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Simplification of the structure and diversity of cocoa agroforests does not increase yield nor influence frosty pod rot in El Soconusco, Chiapas, Mexico

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Abstract Cocoa is traditionally grown in agroforestry systems (AFS). It is essential to the household and regional economy and plays an important role in natural resource and environmental services conservation. In recent years, the vegetation structure and diversity of cocoa AFS throughout the world are being simplified as farmers consider that the removal of trees helps to increase yields and reduce disease incidence. However, debate exists on the relationship between tree shade and diversity and cocoa yields and the incidence of disease such as frosty pod rot, one of the most important fungal infections in cocoa cultivation. The objective of this study was to analyze changes in agroforestry structure, plant species diversity, uses, yields, the incidence of frosty pod rot disease in cocoa agroforestry systems, and discuss the consequences of the simplification of this particular AFS in the municipality of Acacoyagua, Chiapas, Mexico. Inventories were carried out in 27 plots. Interviews were applied to families to assess ecological, technical, and productive variables. Incidence of frosty pod rot disease and yields were estimated on-farm and through interviews over a period of 3 years. Multivariate cluster analysis, Pearson correlation analysis, the Levene test for equality of variances and a non-parametric U Mann–Whitney test were carried out. Three types of cocoa agroforests were identified as a result of a structure simplification: (1) traditional cocoa polyculture; (2) cocoa with Legumes *Inga* spp and *Lonchocarpus* spp.; and (3) cocoa with diverse, scattered, predominantly wild trees. Fifty species were recorded in shade vegetation, with a diversity index of 3.15. Simplification in tree structure did not have a significant effect on cocoa yield nor on the incidence of frosty pod rot disease. On the contrary, it resulted in a decrease in plant diversity and provisioning of food and other products. Farmers undertake few agricultural practices; some practices are eventually carried out, such as the pruning of cocoa trees and shade-trees, removal, and burial of diseased fruits, and weeding. Seven out of 27 plots sampled yielded more than

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300 kg ha^{-1}, and one plot attained a yield of 437.5 kg ha^{-1}; however, yields averaged 155.8 kg ha^{-1} and incidence of frosty pot rot averaged 9.6%, regardless of AFS type. These results highlight the importance of improving AFS management which in this case appears to be the most critical factor for attaining an increase in yields. Low levels of production and the incidence of frosty pod rot subsequently reduces farmers' motivation to continue cultivating cocoa, placing the crop at risk and increasing the possibility of a change in the land-use.

Keywords Maya · Ecosystem services · Land-use change · Multi-strata systems · Perennial crops · Traditional systems

Introduction

Cocoa (*Theobroma cacao* L.) had its origin in Latin America, where it experienced a great boom due to the religious significance procured on it by ancient cultures. Religious castes used it as a "drink of the Gods" and also as a form of currency. However, it is not Latin America where it is produced most, but in Africa. Cocoa has traditionally been cultivated in diverse and complex agroforestry systems; however, simplification of these systems derived from a process of intensification has not necessarily led to higher yields in Mexico and other coca producing countries in the tropical world (Vaast and Somarriba 2014; Tondoh et al. 2015; Salazar et al. 2018; Gasco 2018).

The main factors associated with low yields are plantation age, pests and primarily fungal diseases, poor management, deforestation, and limited government support (Rajpaul-Maguire et al. 2020) and Mexico is certainly not immune to such problems. This country has a long tradition of cultivating cocoa, beginning with the Mesoamerican Postclassic Period (years 900–1200; Gasco 2018; 2005; Díaz-José et al. 2014). Currently, Mexico produces 28 thousand tons of cocoa beans annually, principally in the states of Tabasco (65.2%) and Chiapas (32.8%) (SIAP 2014 http://www.siap.gob.mx), ranking eighth worldwide after the Ivory Coast, Ghana, Indonesia, Nigeria, Cameroon, Brazil, and Ecuador. Nevertheless, Mexico's yield does not meet the national demand and imports cocoa, principally from Ecuador, Ivory Coast, Dominican Republic, Colombia and Ghana (http://www.cedrssa.gob.mx/post_industria_del_-n-cacao_en_mn-xico-n.htm#:∼:text=M%C3%A9xico%20tiene%20un%20d%C3%A9ficit%20de,se%20encuentra%20en%20nuestro%20pa%C3%ADs).

In Mexico, cocoa is cultivated in traditional agroforestry systems (AFS), predominantly grown by small scale peasant families who use traditional low-input agroecological systems, family labour, manual tools, and local knowledge (Ramírez 2008; Díaz-José et al. 2014; Gasco 2018).

As in most of Mexico and Central America, cocoa AFS of the Soconusco region combine wild and cultivated shade trees in a variety of arrangements (Salgado-Mora et al. 2007; Somarriba et al. 2014). However, in recent decades the incidence of fungal diseases such as frosty pod rot (*Moniliophtora roreri* H.C. Evans et al.) and black pod disease (*Phytophthora palmivora* (E.J.Butler) E.J.Butler), have led to government agencies and cocoa purchasers promoting the removal of shade trees in order to reduce forest cover and shade conditions in the AFS, since it is assumed that this would bring about an increase in yields as demonstrated in other countries. However, rarely have new management techniques been promoted or accompanied these changes (Anglaaere et al. 2011; Vaast and Somarriba 2014; Andres et al. 2016; Tondoh et al. 2015). Previous studies in the Soconusco region have reported cocoa yields between 285 and 585 kg ha^{-1} year^{-1} compatible with shade trees (Díaz-José et al. 2014). Others have reported significant carbon stocks by maintaining large trees over 50 Mg C ha^{-1} with similar yields (Somarriba et al. 2013; Schroth et al. 2016). However, general trends point towards simplification (lowering shade plant density and diversity), whose effect on yields and diseases is still controversial (Clough et al. 2011; Daghela et al. 2013; Vebrova et al. 2014).

