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Vegetation structure and productivity in cocoa-based agroforestry systems in Talamanca, Costa Rica

Olivier Deheuvels[a,b,*], Jacques Avelino[c,b,d], Eduardo Somarriba[b], Eric Malezieux[e]

[a] CIRAD/UMR System – SupAgro, Bâtiment 27 – 2, Place Viala – 34 060 Montpellier, France
[b] CATIE, DID – 7170 Cartago, Turrialba 30501, Costa Rica
[c] CIRAD, UR106 Bioagresseurs: Analyse et maîtrise du risque, TA A-106 – Avenue Agropolis, 34398, Montpellier Cedex 5, France
[d] IICA-PROMECAFE, AP 55, 2200 Coronado, San José, Costa Rica
[e] CIRAD/UPR Hortsys – TA B-103/PS4 – Boulevard de la Lironde – 34398 Montpellier Cedex 5, France

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ABSTRACT

In the humid tropics, the remaining forest patches are increasingly isolated within an expanding agricultural matrix. There, a significant area consists of complex agroforestry systems with high structural and functional plant diversity. These anthropogenic habitats are gaining increasing conservation value as deforestation progresses. Cocoa-based agroforests provide habitats for some forest dependent species and play a largely undocumented role in providing other ecosystem services. The high variability of their botanical composition and structure is poorly described and its relevancy in assessing ecosystem services has not yet been investigated. We characterized the structure and productivity of 36 cocoa agroforests in Talamanca, Costa Rica. These agroforestry systems (AFS) were chosen to maximize contrasts in terms of biophysical context, botanical composition and management practices. Results showed significant differences in the vegetation structure that enabled us to distinguish four main clusters: complex and high density canopy AFS, high cocoa density AFS, high Musa density AFS and complex and low density canopy AFS. Changes in vegetation structure reflected differences in the farmers' strategies but did not affect the overall cocoa yield (136 kg ha^{-1} $year^{-1}$) or the aboveground fresh plant volume (400 m^3 ha^{-1}). Cocoa yield per tree in the high Musa density AFS cluster was 454.5 g per cocoa tree, which was significantly twice as much as in lower cocoa density clusters, suggesting that structure affects productivity through spatial distribution more than through botanical composition. These results open new perspectives to improve cocoa orchards' structural complexity and their relative ecosystem services without affecting their overall productivity. Further investigations and additional samplings are needed to fully understand the mechanisms involved.

1. Introduction

In tropical America, a significant amount of the agricultural landscape where cocoa is grown is managed as agroforestry systems (AFS), considered today as an alternative paradigm for rural development (Leakey et al., 2005). Following Somarriba (1992), these AFS can be defined after as *a form of multiple cropping under which three fundamental conditions are met: (i) at least two plant species interact biologically, (ii) at least one of these two species is a woody perennial and (iii) at least one of them is managed for forage, annual or perennial crop production*. In cocoa-based AFS, shade trees are usually associated with traditional cacao varieties and very low levels of chemical inputs (Bentley et al., 2004) in patterns of highly diverse structural and compositional complexity. Cocoa-based agroforests throughout the world can include from one to more than 30 associated tree species (Guiracocha et al., 2001). This variability is found in a range of structural patterns, strongly suggesting that the quality of ecosystem services offered by these AFS should vary in the same proportions. However, there is an overall scarcity in the literature of studies of the vegetation structure of cocoa-based AFS and their influence on ecosystem services. Most publications focus more strictly on ecosystem services (Alves, 1990; Aumeeruddy and Sansonnens, 1994; Beer et al., 2003; Reitsma et al., 2001; Sonwa et al., 2000; Suatunce et al., 2004; Thiollay, 1995), and use little detail to describe the noticeable structural heterogeneity and variability of cocoa agroforests (Somarriba et al., 2003), which are generally clustered in one or two structural types (Rice and Greenberg, 2000). Moreover, most studies of plant and animal biodiversity in cocoa AFS are based on comparisons between one cocoa agroforest type and two "extreme" or "test" references, usually

* Corresponding author at: UMR System – SupAgro – 2, Place Viala – 34 060 Montpellier, France. Tel.: +33 04 99 61 25 52; fax: +33 04 99 61 30 34.
E-mail addresses: olivier.deheuvels@cirad.fr, deheuvel@catie.ac.cr (O. Deheuvels).

