and 1.8 m in total height, 3) medium-growing species which grouped *Calophyllum basilense*, *Guarea grandefolia*, *Swietenia macrophylla,* and *Lonchocarpus* sp. with MAI values of 1.7 cm in diameter and 1.7 m in total height and 4) slow-growing species that clustered *Macrohasselia macroteranha*, *Dalbergia glomerata,* and *Plathymiscium dimophandrum*. Recorded MAI for diameter and total height for this last set of species were 1.5, 1.4, 1.3, 1.2 cm and 1.5, 1.45, 1.3, 1.2 m, respectively.

Commercial timber yield

Commercial timber productivity was statistically different among species ($p < 0.05$). All species gained on average 4.4 m^3 ha^{-1} $year^{-1}$, equivalent to 0.74 m^3 $tree^{-1}$ $year^{-1}$. The ANOVA and DGT tests performed at 18 years cutoff clustered the 12 timber species into five categories: 1) included only *T. donnell-smithii,* with *IMA* values of 2.4 m^3 $tree^{-1}$, 2)

TABLE 2 Summary of measurements and methods used to assess timber growth rates and cacao yields in the experimental site "CEDEC-JAS," La Masica, Ataltida, Honduras.

Component	Variable	Instrument	Method used	Unit	Frequency and recording period
Plantain	Corms + Bundles	Calculator	Harvest records	Corms + Bundles	Annually, 3 years (1997-1999)
Madreado (Gliricidia sepium)	Stake	Calculator	Harvest records	Stake	Annually, 6 years (2000-2008)
Cacao	Healthy and unhealthy pods	Calculator	Harvest records	Healthy pods (%), Frosty pods (%), Black pods (%)	Fortnight, 15 years (2006-2020)
	Pod index	Digital weight	Micro fermentation experiments until market humidity level were reached (6.5%) (López-Sampson et al., 2020)	Number of fruits/pods required to produce 1 kg of dry cacao.	Annually, 13 years (2008-2020)
Timber trees	DBH + Commercial diameter (CD)	Diametric tape	DBH was measured at 1. 3 m above ground and commercial trunk diameter was taken until the first branching point (Ammour et al., 2012)	cm	Annually, 19 years (1998-2020). CD was measure at year 20 (2021).
	Form factor (Ff)	Tree measurements	Ff = RV/VC. Where RV = Real volume calculated from harvested trees and VC = Volume of the Cylinder calculated from basal area at 1.3 m above ground. (Ammour et al., 2012).	Factor range (0–1)	Once, year 20 (2021)
	Total Hight (Th) + Commercial height (Ch)	Telescopic pole + Clinometer	Standard guidelines (Ammour et al., 2012)	m	Annually, Th was measured for 18 years (1998-2014) and Ch was registered for 16 years (2004-2020)
Timber trees	Crown area (m^2)	Metric tape	Standard guidelines (Somarriba, 2002).	m^2	Ten measurements (2006, 2008, 2010, 2012, 2014, 2015, 2016, 2017, 2019 and 2020)
	Shading factor	HabiApp	https://toolbox.coffeeandclimate.org/tools/habitapp-shade-measurement-tool/ Field measurements were done following (Somarriba, 2002; Farfán et al., 2016).	Percentage	
	Basic wood density (Wd)	Core borer	Fresh volume of all core samples was calculated (cm^3) and samples were then oven dried for 24 hours. Wood density was further calculated using the next formulae Wd = Weigh (g)/volume (cm^3) (Ammour et al., 2012).	g cm^{-3}	Year 22 (2021)
	Commercial volume (Cv)	Metric tape	Measuring both standing and harvested trees and using the formulae: Cv: DAP x Ch x Ff Where Cv = commercial volume, DAP = diameter, Ch = commercial height and Ff= Form factor.	m^3	Year 22 (2021)

comprised *Nectandra* sp. and *H. alchornoides* which recorded timber yield of 1.74 y 1.61 m^3 tree^{-1}, respectively; 3) included only *I. tectonica* and reported 1.19 m^3 tree^{-1}. The fourth and fifth categories grouped *G. gradifolia*, *S. macrophylla*, *C. brasiliense*, *C. arborea,* and *Lonchocarpus* sp. and recorded timber productivity in the range of 0.6–0.72 m^3 tree^{-1} (see Appendix 2). Considering timber productivity registered in this study, trees can be gradually harvested from year 15 and onward and according to market prices to maximize revenues.

Evolution of cacao yields over 23 years

No significant correlation was found between cacao density (plants ha^{-1}) and registered cacao yields (kg ha^{-1} year^{-1}) (p = 0.2437), suggesting that recorded crop yields are comparable over time. Moreover, timber shade density (trees ha^{-1}) did not affect registered cacao yields (p = 0.5582) allowing valid comparison. Across experimental plots, the average cacao yield was 765 kg ha^{-1} year^{-1} ranging from 380 to 2,367 kg

TABLE 3 Tree attributes, basic wood density, crown area, shading factor, and cacao pod index under 12 timber shade trees in the experimental site "CEDEC-JAS" La Masica, Atlántida, Honduras.