While some research has found that complex and diverse shade vegetation has resulted in increases of cocoa yields, and a decrease in the intensity of frosty pod rot disease, others have reported the opposite (Clough et al. 2011; Ngo Bieng et al. 2013; Somarriba et al. 2013; Gidoin et al. 2014; Jezeer et al. 2017; Asare et al. 2019; Riedel et al. 2019; Armengot et al. 2020). Other studies have indicated that the biodiversity of microorganisms inhabiting the cocoa plant and associated plants in agroforestry systems can have positive effects on improving crop health (Asman et al. 2020; Wemheuer et al. 2020).

Nonetheless, many of the results revealed wide variability, and multiple factors seem to be affecting both response variables (Ratnadass et al. 2012; Hernandez et al. 2015).

The present study aimed to analyze changes in agroforestry structure, plant species diversity, plant use-value, on yields and the incidence of frosty pod rot disease in cocoa agroforests. It discusses the consequences of a simplification of this system in the municipality of Acacoyagua, in Soconusco, Chiapas, Mexico.

Materials and methods

Study area

The municipality of Acacoyagua is located in the Soconusco, Chiapas, the southernmost region of Mexico, where cocoa is of historical economic and social importance (Gasco 2018). It is located at 15°19′–15°30′ N latitude and 92°32′–92°49′ W longitude (Fig. 1). It is characterised by a warm, humid climate with abundant summer rain and an annual temperature ranging from 14 to 30 °C. Annual rainfall is from 2500 to 4000 mm. Land belongs to the ejido land tenure system -a communal resource-holding institution where a community was granted land by the federal government-. The ejido land is regulated by an assembly and individually managed by each farmer (often through family decision making)-. Forms of land use present in Acacoyagua include pastures (32.54%), agricultural land (0.6%), inhabited areas (0.5%), secondary vegetation (65.4%), and forest (1.1%). Principal crops are mango, coffee, cocoa, and corn, and to a lesser extent, rice, sesame, *mamey* (*Pouteria sapota*), and other fruits. Cocoa is one of the Soconusco region‘s principal cash crops, used to produce chocolate. In Acacoyagua, frosty pod rot disease was first reported in 2007, resulting in estimated crop losses of up to 90%, a figure like other municipalities of Chiapas as well as other Mexican states.

Sampling and agroecological inventories

In the municipality of Acacoyagua, 54 households are engaged in the cultivation of cocoa (SIAP 2014 http://www.siap.gob.mx). For this study, 27 households (50% of the total) from the four largest communities - Los Cacaos, María Esther, Nueva Libertad, and the county seat of Acacoyagua—were selected. The altitude of these villages ranges from between 80 and 640 m a.s.l. Participants were selected using the snowball method (Schensul et al. 1999). Interviews were carried out in each household and applied to both women and men in order to characterize the family household. Inventories were carried out in 20 × 20 m quadrats in each plot, diameter at breast height (DBH) ≥ 5 cm was recorded for each woody plant, shrub, arborescent plant, and tall herb. For each individual, scientific name, biological forms, and uses were identified. The height of every shade tree and cocoa tree was recorded (in m, using a Haga hypsometer). Shade cover percentage was estimated (Medina-Fernandez et al., 2006; adapted to cocoa plots). The number of strata was recorded using photos; densities of coffee shrubs, cocoa trees, banana plants, palms (n ha^{-1}) together with cocoa tree basal area (m^2 ha^{-1}) were estimated. Relative abundance (%) and the ecological importance value of tree species were calculated. Shannon diversity (*H*’) and evenness (*E*) were determined according to the richness and abundance of tree species in each plot.

Tree species were categorized according to their origin and use; those used for shade were categorized according to farmers’ perceptions as “cool or good shade” or “bad shade that negatively affects the crop”. The categories of use and shade quality were identified using data provided by each participant.

Cocoa yields were estimated by averaging data collected from field sampling, interviews, and records taken by farmers (kg $ha^{-1}year^{-1}$); sampling was carried out in 2016 by counting and collecting all the pods from twenty-seven 20 x 20m quadrats then drying and weighing the seeds. Records made by the farmers and interviews took place during 2014, 2015, and 2018. The total number of adult cocoa pods and the pods damaged by frosty pod rot were counted in each sampled plot for one year and farmer estimations were recorded through interviews as carried out for yields.

