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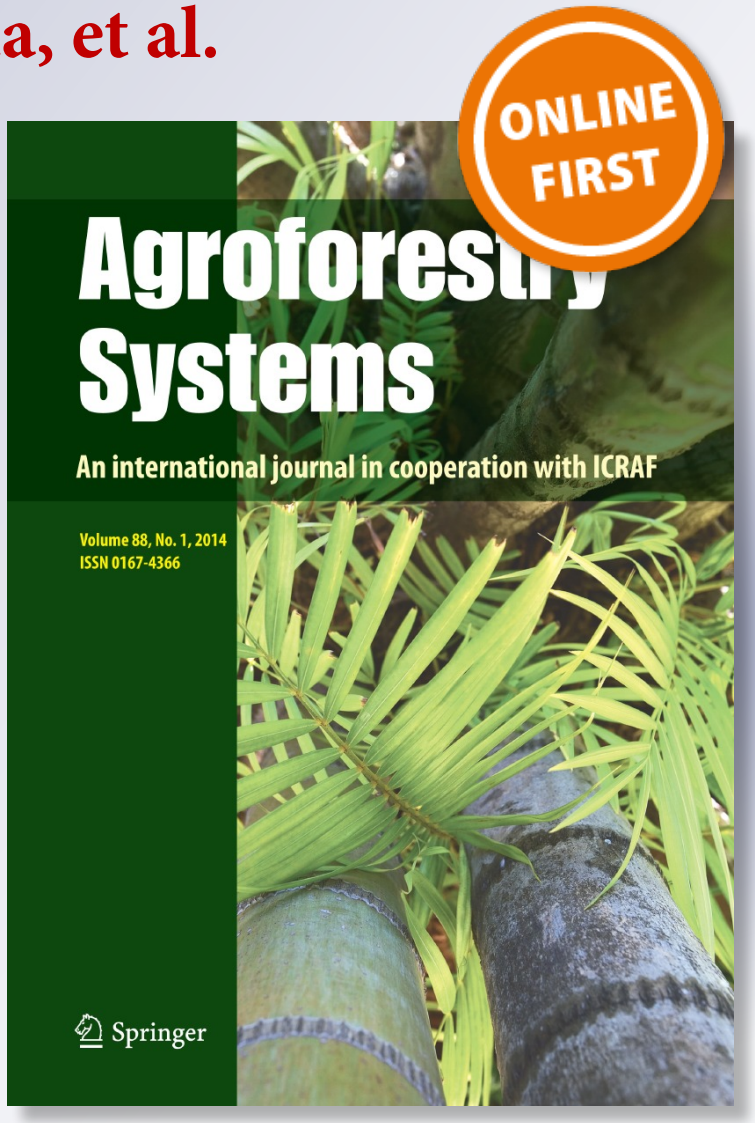

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Abstract While the potential of agroforestry products to contribute to rural livelihoods is well-recognized, the quantification of their yields, incomes, and value for domestic consumption (VDC) and knowledge about their relationships with biodiversity are still scarce. This information is crucial for choosing the best strategy for growing cocoa in tropical landscapes while conserving biodiversity and enhancing ecosystem services. We analyzed the contribution of cocoa agroforestry farming to the incomes and domestic consumption of small farmers' families in 179 cocoa agroforestry systems (CAFS) (254 ha) in five Central American countries. The two hypotheses were: (1) agroforestry products are as important as cocoa in contributing to livelihoods, (2) the typology of CAFS determines the relationships between socioeconomic indicators and yield, biodiversity, and structure of the shade canopy, as well as the relationships between plant species richness and cocoa yield. We quantified the yields of agroforestry products and their contribution to net income, cash flow, and family benefits and developed a typology of CAFS production to evaluate relationships for each CAFS cluster. The main agroforestry products other than cocoa were bananas, oranges, peach palm, other fruits, and timber, which generated modest cash

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incomes but high VDC at low cash costs, thus contributing to family savings and food security. Timber volumes and harvest rates were low but significant increase was deemed feasible. The contribution of the set of agroforestry products to family benefits was similar or higher than cocoa, depending on the typology of the CAFS. Intensified highly diverse-dense CAFS demonstrated remarkably higher yields, net income, cash flow, and family benefits, and had more synergetic relationships than extensive CAFS and traditional highly diverse-dense CAFS, which showed more trade-offs. Our findings point to intensified highly diverse-dense CAFS as feasible for farming within a land-sparing strategy. Further research is needed to better understand the mechanisms that could regulate synergies or trade-offs to improve this type of intensification.

Keywords Biodiversity · Yields · Fruits · Timber · Typology · Trade-offs

Introduction

Cocoa agroforestry systems (CAFS) rank high as a viable diversified land use to improve small farmers' livelihoods and conserve natural resources (Rice and Greenberg 2000; Duguma et al. 2001; Leakey and Tchoundjeu 2001; Schroth et al. 2004; Franzen and Borgerhoff 2007; Smith and Martino 2007). Cocoa agroforestry production contributes to the self-sufficiency of families and their farms through a diversified production of food and cash crops (Degrande et al. 2006; Steffan-Dewenter et al. 2007) and reduced financial and commercialization risk (Ramírez et al. 2001; Leakey et al. 2005).

Most studies on the economics of CAFS focus mainly on cocoa yield, giving less attention to the agroforestry production of fruit, timber, fiber, construction materials, firewood, honey, and many other goods obtained from the shade canopy. Authors have reported in detail the species richness of different taxa (plants, insects, birds, and other animals) in different types of CAFS, indicating their influence (or lack thereof) on cocoa yields. Several authors have contended that biodiversity has little relationship with cocoa yields (Steffan-Dewenter et al. 2007; Clough et al. 2011) while others suggest trade-offs (Bisseleua et al. 2009; Wade et al. 2010; Rousseau et al. 2012; Deheuvels et al. 2014). Studies quantifying yields of cocoa and other products have usually focused on fruits and timber in simple mixed systems, such as cocoa-*Cocus nucifera* and cocoa-*Gliricidia sepium* (Osei-Bonsu et al. 2002), cocoa-rubber (Alvim and Nair 1986; Snoeck et al. 2013), and cocoa-*Nephelium lappaceum* (Sánchez et al. 2002). Timber production from different species in CAFS has also been studied, reporting incomes from timber production (Mussak and Laarman 1989), as well as standing timber volumes, timber harvest ratio, and timber annual increment (Somarriba et al. 2014), growth of timber and incomes (Sánchez et al. 2002), and timber production and gross margin in intensified systems (Gockowski and Sonwa 2011). All these studies report promising results for the production of cocoa, and other goods and services with an adequate management of agroforestry components and their interactions.

Although many goods are obtained from CAFS (Oladokun 1990; Beer et al. 1998; Osei-Bonsu et al. 2002; Laird et al. 2007; Somarriba 2007; Rice 2008; Tscharntke et al. 2011), few studies assess their contribution to household incomes. Simulation models with timber and fruits showed that CAFS performed better than cocoa monocultures in terms of benefit-cost and internal rate of return (Texeira 1999). Data on planting densities, yields and gross incomes (Yamada and Gholz 2002; Gockowski et al. 2010), and gross returns and cash flow (Obiri et al. 2007) were published for different agroforestry products such as cocoa, timber, fruits, and other food crops. The potential contribution of CAFS to the households is often discussed qualitatively more than quantitatively. Most studies on the socioeconomic performance of CAFS do not consider the value of domestic consumption (VDC) provided by agroforestry products, focusing mostly on gross and net margins and incomes from cocoa beans (Obiri et al. 2007; Rice 2008; Herzog and Gotsch 1998). Domestic consumption means savings in household expenses, which is particularly important for small farmers living in remote and poor zones (Leakey et al. 2005). Among the reasons why few researchers take into account the quantification of agroforestry products could be the difficulty of measuring their production, due to farmers usually do not have registers and there can

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be different harvest periods during the year, which makes it hard to estimate the total production of each product, especially when they quantify products in uncommon ways and units.

Since the socioeconomic contribution of agroforestry products has been partially evaluated, information on their trade-offs with biophysical characteristics (species richness, stand densities, and yields) is also scarce. This information is critical for choosing the best strategy for cocoa cultivation, whose design and management will have impacts at the family, farm and landscape levels (Schroth and Harvey 2007; Steffan-Dewenter et al. 2007; Clough et al. 2011). Two management strategies have been proposed to increase production and preserve biodiversity and ecosystem services: (1) system intensification, with high yields in small areas, to reduce pressure on forest land (land sparing), and (2) extensive agriculture, with low yields but in large areas minimizing negative impacts and maintaining biodiversity and ecosystem services (wildlife-friendly farming) (Green et al. 2005).

We quantified and analyzed the socioeconomic contribution of cocoa agroforestry farming to the incomes and domestic consumption of small farmers' families in Central America under two main hypotheses: (1) agroforestry products are as important as cocoa in contributing to family livelihood; (2) the typology of the cocoa agroforestry production system determines: the relationships of socioeconomic indicators with yields, biodiversity, and structure of the shade canopy, as well as the relationships between plant species richness and cocoa yield. We propose different types of cocoa-farming intensification for land sparing and wildlife-friendly farming and advocate for further research on these issues.

Materials and methods

Location and general characteristics of the sampled cocoa agroforestry systems

We studied 179 CAFS (254 ha in total) in the main cocoa-growing areas of five Central American countries: Bocas del Toro (Panama); Talamanca (Costa Rica); Waslala (Nicaragua); Cortés (Honduras); and Alta Verapaz (Guatemala). In these areas CAFS are in hands of either indigenous or mestizo small farmers who base CAFS management on family labor, practically without external inputs (or fertilizers or pesticides). These CAFS were selected to represent as much variability as possible in terms of botanical composition, biophysical conditions, and landscape characteristics of each study area (Deheuvels et al. 2012). Climate, topography, the number of CAFS per growing area, and their size characteristics are shown in Table 1.

Studied variables

Five types of variables were measured in 2010 for each CAFS and family including a series of three on: (1) area (surface of the CAFS); (2) species richness (total and by use) and diversity indexes: Shannon (H), Simpson (D), and Simpson reciprocal index (1/D); and (3) stand density: densities per plant type and trunk basal area of timber trees. Those three types of variables were useful to distinguish the differences in structure and to label the CAFS clusters obtained with the typology analysis (explained below). Two additional variables were particularly useful to construct the typology of CAFS in Central America: (1) production (cocoa, fruits, timber, bananas, and plantains), standing timber volume, and timber harvest rate; which were key data to show the total production and yield by each agroforestry product of the CAFS; and (2) socioeconomic indicators: net income, cash flow, and family benefit. Net income is a traditional indicator used in most studies on the performance of CAFS; cash flow is important to show the balance between the earned and expended cash money, and; family benefit allows demonstrating essential hidden benefits while considering the value of domestic consumption (see the formulas for calculations below).