Timber species	Ratio Ch/Th (0–1)	Form factor	WD (g/cm^3)	Ca (m^2)	Shading factor (%)	Price(U$)	Pod index
H. alchorneoides	0.58	0.77	0,593	76.3	73	1.70	14.4
D. glomerata	0.32	0.86	0,601	33.7	47	1.45	14.4
P. dimorphandrum	0.40	0.86	0,583	39.4	64	1.45	16.1
I. tectonica	0.55	0.75	0,461	41.7	78	1.61	18.9
S. macrophylla	0.57	0.71	0,537	49.8	78	2.39	17.0
Nectandra sp.	0.59	0.79	0,525	82.9	75	1.45	17.6
T. donnell-smithii	0.50	0.87	0,493	51.7	47	1.45	15.9
M. macroterantha	0.34	0.72	0,616	32.3	73	1.69	17.9
C. brasiliense	0.35	0.76	0,552	50.1	73	1.65	20.5
Lonchocarpus sp.	0.41	0.76	0,800	83.1	75	1.45	19.0
G. grandifolia	0.43	0.85	0,528	64.8	86	1,86	19.2
C. arborea	0.28	0.78	0,569	72.5	83	1.79	17.6
Average	0.44	0.79	0.572	55.7	71	1.66	17.8

Ch, Commercial height; Th, total height; Ff, form factor (0–1); WD, wood density (g cm^{-3}); Ca, Crown area; Sf, Shading factor; P. t, pie tablar. Conversion factor: 1 m^3 is equivalent to 200 p.t (Diario Oficial, La Gaceta, 2020). Pod index: is defined as the number of pods required to yield 1 kg of dry beans.

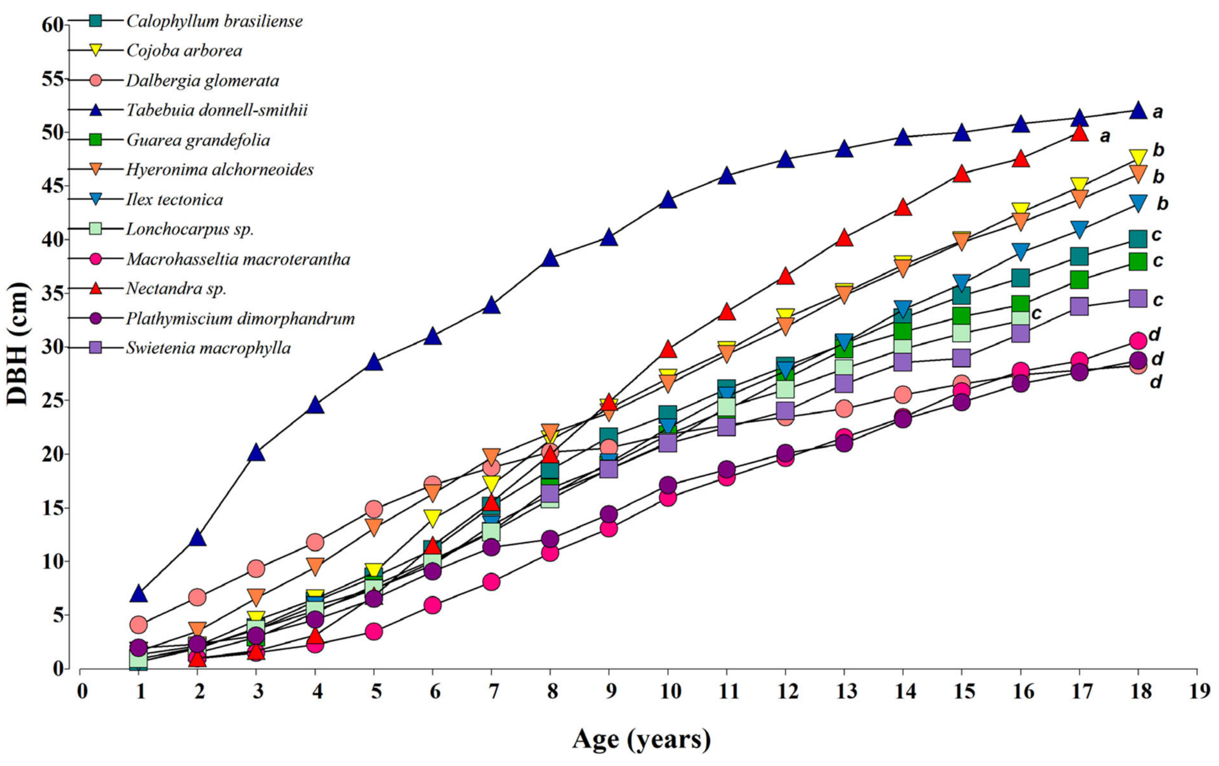

FIGURE 3
Diameter growth rate curves (cm) of 12 timber shade species in the experimental site "CEDEC-JAS", La Masica, Atlántida, Honduras. Means with different letters are statistically different (DGC test, $p < 0.05$).

ha^{-1} year^{-1} (Figure 5). In general terms, mean cacao yield registered in this study were 3× higher than the average national productivity. The lowest and the highest cacao yields were registered under *C. arborea* and *D. glomerata*, respectively. The evolution curves of cacao yields show four clear trends, first; from year 8 to year 12 after planting, crop yields grown under *D. glomerata*, *P. dimorphandrum*, and *H. alchornoides* were in the range of 800–1,100 kg ha^{-1} year^{-1};