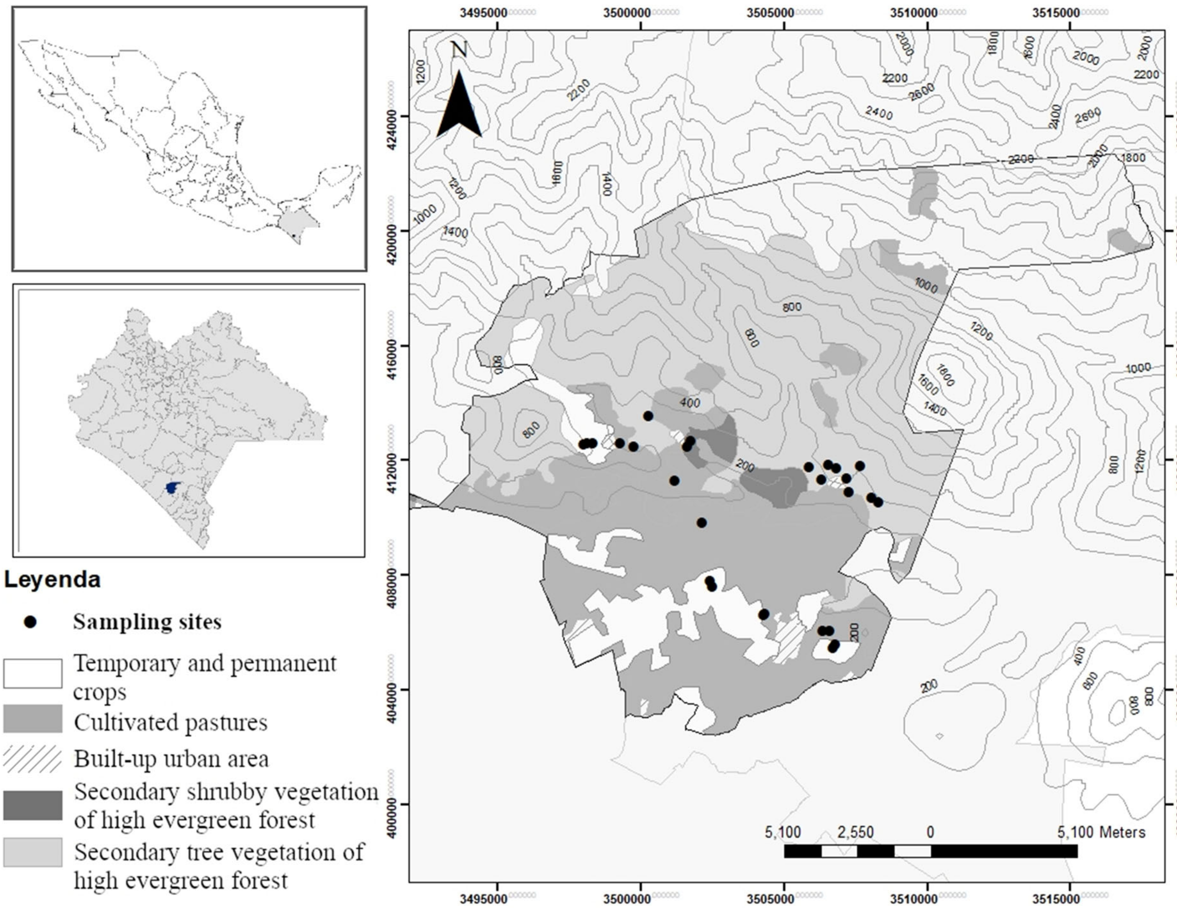

Fig. 1 Sampling plots location in Acacoyagua, Chiapas, México modified from CONABIO 1998 (http://www.conabio.gob.mx/informacion/metadata/gis/cni250kgw.xml?_xsl=%2Fdb%2Fmetadata%2Fxsl%2Ffgdc_html.xsl&_indent=no); INEGI 2016 (http://www.beta.inegi.org.mx/app/biblioteca/ficha.html?upc=889463173359)

When this was completed, workshops were held in the participating communities to report the results.

Data analysis

Descriptive statistics were used to characterize the structure, composition, and management of cocoa agroforests. These agroforests were classified through a hierarchical multivariate cluster analysis using structural variables, botanical composition, and use variables to identify different groups. Three sets of plots resulted from this analysis.

The Levene test for equality of variances and a non-parametric U Mann–Whitney test were carried out to compare structure, composition, and use variables among types of cocoa plots, with a 95% confidence level ($p < 0.05$). A Pearson correlation analysis was conducted using bilateral significance between the mean values for structure, composition, and yield.

Due to the high variability of cocoa yield results, in addition to the cocoa yield mean, confidence intervals for each group of AFS were constructed, using the t distribution at $\alpha = 0.05$.

Analyses were conducted using the R Studio program, version 1.2.1335.

Results

Cocoa producing households

Cocoa is a traditional AFS important for family households. The mean age of farmers interviewed was 62 ± 12.29 years; farmers were native to Acacoyagua

(44.4%) and other regions of the state of Chiapas (55.6%). The main economic activity in the study area was family farming (55.6%), although other activities were also important such as local trade (18.5%), hired farm labour (14.8%), and other jobs. Interviewed women farmers also carried out domestic work in their homes. Over half of the families had at least one migrant member within Mexico or abroad. Principal crops were corn, beans, rice, cocoa, coffee, mango, and rambutan. The land was held according to the ejido system. The family makes most of the decisions regarding cocoa growing. The most frequent practices conducted in plantations were the following: planting cocoa trees, weeding, removal of diseased pods, and harvesting, primarily carried out by men; while women's work included breaking the cocoa pods, washing, and drying the cocoa beans, with the assistance of their children, as well as producing chocolate (drying, selecting, roasting the beans, grinding them with sugar, and moulding the dough), and making *pozol* (a traditional and staple beverage made of roasted and ground maize and cocoa). This crop is mainly produced for commercial purposes although it is also used for family consumption. Other less frequent practices included cocoa tree pruning, shade tree elimination, shade tree pruning, use of ashes and lime, cocoa tree renewal- replacing the criollo variety for monilia-tolerant varieties and old trees for saplings, and the use of grafting. Bean fermentation is not common. However, some organizations have recently promoted this practice to improve cup quality.

Cocoa agroforestry system

Cocoa is traditionally cultivated within a multi-strata AFS, which includes native and introduced shade trees among legumes, and/or plants from other botanical families planted in a random arrangement. Most farmers (74.1%) grew coffee plants for family consumption, interspersed with cocoa trees.

Cocoa trees in Acacoyagua belong to the "Forastero" and "Trinitario" varieties. Renewal has almost eliminated "criollo" varieties. Cocoa agroforests were 27.5 ± 18.7 years old. Since 2005, cocoa has been attacked by frosty pod rot disease, which has reduced yields by up to 60%. Seven out of 27 plots sampled produced more than 300 kg ha^{-1}, with one plot attaining 437.5 kg ha^{-1} of cocoa yield. The mean yield for the total number of plots was 155.8 ± 99 kg $ha^{-1}year^{-1}$. Yields are considered low in comparison to other neighbouring areas where more intensive practices are applied. Despite this, farmers continue to produce cocoa as the population manages multiple land uses, cultivating several products at the same time: maize, coffee, and fruits and also working outside the farm to complement their income as mentioned in these testimonies:

> In each harvest, we obtain between 20 and 30 kilograms. What I produce on my cocoa agroforest helps me to buy corn, sugar, soap. That's why I keep it. 85-year-old man
> In actual fact I don't have to cut down my plantation, I have other crops, I have my coffee, corn, and fruits. 64- year-old man

A total of fifty species among trees, shrubs, arborescent plants, and tall herbs were recorded, almost all (94.1%) of which have a use-value; one-fifth of these had multiple uses (Table 1). Most cocoa AFS products were used for family consumption, but some others have a commercial value. Native trees were used for making furniture, building homes, or as savings to be sold to pay for medical or other domestic expenses. The most highly valued woody species were *primavera* (*Roseodendron donnell-smithii*) and cedar (*Cedrela odorata*).