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tropical forest fragments on the one hand and banana monocrop plantations on the other (Guiracocha et al., 2001; Harvey et al., 2006). Indeed, very few authors have tried to link the structural variability of each land use to productivity as an ecosystem service (Cheatham et al., 2009; Steffan-Dewenter et al., 2007). In Costa Rica, cocoa based AFS in the Talamanca region have been extensively described with respect to the environmental and ecosystem services they provide such as carbon sequestration and biodiversity conservation but far less concerning cocoa and overall productivity related to their structure (Somarriba and Harvey, 2003; Suatunce et al., 2003). Our objective was to analyze a set of vegetation and productivity characteristics using cluster analyses to build a quantitative typology of cacao agroforestry systems in south east Costa Rica. We hypothesized that botanical composition and structural diversity from the ground to the canopy strata would be enough to separate cocoa-based AFS into significantly different structural types. We also hypothesized that there would be significant differences in the typology regarding cocoa yield and fresh aboveground plant volume.

2. Materials and methods

2.1. Study area and selection criteria for cocoa agroforests

The Talamanca region (Costa Rica) was chosen because it contains cocoa AFS structures ranging from highly complex canopies to low density canopies.

Data were collected between May 2008 and August 2009 in the Bribri Indigenous Reserve, Talamanca, south-east Costa Rica (9°00′–9°50′N, 82°35′–83°05′W). The reserve covers around 44,000 ha and belongs to tropical humid forest and premontane wet forest life zones (Holdridge et al., 1971).

Mean daily air temperature is 25.9 °C, and mean annual precipitation is 3,570 mm (IMN, 2010) with a relatively homogeneous distribution, due to the strong Caribbean influence. However two slight decreases in rainfall in March-April and September–October are observed (Herrera, 1985), just before each main cocoa harvest.

In the 10 km × 10 km area of lowlands and foothills of the reserve where the 36 cocoa agroforests were selected, the agricultural landscape can be described as an annual floodplain located between 50 and 100 m above sea level, with seven main streams and their affluents. This floodplain is a mosaic of dominant banana-based AFS and small plantain monocrop plantations, interspersed with cocoa-based AFS and some grazing lands. The foothills are located between 100 and 400 m above sea level. There, secondary forest patches alternate with cocoa-based AFS, planted beans and rice in slash-and-mulch shifting agriculture and with fallow lands between 5 and 15 years old.

Less than 25% of the area remains forested (Somarriba et al., 2003). Soil biogeochemical patterns in the neighboring Cabecar indigenous territory showed that Typic Hapludults are found on both ridge tops and mid slopes, Typic Dystrudepts and Dystric Eutrudepts occupy the footslopes, and Udifluvents and Fluventic Eutrudepts occupy the floodplain (Winowiecki, 2008; Xavier-Rousseau et al., unpublished data).

From an initial sample of 250 AFS located in both lowlands and foothills, we selected a sub-sample of 36 cocoa agroforests that presented the greatest contrasts regarding shade management. The criterion used to characterize shade management was botanical composition considering the four most abundant plant species associated with cocoa. All 36 agroforests were farmers' plots managed under an organic certification scheme. Farmers were introduced to the methodology of the investigation which did not require any change in their existing practices.

2.2. Sampling

The area and the shape of each selected cocoa agroforest were mapped using a GPS track function. An estimated center was located visually on the GPS screen. Permanent sampling units of 50 m × 20 m were installed at the center and oriented according to the shape of each cocoa agroforest in order to avoid border effects. Each 1000 m^2 sampling unit was then divided into ten 10 m × 10 m subplots that were used to organize the assessments.

2.2.1. Vegetation structure

Cocoa agroforests were divided into three vertical strata that were used to describe their vegetation structure:

The ground cover stratum: from 0 to 2.5 m in height. Here the proportions of ligneous, herbaceous, mosses, ferns and soil litter were visually evaluated on ten 1 m^2 square units located at the center of each subplot;

The cocoa stratum that was specifically defined as the cocoa tree understory layer: the age, variety and mode of propagation of cocoa trees were noted in interviews with farmers. Cocoa trees were counted. Their basal area at a height of 30 cm from the ground and their total height were measured.

The canopy stratum: all plants 2.5 m in height or over and associated with cocoa trees were identified, counted and their total height and basal area at 130 cm were measured.