Plant species richness, diversity, and density

Plants in the entire CAFS area were inventoried. In each CAFS, all plants with diameter at breast height (dbh) >5 cm were identified at the species level, dbh was measured, and classified according to plant type: cocoa, timber, fruit (including palms), firewood, and service trees (only provide shade, improve soils, etc.) and bananas/plantain. The main (primary) and secondary uses of each species were asked to the farmers and classified in: fruits, timber, firewood, service, medicinal and construction materials (round wood and palm leaves); farmers were also asked about the productive stage of fruit trees: young (when the tree is

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Table 1 Main characteristics of cocoa agroforestry systems in selected countries in Central America

Characteristics	Guatemala	Costa Rica	Nicaragua	Honduras	Panama
Precipitation (mm year^{-1})	1,700–2,300	3,000–4,500	2,000–2,700	2,000–2,500	2,800–3,500
Temperature (°C)	29–35	26–30	26–30	30–35	25–30
Relative humidity (%)	75–80	75–99	70–85	80–85	80–90
Altitude (m)	190–500	62–400	153–774	17–556	22–410
Number of CAFS[a]	36	36	35	34	38
Mean CAFS area (ha)	0.5 ± 0.7	1.1 ± 1.0	1.0 ± 0.5	2.4 ± 2.3	2.1 ± 1.8
Total CAFS area (ha)	19.1	39.9	34.5	82.0	79.4

CAFS cocoa agroforestry systems

[a] Number of CAFS sampled for this study

growing and not producing yet), productive (when the tree is adult, vigorous and produce) and old (when the tree is weak and the production has declined considerably). Data on standing marketable timber volume of trees with dbh >30 cm was estimated by "eye" by local experts, chainsaw operators involved in buying standing timber from farmers and selling boards and block wood to local consumers. Finally all stumps of trees harvested in the plantation were located, identified at species level, stem diameter measured, and the year of harvest and amount of marketable timber and cost of harvesting were determined by the farmer. Field data was used in the following calculations: (1) basal area (m^2 ha^{-1}) of timber trees, (2) shade canopy diversity indexes: Shannon (H), Simpson (D) and 1/D, (3) species accumulation curves by country using the QEco-Quantitative ecology software (Di Rienzo et al. 2010); (4) percentage of species dedicated to each use, and (5) annual rate of timber harvest.

Agroforestry production and socioeconomic indicators

Management practices, costs, production and destination (sale or domestic consumption) of cocoa, fruits, timber, bananas, and plantains were estimated for 2010 based on semi-structured interviews with the family. Questions were asked to both man and woman heads of the household. Questions included what management practices were done in the CAFS, how many days to accomplish each practice, what practices were done by family members or by hired labor (hired persons), and inputs applied during the year. Costs were classified in two types: in-kind costs, represented by all the days invested by family labour multiplied by the cost of one day of labour, and cash costs, which were all the costs that required a payment in cash money. In the main cocoa growing areas of Central America, almost all the small cocoa farmers do not use any input (pesticides or fertilizers); therefore, cash costs were mainly the payments to hired labor. The production of each agroforestry product were separated in two types according to the destination: the amounts sold to local intermediaries or to the cooperatives of farmers, and the amounts for domestic consumption, which were the products consumed by the family and/or domestic animals, and the products used for in-farm constructions. The units used for analyzing fruits production were kilograms whenever possible, when farmers reported productions in pounds the data were transformed to kg (1 pound = 0.453 kg), when not possible to estimate weight the production of several fruits were analyzed as units of fruits. For timber the most common production unit is called "board foot" (*pie tablar* in Spanish) in Central America, but this unit does not represent the same volume among countries, and therefore productions were transformed into cubic meters (m^{-3}) with the particular equivalence of each country.

The prices used to calculate the value of agroforestry products were influenced by international and national (local) markets. The cocoa price paid by the cooperatives to their farmers is influenced by international prices. In Central America this price was (according to the norms of each cooperative and characteristics of the countries) between US$ 2.21–3.00 per dry cocoa kg. The prices used for other agroforestry products were the local prices, given by the amounts that families received from the intermediary buyers in their communities. The prices for the

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most relevant agroforestry products were between: US$ 0.10–0.29 per banana kg, US$ 0.25–0.45 per peach palm kg, US$ 0.20–0.50 per orange and other citrus kg, US$ 0.10–0.60 per unit of other fruits, and US$ 101–148 per laurel timber m^3. Laurel (*Cordia alliodora*) is the most common timber tree harvested from CAFS.

Finally, gross income (GI), net income (NI), cash flow (CF), family benefit (FB), value of domestic consumption (VDC) and Family Benefit per Labor-Day ratio (FBLD) coming from the CAFS to the household were calculated as followed:

- $GI = AS \times MP$
- $NI = GI - (CC + KC)$
- $CF = GI - CC$
- $VDC = ADC \times MP$
- $FB = CF + VDC$
- $FBLD = FB/LD$

where: GI = gross income from sale of agroforestry products; AS = amount of agroforestry products for sales; MP = market price; NI = net income; CC = cash costs; KC = in-kind costs; CF = cash flow; FB = family benefit; VDC = value of domestic consumption; ADC = amount of agroforestry products for domestic consumption; FBLD = family benefit per labor-day; LD = number of days worked (by family members) in the CAFS. Results were expressed in United States of America dollars as US$.

Data analysis

Analysis of variance among growing areas (countries)

To evaluate differences of the studied variables among countries, analysis of variance using a completely random design were performed ($\alpha = 0.05$). Fisher's least significant difference (LSD) test was used for comparison of means.

Overview of the relationships

To explore the relationships of each growing area with all the five types of variables, a nonmetric multidimensional scaling (NMS) was performed (Clarke 1993). Before generating ordination, the variables were standardized (to the normal standard) to avoid the effect of outliers.

Typology and analysis of variance

A multivariate conglomerate analysis was performed using the Ward grouping algorithm and the standardized Euclidean distance with the socioeconomic indicators (NI, CF, and FB) to obtain the typology of CAFS. The dendrogram was obtained with the correlation matrix. The significance of the clusters was tested with multivariate analysis of variance. A contingency table analysis was also performed to evaluate the relationships between formed clusters and growing areas (Di Rienzo et al. 2013).

To evaluate differences of the studied variables among clusters, analyses of variance using general linear mixed models declaring growing areas as a random effect were performed (Pinheiro and Bates 2000). In case of finding statistical differences ($\alpha = 0.05$), Fisher's least significant difference (LSD) test was used for comparison of means. Graphics of residuals and predicted values were assessed; whenever variables did not meet the homogeneous variance assumption, models with heterogeneous variances were run, declaring a function of independent variances for each cluster.

Relationships

A covariance analysis was adjusted under the generalized linear mixed models (Bates et al. 2011) in order to evaluate the effect of the clusters (typology), the studied variables, and their interactions on socioeconomic indicators (response variables). Growing areas were declared as a random effect and model assumptions (normality and homogeneous variances) were evaluated. Since the variances assumption was not met, a heterogeneous variance function was adjusted for each cluster. Curves were fitted for each cluster and the coefficient of determination (R^2) for the entire model was reported. To assess the effect of the clusters (typology), cocoa yields, and their interactions on plant species richness, a covariance analysis was adjusted under the generalized linear mixed models, using a Poisson distribution as the family of the model, and a pseudo-coefficient of determination (R^2) was obtained for the entire model. All analyses were run using the statistical package Infostat (Di Rienzo et al. 2013).

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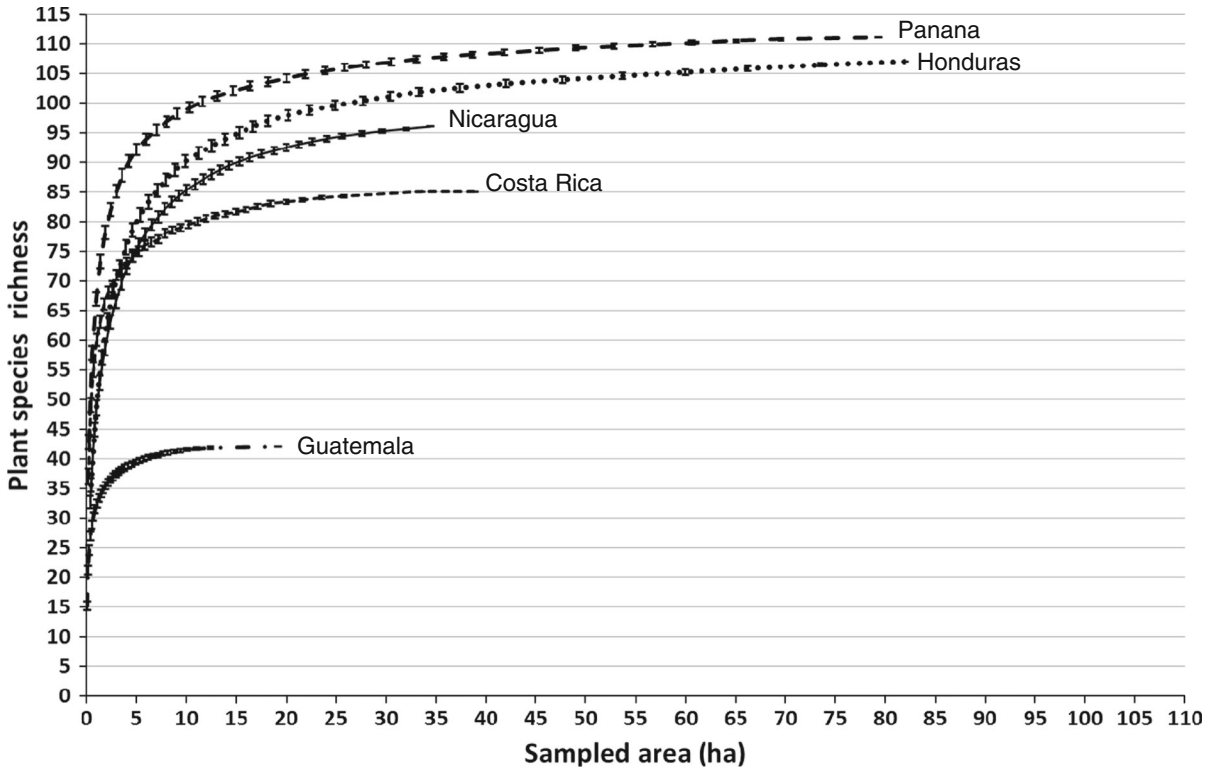

Fig. 1 Rarefaction curves for plant species richness in the shade canopy of cocoa agroforestry systems in Central America

Table 2 Plant diversity indexes for shade canopies in cocoa agroforestry systems in Central America

Country	Species richness at 20 ha[a]	Shannon–Weaver (H)		Simpson (D)		D reciprocal index (1/D)	
		Mean ± SD	Min–Max	Mean ± SD	Min–Max	Mean ± SD	Min–Max
Guatemala	42	0.8 ± 0.5	0.0–1.9	0.7 ± 0.2	0.2–1.0	1.8 ± 1.0	1.0–5.0
Costa Rica	83	2.2 ± 0.5	1.1–3.1	0.2 ± 0.1	0.1–0.6	6.9 ± 3.3	1.8–15.5
Nicaragua	92	2.2 ± 0.4	1.4–3.2	0.2 ± 0.1	0.1–0.4	6.7 ± 2.7	2.7–6.5
Honduras	97	1.8 ± 0.6	0.5–2.8	0.3 ± 0.2	0.1–0.8	4.7 ± 2.5	1.3–11.1
Panama	104	1.9 ± 0.5	0.7–3.0	0.3 ± 0.2	0.1–0.7	4.3 ± 2.7	1.4–13.0

SD standard deviation

[a] Number of plant species (see also Fig. 1)

Results

Botanical composition

A total of 253 plant species were identified in Central American CAFS, with notorious differences among the countries in shade-canopy plant species richness (Fig. 1). The simplest, cocoa shade canopy with the least number of species, was found in Alta Verapaz, Guatemala (43 species), and the richest in both Panama (110 species) and Honduras (105). The diversity indexes separated Guatemala from the rest of countries, which did have similar diversity values (Table 2). The percentage of species according to the main use was variable among growing areas, but taking into account the Central American mean: fruit consumption, timber and firewood production, and finally shading were the most common uses (Fig. 2).