Among the total species recorded in the inventories, 16.7% were considered by farmers to provide "cool or good shade", principally legumes, including *Inga spp.* and *Lonchocarpus hondurensis*. Another 22.7% were "bad shade that negatively affects the crop", including *palo de chiche* (*Aspidosperma spp.*), cedar, and mango *(Mangifera indica)* (Table 1). Despite their lack of suitability for providing shade, these species are highly valued as their timber or fruit may be marketed.

Farmers confirmed the elimination of trees with the idea of improving production in their cocoa agroforests:

> Because of frosty pod rot disease, in general, we do not leave huge trees, but we leave some trees that were already in the agroforests (*primavera*, cedar, laurel). Also, we replace some tall wild trees with fruit trees such as rambutan, avocado, and *mamey* (48-year-old man, Los Cacaos, Acacoyagua).

Table 1 List of species of three cocoa agroforestry systems in Acacoyagua, Chiapas, Mexico

Common name	Species	Botanical Family	BF	G	Use	SQ	IVI	PAFS
Canaque	*Alchornea latifolia* Sw.	Euphorbiaceae	1	1	5,6	–	4.66	1
Guanábana	*Annona muricata* L.	Annonaceae	1	1	2	–	13.05	1
Palo de chiche	***Aspidosperma megalocarpon* Müll. Arg.	Apocynaceae	1	1	4	2	1.76	1
Palo de chiche	*Aspidosperma spruceanum* Benth. ex Müll. Arg.	Apocynaceae	1	1	4	2	18.85	1
Árbol de manaco o corozo	*Attalea butyracea* (Mutis ex L. f.) Wess. Boer	Arecaceae	3	1	6	–	–	1
Nance	*Byrsonima crassifolia* (L.) Kunth	Malpighiaceae	1	1	5,2	–	4.71	1
Hoja blanca	*Calathea lutea* (Aubl.) Schult. (R)	Marantaceae	4	1	2	–	–	1,3
Leche marío	*Calophyllum brasiliense* Cambess.	Clusiaceae	1	1	4	2	4.66	1
Chile	*Capsicum annuum* L. (R)	Solanaceae	4	1	2	–	–	3
Hule	*Castilla elástica* Sessé	Moraceae	1	1	6	–	2.90	1
Cedro	*,***Cedrela odorata* L.	Meliaceae	1	1	4	2	22.93	1,2
Sin nombre	*Cestrum* sp.	Solanaceae	2	1	5	–	–	1
Pacaya	*Chamaedorea tepejilote* Liebm.	Arecaceae	3	1	2,5,7	–	–	1,2
Lim	*Citrus aurantiifolia* (Christm.) Swingle	Rutaceae	1	2	2	–	2.90	1
Limón	*Citrus medica* L.	Rutaceae	1	2	2	–	2.90	1
Mandarina	*Citrus reticulata* Blanco	Rutaceae	1	2	2	–	9.88	1,2
Naranja	*Citrus sinensis* (L.) Osbeck	Rutaceae	1	2	2	–	5.80	1
Lima-limón	*Citrus x latifolia* Tanaka ex Q. Jiménez	Rutaceae	1	2	2	–	2.90	1
Café	*Coffea arabica* L.	Rubiaceae	2	2	2	–	–	1,2,3
Café	*Coffea canephora* Pierre ex A. Froehner	Rubiaceae	3	2	2	–	–	1,2,3
Laurel	***Cordia alliodora* (Ruiz & Pav.) Oken	Boraginaceae	1	1	4	–	7.18	1,2
Palo de agua	*Critonia morifolia* (Mill.) R.M. King & H. Rob.	Asteraceae	2	1	5	–	–	1
Chipilín	*Crotalaria longirostrata* Hook. & Arn. (R)	Fabaceae	4	2	2	–	–	1
Unknown	*Geonoma interrupta* (Ruiz & Pav.) Mart. (R)	Arecaceae	3	1	6	–	–	1
Platanillo	*Heliconia* sp. (R)	Heliconiaceae	4	1	2	–	–	3
Cuil paterna	*Inga inicuil* Schltdl. & Cham. ex G. Don	Fabaceae	1	1	5	1	2.90	1
Caspirol	*Inga laurina* (Sw.) Willd	Fabaceae	1	1	5,1,2	1	7.18	1,3
Guagua	*Inga nobilis* Willd.	Fabaceae	1	1	5,2	1	6.52	2
Chalum	*Inga oerstediana* Benth. Ex Seem.	Fabaceae	1	1	5,1,2,3	1	14.03	1,2
Cuil	*Inga vera* Willd.	Fabaceae	1	1	5,1,2,3	1	21.27	1,2
Cuil de agua	*Inga vera* subsp. *spuria* (Humb. & Bonpl. ex Willd.) J. León	Fabaceae	1	1	5,1	1	6.52	–
Sinsapote	*Licania platypus* (Hemsl.) Fritsch	Chrysobalanaceae	1	1	7	–	2.90	1
Chaperna	*Lonchocarpus hondurensis* Benth.	Fabaceae	1	1	5,1	1	26.22	1,2
Mango	*Mangifera indica* L.	Anacardiaceae	1	2	2	2	6.42	1
Guineo	*Musa acuminata* Colla	Musaceae	4	2	2	–	–	1,3
Plátano macho	*Musa x paradisiaca* L.	Musaceae	4	2	2	–	–	1,3
Tepeaguacate	*Nectandra reticulata* (Ruiz & Pav.) Mez	Lauraceae	1	1	4	–	2.90	1
Aguacate	*Persea americana* Mill.	Lauraceae	1	1	2,5	2	11.71	1
Mamey	*Pouteria sapota* (Jacq.) H.E. Moore & Stearn	Sapotaceae	1	1	2	–	18.03	1
Mulinillo	*Quararibea funebris* (La Llave) Vischer	Malvaceae	1	1	7	–	2.90	1