2.2.2. Productivity

Cocoa productivity was measured by counting all healthy ripe pods on each cocoa tree within the 1000 m^2 sampling unit, just before the two peak harvests, between April and May and between October and November 2008. On each sampling unit, we harvested 30 cocoa pods during the dry season (April) and during the rainy season (November). When a sampling unit did not provide 30 pods, we extended our search to the neighboring cocoa trees in the same cocoa field until we obtained the required number.

We weighed the corresponding fresh cocoa beans in the field. We applied a 56% discount to the average weight of fresh beans per pod in each season to obtain the dry cocoa commercial yield according to Braudeau (1969).

Fresh aboveground plant volume (B) was estimated by measuring the total height and the diameter of each cocoa tree and each associated plant more than 2.5 m tall. Total height was measured with a clinometer. The diameter of associated plants was measured at breast height (dbh) with a measuring tape for associated plants and of cocoa trees at 30 cm height in order to determine a basal area for each plant. Finally, fresh aboveground plant volume was estimated for each associated plant and for cocoa as (B) = basal area × total height.

2.3. Analytical methods

2.3.1. Vegetation structure

Both qualitative and quantitative variables were measured. The quantitative variables were converted into classes of equivalent size to enable joint analysis of the information. This method helped avoid problems of extreme values, standardizing distributions, and homogenizing data. The latter is especially useful when all variables are not measured with equal precision (Avelino et al., 2006; Savary et al., 1994, 1995).

Second, we performed a multiple correspondence analysis (MCA) of each category of variables. This technique is suitable for qualitative variables. The data were binary codes expressing the absence (0) or presence (1) of each modality. The MCA was used to calculate the factorial coordinates of the plots on the first seven axes, those that grouped the most representative information. These first seven dimensions out of a total of 20 explained

64% of the variation and individually not less than 5%. This procedure allowed us to give less weight to non-standard individuals, i.e. those that were well explained by last MCA axes. Otherwise, those individuals would have been singled out when the typologies were being created.

Third, the coordinates of the individuals on the selected axes were used in a cluster analysis (aggregation criterion: second order moment) which led to the creation of typologies. The combination of a MCA and a cluster analysis is a common way to create typologies (Avelino et al., 2006; Kristensen, 2003).

Finally, we tested all initial qualitative and quantitative variables for their relevance in distinguishing clusters with ANOVA for quantitative variables and with χ^2 tests for qualitative ones. Quantitative variables were log transformed when necessary to respect the assumption of homoscedasticity. Mean comparisons of and assignment to clusters were made using the least significant differences (LSD) test at $p < 0.01$, using the R software (2010).

2.3.2. Productivity

Log transformed productivity variables for estimated yield and for estimated aboveground fresh plant volume were tested by ANOVA. Comparisons of and assignment to clusters were made using the least significant differences (LSD) test at $p < 0.01$, using the R software (2010).

Finally, correlation has been tested between the annual cocoa yield per tree and the relative proportion of the following four groups of plants: cocoa trees, Musaceae, palm trees and ligneous trees associated with cocoa.

3. Results

3.1. Structure variability

The statistical analysis grouped the sampled cocoa AFS into four clusters: complex and high density canopy AFS, high cocoa density AFS, high Musa density AFS and complex and low density canopy AFS (Table 1).

3.1.1. Complex and high density canopy AFS

The ground stratum of this category of AFS differed from the other three clusters as it had the highest proportion of young tree seedlings (3.92%) and one of the lowest proportions of weeds (Table 1).

The cocoa stratum of AFS belonging to this cluster had medium ranked cocoa tree density and diameters comparable to the cluster containing complex and low density canopy AFS. These cocoa trees were the tallest of all the clusters with 40% of the cocoa trees taller than 5 m (Table 1).

The canopy stratum of these AFS showed the second highest density of plants associated with cocoa, after the high Musa density AFS cluster. These cocoa agroforests were the most heavily shaded, with almost 93% of shade 1 m above the ground (Table 1). Most of the associated plants (90%) belonged to the lower and medium canopy, between 2.5 and 20 m in height. These relatively small plants were mainly trees (64%) and palm trees (18%), the highest proportion of palm trees being in this cluster. This cluster had the highest Shannon index of diversity (2.06) and the lowest Simpson index of equity (0.17), this being the result of a high number of poorly represented associated species.