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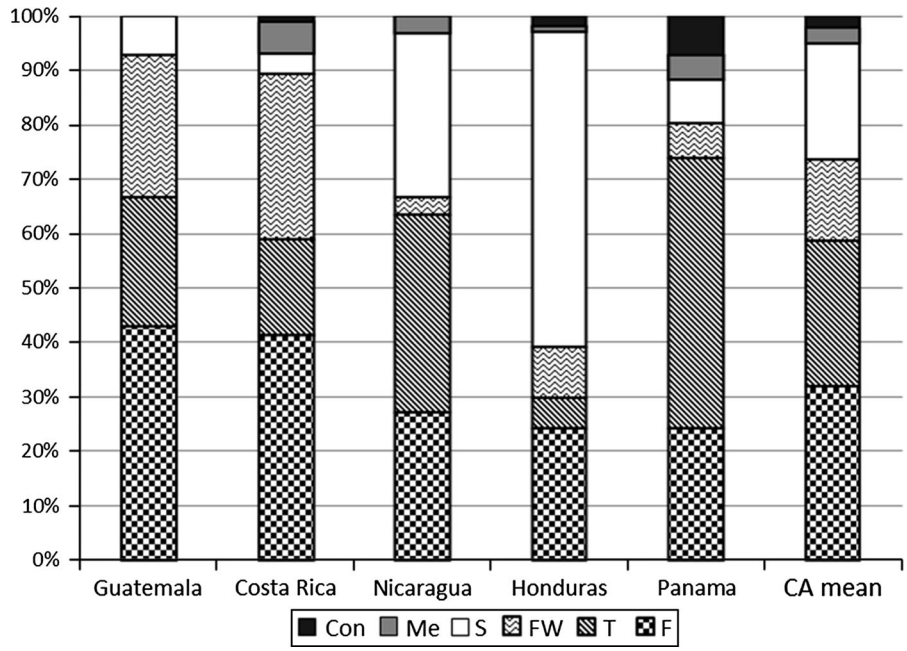

Fig. 2 Percentage of plant species according to their main use in cocoa agroforestry systems in Central America. *F* fruits, *T* timber, *FW* firewood, *S* only shade service, *Me* medicinal, *Con* construction materials, *CA* Central America

Details on the list of plant species, main and secondary uses, and presence in each growing area, are provided in Table 3.

The most abundant woody species in Central American CAFS were *C. alliodora* (29.8 % of relative abundance of total individuals), *G. sepium* (15.2 %), *Bactris gasipaes* (7.7 %), *Inga* spp. (5.5 %), *Cedrela odorata* (2.7 %), *Citrus sinensis* (2.3 %), *Persea americana* (1.9 %), *Mangifera indica* (1.3 %), *Guazuma ulmifolia* (1.2 %), *Swietenia macrophylla* (1.1 %), and *Pterocarpus officinalis* (1.0 %).

Yield of agroforestry products

The most important yields originated from fruits harvested every year (in particular: cocoa, banana, citrus, and peach palm), while timber showed volumes of potential importance (Table 4), and others such as medicinal and construction materials were of low relevance due to their very low yields. Fruit products such as bananas, peach palm (*B. gasipaes*), and citrus (especially oranges—*C. sinensis*) represented noticeable yields destined for both sales and domestic consumption. There were other fruits well-known by the farmers, such as plantains, *P. americana*, *M. indica*, *C. nucifera*, *Eugenia stipitata*, *Mammea americana*, *Rollinia mucosa*, *Sizygium malaccensis*, various species of *Pouteria*, and other less common and more infrequent traditional fruit species destined mainly for domestic consumption (Table 3). Timber was a dominant feature in both Panama and Costa Rica. The most common trees harvested for timber were *C. alliodora*, *C. odorata*, *S. macrophylla*, *Tabebuia rosea*, *Terminalia lucida*, and *Hyeronima alchorneoides*. All CAFS had variable amounts of standing timber (trees with dbh >30 cm); high volumes of standing timber are found in Panama and Costa Rica. The harvested quantities of medicinal products were very low and besides impossible to quantify accurately. Generally, farmers just reported that sometimes they use "some branches" or "a handful of leaves" from CAFS to prepare a medicine. Construction materials were harvested only in few CAFS and not every year, only when farmers needed to make minor repairs of houses or other constructions, and the reported quantities were low; for instance, for a minor repair farmers usually use 3–5 trunks or 5–10 palm leaves for their roofs, and furthermore those materials did not originate solely from CAFS.

Socioeconomic indicators

Central American cocoa-farming operations differed in terms of NI, CF, and FB. On average, only 35 % of Central American CAFS showed a positive NI. For instance, in Nicaragua 60 % of the cocoa farms had positive NI, followed by Guatemala (56 %), Honduras

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Table 3 Plant species and their uses identified in at least 3 % of the cocoa agroforestry systems in five cocoa growing areas of Central America

Scientific name	Relative frequency	Relative abundance	Main use	Secondary use	Countries				
					PA	CR	NI	HO	GU
Cordia alliodora (Ruiz & Pav.) Oken	77.3	29.9	T		X	X	X	X	X
Persea americana Mill	66.3	1.9	F	FW	X	X	X	X	X
Citrus sinensis Osbeck	62.4	2.3	F		X	X	X	X	X
Inga sp. Mill.	55.8	5.5	F	FW	X	X	X	X	X
Cedrela odorata L.	50.8	2.7	T		X	X	X	X	X
Mangifera indica L.	40.3	1.3	F		X	X	X	X	X
Spondias mombin L.	38.7	1.0	F	T	X	X	X	X	
Bactris gasipaes Kunth	32.6	7.7	F		X	X	X		
Pterocarpus officinalis Jacq.	27.6	1.0	S		X	X	X		
Cecropia sp. Loefl.	26.0	0.7	S		X	X	X	X	X
Pouteria sapota (Jacq.) H.E. Moore & Stearn	24.9	0.4	F		X	X	X	X	X
Guazuma ulmifolia Lam.	23.8	1.2	S		X		X	X	
Erythrina sp. L.	23.2	0.8	S		X	X	X	X	
Cocos nucifera L.	22.1	0.6	F		X	X	X	X	X
Psidium guajava L.	21.0	0.3	F	FW	X	X	X	X	X
Citrus sp. L.	19.3	0.4	F		X	X	X	X	X
Iriartea deltoidea Ruiz & Pav.	19.3	0.4	FW		X	X			
Lonchocarpus minimiflorus Donn. Sm	17.1	0.5	S				X	X	
Carapa guianensis Aubl.	16.0	0.5	T		X				
Thouinidium decandrum (Bonpl.) Radlk	15.5	0.9	FW		X	X	X		
Syzygium malaccense (L.) Merr. & L.M. Perry	15.5	0.4	F		X	X			
Annona muricata L.	15.5	0.3	F		X	X	X	X	X
Bursera simaruba (L.) Sarg.	15.5	0.2	Me		X	X	X	X	
Cordia collococca L.	15.5	0.2	S		X		X		
Rollinia mucosa (Jacq.) Baill.	13.8	0.4	F		X	X			
Swietenia macrophylla King	13.3	1.1	T		X		X	X	X
Nephelium lappaceum L.	13.3	0.8	F		X	X	X	X	
Terminalia lucida Hoffmanns. ex Mart.	13.3	0.3	T		X		X		
Minquartia guianensis Aubl.	12.7	0.3	T		X				
Gliricidia sepium (Jacq.) Kunth ex Walp.	11.6	15.2	FW	T		X	X	X	X
Inga sp. Mill.	11.6	0.4	FW			X			
Chamaedorea elegans Mart.	11.0	2.5	F					X	
Pouteria campechiana (Kunth) Baehni	11.0	0.3	F			X		X	
Inga sp. Mill.	10.5	0.9	FW					X	X
Coffea arabica L.	10.5	0.8	F			X		X	X
Ochroma pyramidale (Cav. ex Lam.) Urb.	10.5	0.2	Me	T	X	X	X		
Artocarpus altilis (Parkinson) Fosberg	10.5	0.2	F		X	X	X		
Genipa americana L.	9.9	0.1	T		X				
Acacia sp. Mill.	9.4	0.5	S				X		
Tabebuia rosea (Bertol.) A. DC.	9.4	0.5	S		X	X	X	X	
Pimenta dioica (L.) Merr.	9.4	0.4	S				X	X	X
Vochysia guatemalensis Donn. Sm.	9.4	0.3	S	FW	X		X	X	X
Byrsonima crassifolia (L.) Kunth	9.4	0.3	F		X		X	X	X

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Table 3 continued

Scientific name	Relative frequency	Relative abundance	Main use	Secondary use	Countries				
					PA	CR	NI	HO	GU
Dialium guianense (Aubl.) Sandwith	9.4	0.2	T				X	X	
Orbignya cohune (Mart.) Dahlgren ex Standl.	8.8	0.4	S					X	X
Citrus sp. L.	8.8	0.2	F		X			X	X
Ficus citrifolia Mill.	8.8	0.2	T		X				
Vitex cooperi Standl.	8.8	0.1	T		X	X			
Bombacopsis quinata (Jacq.) Dugand	8.3	0.5	Con	T	X	X	X	X	
Hyeronima alchorneoides Allemão	8.3	0.2	T	FW	X	X	X		
Sterculia apetala (Jacq.) H. Karst.	8.3	0.2	F		X	X			X
Lonchocarpus spp. Kunth	8.3	0.1	T		X				
Heliocarpus americanus L.	8.3	0.1	S				X		
Cinnamomum costaricanum (Mez & Pittier) Kosterm.	7.7	0.1	F				X		
Castilla elastica Sessé	7.2	0.3	S		X	X	X	X	
Welfia georgii H. Wendl.	7.2	0.3	Con		X				
Dipteryx panamensis (Pittier) Record & Mell	7.2	0.2	T		X	X	X		
Miconia sp. Ruiz & Pav.	7.2	0.2	FW		X				
Cassia grandis L. f.	7.2	0.2	S		X		X	X	
Eugenia stipitata McVaugh	7.2	0.1	F		X	X			
Acosmium panamense (Benth.) Yakovlev	7.2	0.1	T				X		
Enterolobium cyclocarpum (Jacq.) Griseb.	7.2	0.1	S		X		X	X	
Taxus sp. L.	6.6	0.2	S					X	
Hevea brasiliensis (Willd. ex A. Juss.) Müll. Arg.	6.1	0.2	S		X				
Zygia longifolia (Humb. & Bonpl. ex Willd.) Britton & Rose	5.5	0.2	S		X				
Crescentia alata Kunth	5.0	0.2	F		X	X	X		X
Platymiscium dimorphandrum Donn. Sm.	4.4	0.1	T					X	
Bixa orellana L.	3.9	0.1	F	Me	X		X	X	
Tectona grandis L. f.	3.3	0.2	T		X		X	X	
Ocotea austinii C.K. Allen	3.3	0.1	F			X	X	X	

Relative frequency percentage of cocoa agroforestry systems ($N = 179$) where the species ($N = 253$) was identified

Relative abundance percentage of individuals of the species respect to the total abundance of plants ($N = 30{,}517$ in 254 ha in total)

Countries countries where the species was identified in cocoa agroforestry systems

PA Bocas del Toro (Panama), *CR* Talamanca (Costa Rica), *NI* Waslala (Nicaragua), *HO* Cortés (Honduras), and *GU* Alta Verapaz (Guatemala), *F* fruits, *T* timber, *FW* firewood, *S* only shade service, *Me* medicinal, *Con* construction materials

(26 %), Panama (18 %), and Costa Rica (17 %). Negative NI were caused by high in-kind costs, mainly represented by the cost value of family labor. Cash costs were very low. On the contrary, CF and FB were positive in all CAFS. Nicaragua showed an FB at least three times higher (>US$ 3,700 ha^{-1} year^{-1}) than any other country (Table 4).