Table 1 continued

Common name	Species	Botanical Family	BF	G	Use	SQ	IVI	PAFS
Higuera	*Ricinus communis* L.	Euphorbiaceae	2	1	7	–	–	1
Tepenahuaste	*Samanea saman* (Jacq.) Merr.	Fabaceae	1	1	4	–	7.09	1,3
Sin nombre	*Sapium lateriflorum* Hemsl.	Euphorbiaceae	1	1	5	–	2.90	1
Palo blanco	*Sapium* sp.	Euphorbiaceae	1	1	3	–	2.90	1
Cuchillal	*Schizolobium parahyba* (Vell.) S.F. Blake	Fabaceae	1	1	5	–	1.76	1
Castaño	*Sterculia apetala* (Jacq.) H. Karst.	Malvaceae	1	1	4	–	2.90	1
Primavera	*Roseodendron donnell-smithii* (Rose) Miranda	Bignoniaceae	1	1	4, 5	2	22.13	1,2
Roble	*Roseodendron rosea* (Bertol.) DC.	Bignoniaceae	1	1	4	–	7.56	1
Volador	*Terminalia oblonga* (Ruiz & Pav.) Steud.	Combretaceae	1	1	4	2	7.61	1
Pataste	*Theobroma bicolor* Bonpl.	Malvaceae	1	1	2	–	7.71	1
Capulín cimarrón	*Trema micrantha* (L.) Blume	Cannabaceae	1	1	5,3	–	2.90	1

BF Biological form (1 tree, 2 shrubs, 3 arborescent plant, 4 herbaceous plant; *G* Geographic origin 1: native; 2: introduced. Use: 1 green manure, 2 foods, 3 firewood, 4 wood for construction, 5 shade, 6 no use reported, 7 other uses; *SQ* Shade quality from local perception (1 cool shade, 2 bad shade that negatively affects the crop); IVI: Importance value index; *PAFS* Presence in the AFS type 1: cocoa in traditional polyculture; 2: cocoa with Leguminous trees (*Inga* spp and *Lonchocarpus* hondurensis), 3: cocoa with scattered trees; *Species under risk categories in the Official Mexican Regulation (NOM-059-SEMARNAT-2010)

** Species in the Red List of the International Union for Conservation of Nature (IUNC)

> Due to frosty pod rot disease, some years we didn't harvest even a kilogram of cocoa to make chocolate. No, the frosty pod rot disease hit awfully hard. We have *mamey* trees as cocoa shade, but some of them do not give fruit. I want to cut these shade trees down because I really want to see if cocoa can yield fruits, in full sun (52-year-old woman, county seat of Acacoyagua).

Cocoa beans are marketed through intermediaries. One-third of families interviewed transform cocoa beans into chocolate or *pozol* for self-consumption, and as gifts to other families. Throughout the year, cocoa bean prices vary from $32.00 pesos MXN to $50.00 pesos MXN ($1.63 to $2.55 USD in 2019) per kilogram.

Farm families perceive that cocoa is an ideal crop because, as a 48-year-old woman pointed out:

> "it involves little labour and monetary investment; it yields fruits all year, although varying in quantity; and it provides continuous income to help families to cover the cost of food, medical, and community expenses."

Most farmers (41%) plan to pass on their cocoa plot to one of their male children or grandchildren interested in cultivating it. Very few intend to pass on their plot to female descendants. Some intend to sell their land since they have no offspring interested in continuing to farm it (11%). Some did not have plans for their cocoa AFS (37%). A small number of farmers (11%) considered eliminating cocoa crops due to production and marketing constraints.

No private or government source of financing of cocoa production was reported. Few farmers in Acacoyagua or other municipalities of Chiapas belonged to organizations that promote cocoa cultivation or marketing. Farmers regularly come together to organize religious celebrations and other festivities or communal work, but they rarely organized into associations to foment cocoa production or marketing. According to farmers, the most significant problem faced with their cocoa AFS was frosty pod rot disease. In searching for solutions, some farmers are undergoing a process of transforming their cocoa agroforests by reducing shade trees or replacing native trees with commercial fruit and timber species to increase their land and labour value. Other common problems mentioned were loss of cocoa pods due to squirrels, variation in cocoa prices, and loss of cocoa flowers due to heavy rain or hail. Furthermore, the future of cocoa production in the study area seemed to be at risk, given that while older farmers stop cultivating, few young people wish to remain in the communities, especially as there is little opportunity to obtain land and investment capital or paid work.

Typology of cocoa crops The cluster analysis (Fig. 2) resulted in three types of cocoa agroforests: 1) cocoa in traditional polyculture (n = 13; Fig. 3a) (CTP), 2) cocoa with legumes (*Inga* and *Lonchocarpus*; n = 7, Fig. 3b) (CWL), and 3) cocoa with diverse, scattered trees (n = 7; Fig. 3c, Table 2) (not a full-sun cocoa plantation) (CWST) which have been recently increasing in number as part of a transformation process.

CTP was more complex in structure, showed higher diversity than cocoa with legumes and cocoa with scattered trees, and presented a higher number of different species uses. CTP and CWL presented more strata and a higher shade tree density than cocoa with scattered trees (Fig. 3). Although shade cover did not show significant differences among types of AFS (CWST had substantially lower tree density but still presented shade cover of 71% with a high and wide canopy), the following parameters were higher in CTP and CWL than in CWST ($p < 0.05$): species richness, number of useful species, number of use categories, number of native species, density of trees used for fruit and construction materials, and number of construction materials (Table 2). Cocoa tree density was similar in all three AFS, with approximately 475 cocoa trees ha^{-1}. There were no significant differences in yields among the three types of cocoa agroforests ($p > 0.05$). The confidence intervals for yields were for CTP $(91.19, 218.65)_{0.05}$, for CWL $(97.1, 254.8)_{0.05}$, and for CWST $(50.4, 232.9)_{0.05}$.