3.1.2. High cocoa density AFS

The ground stratum of this category of AFS had an intermediate proportion of young trees and one of the lowest proportions of weeds (Table 1).

The cocoa stratum of AFS in this cluster had the highest density of cocoa trees (693 trees ha^{-1}) and medium ranked diameters comparable to the cluster containing complex and low density canopies. These cocoa trees were not as tall as those in the complex and high density canopy AFS cluster, probably due to their lower density and the lower amount of shade provided by the canopy (Table 1).

The canopy stratum of these AFS had the lowest density (243 plants ha^{-1}) of plants associated with cocoa. These cocoa agroforests were still heavily shaded, with almost 88% of shade 1 m above the ground. Most of the associated plants (70%) belonged to the medium and high canopy levels, i.e. 10 m tall or taller. These relatively tall plants were almost all trees (86%). Musa and palm trees were almost absent. A relatively low diversity index and a high equity index indicate a much poorer mix of species among these associated trees with a few particularly abundant species, such as *Cordia alliodora* (Table 1).

3.1.3. High Musa density AFS

The ground stratum of this category of agroforests included almost no tree seedlings, partly because of the poor canopy cover and partly because most of them are flooded at least once a year (Table 1). Seeds, seedlings and litter are thus regularly washed out to the rivers. Their ground cover had the highest proportion of weeds (50%) of all clusters.

The cocoa stratum of AFS belonging to this cluster had the lowest density of cocoa trees (364 trees ha^{-1}) of all the clusters (Table 1). The proportion of short thin trunked cocoa trees was especially high but the cocoa trees were pruned twice a year and auto shading was much lower than in the other clusters (Table 1).

The canopy stratum had a higher density of associated plants (471 plants ha^{-1}) than in any other cluster and higher than the density of cocoa trees (364 trees ha^{-1}). The majority of the plants (60%) were small sized Musaceae (Table 1). In this cluster, the canopy stratum had the lowest proportion of trees (33%) and the lowest proportions of both tall (12%) and medium sized (12%) associated plants (Table 1). Overall shade (72%) was the lowest of all the clusters (Table 1). Finally, this cluster had the lowest diversity index (1.41) coupled with the highest equity index (0.38) (Table 1).

3.1.4. Complex and low density canopy AFS

The ground stratum of AFS belonging to this cluster had the highest proportion (3.96) of tree seedlings (Table 1), together with complex and high density canopy AFS (3.92). The main difference between this cluster and the high cocoa and high Musa density clusters was the high proportion of weeds (32%) which was the second highest among the clusters.

The cocoa stratum showed the second highest cocoa tree density (543 trees ha^{-1}) of all the clusters. In this cluster, cocoa trees were pruned regularly and for this reason were neither particularly small nor particularly tall (Table 1).

The canopy stratum had the second lowest density of associated plants (294 plants ha^{-1}). However, overall shade was among the highest (88%) of all the clusters (Table 1). Shade was mainly provided by a canopy stratum with three well represented layers. The plants associated with cocoa were mainly trees (67%) found in lower but nevertheless quite high proportions in the short (45%) and medium sized (19%) plant layers. They represented one of the highest proportions of all clusters in the upper layer (35%). This cluster also had the lowest equity index (0.17) and one of the highest (2.03) diversity indexes (Table 1), indicating a more diverse community of associated plants than in high cocoa and high Musa density AFS, and almost equivalent to complex and high density canopy AFS (Table 1).

3.2. Productivity

Table 2 shows our 36 cocoa-based AFS samples according to the productivity indicators. The estimated annual cocoa yield ranged

Table 1
Description of the vegetation structure patterns[a] (quantitative factors: means; qualitative factors: % of plots).