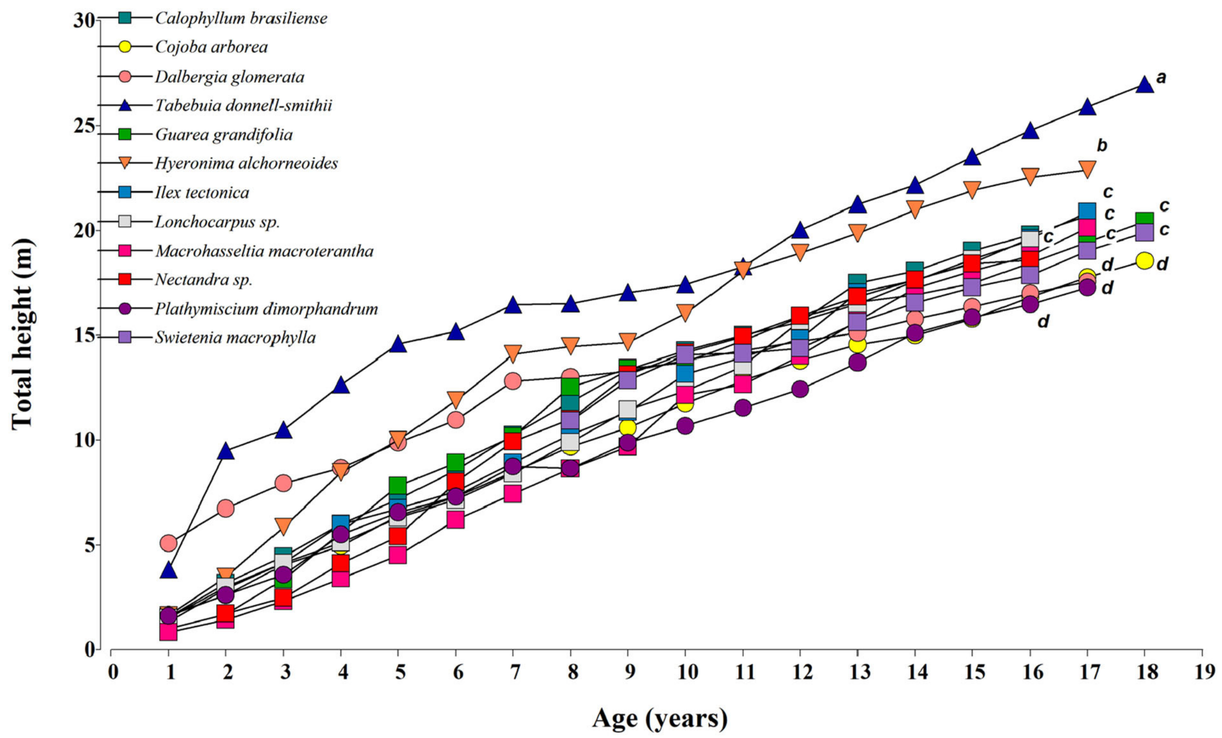

FIGURE 4
Total height growth rate curves (m) of 12 timber shade species in the experimental site "CEDEC-JAS", La Masica, Atlántida, Honduras. Means with different letters are statistically different (DGC *test*, $p < 0.05$).

second; from year 13 to year 16 yields picked from 1,200 to 2,300 kg ha^{-1} $year^{-1}$ and from year 18 and downward crop yields decreased to the range reported earlier. Third, a slight increase in cacao yields was noted from years 22 and 23, but more data are required to detect a consistent trend. Lastly, cacao yields registered under the remaining eight timber species were consistently low in the range of 300–765 kg ha^{-1} $year^{-1}$. Cacao production curves of the four best-performing cacao agroforestry systems reached the best yields between 15 and 18 years after planting. The production peak of other experimental plots was detected from years 10 to 13. For over a decade (year 10–21) cacao productivity under *C. arborea* was very low (under 380 kg ha^{-1} $year^{-1}$) due to heavy shading, although a slight recovery was shown afterward as a response to thinning/harvesting of timber shade trees.

Effect of tree cover on cacao yields and incidence of cacao pod diseases

We found negative and significant correlations between tree cover (%) and cacao yields in four out of 12 timber species assessed. Cacao yields under S. *macrophylla, P. dimorphandrum, C. brasiliense,* and *I. tectónica* showed Pearson correlation coefficients of −0.90, −0.85, −0.81 y −0.77, respectively (Figure 6, Appendix 3). Tree cover across experiment plots ranged from 12 to 45% according to crown features (mainly crown diameter and shading factor) and silvicultural management given to shade trees. The effect of tree cover on cacao yields of the remaining eight timber species was not significant.

The incidence of frosty pod and black pod ranged between 3 and 12% and 4–10%, respectively (Figure 6, Appendix 3). Regardless of shade species, no significant effect of tree cover on the incidence of frosty pod and black pod was detected, suggesting that the frequency and timing of disease control measures applied at the experimental sites were effective. Both frosty pod and black pod were inversely correlated (Appendix 3). Tree cover was negatively correlated with the incidence of diseases only for cacao grown under *Lonchocarpus* sp. Finally, timber basal area correlated positively with tree cover and negatively with cacao yields (Figure 6). In general terms, the greater the timber basal area the larger the tree cover within plots.