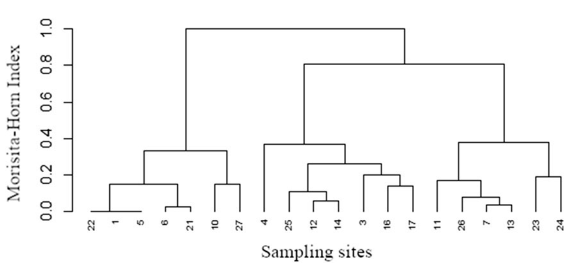

Fig. 2 Results from the multivariate cluster analysis for plots with density > 50 ind ha^{-1}

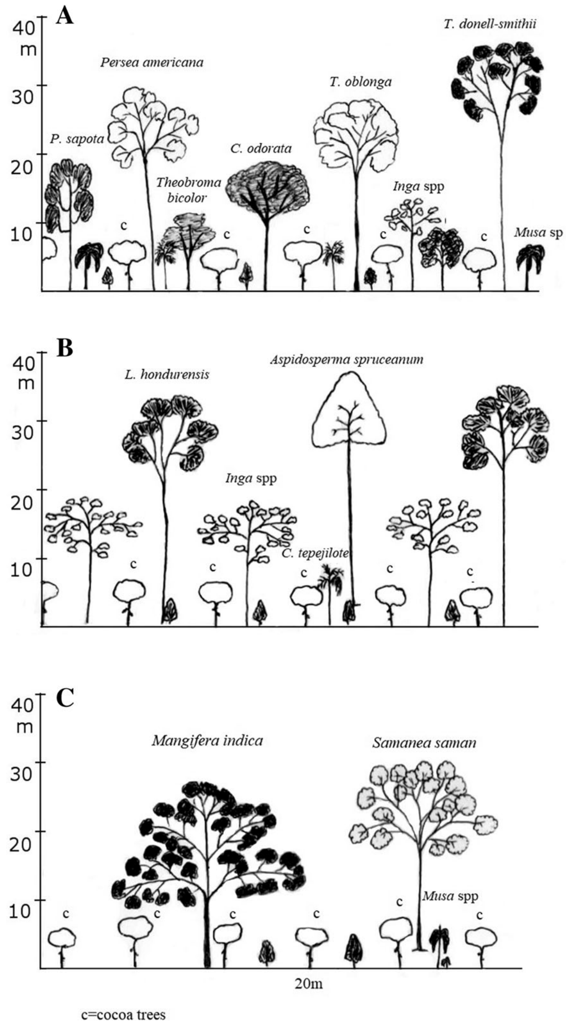

Fig. 3 Three types of cocoa AFS derived from a simplification process in Acacoyagua, Chiapas, Mexico. A) cocoa in traditional polyculture (CTP), B) cocoa with legumes (CWL), and C) cocoa with scattered trees (CWST)

An estimate of 87.6 (± 25) % of healthy cocoa pods was found with a mean of 9.6 (± 20.2) % of pods attacked with frosty pot rot, with high variability within the same types of AFS (Table 2). Other types of damage were caused by squirrels, other animals, rots caused by bacteria and fungi such as the complex of *Phytophtora* spp, and other unidentified fungi.

In the 27 plots inventoried, 50 species were recorded that comprised the shade vegetation. These species belonged to 35 genera and 23 botanical families; 80% were trees, 11.1% shrubs, 4.4% arborescent plants, and 4.4% tall herbaceous plants (*Musa* spp). Most species were native (80%).

Table 2 Structural and compositional characteristics, species usefulness and cocoa yields in three cocoa AFS in Acacoyagua, Chiapas, México

Variables	Cocoa in traditional polyculture	Cocoa with *Inga* and *Lonchocarpus*	Cocoa with scattered trees
Shade structure			
Number of strata	2.92 ± 0.76 a	2.29 ± 0.49 ab	1.86 ± 0.69 bc
Density of shade trees (nha^{-1})	209.62 ± 105.35 a	117.86 ± 57.22 ab	25 ± 20.41 b
Density of coffee plants (nha^{-1})	132.69 ± 147.33 a	192.86 ± 180.69 a	92.86 ± 158.58 a
Density of banana plants (nha^{-1})	13.46 ± 26.25 a	0 ± 0 b	7.14 ± 18.9 ac
Density of ≥ 5 cm DBH palms (nha^{-1})	19.2 ± 27.3 a	17.9 ± 31.3 ab	0 ± 0 c
Shade cover (%)	82.29 ± 18.61 a	76.27 ± 18.42 a	71.5 ± 28.39 a
Shade tree basal area (m^2ha^{-1})	2.22 ± 1.34 a	3.08 ± 1.08 ab	4.83 ± 6.56 c
Height of shade trees (m)	16.16 ± 5.35 a	21.05 ± 8.93 ab	24.25 ± 10.76 b
Botanical Composition			
Richness (number of species in 400 m^2)	7.77 ± 3.17 a	3.00 ± 1.73 ab	1.43 ± 0.79 c
Number of native species (in 400 m^2)	5.54 ± 2.33 a	2.14 ± 1.21 ab	0.57 ± 0.53 c
Number of introduced species (in 400 m^2)	2.08 ± 1.55 a	0.71 ± 0.49 b	0.86 ± 0.69 ab
Number of tree species (in 400 m^2)	5.54 ± 1.76 a	1.86 ± 0.90 b	0.86 ± 0.69 c
Use attributes of shade species			
Number of useful species (in 400 m^2)	7.15 ± 2.67a	3.00 ± 1.73ab	1.29 ± 0.76c
Number use categories (in 400 m2)	4.54 ± 1.45a	2.57 ± 1.27a	1.14 ± 0.69ab
Density of fruit trees (nha^{-1})	71.15 ± 45.47a	14.29 ± 37.80ab	10.71 ± 13.36b
Density of timber trees (nha^{-1})	80.77 ± 70.82a	14.29 ± 19.67b	10.71 ± 19.67bc
Food products (n in 400 m^2)	2.77 ± 1.59a	1.43 ± 0.53b	0.86 ± 0.38c
Timber products (n in 400 m^2)	2.15 ± 1.63a	0.43 ± 0.53b	0.29 ± 0.49bc
Characteristics of the cocoa trees			
Density of cocoa trees (nha^{-1})	475 ± 160.40a	478.57 ± 170.43a	475 ± 199.48a
Basal area of cocoa trees (m^2ha^{-1})	1.06 ± 0.61a	1.29 ± 1.16a	2.86 ± 3.42ab
Height of cocoa trees (m)	6.01 ± 1.37a	5.56 ± 1.20a	6.74 ± 1.32a
Age of cocoa trees	29.00 ± 18.67a	21.70 ± 22.10a	29.64 ± 17.58a
Yield (kg $ha^{-1}year^{-1}$)	151.31 ± 111.88a	197.58 ± 73.78a	137.14 ± 102.19a
Frosty pod rot (%)	6.2 ± 15.6a	4.8 ± 8.3a	17.9 ± 36.6a

Although legumes (Fabaceae) and citrus trees (Rutaceae) were the most abundant components, tree species diversity was high (H' = 3.15), as was evenness (E = 0.87), suggesting that no one shade species was dominant.