Vegetation structure patterns (number of cocoa agroforests)	Complex and high density canopy AFS (6)	High cocoa density AFS (11)	High Musa density AFS (10)	Complex and low density canopy AFS (9)	Overall (36)	F value (Df = 3)	χ^2 value (Df = 3)
Canopy compartment							
Mean number of associated plants per hectare	420.0ab	247.3c	471.0a	294.4bc	350.0	7.86**	
Mean basal area for associated plants (m^2)	1.36a	1.15a	0.80a	1.34a	1.97	1.35 NS	
Mean % of shade at 1 m height	92.74a	87.59a	72.08b	88.28a	84.31	18.23**	
Mean % of short associated plants [2.5–10 m]	62.48ab	25.89c	75.13a	44.53bc	50.33	22.09**	
Mean % of medium sized associated plants	27.21a	23.73a	12.26b	19.29ab	20.01	5.36**	
Mean % of tall associated plants [>20 m]	10.32b	46.39a	11.68b	35.36a	27.98	22.00**	
Mean % of Ligneous associated to cocoa	64.30b	85.75a	32.52c	67.44ab	62.81	24.16**	
Mean % of Musacea associated to cocoa	17.54b	9.48b	61.70a	17.61b	27.36	27.76**	
Mean % of Palmacea associated to cocoa	18.16a	4.77a	5.77a	14.95a	9.83	3.12*	
Diversity Shannon–Wiener index	2.06a	1.54bc	1.41c	2.03ab	1.71	6.21**	
Equity Simpson index	0.17b	0.30ab	0.38a	0.17b	0.27	6.38**	
Cocoa trees compartment							
Mean number of cocoa trees per hectare	543.3ab	692.7a	364.0b	558.9ab	543.1	6.90**	
Mean age of cocoa field (years)	18.00a	18.55a	31.20a	22.11a	22.86	1.76 NS	
Cocoa variety (% local vs introduced)	11.8a	23.5a	41.2a	23.5a	47.2	–	3.09NT
Cocoa propagation mode (% sown vs planted)	6.7a	40.0a	33.3a	20.0a	41.7	–	2.84NT
Mean % of short cocoa trees [<2.5 m]	9.17b	9.73b	37.10a	19.22b	19.61	6.20**	
Mean % of medium low cocoa trees [2.5–5 m]	50.67a	53.73a	50.20a	53.56a	55.25	0.89 NS	
Mean % of medium high cocoa trees [5–7.5 m]	36.17a	18.82b	11.30b	21.78ab	20.36	2.91*	
Mean % of high cocoa trees [>7.5 m]	3.83a	7.82a	1.70a	5.22a	4.81	0.42 NS	
Cocoa trees basal area (m^2)	0.91ab	1.39a	0.79b	0.88ab	1.02	2.84*	
Ground compartment							
Mean % of mosses and ferns ground coverage	8.88a	8.80a	5.41a	10.35a	8.26	1.13 NS	
Mean % of ligneous plant ground coverage	3.92a	2.48ab	0.62b	3.96a	2.57	8.55**	
Mean % of herbaceous plant ground coverage	23.37b	28.66b	49.52a	32.37ab	34.50	5.22**	
Mean % of soil litter ground coverage	63.01a	58.32a	44.43a	51.91[a]	53.64	2.16 NS	
Mean % of bare soil ground coverage	0.82a	1.74a	0.02a	1.42a	1.03	0.90 NS	

NS: non significant; NT: not tested (expected values under 5). Values in the same line with the same letters are not significantly different [LSD test at $p < 0.01$].
[a] Vegetation structure patterns obtained by cluster analysis of the 7 leading factorial coordinates calculated by multiple correspondence analysis. The first 7 dimensions on a total of 20 explained 64% of the variation.
* Significant at $p < 0.05$.
** Significant at $p < 0.01$.

from 50 to almost 300 kg ha^{-1} year^{-1} in dry weight, with an overall mean of 136 kg ha^{-1} year^{-1}. Estimated annual cocoa yield per tree ranged from 108 to 991 g tree^{-1} year^{-1} in dry weight, with an overall mean of 290 g tree^{-1} year^{-1}.

Finally, in our 36 cocoa-based AFS, fresh aboveground plant volume of associated plants and overall fresh aboveground plant volume ranged from 108 to 985 m^3 ha^{-1} and from 172 to 1037 m^3 ha^{-1}, respectively. The cocoa trees fresh aboveground plant volume ranged from 9 to 214 m^3 ha^{-1}, reflecting the range of densities for this stratum (Table 2).

Table 2 shows that there was no significant difference among the clusters in fresh aboveground plant volume, either in the cocoa stratum, the canopy stratum or in overall fresh aboveground plant volume (Table 2). Dry cocoa bean yield per ha was also statistically identical among clusters.