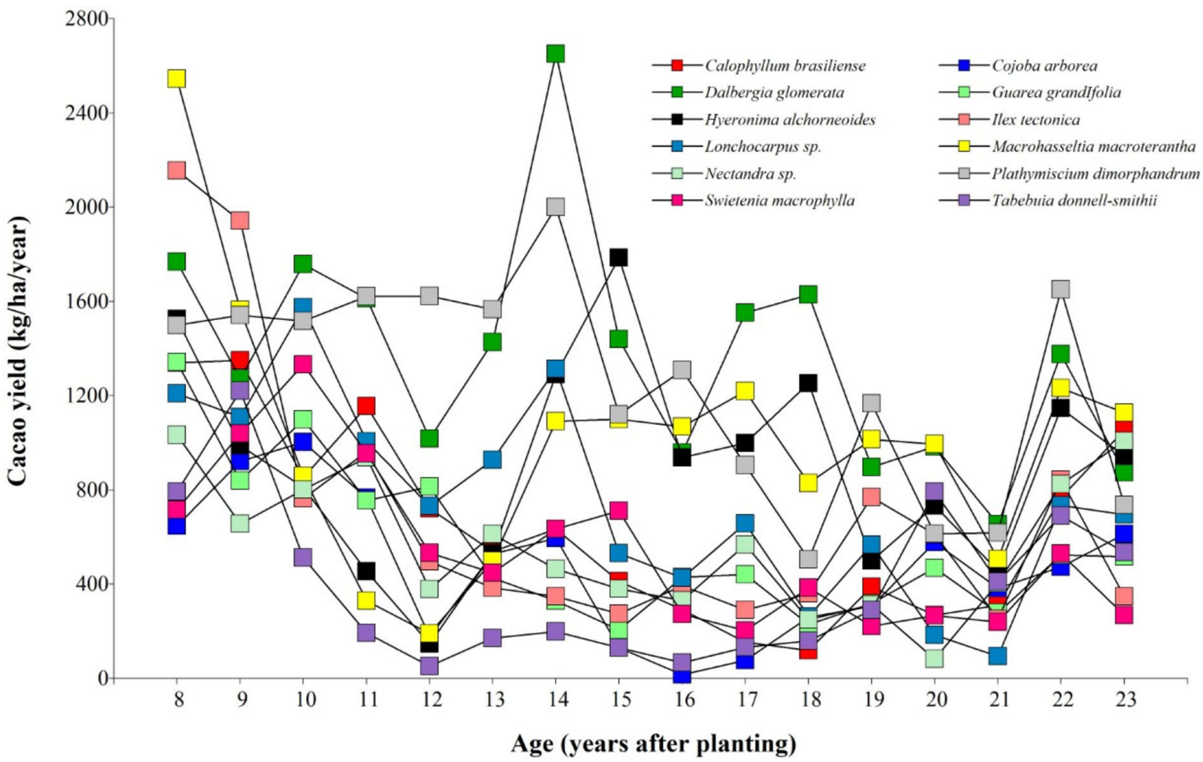

FIGURE 5
Yield (kg ha^{-1} year^{-1}) evolution curves of cacao grown under 12 timber-based agroforestry systems in the experimental site "CEDEC-JAS", La Masica, Atlántida, Honduras.

Combined effect of tree cover and timber basal area on cacao yields

Across experimental plots, the average timber basal area was 12 m^2 ha^{-1} but varied widely (3–22 m^2 ha^{-1}). A strong and inverse effect of tree cover (%) and timber basal area on cacao yield was detected. Cacao yields were greater when tree cover and timber basal area were below 40% and 10 m^{2}ha^{-1}, respectively (Figure 7). The combined effect of tree cover + timber basal area on crop yields was marked when cacao plots surpass both thresholds, some plots registered a yield reduction in up to 20–25%. Based on this finding, timber basal area could be used as a proxy to better manage tree density and thinning events in shaded cacao plots aimed at producing acceptable cacao yields and lumber production.

Revenues from good and products delivered by timber-based cacao agroforestry systems

After 22 years of evaluation, five out of 12 timber-based agroforestry systems accumulated more than U$90,000 of combined net revenues (cacao + plantain (corms and bundles) + *G. sepium* stakes and commercial standing timber). This amount is equivalent to annual incomes of US$3770 ha^{-1} year^{-1} (Appendix 1). The most profitable plantation was cacao under *H. alchornaides* which generated US$95,355 equivalent to US$3,973 ha^{-1} year^{-1}. The less lucrative plantation was cacao under *C. arborea* providing accumulated incomes of US$37,570, corresponding to annual revenues of US$1,565 ha^{-1} year^{-1}. Principal component analysis run with a set of 12 income-cost variables revealed that total revenues were determined by the proportion of incomes provided by each component of the agroforestry systems assessed (Figure 8). For instance, accumulated incomes from the most profitable plantation (cacao under *H. alchorneoides*) came at a similar proportion from timber and dried cacao beans (46% each). Total incomes from cacao + *D. glomerata* plantation derived from cacao beans (86%) and timber (6%) given the low timber yield and low market price for its lumber (Figure 8). Revenues from cacao + *T. donnell-smithii* plantation were offered by timber (70%), cacao beans (15%), plantain (corms and bundles), and madreado stakes (15%). See more details on accumulated revenues in Appendix 4–6.