Discussion

This study showed that traditional cocoa AFS have undergone structural and functional simplification during recent decades due to the assumption that shade reduces cocoa yields and results in higher levels of humidity and therefore fungal diseases, as demonstrated by farmers' testimonies. However, no differences in yield or incidence of frosty pod rot disease were found among different cocoa AFS.

Mean yields were highly variable. Although three out of 27 plots sampled produced more than 300 kg ha^{-1} and one plot achieved 437.5 kg ha^{-1} of cocoa, the most frequent yields were close to 155 kg ha^{-1}. Plots were characterized by a variable basal area, high shade cover, and old cocoa trees. The plantations were subject to a low level of management from the farmers; unproductive branches (old branches that have already produced fruits) and shade trees were infrequently pruned, and plantations were rarely fertilized. Other management activities included weeding, which usually takes place once or twice a year, the application of ash, and the burial of diseased pods to control disease. Although some farmers reduce the number of shade trees, they did not intensively manage AFS. However, the lack of agricultural practices was probably the most relevant factor in lowering yields and increasing the risk of infestation by fungal disease. Several authors have reported that regular tree pruning, frequent pod harvest, regular removal of infested pods and weed management are crucial agricultural practices to achieve sufficient yields (Armengot et al. 2020), and that more intensive practices produce higher yields and reduce fungal infections, even in polycultures with high tree density and diversity (Vaast and Somarriba 2014; Schroth et al. 2016). If farmers do not implement appropriate management techniques, then the type of shade or AFS will be relatively insignificant; yields will remain low and the opportunity to take advantage of the benefits of polycultures will be lost. Other farmers in the region that apply intensive agricultural practices have obtained yields of up to 300–600 kg ha^{-1} year-^{1} (Luis Villafuerte from DERMAC, Pers. Comm.; SIAP 2014; http://www.siap.gob.mx) in Acacoyagua. Several authors have observed contradictions between the environmental benefits of the shade cocoa system and its simplification, on one hand recognizing that shade increases the incidence of fungal disease and the need to eliminate it, and on the other, the need to maintain the social and environmental benefits of shade vegetation (Somarriba et al. 2013; Vaast and Somarriba 2014; Asare et al. 2019; Riedel et al. 2019). However, in the present study, a reduction in tree density and diversity did not have significant consequences on yield nor influence frosty pod rot incidence, as confirmed by data and local testimonies. However, more studies comparing different AFS are necessary to clarify the relationship between shade, yields, and frosty pod rot occurrence.

It is important to note that the reported incidence of frosty pod rot (average 9%) may be at least 40% lower than the real figure, since only the total and diseased adult pods (> 10 cm) were counted.

In the past, in the study area as well as in other parts of the world, farmers planted cocoa in evergreen rainforests and in diverse traditional AFS. However, due to multiple constraints, they have been gradually simplifying their cocoa agroforests. This trend has affected the structure as well as species and functional diversities of cocoa AFS, specifically density and diversity of shade trees, number of strata, usefulness, and ecosystem and social services derived from this AFS. In other countries (Kazianga and Masters 2006; Vaast and Somarriba 2014; Schroth et al. 2016), according to farmers and scientific studies the reduction of forest cover over in recent years is due to the influence of markets to increase productivity. However, as well as deforestation not necessarily leading to an increase in yields, it also limits the possibility of the provision of goods, cultural services, biodiversity conservation, and ecosystem functions, such as providing habitat, resources, biological corridors, and a smallholders' ability to adapt to global change (Schroth and Harvey 2007; Vaast and Somarriba 2014; Riedel et al. 2019), especially in areas with high biodiversity but also a high level of social-environmental fragility (Franzen and Mulder 2007). Nevertheless, other authors have reported that low tree density and slight shade cover increases yields and reduce frosty pod rot intensity (Ngo Bieng et al. 2013; Gidoin et al. 2014).

Low productivity, high production costs, intermediaries, and dependence on international prices were the main drivers leading farmers to abandon or substitute cocoa crops, favouring livestock, oil palm, and other crops as well as associating cocoa with coffee which is not suited to low altitudes where cocoa thrives (Flores-García et al. 2019; Läderach et al. 2019). These conditions result in a vicious cycle of low productivity, crop abandonment, land-use change, and high incidence of fungal diseases, as has occurred in other cocoa-producing regions and with other types of AFS (Greenberg 2008). Cocoa is retained thanks to the fact that the population manages multiple land uses, cultivates several products at the same time and works outside the community to complement income.

The global cocoa situation is similar to the Mexican condition. According to the International Cocoa Organization (ICCO) annual report, world cocoa production fell 6% during the last decade. Furthermore, cocoa faces other problems such as the predominance of small production units, low productivity, old plantations, price volatility, and the presence of pests and diseases (ICCO 2013 https://issuu.com/icco/docs/icco_cooperation_annual_report_2013). Despite this problem, the prospects for cocoa production are encouraging, given a 2.5% growth in demand.

The importance of cocoa AFS as a diversity reservoir is high due to the total number of native tree species recorded in the plots, close to 20% of the flora previously described (Matuda 1950; López et al. 2010) at altitudes below 800 m. Unfortunately, this diversity may be under threat due to the deforestation process in cocoa plots and a similar process occurring in coffee plots (Jurjonas et al. 2016; Soto-Pinto 2019). In addition, several species recorded are listed in threatened species catalogues - for example, *Cedrela odorata*, *Aspidosperma megalocarpon*, and *Cordia alliodora* (Red List of the International Union for Conservation of Nature, IUCN and NOM-059-SEMARNAT-2010). Compared with lists of plant species published in previous studies, many species that formed part of cocoa plantations are no longer present (Matuda and Miranda cited by Gasco 2018).