However, differences in dry cocoa bean yield per cocoa tree were highly significant ($p < 0.01$), and the highest productivity (455 g tree^{-1} year^{-1}) was in high Musa density AFS (Table 2).

We tested correlations between yield per cocoa tree and structural factors, and found that cocoa yield per tree decreased

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Table 2
Results of ANOVA conducted on cocoa yield and fresh aboveground plant volume for the four vegetation structure patterns[a] (mean values).

Vegetation structure patterns (number of cocoa agroforests)	Complex and high density canopy AFS (6)	High cocoa density AFS (11)	High Musa density AFS (10)	Complex and low density canopy AFS (9)	Overall ± SD (36)	Median [Min–Max] (36)	*F* value (Df = 3)
Productivity							
Estimated overall aboveground fresh plant volume (m^3 ha^{-1})	371.7a	406.4a	343.0a	464.4a	397.4 ± 190.2	356.1 [172.0–1036.8]	0.67
Estimated canopy aboveground fresh plant volume (m^3 ha^{-1})	331.7a	340.0a	314.0a	423.3a	351.2 ± 190.4	289.8 [107.8–985.1]	0.54
Estimated cacao aboveground fresh plant volume (m^3 ha^{-1})	41.7a	66.4a	29.0a	42.2a	46.1 ± 40.1	37.8 [8.7–214.4]	2.08
Dry cocoa yield (kg ha^{-1} $year^{-1}$)	105.67a	148.64a	147.30a	127.89a	136.02 ± 50.31	125.69 [56.25–295.69]	1.20
Dry cocoa yield per cocoa tree (g $tree^{-1}$ $year^{-1}$)	197.17b	235.27b	454.50a	237.11b	290.33 ± 176.11	248.05 [108.18–991.07]	5.52**

Values in the same line with the same letters are not significantly different [LSD test at $p < 0.01$].
[a] Vegetation structure patterns obtained by cluster analysis of the 7 leading factorial coordinates calculated by multiple correspondence analysis. The first 7 dimensions on a total of 20 explained 64% of the variation.
** Significant at $p < 0.01$.

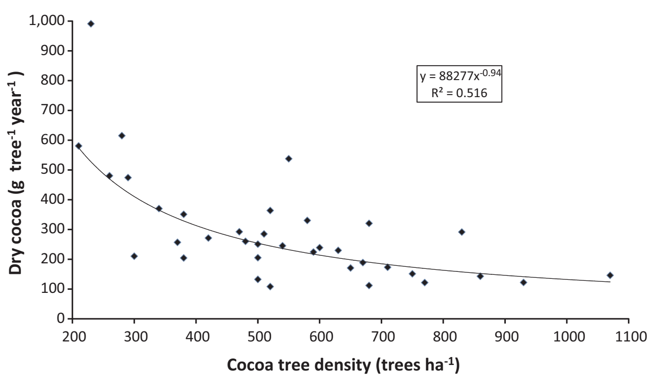

Fig. 1. Correlation between the annual cocoa yield per tree and the cocoa tree density in 36 cocoa-based agroforestry systems (Talamanca, Costa Rica).

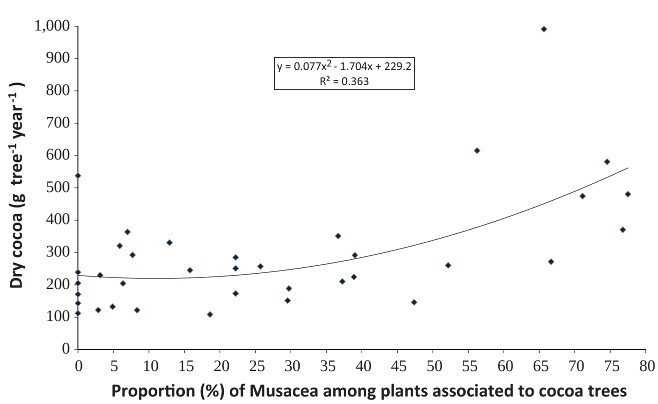

Fig. 2. Correlation between the annual cocoa yield per tree and the relative proportion of Musaceae among plants associated with cocoa in 36 cocoa-based agroforestry systems (Talamanca, Costa Rica).

with increasing density of cocoa trees (Fig. 1) and increased when the relative proportion of Musaceae in the agroforest was above 15% (Fig. 2). Correlations were also tested with palm trees and ligneous trees and no clear relations were found.