Overview of the relationships among growing areas and the studied variables

Nicaraguan CAFS were mostly associated with high cocoa and fruit yields and with high values of socioeconomic indicators. Panamanian CAFS were the most associated with high species richness, high

Table 4 Yields and stand densities of the main agroforestry products and socioeconomic indicators in cocoa agroforestry systems in Central America

Agroforestry product	Variable	Costa Rica Mean ± SD	Guatemala Mean ± SD	Honduras Mean ± SD	Nicaragua Mean ± SD	Panama Mean ± SD	*F*	*P*	C.A Mean ± SD
Cocoa	%FHP	100	100	100	100	100			100
	Dry kg ha^{-1} $year^{-1}$	146 ± 97a	296 ± 149b	119 ± 85a	494 ± 302c	163 ± 118a	30.06	<0.0001	243 ± 217
	Individuals ha^{-1}	592 ± 218a	605 ± 126a	569 ± 221a	654 ± 135a	581 ± 211a	1.07	0.3720	600 ± 187
Banana	%FHP	58	11	62	94	100			65
	kg ha^{-1} $year^{-1}$	427 ± 512a	13 ± 49a	88 ± 152a	2728 ± 2643b	6884 ± 6835c	28.15	<0.0001	2100 ± 4276
	Individuals ha^{-1}	171 ± 201a	7 ± 14b	16 ± 31b	159 ± 140a	134 ± 114a	15.09	<0.0001	98 ± 140
Orange	%FHP	42	42	0	63	26			35
	kg ha^{-1} $year^{-1}$	318 ± 553a	62 ± 175bc	0 ± 0c	138 ± 183 b	10 ± 22c	8.28	<0.0001	105 ± 294
	Individuals ha^{-1}	11 ± 14ab	17 ± 22a	0 ± 0c	6 ± 12bc	1 ± 3c	10.41	<0.0001	7 ± 14
Peach palm	%FHP	72	0	0	71	92			48
	kg ha^{-1} $year^{-1}$	377 ± 503a	0 ± 0b	0 ± 0b	412 ± 847aa	711 ± 742c	10.79	<0.0001	305 ± 613
	Individuals ha^{-1}	24 ± 24a	0 ± 0c	0 ± 0c	11 ± 16b	20 ± 16a	19.24	<0.0001	11 ± 18
Other Fruits	%FHP	39	22	21	97	58			48
	units ha^{-1} $year^{-1}$	403 ± 964a	571 ± 1977a	116 ± 335a	9265 ± 8338b	278 ± 1124a	37.79	<0.0001	2089 ± 5208
	Individuals ha^{-1}	36 ± 30a	29 ± 41a	33 ± 51a	13 ± 11b	14 ± 17b	3.96	0.0042	25 ± 34
Timber	%FHP	39	14	24	14	87			36
	THR (m^3 ha^{-1} $year^{-1}$)	0.3 ± 0.7a	0.5 ± 1.6a	0.7 ± 2.0a	0.1 ± 0.4a	0.5 ± 0.5a	1.13	0.3457	0.4 ± 1.2
	STV30 (m^3 ha^{-1})	16.3 ± 11.0a	2.2 ± 6.6c	5.1 ± 7.9c	5.6 ± 4.1c	25.4 ± 16.0b	34.17	<0.0001	11.2 ± 13.3
	Individuals ha^{-1}	67 ± 45a	14 ± 23d	23 ± 29cd	44 ± 35c	121 ± 81b	20.38	<0.0001	55 ± 61
Socioeconomic indicators	NI (US$ ha^{-1} $year^{-1}$)	−934 ± 867a	−259 ± 1214b	−568 ± 838ab	423 ± 974c	−350 ± 602b	10.40	<0.0001	−339 ± 1011
	CF (US$ ha^{-1} $year^{-1}$)	337 ± 250a	1043 ± 761b	266 ± 200a	1027 ± 832b	270 ± 365a	19.88	<0.0001	586 ± 654
	FB (US$ ha^{-1} $year^{-1}$)	520 ± 247a	1349 ± 1106b	352 ± 263a	3703 ± 2498c	1162 ± 1392b	33.26	<0.0001	1413 ± 1812

Different letters within a row indicate significant differences among countries (LSD Fisher, $p < 0.05$)

SD standard deviation, *C.A.* Central America, *%FHP* percentage of farms harvesting the product in 2010, *THR* timber harvest rate, *STV30* standing timber volume of timber trees with dbh >30 cm, *Other fruits* the sum of fruit units of *Persea americana*, *Mangifera indica*, *Cocus nucifera*, *Eugenia stipitata*, *Mammea Americana*, *Rollinia mucosa*, *Sizygium malacensis*, and *Pouteria sapota*; Socioeconomic indicators here (*NI* net income, *CF* cash flow, *FB* family benefit) are the total sum of contributions of cocoa, bananas, all the fruits, and timber

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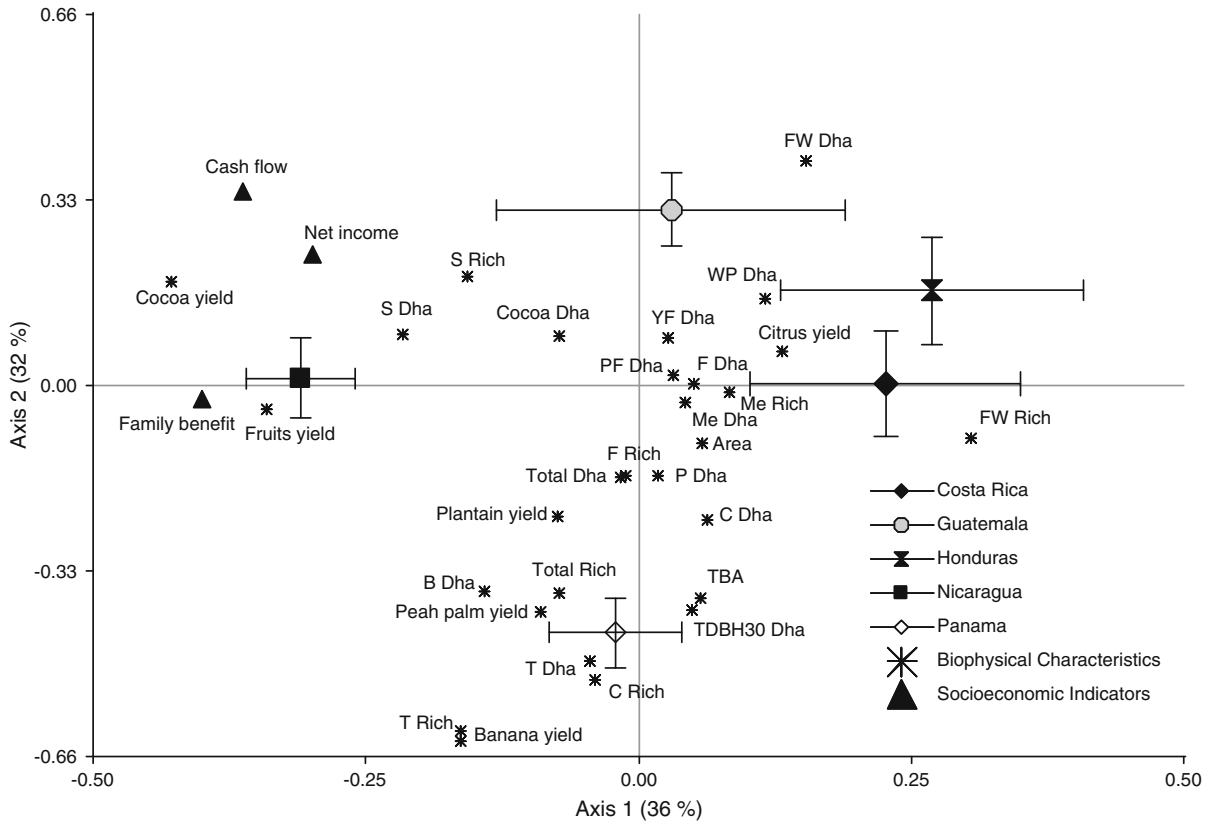

Fig. 3 Exploratory relationships among biophysical characteristics and socioeconomic indicators of cocoa agroforestry systems in Central America. Socioeconomic indicators here (net Income, cash flow, and family benefit) are the sum of contributions of cocoa, bananas, fruits, and timber. *Dha* density of individuals per hectare, *Rich* species richness, *F* fruit species, *YF* young fruit species, *PF* productive fruit species, *Me* medicinal species, *FW* firewood species, *C* species for construction materials, *B* banana, *P* plantain, *T* timber species, *TBA* timber trees basal area, *TDBH*30 timber trees with diameter at breast height >30 cm, *S* species which only provide shade and no products, *WP* woody perennial species (not including cocoa), Total *Dha* total shade canopy density (woody and no woody plants; not including cocoa), *Total Rich* total species richness in the shade canopy (not including cocoa)

timber-tree densities, total high densities and basal areas of timber trees, high banana densities, and high banana and peach palm yields. Costa Rican CAFS were especially associated with high fruit-tree densities, high medicinal-species richness, and total high densities. Guatemalan CAFS were clearly associated with high densities of firewood trees, particularly *G. Sepium*, the dominant shade-canopy species. Honduran CAFS were correlated with high densities of all the woody perennial trees. The first two axes of the NMS explained 68 % of the total variation in the sample (Fig. 3).