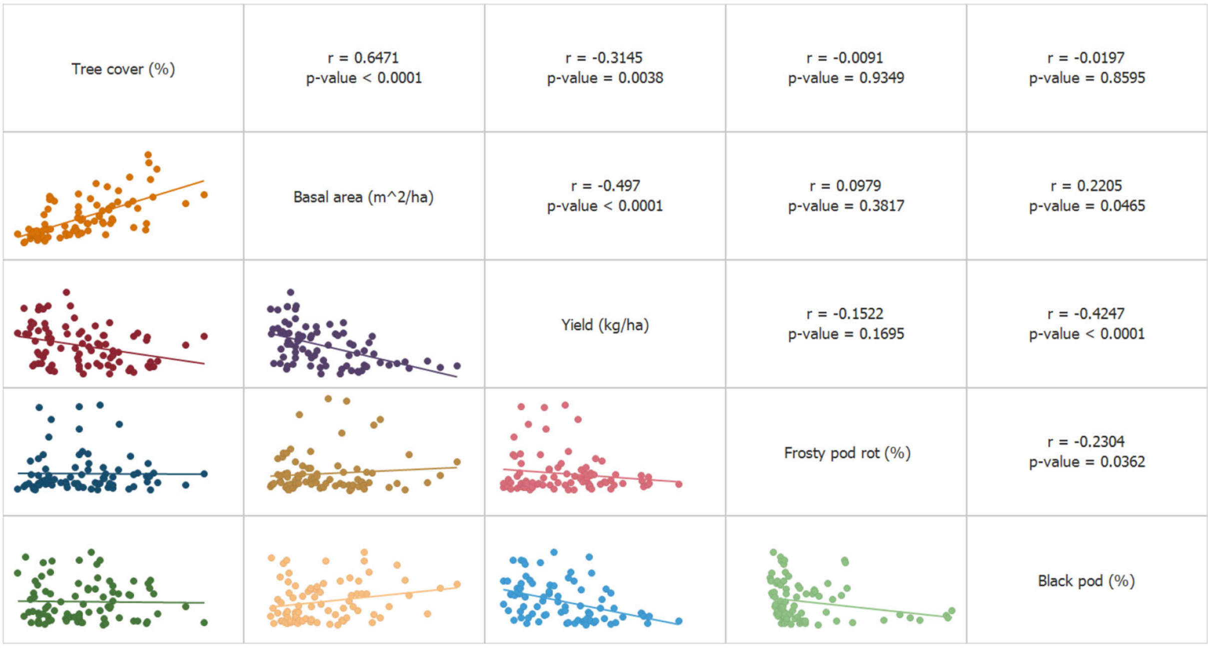

FIGURE 6
Correlations between tree cover (%), cacao yields (kg ha^{-1} year^{-1}) and the incidence of pod diseases in 12 timber-based cacao agroforestry systems in the experimental site "CEDEC-JAS" La Masica, Atlántida, Honduras.

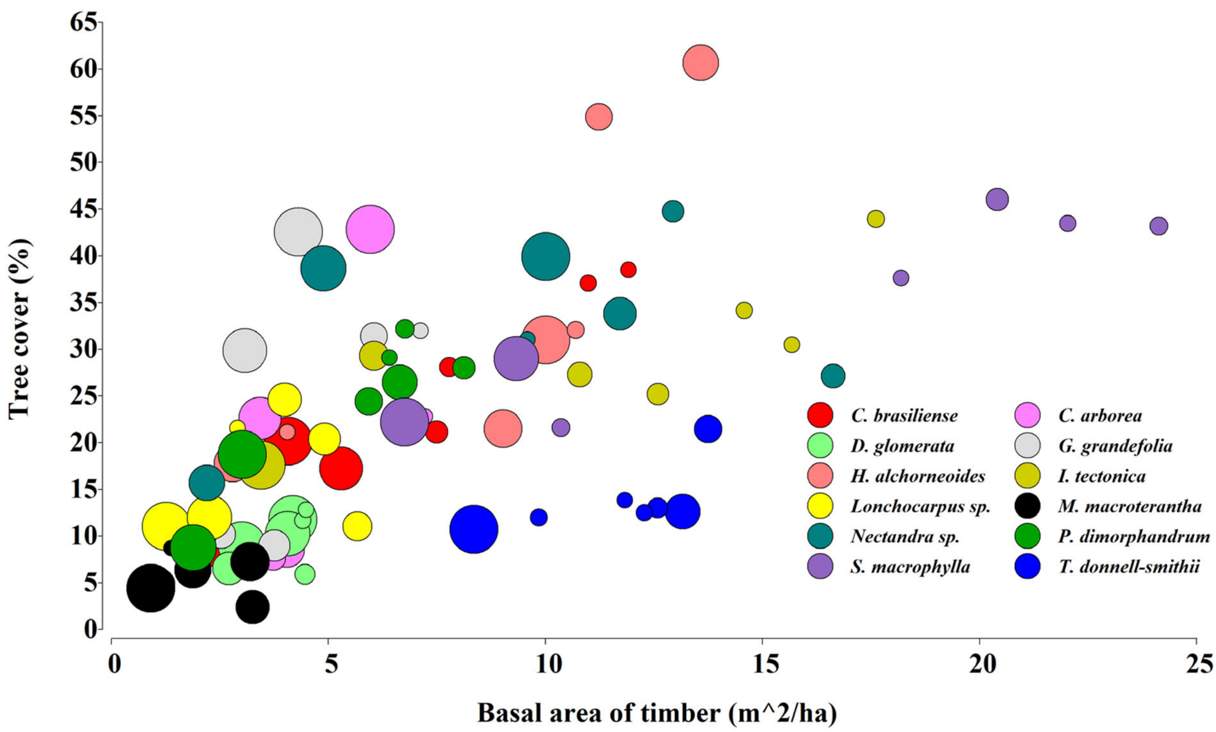

FIGURE 7
Combined effects of tree cover (%) and timber basal area (m^2 ha^{-1}) on cacao yields (the larger the circle size the greater the yields) of 12 timber-based agroforestry systems in the experimental site "CEDEC-JAS", La Masica, Atlántida, Honduras.