4. Discussion

4.1. Cocoa yield in our sample

All the cocoa-based systems that were selected in our 36 AFS sample could be considered as low-yielding in terms of cocoa productivity. In particular, yields appear to be below the average yields of full sun systems in cocoa producing regions in Africa, Asia and also Latin America. Many low-yielding cocoa AFS exist in the world and especially in Latin America, and even in major cocoa producing countries, where recent data showed that average cocoa yields based on 60 AFS samples were 456 and 214 kg ha^{-1} $year^{-1}$ in Ghana and Ivory Coast, respectively, (Gockowski and Sonwa, 2010). Similar values based on a sample of 800 cocoa-based AFS were found by Assiri et al. (2009) in Ivory Coast. Our sample of 36 AFS showed yields ranging from 50 to 296 kg ha^{-1} $year^{-1}$, with an average cocoa yield of 136 kg ha^{-1} $year^{-1}$. In common with most other tropical crops, the cocoa harvest is not limited to one short period, but is spread out over several months, with one or two peak harvest periods per year (Wood, 2001). In many countries, including in Costa Rica, some cocoa can be harvested all year round, outside peak periods. In Talamanca, the cropping pattern has two peak harvest periods per year (Somarriba and Beer, 2011) between April and June (minor peak) and between October and January (major peak). Records show that 70–80% of the annual crop is produced during these two peaks. The other 20–30% is produced outside the peak periods. As we only counted pods during these two peaks, we can assume that cocoa productivity was underestimated by about 20–30%. Finally, we assessed the cocoa yield based only on healthy pods and not overall pod production throughout the year. In our sample, losses due to frosty pod rot (*Moniliophtora roreri*) were about 35% on average (Avelino and Deheuvels, unpublished data) and can easily reach 87% in Talamanca (Krauss and Soberanis, 2002; Somarriba and Beer, 2011). As a consequence, real potential yield is not so low and is even comparable to West African yields, especially considering the high density of the canopy and the low density of cocoa trees in Talamanca compared to African orchards.

4.2. Aboveground plant volume, cocoa yield and structure clustered AFS

What we showed here is that for the same yield and fresh aboveground plant volume levels, significant differences in structure

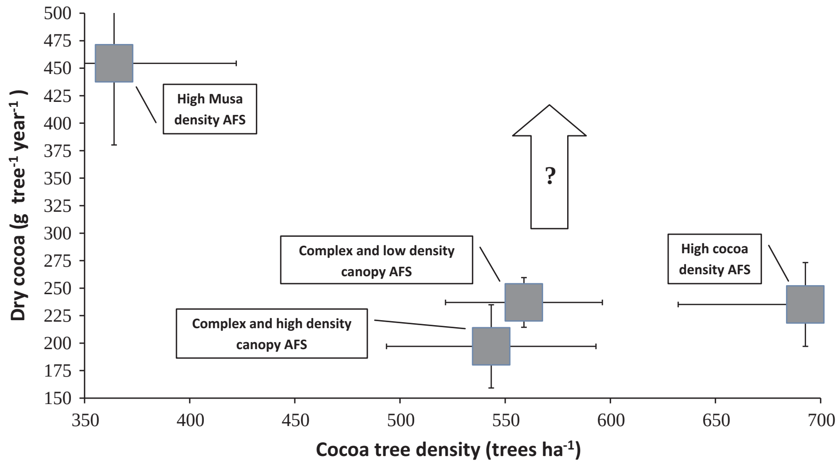

Fig. 3. The use of cocoa tree density as a structural indicator to evidence four situations of production where four significantly different structural clusters made of agroforestry systems (AFS) with equivalent plant volume and productivity levels per ha illustrate four different farmers' strategies.

reveal significant farmers' strategies regarding cocoa and regarding shade management of associated plants. Dry cocoa bean yields per ha did not statistically differ among clusters. This suggests that, despite significantly different structures, it is possible to maintain similar plant volume and yield levels. This first result opens the way to improve other ecosystem services, especially those linked with structure such as habitat quality for wild fauna and flora or water and soil conservation (Clough et al., 2009; Schroth and Harvey, 2007; Schroth et al., 2004). We can assume that if such a wide range of structure was evidenced in 36 cocoa-based agroforests, the range would even be wider in a larger sample and if sampling was extended to other regions.