Our results also showed the importance of these systems not only for conserving native flora but also for provisioning goods and affording ecological and cultural services that contribute to the way of life of peasant communities in cocoa-producing regions as in other regions (Salazar et al. 2018). Farmers self-supply basic needs using agroecological strategies; through the combination of low densities of cocoa trees and high densities of other components such as palms, bananas, and multipurpose trees; practicing beekeeping, and producing a variety of crops in homegardens and milpas, thus increasing the benefits obtained from their land (Cerda et al. 2014; Salazar et al. 2018; Waha et al. 2018). Other studies in Africa and Latin America have found that it is possible to reconcile productivity and shade, biodiversity conservation, as well as carbon sequestration in cocoa AFS by maintaining a shade cover level of 30 to 60% (Krauss and Soberanis 2001; Díaz-José et al. 2014; Vaast and Somarriba 2014; Schroth et al. 2016; Jezeer et al. 2017; Armengot et al. 2020).

Conversely, reducing agrobiodiversity limits the reproduction of farmers‘ livelihoods and increases their vulnerability by modifying their diet and local knowledge (Benítez et al. 2020). Another agroecological strategy consists of associating commercial crops with cocoa, as documented in Central America and other cocoa-producing regions (Deheuvels et al. 2012; Cerda et al. 2014; Vebrova et al. 2014; Nunoo and Owusu 2017; Salazar et al. 2018). This association in Mexico, as in other areas of the world, is part of a trial and error process by which, in times of crisis, farmers make decisions based on their observations, trade-offs, and thresholds.

Tree species diversity (*H'* = 3.15) was similar to that recorded in cocoa AFS in other municipalities of Chiapas and Tabasco, Mexico (Salgado-Mora et al. 2007; Ramírez-Meneses et al. 2013), southern Bahia, Brazil (*H'* = 2.05; Sambuichi 2002); higher than Central America (*H'* = 1.78; Cerda et al. 2014), the Peruvian Amazon (*H'* = 2.47; Vebrova et al. 2014), and central region of Bahia, Brazil (Guimarães et al. 2017); but lower than Southeast Cameroon (*H'* = 3.73; Sonwa et al. 2014). Those species that provide well-recognized benefits and economic incentives for farmers presented the highest abundance values, consistent with their preferences for self-supply and meeting market demands (Bisseleua et al. 2013; Jacobi et al. 2014; Sonwa et al. 2014; Nunoo and Owusu 2017).

Cocoa agroforests in the studied region are old and require renewal and more intensive management (Díaz-José et al. 2014), as well as financial support, technical assistance, and improved management (Ramírez 2008; Díaz-José et al. 2014). Moreover, farmers do not have adequate tools for pruning, grafting, and cutting branches of shade trees, almost all these cultural practices are carried out with a machete. To increment yields and reduce fungal diseases, some recommendations from the literature and local practices already conducted in the study region indicate the following needs: pruning cocoa and shade trees; renewal of cocoa trees; increasing cocoa density to 500–800 tree ha^{-1}; application of local inputs such as domestic ash; weekly removal of diseased pods (Armengot et al. 2020); removal of young shoots; and the application of authorized agrochemicals such as Bordeaux mixture, copper hydroxide, copper oxychloride (http://www.fao.org/3/Y2772E/y2772e0c.htm), calcium silicate sulphide broth, calcium polysulfide (Ochoa Fonseca et al., 2015), or three monthly sprays with copper hydroxide; and cocoa tree grafting with elite varieties (Peña-López 2019; Torres de la Cruz et al. 2011). Additional improvements to the cocoa system could include the ability to process, ferment and convert cocoa beans into better quality chocolate that could be sold in local, regional, and national markets; this would also help meet the national demand for cocoa derivatives and enter a quality niche market (Rajpaul-Maguire et al. 2020

Results such as those presented in this study could be used as educational tools in cocoa territories, a frequently underutilized resource in extension programs (Rajpaul-Maguire et al. 2020).

Conclusions

The cocoa agroforestry systems within the study area are ecologically complex and are low intensive family managed. Farmers are making changes to the shade vegetation structure of their cocoa AFS, mainly reducing tree density and species composition to increase yields and control frosty pod rot disease. Following this trend, three types of cocoa systems were identified: cocoa in traditional polyculture, cocoa with legumes *Inga* and *Lonchocarpus*, and cocoa with scattered trees. This typology denotes a process of simplifying the AFS structure, which is leading to a loss of social-environmental functions. Polycultures resulted in the highest number of vegetation strata, tree density, timber and fruit density, banana and palm tree density, tree height, and species richness. Our results showed that eliminating shade trees did not increase yields, nor reduce frosty pod rot disease (Monilia). Yields averaged 155.8 kg ha^{-1}, and frosty pot rot incidence was 9.6%. Yields were extremely low, demonstrating that the removal of shade trees is not sufficient to obtain an increase in production. According to these results and those of other authors, if farmers implement more intensive agricultural practices, yields may increase, and frosty pod rot will be reduced, even in polycultures with shade. In fact, in some areas of Soconusco and Pichucalco, in Chiapas, some farmers achieve cocoa yields of 800 kg ha^{-1} in polyculture systems (Hernandez et al. 2015). However, there is a need for research, as well as financial support, technical assistance and training for farmers in order to improve their agricultural practices, encourage fermentation of cocoa beans for further processing, and promote marketing.

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Authors' contributions ALC designed and implemented the research, fieldwork, database, analysis, synthesis and discussion of results. LSP designed and implemented the research, fieldwork, database management, statistical analysis, synthesis and discussion of results, corrected and translated the manuscript. MSM participated in designing the research, discussion and the reviewing process. GH participated in discussion and the reviewing process.

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Availability of data and material The data base is available to editors and reviewers.

Compliance with ethical standards

Conflicts of interest We, the authors do not have any conflict of interest nor competing interests. Our only interest is to generate knowledge concerning agroforestry systems and make it known to the general public, technical and research institutions, as a scientific contribution of for different applications.

Consent to participate All participant farmers and community authorities consented their participation at the beginning of the research work.

Consent for publication Each co-authors of this manuscript consented to co-authorship.

Ethics approval We always obtained permission from all the people who participated in this investigation. The names of the people who offered information and allowed us undertake research in their plots were omitted to avoid any conflict of interest of the participants.

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