Typology of cocoa agroforestry systems

A typology of three well-differentiated CAFS clusters was obtained. The Cluster 1 (C1) was composed mostly by CAFS from Panama and Honduras, Cluster 2 (C2) mostly by CAFS from Costa Rica, and Cluster 3 (C3) mostly by CAFS from Nicaragua and Guatemala; the way that the CAFS were distributed in the clusters and the contingency analysis showed that this typology was not independent of the cocoa-growing areas (χ^2 $p < 0.0001$) (Table 5). Based on the comparison of their size, densities in the shade canopy, and yields of agroforestry products, under the context of cocoa growing characteristics in Central America (Table 6), they were labeled as follows:

- (C1): large-size, moderate woody species density and low-yield CAFS
- (C2): small-size, high woody species density, and low-yield CAFS

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Table 5 Number of cocoa agroforestry systems per cluster and per cocoa-growing area in Central America

Country	C1: large size, moderate woody species density and low yields	C2: small size, high woody species density and low yields	C3: moderate size, high woody species density and high yields	Total
Nicaragua	7	0	28	35
Guatemala	10	8	18	36
Panama	28	5	5	38
Costa Rica	17	16	3	36
Honduras	27	6	1	34
Total	89	35	55	179
% of the total	50	19	31	100

Contingency analysis: (χ^2 $p < 0.0001$)

- (C3): moderate-size, high woody species density, and high-yield CAFS

The C3 CAFS showed the best socioeconomic indicators. It would have been expected that the total value of socioeconomic indicators provided by the total area of the CAFS were higher for C1 CAFS due to the fact that its area was at least double than the ones of other clusters, but despite this, C3 CAFS presented higher values (Table 7). This is a strong indication that the benefits derived from larger areas with low yields are not equivalent to those from high yields in smaller areas. The differences among clusters were much more evident when the values of socioeconomic indicators were presented per hectare, showing that C3 CAFS were undoubtedly the most efficient and C2 CAFS the least efficient; for instance, FBLD of C3 CAFS was three to six times higher than the other clusters (Table 8).

Contribution of agroforestry products to socioeconomic indicators

The main agroforestry products contributing to socioeconomic indicators were cocoa, bananas, fruits, and timber. The NI of all agroforestry products was negative for C1 and C2; while in C3, cocoa, fruits, and timber showed positive NI values, indicating that only these CAFS were successful in terms of profitability. As for CF, it was demonstrated that cocoa is undoubtedly the main cash crop with higher values than any other agroforestry products in all three clusters, especially in C3. Only timber showed slightly negative CF in C1 and C2, contrasting with the results in C3 where the CF from timber was comparable with CF from bananas and fruits. In terms of FB, cocoa was no longer found to be the most important agroforestry product. For C1 and C2, cocoa and bananas were the most important for FB, while in C3 fruits also had the same importance (Table 9). By comparing the contributions of cocoa against the set of other agroforestry products (banana + fruits + timber altogether), it can be shown that the same tendency was registered for NI (Fig. 4A) and for CF (Fig. 4B), where cocoa was still most important with higher values, but for FB in two clusters (C1 and C3), the set of agroforestry products had higher values than cocoa (Fig. 4C).

Relationships between socioeconomic indicators and all studied variables

Socioeconomic indicators had significant relationships only with cocoa yields, fruit yields, fruit tree density, plant species richness, and area. The relationships of NI with area and with cocoa yield were evidently positive in C3 CAFS and almost neutral in the other clusters. On the other hand, the relationship between NI with fruit trees density where negative for C1 and C3 and slightly positive in C2. Cocoa is undoubtedly the most important cash crop as cocoa yield was the only variable positively related to CF in the three clusters. The relationships of FB with fruit yields and with plant species richness were significantly positive in C3 CAFS and almost neutral in the other clusters. The relationships between total plant-species richness and cocoa yields were clearly negative for C1 and C2 and slightly positive for C3. Therefore, several of the relationships

Table 6 Size, species richness, stand density, and yield characteristics in a three-cluster typology of cocoa agroforestry systems in Central America

Variable	C1: large size, moderate woody species density and low yields mean ± standard error	C2: small size, high woody species density and low yields mean ± standard error	C3: moderate size, high woody species density and high yields mean ± standard error	*F*	*P*
Area (ha)	1.9 ± 0.2a	0.6 ± 0.2b	0.9 ±0.2c	21.43	<0.0001
Total species richness	19.2 ± 2.9a	15.2 ± 3.1b	19.8 ± 3.1a	3.86	0.0228
Fruit species richness	6.2 ± 1.1a	5.8 ± 1.2a	6.4 ± 1.2a	0.35	0.7035
Timber species richness	5.4 ± 2.2a	5.3 ± 2.2a	4.9 ± 2.2a	1.79	0.1702
No of harvested species	3.2 ± 0.8a	3.0 ± 0.8a	4.2 ± 0.8b	4.45	0.0131
Shannon index (H)	1.8 ± 0.3a	1.7 ± 0.3a	1.8 ± 0.3a	0.54	0.5809
Simpson reciprocal index (1/D)	5.0 ± 1.0a	4.8 ± 1.0a	4.7 ± 1.0a	0.15	0.8593
Cocoa tree density*	603.0 ± 19.9a	576.0 ± 31.8a	610.8 ± 25.4a	0.39	0.6786
Firewood tree density*	57.5 ± 31.3a	106.0 ± 37.3b	82.3 ± 33.9ab	4.03	0.0195
Fruit tree density*	30.3 ± 7.4a	55.3 ± 10.4b	47.2 ± 8.2b	6.62	0.0017
Timber tree density*	46.1 ± 19.2a	55.8 ± 19.8ab	61.6 ± 19.7b	3.51	0.0319
Banana plant density*	61.7 ± 25.2a	65.5 ± 27.7a	111.2 ± 29.0b	3.55	0.0309
Woody perennial density*	163.4 ± 41.4a	219.0 ± 43.5b	203.4 ± 44.1ab	4.27	0.0155
Total density**	250.6 ± 44.2a	300.7 ± 50.3b	339.1 ± 50.1b	3.79	0.0245
TDBH30 density	15.8 ± 6.9a	23.4 ± 7.4b	21.6 ± 6.9b	3.39	0.0359
TBA30 (m^2 ha^{-1})	4.3 ± 1.7a	5.7 ± 1.8b	4.9 ± 1.7ab	3.29	0.0397
STV30 (m^3 ha^{-1})	7.8 ± 4.9a	13.7 ± 5.3b	14.1 ± 5.0b	6.82	0.0014
THR (m^3 ha^{-1} $year^{-1}$)	0.2 ± 0.1a	0.3 ± 0.1ab	0.6 ± 0.2b	3.36	0.0370
Cocoa yield (dry kg ha^{-1} $year^{-1}$)	137.9 ± 18.5a	156.0 ± 21.2a	457.7 ± 33.4b	48.05	<0.0001
Banana yield (kg ha^{-1} $year^{-1}$)	822.3 ± 639.0a	1275.9 ± 698.3a	2618.4 ± 732.0b	10.09	0.0001
Orange (kg ha^{-1} $year^{-1}$)	61.9 ± 31.3a	207.3 ± 88.0a	110.8 ± 45.0a	1.96	0.1492
Peach palm (kg ha^{-1} $year^{-1}$)	234.6 ± 141.4a	349.5 ± 159.2a	367.8 ± 171.5a	1.04	0.3554
Other fruits yield (units ha^{-1} $year^{-1}$)	1023.0 ± 925.0a	1117.9 ± 930.6a	2169.8 ± 1014.0b	3.24	0.0417

Different letters within a row indicate significant differences among clusters typology (LSD Fisher, $p < 0.05$)

*TDBH*30 *density* number of timber trees with dbh >30 cm per hectare, *TBA*30 basal area of timber trees with dbh >30 cm

STV30 standing timber volume of timber trees with dbh >30 cm, *THR* timber harvest rate

Other fruits the sum of fruit units of *Persea americana*, *Mangifera indica*, *Cocus nucifera*, *Eugenia stipitata*, *Mammea Americana*, *Rollinia mucosa*, *Sizygium malacensis*, and *Pouteria sapota*

[a] Density is given in individuals per hectare

[b] Total density is total density of woody and no woody associated plants, not including cocoa

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Table 7 Values of socioeconomic indicators provided by the total area of the system in a three-cluster typology of cocoa agroforestry systems in Central America

Socioeconomic indicators[a]	C1: large size, moderate woody species density and low yields mean ± standard error	C2: small size, high woody species density and low yields mean ± standard error	C3: moderate size, high woody species density and high yield mean ± standard error	*F*	*P*
NI (US$ year^{-1})	−340 ± 96a	−977 ± 133b	528 ± 182c	29.17	<0.0001
CF (US$ year^{-1})	398 ± 55a	151 ± 30b	1101 ± 163c	25.33	<0.0001
FB (US$ year^{-1})	965 ± 255a	600 ± 239b	2307 ± 348c	21.63	<0.0001
GI (US$ year^{-1})	509 ± 52a	170 ± 26b	1171 ± 171c	35.13	<0.0001
VDC (US$ year^{-1})	605 ± 296a	507 ± 289a	1109 ± 335b	5.05	<0.0074
CC (US$ year^{-1})	110 ± 24a	29 ± 18b	70 ± 21a	7.98	0.0005
KC (US$ year^{-1})	741 ± 110a	1109 ± 142b	582 ± 102a	8.21	<0.0004
ST value (US$)	1665 ± 570a	756 ± 455b	1163 ± 541ab	6.82	0.0014
LD (days year^{-1})	100 ± 16a	146 ± 19b	91 ± 16a	5.67	0.0042
Area (ha)	1.9 ± 0.2a	0.6 ± 0.2b	0.9 ± 0.2c	21.43	<0.0001

Different letters within a row indicate significant differences among clusters typology (LSD Fisher, $p < 0.05$)

NI net income, *CF* cash flow, *FB* family benefit, *GI* gross income, *VDC* value of domestic consumption, CC cash costs, *KC* in-kind costs, *ST value* standing timber value, *LD* number of labor days invested by family members

[a] Socioeconomic indicators here are the sum of contributions of cocoa, bananas, fruits and timber

Table 8 Values of socioeconomic indicators provided per hectare of the system in a three-cluster typology of cocoa agroforestry systems in Central America

Socioeconomic indicators[a]	C1: large size, moderate woody species density and low yields mean ± standard error	C2: small size, high woody species density and low yields mean ± standard error	C3: moderate size, high woody species density and high yield mean ± standard error	*F*	*P*
NI (US$ ha^{-1} year^{-1})	−272 ± 48a	−1724 ± 129b	433 ± 135c	80.21	<0.0001
CF (US$ ha^{-1} year^{-1})	276 ± 67a	282 ± 75a	1282 ± 116b	47.79	<0.0001
FB (US$ ha^{-1} year^{-1})	600 ± 145a	824 ± 162b	3098 ± 322c	37.71	<0.0001
GI (US$ ha^{-1} year^{-1})	335 ± 51a	324 ± 57a	1336 ± 115b	60.22	<0.0001
VDC (US$ ha^{-1} year^{-1})	369 ± 388a	750 ± 421a	1617 ± 410b	12.04	<0.0001
CC (US$ ha^{-1} year^{-1})	53 ± 18a	29 ± 18b	87 ± 25a	4.36	0.0142
KC (US$ ha^{-1} year^{-1})	520 ± 85a	1988 ± 239b	872 ± 115c	23.85	<0.0001
FBLD (US$ person^{-1} day^{-1})	10 ±2a	5 ± 2b	31 ± 4c	40.72	<0.0001
ST value (US$ ha^{-1})	758 ± 475a	1327 ± 508b	1370 ± 482b	6.82	0.0014
LD (days ha^{-1} year^{-1})	78 ± 12a	259 ± 25b	142 ± 24c	34.16	<0.0001
Area (ha)	1.9 ± 0.2a	0.6 ± 0.2b	0.9 ± 0.2c	21.43	<0.0001

Different letters within a row indicate significant differences among clusters typology (LSD Fisher, $p < 0.05$)

NI net income, *CF* cash flow, *FB* family benefit, *GI* gross income, *VDC* value of domestic consumption, *CC* cash costs, *KC* in-kind costs, *FBLD* family benefit per labor day, *ST value* standing timber value; *LD* number of labor days invested by family members

[a] Socioeconomic indicators here are the sum of contributions of cocoa, bananas, fruits and timber

were different in direction (+ or −, or almost neutral) among clusters, meaning that they were determined by the CAFS typology. In C3, most of the relationships were positive, showing synergies; whereas in the other clusters several were negative, denoting trade-offs (Fig. 5).