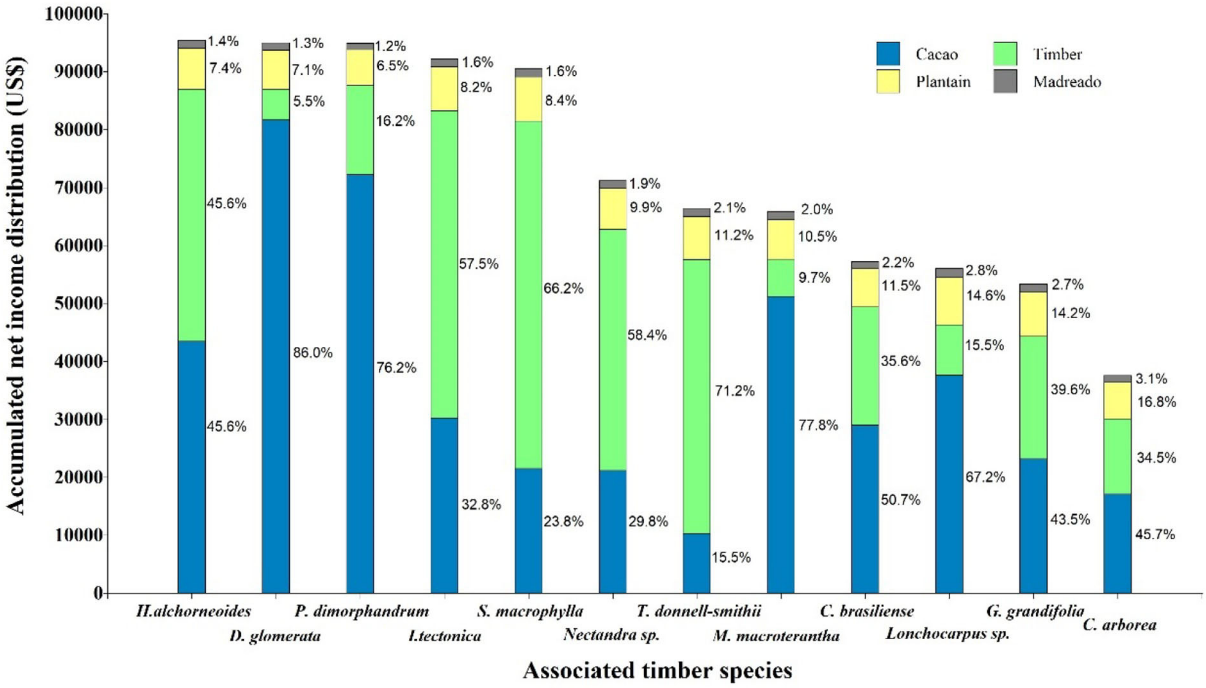

FIGURE 8
Distribution (%) of accumulated net incomes from 12 cacao timber-based agroforestry systems over 22 years in the experimental site "CEDEC-JAS", La Masica, Atlántida, Honduras.

Discussion

Growing performance of timber trees

Timber trees are a frequent component in cacao shade canopies, and various authors have recommended cacao–timber-based agroforestry systems as a viable strategy for the intensification of cacao cultivation (Somarriba and Beer, 2011; Tscharntke et al., 2011; Vaast and Somarriba, 2014; Notaro et al., 2020) and to increase the sustainability and financial performance of cacao farming (Ramirez et al., 2001; Gockowski and Sonwa, 2011; Ruf, 2011; Jaimez et al., 2013; Cerda et al., 2014). However, to be able to demonstrate the full benefits of timber-based cacao agroforestry systems and to better understand the evolution of cacao yields and assess expected incomes long-term field evaluation is needed. To our knowledge, this study is the first prolongated experimental trial that provide sound information on timber growth rates, cacao yields, pests, and diseases dynamic and the accumulated revenues for over two decades. Moreover, the experimental site where the study was conducted has served as a learning field for several farmers, technical staff, decision-makers, and private investors which have witnessed the overall performance of timber-based cacao plantations in the humid lowland of Honduras.

Timber growth curves are key to show farmers that timber trees can be harvested at different time frames according to market prices to maximize revenues. Few studies have demonstrated significant revenues of timber trees harvested from shaded cacao and coffee plantations in the region (Ryan et al., 2009; Cerda et al., 2014; de Sousa et al., 2016). We monitor growth rates, crown and shading features, cacao productivity, and incidences of cacao diseases of 12 native timber species for over two decades. This set of species was not previously assessed in Central America but most of them exhibited promising market potential. In this regard, we statistically demonstrated that timber species grew at different rates in terms of diameter, tree height, and commercial volume yields. Five out of 12 species were categorized as very fast- and fast-growing species reaching the minimum harvesting diameter (25 cm) at 13–15 years after planting. The remaining seven species recorded 25 cm in diameter between 16 and 18 years after planting. Standing volume yield differed among species evaluated. Overall, timber trees gained on average 0.74 m^3 $tree^{-1}$ $year^{-1}$, equivalent to 4.4 m^3 ha^{-1} $year^{-1}$, which is considered a satisfactory timber yield for shade trees (Orozco, 2005; Somarriba et al., 2012; Almendarez et al., 2013). Greater timber yield (1.6 m^3 of roundwood $tree^{-1}$) is reported for medium size cacao plantations mixed with *Tectona grandis* aged 20 years in Bahia, Brazil (Gama-Rodrigues et al., 2021).