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Table 9 Contribution of the main agroforestry products to net income, cash flow, and family benefit in three clusters of cocoa agroforestry systems in Central America

Indicator	Typology	Cocoa mean ± standard error	Banana mean ± standard error	Fruits mean ± standard error	Timber mean ± standard error	*F*	*P*
Net income (US$ ha^{-1} year^{-1})	C1	−152 ± 26a	−106 ± 15a	−12 ± 7b	−7 ± 4b	23.85	<0.0001
	C2	−1234 ± 133a	−411 ± 73b	−97 ± 15c	−12 ± 5d	46.42	<0.0001
	C3	540 ± 124a	−209 ±55 b	26 ± 33c	103 ± 63c	12.24	<0.0001
Cash flow (US$ ha^{-1} year^{-1})	C1	203 ± 23a	23 ± 6b	28 ± 7b	−3 ± 4c	31.18	<0.0001
	C2	294 ± 42a	8 ± 4b	15 ± 9b	−4 ± 3c	18.9	<0.0001
	C3	1083 ± 84a	30 ± 26b	80 ± 35b	109 ± 65b	48.37	<0.0001
Family benefit (US$ ha^{-1} year^{-1})	C1	210 ± 23a	155 ± 25ab	138 ± 24b	31 ± 12c	21.19	<0.0001
	C2	310 ± 42a	225 ± 82ab	132 ± 28b	11 ± 8c	22.5	<0.0001
	C3	1133 ± 83a	796 ± 167ab	1224 ± 248a	151 ± 84b	24.75	<0.0001

Different letters within a row indicate significant differences among agroforestry products (LSD Fisher, $p < 0.05$)

Countries are ordered from left to right according to the increase of species richness showed in Fig. 1

C1 large size, moderate woody species density and low yields CAFS, *C2* small size, high woody species density and low yields CAFS, *C3* moderate size, high woody species density and high yields CAFS

Discussion

Agroforestry structure and yields

In Central America, small cocoa farmers manage their plantations with low cocoa-tree densities and high densities of bananas and woody perennials (trees, palms), with the special aim of producing fruit and timber. The 600 cocoa trees ha^{-1} in Central America are low especially compared with cocoa plantations in Africa in the range of 800–1,300 cocoa trees ha^{-1} (Jagoret et al. 2011, 2012) or with commercial shaded or unshaded plantations around the world that even surpass 2,000 cocoa trees ha^{-1}. But the densities of the shade canopy appear to be higher in Central America, where the majority of CAFS have about 200 trees ha^{-1} plus at least 60 bananas ha^{-1}, compared to other parts of the world; for instance, densities in Africa are about 160 trees ha^{-1} (Gockowski et al. 2010) or 120 trees ha^{-1} (Jagoret et al. 2011), and lower in Bolivia with less than 30 trees ha^{-1} (Orozco et al. 2008); while in rustic (*cabruca*) plantations in Brazil the densities are about 70 trees ha^{-1} but their basal areas are high (23 m^2 ha^{-1}) (Sambuichi 2006). As for uses of the species, while the predominant use globally is fruits, the second main use depends on the region—timber in Central America. Around the world, as well as in this study, mango (*M. indica*), avocado (*P. americana*), and orange (*C. sinensis*) are the most common fruit trees reported in mixed diversified CAFS (Aulong et al. 2000; Tejada and Andujar 2004; López and Somarriba 2005; Jagoret et al. 2009; Gockowski et al. 2010).

The differences in densities and management of cocoa and shade-canopy plants and trees also result in yield differences of agroforestry products. With high densities of cocoa trees along with chemical or systematic manual control of pest and diseases, cocoa yields easily reach 1,000 dry kg ha^{-1} year^{-1}, and higher intensified systems surpass 2,000 dry kg ha^{-1} (Alvim and Nair 1986; Osei-Bonsu et al. 2002; Bisseleua et al. 2009). In our study the best cluster (C3) registered 458 dry kg ha^{-1} year^{-1} and the others less than 160 dry kg ha^{-1} year^{-1}. Cocoa yields in Central America are affected by several factors such as diseases, management and arrangement of shade, soil fertility, and incompatibility and variability of cocoa trees, among others. The most negative impact is caused by disease incidences such

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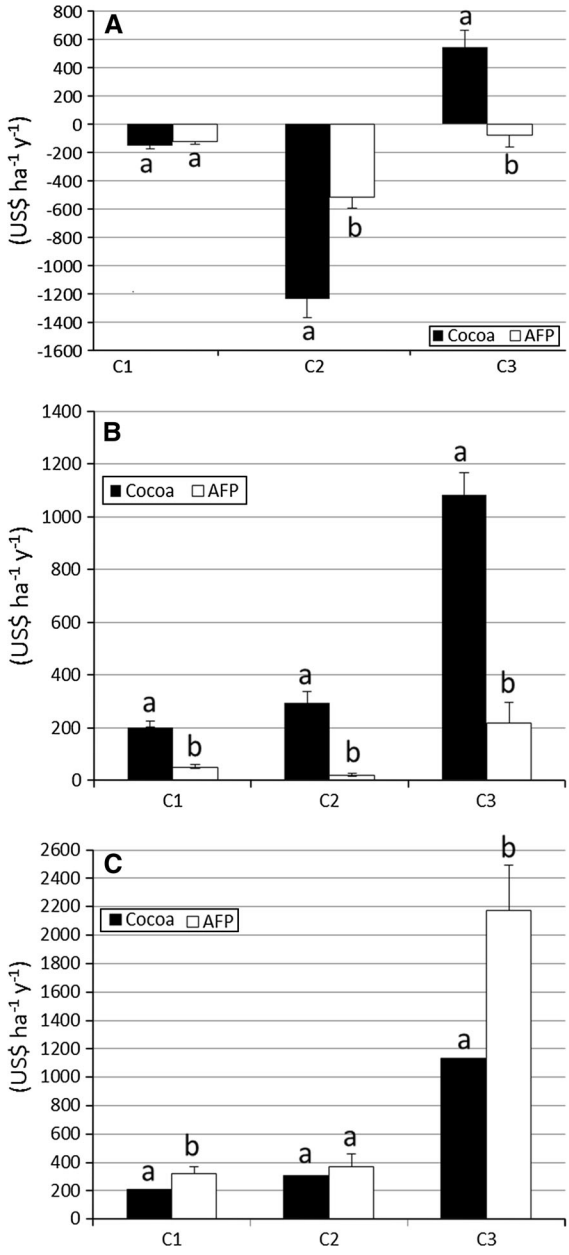

Fig. 4 Comparison between contributions of cocoa and agroforestry products to **A** net income, **B** cash flow, and **C** family benefits in the three clusters of cocoa agroforestry systems in Central America. Different letters between bars indicate significant differences between cocoa and AFP (LSD Fisher, $p < 0.05$). *AFP* agroforestry products (banana + fruits + timber). *C1* large size, moderate woody species density and low yields CAFS; *C2* small size, high woody species density and low yields CAFS; *C3* moderate size, high woody species density and high yields CAFS

as monilia (*Moniliophthora roreri*) and black pod (*Phytophthora palmivora)* since their control is not adequate. The most important recommendation is to eliminate infected pods and to harvest healthy ones as often as possible, at least every 4-weeks loss of cocoa pods can be reduced (Leach et al. 2002). A clustered pattern of shade trees appears to promote a higher production of pods but with a higher number of diseased pods than random and regular spatial organization; therefore, the study of interactions between cocoa diseases and spatial structure is useful in giving us more insights on ways to increase yields (Ngo Bieng et al. 2013).

Regarding timber, the basal area and standing timber volume of commercial timber trees in complex, mixed CAFS managed by small farmers are in the range of 4–7 m^2 ha^{-1} and about 14 m^3 ha^{-1}, respectively, as reported in this study and other CAFS in Africa (Gockowski et al. 2010). In simple mixed CAFS, such as in Bolivia, the values are less than 1 m^2 ha^{-1} and 3 m^3 ha^{-1}, respectively (Orozco and Somarriba 2005). Timber harvest rate in CAFS is low in Central America, with 0.6 m^3 ha^{-1} $year^{-1}$ in the best cluster (C3) because farmers do not harvest every year and at each harvest they generally cut down only one or two trees. At this rate, the cumulative timber yield in 14 years would be 8.4 m^3 ha^{-1}. In cocoa-timber agroforestry systems, over the same period, reported timber yields were 138 m^3 ha^{-1} for *C. megalantha* and 94 m^3 ha^{-1} for *C. odorata* (Sánchez et al. 2002); in 12 years ~82 m^3 ha^{-1} for *C. alliodora* (Ramírez et al. 2001); in 10 years the overbark stem volume was 128 m^3 ha^{-1} for *C. alliodora*, 97 m^3 ha^{-1} for *T. rosea*, and 172 m^3 ha^{-1} for *T. ivorensis* (Somarriba and Beer 2011). In another study, the cumulative timber rate for *C. alliodora* was 4–6 m^3 ha^{-1} $year^{-1}$ (Beer et al. 1998). It would not be expected that Central American CAFS achieve those timber volumes since they are not only cocoa-timber but diversified systems; however, this indicates that high timber production in CAFS is achievable.

Regarding fruits, several studies report yields and/or incomes in complex or simple mixed CAFS (Duguma et al. 2001; Osei-Bonsu et al. 2002; Tejada and Andujar 2004; Villareal et al. 2006; Gockowski et al. 2010). Their reported data are informative, but unfortunately, comparisons are difficult due to the fact that many fruit species in their shade canopies are different to the ones found in Central American CAFS, or because the yields of species in common are reported in different units.