Evolution of cacao yields and interaction between tree cover and pest and diseases

Despite a similar pool of cacao clones were grown and evaluated across experimental plots, crop yields differed among timber shade species with a mean value of 765 kg ha^{-1} $year^{-1}$ (467–2,367 kg ha^{-1} $year^{-1}$), which was three times higher than the average cacao yield reported for traditional shaded cacao plantations in Honduras (Orozco-Aguilar et al., 2015; Sanchez and Dudon, 2016; Wiegel et al., 2020; López et al., 2021). Similar cacao yields were reported for a 10-year cacao plantation grown under leguminous and timber trees in Talamanca, Costa Rica and Changuinola, Panama. Higher cacao yields (850–950 kg ha^{-1} $year^{-1}$) were achieved in a long-term conventional trial shaded by native timber trees in Alto Beni, Bolivia (Schneider et al., 2016). Equivalent cacao yields (650–950 kg ha^{-1} $year^{-1}$) are reported in 20-year-old cacao + *T. grandis* combination in Bahia, Brazil, with similar densities for cacao and timber trees (Gama-Rodrigues et al., 2021).

The yield evolution curves depicted in this study allowed us to devise clear trends across experimental plots and overtime. First, the cacao production peak was detected from year 15 to 17 years after planting, a consistent decrease in crop yields was detected afterward. Second, overtime; seven out of 12 timber-based cacao plantations evaluated registered 800 kg ha^{-1} $year^{-1}$ or lower and, third, we detected that a year of good cacao productivity was followed by 1–2 years of lower yields. These findings might inform farmers and investors on the best moment to plan both rehabilitation and renovation interventions and to better schedule timber harvest to reduce crop and economic losses due lumber extraction (Quiroz and Amores, 2002; Dubón and Sánchez, 2016).

Tree cover (%) across experiment plots varied according to crown features (mainly crown diameter and shading factor) with an average value of 35% and ranged between 12 and 45%. Shade management is key to maintain uniform shade levels, create a favorable microclimate for cacao plants to grow and yield, and to allow enough airflow to reduce beneficial conditions for pathogens (Beer et al., 1998; Tscharntke et al., 2011; Leandro-Muñoz et al., 2017). The negative and significant effect of tree cover on cacao yields was found in those plots exceeding 40%, typical of those shade species having medium tree height (13–15 m), medium crown size (8–10 m), and greater shading factors (75–85%) such as *S. macrophylla, C. brasiliense,* and *I. tectónica.* Tree high and crow size are key features driving the quality and quantity of shade for perennial crops (Somarriba et al., 2018). Recent research has demonstrated that shade trees with elevated crowns had large positive effects on carbon storage and neutral effects on cacao yields, while shade trees with low crowns had smaller effects on carbon storage and simultaneously caused larger reductions in incoming light, which was associated with lower yields (Wartenberg et al., 2019; Blaser-Hart et al., 2021).

The optimum shade level for cacao is still an open debate topic since it is site-specific and seems heavily influenced by the silvicultural management given to associated shade trees (Abdulai et al., 2018; Norgrove, 2018; Sauvadet et al., 2020). Some authors suggest that 35–45% of shade level might sustain acceptable cacao yields while providing environmental services such as carbon sequestration, pollination, and nutrient cycling (Somarriba et al., 2013; Montagnini et al., 2015; Vaast et al., 2015; Blaser et al., 2018; Middendorp et al., 2018; Niether et al., 2020). Results from medium-term field trails in Costa Rica and Panama suggest that frequency, timing, and severity of thinning and pruning guarantee non-competitive shade levels with cacao, while allowing acceptable timber yields (Somarriba and Beer, 2011). In this study, we found negative and significant correlations between tree cover and cacao yields in four out of 12 timber species but this correlation was no significant for the incidence of frosty pod and black pod, suggesting that control measures applied (namely fortnightly harvest and diseased pod removal) were effective. Similarly, in the long-term trial in Alto Beni, Bolivia cacao agroforestry systems do not increase pest and disease incidence compared to monocultures when good practices are implemented (Armengot et al., 2020).

Regular planting and pruning are also key interventions to keep homogenous shade levels throughout the year (Beer et al., 1998; Tscharntke et al., 2011; Somarriba et al., 2018). In our study, tree density and spacing across experimental plots were kept as recommended for perennial crops ranging from 80 to 120 trees ha^{-1} (Sanchez and Dudon, 2016; Somarriba et al., 2018). Clustered and random trees rather than regularly distributed trees over the plot significantly affected the incidence of frosty pods in small cacao plantations, which are further aggravated by poor agronomic management (Ngo Bieng et al., 2013). Recent research from traditional cacao plantations in the Dominican Republic showed that cacao tree productivity increased in the presence of leguminous trees, even when at a short distance (<3 m), and to a lesser extent in the presence of timber trees (Notaro et al., 2021).