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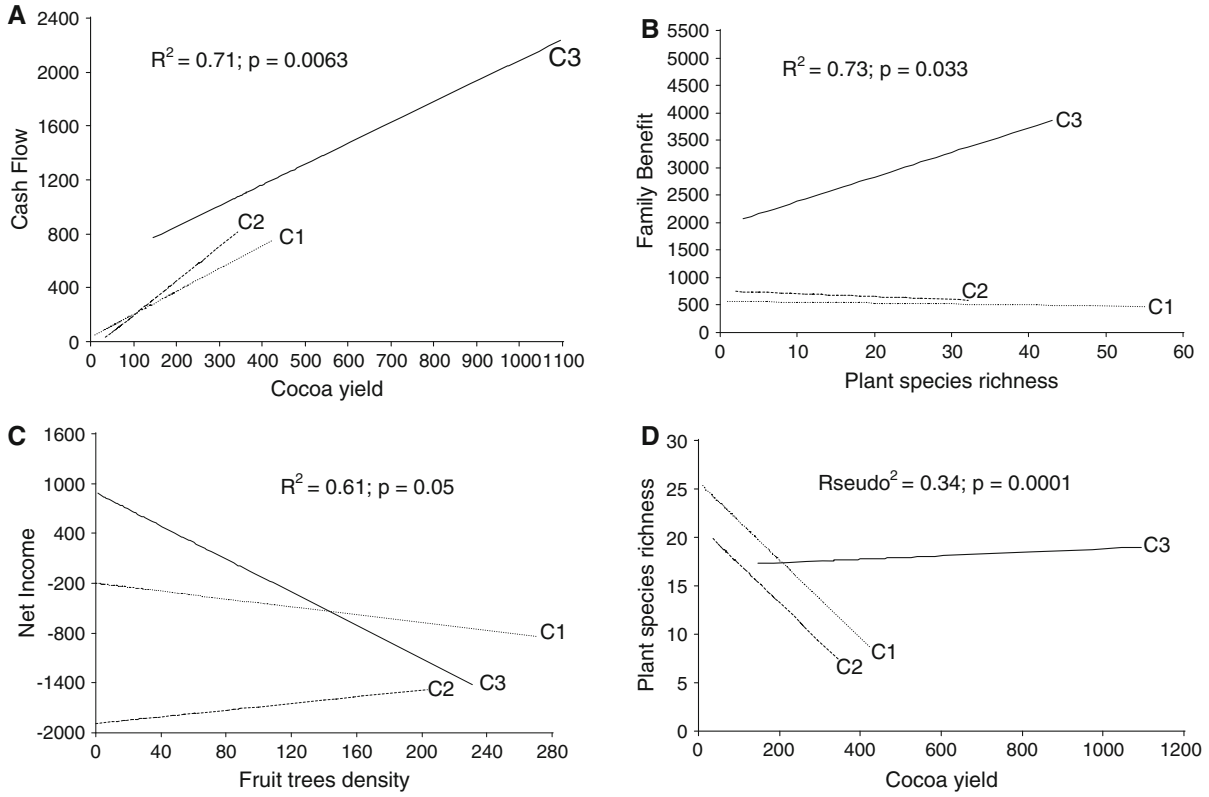

Fig. 5 Most significant relationships between socioeconomic and biophysical indicators in three clusters of cocoa agroforestry systems in Central America. *C1* large size, moderate woody species density and low yields CAFS; *C2* small size, high woody species density and low yields CAFS; *C3* moderate size, high woody species density and high yields CAFS. Coefficients of determination (R^2 and Rseudo2) represents the entire model

Contribution of agroforestry farming to family livelihoods

Our findings show that the main contribution of agroforestry farming to small farmers' families is the generation of both cash incomes and products for domestic consumption, using only family labor and involving very small cash amounts. Undoubtedly, the main contribution to CF is made by cocoa—little by agroforestry products. However, agroforestry products are as important in terms of FB as cocoa. For domestic consumption bananas and fruits are much more important than cocoa to family livelihoods, food security, and nutrition (Jamnadass et al. 2011). Another advantages of this cocoa agroforestry farming is that bananas are easy and cheap to manage and produce year-round (Sharrock and Frison 1999; Dahlquist et al. 2007), the differences in seasonal fruiting pattern of these species results in the production of various fruits during all year long (Leakey and Tchoundjeu 2001; Leakey et al. 2005; Jamnadass et al. 2011), and families can sell timber in case of emergency (Somarriba and Beer 2011). Regarding strict economic profitability (NI), only in C3 CAFS most of agroforestry products are profitable while in the other clusters NI is negative; this situation is not caused by cash costs but by in-kind costs, indicating that family labor is not efficient in terms of NI.

CF and FB help highlight the real contribution from shade canopies to households, instead of relying solely on profitability indicators, and also broaden the understanding of the small farmer's strategies in growing cocoa. In most CAFS, the main strategy is to combine cocoa trees with moderate or high densities of other plants and trees, which could be viewed as inadequate because it implies an increase in shade with a consequent reduction in cocoa yields, and additional family labor. But CF demonstrates that shade canopy is capable of generating cash incomes with very low cash costs while FB and FBLD demonstrate that

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working in the CAFS can potentially offer more benefits than working outside the farm. For example, in C3 CAFS, the FBLD was US$31 person^{-1} day^{-1}, which is much better than the US$10–15 person^{-1} day^{-1} a person earns working on other farms. These kinds of indicators also reflect on the savings from use of products produced on the farm (Leakey et al. 2005) and the efficiency of the farming activity (Herzog and Gotsch 1998; Rice 2008). Therefore, through CF and FB it is possible to show that with respect to small farmer's strategy, associated trees and plants have the same importance than cocoa for family livelihood despite the fact that cocoa trees are the most abundant component in the system.

Considering the yields of agroforestry products and socioeconomic contributions, an important question arises: Can agroforestry products compensate for low cocoa yields? In terms of CF it is difficult for agroforestry products to compensate for low cocoa yields and incomes, although the modest incomes from these products always represent an aid to household economy. But in terms of FB, the set of agroforestry products could compensate for current cocoa yields and/or incomes and even enable farmers to face a decrease of them since they had similar or higher FB than cocoa. For example, in C3 CAFS, cocoa yields and incomes could double with less species richness and less abundance of trees in the shade canopies and with external inputs such as used in other cocoa-growing areas of the world (Sánchez et al. 2002; FHIA 2007; Gockowski and Sonwa 2011; Steffan-Dewenter et al. 2007; Wade et al. 2010). In that case, though its hypothetical FB would mainly come from cocoa bean income and might be similar to the current FB, it would have fewer other benefits such as ecosystem services and higher financial risk due to the dependence on only one product (Ramírez et al. 2001; Leakey et al. 2005). In Cameroon it was also demonstrated that the highest and most stable revenues were generated by intensive cocoa-fruit agroforestry, which had about 170 trees and 56 bananas ha^{-1} (Gockowski and Dury 1999), densities similar to Central American CAFS.

Typology of cocoa farming in Central America

Each of the three CAFS clusters found in this study represents a contrasting type of cocoa farming, with C3 CAFS as the most efficient one. The C1 cluster represents an extensive management of cocoa with shade trees, due to its characteristics of larger areas and lower densities and yields; whereas C2 and C3 represent a type of intensification in terms of managing high densities of productive trees in the shade canopy along with the main crop. However, C2 and C3 are not equal in socioeconomic benefits. Although C2 and C3 have similar densities in the shade canopy, farmers of C3 invest significantly less family labor (in-kind costs) and obtain remarkably higher yields of agroforestry products, NI, CF, FB, and FBLD. Efficiency of this type on small to medium farms has been noted before; these farms can present higher productivity in fruits per hectare and are also more efficient in fruits per dollar input than larger operations (Rice and Greenberg 2000), the success of the system also depends on the cultural practices (Jagoret et al. 2008), which allows us to assume that the main differences between C2 and C3 stem from the agroforestry management (efficiency and technique) and the objectives of the farmers. C3 is made up mainly of CAFS managed by mestizo farmers in Nicaragua, whose objectives clearly involve both cash income and food production. C1 and C2 are mostly made up of CAFS of indigenous people in Costa Rica and Panama; several of the main objectives of indigenous farmers have to do with traditional/cultural and conservation factors, which do not necessarily result in high yields (Dahlquist et al. 2007; Laird et al. 2007). Another important factor within the objectives of indigenous farmers could be the economic resilience of CAFS, because when prices are low they reduce the management to the point that CAFS could appear to be abandoned, and when after several years the prices are again attractive, they invest again in agriculture management in order to recover the cocoa production; this dynamic could also explain the maintenance of C1 and C2 CAFS. Within this context, in Central America 50 % of CAFS are extensive (C1), 19 % are traditional highly diverse-dense (C2), and 31 % are intensified highly diverse-dense (C3), as shown in Table 5.

Relationships according to CAFS typology

Several implications can be deduced from our results of relationships:

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1. The direction of significant relationships depend on the typology of CAFS; therefore, synergies or trade-offs cannot be generalized. Intensified highly diverse-dense CAFS can have more synergies, whereas extensive CAFS and traditional highly diverse-dense CAFS tend to have more trade-offs.
2. FB can increase with increasing fruit yields and plant species richness, and is not related to densities of the shade canopy. This finding is important when promoting or justifying incentives that aim to increase species richness and abundance that can provide products for a family's domestic consumption, especially on farms in remote and poor zones (see also Deheuvels et al. 2014).
3. CF and NI do not have relationships with plant species richness or with stand densities (cocoa, bananas, timber trees, firewood trees), allowing us to discard trade-offs between those variables. Thus, banana densities can be maintained without affecting cash incomes originated from cocoa to continuously produce bananas for family domestic consumption. The same situation exists for timber trees, though they have the potential to contribute to cash incomes and ecosystem services. With timber tree densities similar to those found in this study, high timber volumes can be reached producing high incomes without affecting cocoa yields (Ramírez et al. 2001; Sánchez et al. 2002; Somarriba and Beer 2011); and biomass and carbon sequestration could be increased dramatically, avoiding excessive shade, by manipulating the morphological characteristics of timber trees (Somarriba et al. 2013). The current timber harvest rate in Central American CAFS could be increased significantly without endangering the sustainability of timber stock (Somarriba et al. 2014). The small farmer's fear of planting or harvesting timber trees should no longer be a constraint because it has already been demonstrated that well-conducted harvesting of timber does not cause significant damage to cocoa trees (Ryan et al. 2009). In Central America farmers are able to harvest and sell the trees planted in their farms with a previous permission of local governments, as long as the timber species is not in danger of extinction.
4. Regarding biodiversity and cocoa yields, results from several studies are in agreement with ours, suggesting that the relationship also depends on the typology of the CAFS. It can range from slightly positive or almost neutral (Steffan-Dewenter et al. 2007; Clough et al. 2011) to negative relationships, denoting trade-offs (Bisseleua et al. 2009; Wade et al. 2010). Another study reported trade-offs within varying levels of agroforestry intensification, suggesting that plant biodiversity can be maintained if it has economic value derived from the shade canopy (Gockowski and Sonwa 2011). We support this suggestion because C3 CAFS registered high socioeconomic value and showed synergetic relationships, also confirming that a win–win situation can be attained by intercropping a mix of species that provide benefits to small farmers and maximize biodiversity conservation (Leakey and Tchoundjeu 2001; Clough et al. 2011; Kessler et al. 2012; Deheuvels et al. 2014). C3 CAFS merit further detailed studies on the relationships between their management and the provision of ecosystem services such as carbon sequestration (Somarriba et al. 2013), soil quality (Rousseau et al. 2012), pollination and conservation of wild species, among others.

There is also evidence that trade-offs with yields and incomes are caused by shade cover and system structure rather than biodiversity *per se*. The negative effect of increasing shade on cocoa yields has been clearly demonstrated (Zuidema et al. 2005), and it is suggested that spatial distribution of plants and trees in the shade canopy affects productivity more than does botanical composition (Deheuvels 2011; Deheuvels et al. 2012; Ngo Bieng et al. 2013). Therefore, trade-offs could be reduced with sustainable agroforestry management that involves establishment and maintenance of multipurpose trees through optimal pruning to regulate shade, instead of eliminating trees (Tscharntke et al. 2011). For instance, in CAFS in Indonesia, a reduction of shade cover from 80 to 35–50 % doubled income with limited losses to biodiversity and functioning of the ecosystem (Steffan-Dewenter et al. 2007); in Africa, good cocoa yields are obtained with 28–48 % of shade cover (Bisseleua et al. 2009).

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All of these findings confirm that trade-offs between income and biodiversity in CAFS are less severe than expected (Steffan-Dewenter et al. 2007; Bisseleua et al. 2009; Clough et al. 2011) and that shade management is key for increasing yields using highly diversified agroforestry systems (Bos et al. 2007). We hypothesize that through adequate silvicultural management and arrangement of plants in the shade canopy, based only on family labor and low cash costs, trade-offs in extensive or traditional CAFS could be turned into neutral or synergetic relationships for increasing cash income, domestic consumption, and ecosystem services, conserving biodiversity at the same time.

Cocoa farming intensification for land sparing and wildlife-friendly strategies

Considering resource investments and a gradient of shade-canopy complexity, we identify four types of cocoa-farming intensification around the world:

(1) The most common type of intensification is a monoculture of high cocoa-tree density with high inputs (fertilizers and pesticides) and high cash costs (Steffan-Dewenter et al. 2007; Gockowski and Sonwa 2011)

(2) High cocoa-tree density with specialized-simple-productive shade with high inputs and intermediate cash costs, involving only one productive species in the shade canopy, either cocoa-fruit species or cocoa-timber species (Alvim and Nair 1986; Egbe and Adenikinju 1990; Osei-Bonsu et al. 2002; Sánchez et al. 2002; FHIA (Fundación Hondureña de Investigación Agrícola) 2007; Somarriba and Beer 2011)

(3) High cocoa-tree density with mixed productive shade with intermediate cash and in-kind costs, involving generally two species with intermediate densities in the shade canopy—the most common being cocoa-fruit-timber (Ramírez et al. 2001; Yamada and Gholz 2002; Villareal et al. 2006; Dahlquist et al. 2007; Gockowski and Sonwa 2011)

(4) Low cocoa-trees density but with complex mixed productive shade (cocoa-banana-fruits-timber) with high species richness and high densities in the shade canopy, low cash costs and high in-kind costs, capable of producing high total production represented by yields of cocoa and agroforestry products. Intensified highly diverse-dense CAFS (C3) of this study represent this type of intensification as do similar systems reported by other authors (Gockowski and Dury 1999; Yamada and Gholz 2002; Gockowski et al. 2010)

Farmers can choose the type of intensification best in line with their objectives and resources, but they should also consider the attainable benefits and financial risks. We suggest that types (1) and (4) can provide the maximum FB per year: type (1) because of its high cash income that compensates for the lack of products for domestic consumption and type (4) for its combination of cash income and domestic consumption. Type (3) would rank third because its contribution to domestic consumption is not as high as type (4). Type (2) would be in the last place due to its low-medium contribution to domestic consumption and a cash income lower than in type (1). Financially, types (1) and (2) depend on a high cocoa price, thus they are economically risky (Duguma et al. 2001; Bisseleua et al. 2009). On the other hand, multipurpose shade trees namely types (3) and (4), play an important role in lessening farm income variability throughout the year and provide economic resilience when cocoa prices fall (Leakey et al. 2005; Somarriba 2007; Jagoret et al. 2009; Tscharntke et al. 2011). Therefore, with a decrease in cocoa prices, the expected impact from reduced cash flow and family benefit would be proportionally more severe in types (1) and (2) than in types (3) and (4).

Based on the preceding analysis, (3) and (4) would be the most suitable types of intensification for medium and small cocoa farmers, especially for those with low cash resources, who depend on family labor. At the beginning of implementation, these types of intensification would involve increasing complexity (shade) and family labor; possibly resulting in a reduction of benefits. But lower benefits in shaded systems could be a trade-off only in the short-term, in the future the system will produce continuously (Franzen and Borgerhoff 2007) and would be capable to achieve high FB. Regarding the conservation of biodiversity and provision of ecosystem services, none of cocoa-farming types could equal primary forests; but diverse-dense CAFS can perform much better than extensive CAFS or unshaded cocoa intensifications (Perfecto et al. 1996; Schulze et al. 2004; Steffan-Dewenter et al. 2007; Wade et al. 2010; Somarriba

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et al. 2013; Deheuvels et al. 2014). Therefore, we also suggest that types (3) and (4) would be suitable alternatives for land sparing and wildlife-friendly strategies in cocoa-growing landscapes, as detailed bellow.

At the landscape level, it has been suggested that intensification is a better option in a land-sparing strategy than extensive farming with a context of wildlife-friendly strategy. In extensive shaded cocoa farming, the cocoa yields are so low that forests would be continuously cleared in order to increase production; on the contrary, in intensified unshaded or low-shaded systems, cocoa yields are very much higher, requiring less land for production and therefore reducing deforestation. So larger areas of original forests can be maintained, with higher biodiversity and ecosystem services than similar areas under extensive wildlife-friendly cocoa farming (Wade et al. 2010; Kuwornu et al. 2011; Kessler et al. 2012), while degradation of lands and emissions of CO_2 can be avoided (Gockowski and Sonwa 2011). However, there is an important disadvantage of intensified unshaded or low-shaded systems: they offer poor landscape connectivity, which implies a risk of local species extinction (Perfecto and Vandermeer 2008). This opens the possibility of proposing intensified highly diverse-dense CAFS as an alternative to those systems for a land-sparing strategy since they would offer more environmental benefits to the landscape.

Shade trees in intensified CAFS are capable of producing synergetic relationships between biodiversity and ecosystem services. CAFS with a structurally complex shade canopy have high fauna and plant diversity (Deheuvels et al. 2014), improve habitat availability and landscape connectivity, and enhance overall ecosystem resilience (Schroth and Harvey 2007; Steffan-Dewenter et al. 2007). The beneficial impacts of agroforestry on soil health-quality and land recovery have been well-documented (Place and Dewees 1999; Palm et al. 2005; Nair et al. 2010; Chitakira and Torquebiau 2010; Guillerme et al. 2011; Somarriba et al. 2012; Jagoret et al. 2012; Rousseau et al. 2012). Trees also increase the functional biodiversity, improve tolerance to drought stress, and contribute to the control of pests and diseases (Tscharntke et al. 2011). For climate change mitigation, trees offer great potential for carbon sequestration (Gockowski and Sonwa 2011; Somarriba et al. 2013). Since FB is high in intensified highly dense-diverse CAFS, this type of intensification can be a form of wildlife-friendly farming in a land-sparing strategy.

The potential of intensified highly dense-diverse CAFS could be even stronger in increasing yields of agroforestry products, thus promoting higher land sparing, but further research is needed. Low cocoa-tree density in these systems would not be a constraint since cocoa yields are more influenced by shade trees and management (Bisseleua et al. 2009), but the use of better cocoa varieties could significantly increase yields (Rosenberg and Marcotte 2005; Obiri et al. 2007). For instance, clonal cocoa trees are being planted in large areas around the world; nonetheless, research on the response of these cocoa trees under intensified shade canopies is still critically needed. The response of fertilizers and pesticides under shade is not yet well-known, and there is a need for alternative sources of inputs (Rosenberg and Marcotte 2005; Gockowski and Sonwa 2011). The effect of spatial distribution of trees in the shade canopy on the impact of pest and diseases could give us insight into better control (Deheuvels et al. 2012; Ngo Bieng et al. 2013). Therefore, a new paradigm for research and action should integrate productivity and income generation, ecosystem services, food security, and climate regulation, involving a "win–win–win–win" approach (Scherr et al. 2010). For that, we need a multidimensional quantitative analysis of synergies or trade-offs among socioeconomic indicators, yields of agroforestry products, biodiversity (plants and animals), and ecosystem services that could shed further light on the mechanisms that could regulate them.

Farmers' education, incentives, markets and better prices not only for cocoa, but also for other agroforestry products are necessary to promote intensified highly dense-diverse CAFS. Farmers must be trained on the silvicultural management of timber trees and techniques to optimize the production of fruit trees, and the importance of ecosystem services to the farm and the environment, highlighting the potential economic benefits of the sale of services (Leakey et al. 2005; Rosenberg and Marcotte 2005; Degrande et al. 2006; Jagoret et al. 2008; Gockowski and Sonwa 2011; Jamnadass et al. 2011). The best suggested incentives are in the form of certifications (e.g. organic production, fair trade, wildlife friendliness, carbon credits), aiming to improve the prices and generate additional incomes (Steffan-Dewenter et al. 2007;

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Bisseleua et al. 2009; Clough et al. 2009; Tscharntke et al. 2011). Buyers and industries now play an important role since they no longer look only for quantity and quality, but request an acceptable social production that generates ecosystem services (Millard 2011). Therefore, farmers' organizations should look for either national or international markets for agroforestry products and ecosystem services; there are already several voluntary market-compatible standards for tandem certifications that they can choose from (Somarriba et al. 2013).

Main methodological difficulty and ways to cope with it

The main methodological difficulty was the estimation of the production of fruits and other products different from cocoa and timber. It was evident that it is hard for the families to remember all the products obtained from CAFS and quantify their annual production, the men remembers the quantities of products sold better than the quantities of products consumed, and rarely in terms of units and quantity per area.

In this study both the full inventories of CAFS and the way to do the interviews helped to have reliable data estimations. A full inventory avoids forgetting important species and their abundances since it is common to find several species clustered in different places of the system; and helps the family to remember the presence of certain plants and trees, which can be providing benefits. When estimating the production, the participation of both man of woman head of the house was essential; man remembers better the quantities sold, while woman the quantities consumed by the family. For fruits such as bananas, which are harvested once or twice a month, depending on the season and management; in the interview the production in months with more or with less harvests first was differentiated and finally summed. When farmers reported uncommon units of production, for instance "bags" or "boxes", it was necessary to ask them to show how many fruits can be accommodated in those materials, in order to estimate the quantities and/or weight. When the production is very low, as happened in this study with medicinal and construction materials, we suggest that is not adequate to include them in the analysis in order to avoid overestimations.

Conclusion

Plants and trees in the shade canopy of CAFS produce diverse types of fruits and timber that can generate modest cash incomes and provide high value for domestic consumption at low cash costs, contributing to family savings and food security. The contribution of the set of agroforestry products to family benefit is similar or higher than cocoa beans, depending on the typology of CAFS, becoming as important as the main crop for the livelihoods of small farmers' families.

The relationships between socioeconomic indicators and yields of agroforestry products, plant species richness, and stand densities, and the relationship between plant species richness and cocoa yields are determined by the typology of CAFS. Intensified highly diverse-dense CAFS are the most efficient in terms of production and providing benefits for the family, and have more synergetic relationships, whereas extensive CAFS and traditional highly diverse-dense CAFS tend to have more trade-offs.

Our findings support our proposal of intensified highly diverse-dense CAFS for medium and small cocoa farmers as a feasible wildlife-friendly farming within a land-sparing strategy in order to conserve biodiversity and ecosystem services in cocoa-growing landscapes. A multidimensional quantitative analysis of relationships among socioeconomic indicators, yields, biodiversity (plants and animals), and ecosystem services is needed for a better understanding of the mechanisms that could regulate synergies or trade-offs to improve this type of intensification.

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