Combined effects of tree cover and timber basal area on cacao yields

In the analysis of shade canopy design using basal area allocation as indirect means for tree biomass, carbon stock, or shade level, basal area is considered a good predictor of crop yields (Somarriba, 1992; Jagoret et al., 2017; Somarriba et al., 2018). In this study, a strong and inverse effect of tree cover and timber basal area on cacao yield was detected; therefore, we confirmed the applicability of the competitive allocation of basal area model proposed by Somarriba et al. (2018) as a proxy for a better design and management of shaded perennial crops such as cacao and coffee. Across experimental sites, cacao yields were greater when shade levels and timber basal area were below 40% and 10 m^2, respectively. The combined effect of tree cover + timber basal area on crop yields was marked when cacao plots surpass both thresholds. Various management options can modify the competitive effects between cacao and shade canopy plants, and between the production of timber and other goods and services in the shade canopy (Beer, 1987; Somarriba and Beer, 1987; Rapidel et al., 2015; Asare et al., 2017; Mortimer et al., 2018). For instance, pruning lower branches increases the length of the tree bole with clean wood (free of knots) fetching higher prices and improves the shading conditions in the plantation. In addition, timber trees shall not be pruned or thinned considering only the light regime needed by the cacao plants but also to ensure that: 1) high-quality timber is produced, 2) only the best formed, and fastest-growing trees are kept for future harvest; and 3) the right number of timber trees are retained in the plot to gain significant returns and avoid overshading (Somarriba et al., 2018; Blaser-Hart et al., 2021; Notaro et al., 2021).

Accumulated revenues from timber-based cacao agroforestry systems

Based on recorded revenues and supported by the PCA test done, we were able to elucidate which cacao + timber association are more and less profitable overtime. The most profitable plantation was cacao under *H. alchornoides* that generated US$95,355 equivalent to US$3,973 ha^{-1} $year^{-1}$. The least lucrative plantation was cacao under *C. arborea* with accumulated incomes of US$37,570, equal to annual revenues of US$1,770 ha^{-1} $year^{-1}$. Moreover, total revenues registered in our study were determined by the proportion of incomes provided by each component of the cacao timber-based agroforestry systems assessed. The most lucrative association provided similar incomes from both cacao and harvested timber (approximately 45% each) and incomes from the least profitable association came mostly from cacao and to a lesser extent from timber. It has been shown that the contribution of the set of agroforestry goods and products to family benefits across Central America and Dominican Republic is similar to or higher than cacao yields (Cerda et al., 2014; Notaro et al., 2020). However, these cacao plantations were described as having low timber volumes and unsustainable harvest rates. Likewise, it has been demonstrated that the accumulative yields of all goods and products harvested from cacao agroforestry systems of Alto Beni, Bolivia, were significantly higher (+160%) compared to the monocultures. The overall productivity of by-crops in shaded cacao may contribute to local food security and risk distribution in smallholder contexts (Schneider et al., 2016).

Limitation and strengths of our study

The main limitation is that the trials of the 12 shaded cacao plots tested lack truly replicates. However, soil and climatic conditions across the experimental site are quite homogenous and the genetic pool of both cacao clones and shade timber trees are uniform so recorded data from all plots are consistent and reliable (Casanoves et al., 2017; Suárez Salazar et al., 2018, 2021). Moreover, having recorded data on tree growth rates, incidences of pests and diseases, and cacao yields for over two decades give robustness and reliability to the findings and grant practical implications to our study. In fact, the experimental site at FHIA is the only long-term trial across Mesoamerica that tested the overall performance of cacao under a wide list of native timber species, providing a sound ground to explore the feasibility and profitability to grow cacao under timber shade trees. A second limitation is that we did not record cacao yields for the first seven years after planting, so we were unable to build the production curves for all plots and clones at early stages. Initial cacao yield data are key to better inform farmers and investors regarding total systems revenues overtime (Schneider et al., 2016, Notaro et al., 2020). Finally, due to operational cost and time constraints, we were unable to measure tree cover more frequently, hence we did not capture the shading patterns of associated timber species throughout the calendar year (Carrillo et al., 2012; Koko et al., 2013), consequently, no effect of tree cover on the cacao phenological cycle can be drawn.

Conclusions

Based on findings, it is sound to state that timber trees are a feasible and profitable options to plant cacao in La Masica, Atlántida, Honduras. In addition, we statistically demonstrated that timber species grew at different rates in terms of diameter, tree height, and commercial volume yields indicating that farmers may harvest timber trees at different time frames according to market prices to maximize revenues. Agricultural practices such as fortnightly harvest and diseased pod removal coupled with differential management of shade trees are key interventions to keep homogenous shade levels throughout the year, create a favorable microclimate for cacao plants to grow and yield, and reduce pests/diseases pressure. In this study, timber basal area coupled with tree cover was proven to be a good predictor of cacao yields. Total revenues registered in our study were determined by the proportion of incomes provided by each component of the timber-based cacao agroforestry system assessed. Based on recorded revenues and supported by the PCA test, we were able to elucidate that cacao + timber association are more and less profitable overtime, which is crucial data to better inform farmers, development projects, and investors on the projected revenues of timber-based cacao plantations.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author/s.

Author contributions

AD, JS, OR-A, FJD, and LO-A contributed to conception and design of the study. OR-A, AD, and FJD organized the database. OR-A and FC performed the statistical analysis. LO-A and OR-A wrote the first draft of the manuscript. OR-A, FJD, FC, AD, and LO-A wrote sections of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2022.941743/full#supplementary-material

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