Shaded crops, such as cocoa (*Theobroma cacao*), are managed by smallholders in 50 countries in the humid tropics of Asia, Africa, Central and South America (Franzen and Borgerhoff Mulder, 2007; Rice and Greenberg, 2000). In most cocoa producing countries, cocoa and associated crops are the main source of income for local indigenous and poor communities (Dahlquist et al., 2007). With a sustained increase in world chocolate consumption of 2–3% per year, and growing human populations in many of the cocoa producing regions, pressure to intensify cocoa production is likely to increase (Schroth and Harvey, 2007). However, links between cocoa productivity and vegetation structure are poorly described in the literature. Since the original structure-based analysis of a cocoa agroforest by Johns (1999), the structure of cocoa-based AFS has been described with increasing accuracy. Rice and Greenberg (2000) suggested classifying cocoa-based AFS in two groups with contrasting habitats for wild biodiversity: rustic or planted shade cocoa-based AFS. A third type, called "technified cocoa", consisting of monocrop and full sun cocoa plantations, was used as a control. The difference between the rustic and the planted shade types was mainly due to the lack of tall forest remnants in the latter. This paper paved the way for structural differentiation of cocoa AFS. Later, Somarriba and Harvey (2003) provided a more specific and detailed typology of the Talamanca region (Costa Rica): six types of cocoa-based agroforests were characterized based on the density of up to five species in three strata. Finally, Somarriba (2005) produced a theoretical combined representation of plant species, strata and densities per stratum. This last representation was the first to include a specific ground stratum from 0 to 1 m in height and is one of the most accurate proposal to characterize the variability of structure found in these AFS. Our work allows to confirm this representation with field data and to characterize with more precision the botanical composition, the strata organization and composition from the ground to the top of the canopy. Our work also highlights the missing relationship between structural variability and productivity.

In our sample, the description of the vegetation structure should be completed by some elements concerning the local context, in order to better link the observed structures with farmers strategies. The complex and high density canopy AFS cluster included typical hilltop cocoa agroforests. These are small plots, from 0.4 to 0.6 ha in size, located on steep slopes (16–35°) at altitudes between 250 and 400 m above sea level. These agroforests are found in remote places, and are often in direct contact with well conserved forest patches. They are poorly managed with one removal of young cocoa shoots by hand per year and no pruning, two sanitary harvests at the same time as the main two harvests and three to four weed removals with machete per year. The farmers' strategies regarding shade management in these AFS reflect this situation. The plots are heavily shaded, relatively younger and have a canopy mostly represented in the low and medium layers. They are difficult to access because they are located far away and on steep slopes. The harvest has to be carried on one man's back and this is the main reason why the plots are small and so diversified. Finally, the composition of the associated plant species is influenced both by the heavily forested landscape and the remote location of these plots which makes them hard to weed or prune frequently. Harvests from cocoa or associated plants can hardly be brought to markets and self consumption is the main explanation for the diversification level of these complex and high density canopy AFS.

The high cocoa density AFS cluster includes unpruned foothill cocoa agroforests. These plots are slightly bigger (0.2–1.0 ha) and are located on steep slopes (10–35°) at lower altitudes, between 150 and 300 m above sea level, and in a less forested landscape. They are managed in the same way as complex and high density canopy AFS except that young cocoa shoots are cut one more time per year. Farmers managing high cocoa density AFS have easier access to transport and to market. These AFS are more oriented towards cocoa production than complex and high density canopy AFS. They contrast with the high Musa density cluster which includes agroforests that are typical of lowlands and floodplains. They are the biggest plots (0.8–2.75 ha) and are located on flat lowlands at altitudes between 60 and 100 m above sea level. These agroforests are by far the most intensively managed in Talamanca. Cocoa and banana harvest can easily be transported by land or water to the market places and collecting network is organized (Dahlquist et al., 2007). Cocoa trees are pruned once or twice a year, during which young shoots are removed. Sanitary harvests are done two to three times a year and weeds are cut five times a year, mainly because

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these agroforests are more accessible and more frequently harvested than those in the other clusters, especially between the main harvests.

This confirms that these agroforests could be more appropriately described as banana-based agroforests, even if farmers call them cocoa fields. The negative relationship between cocoa yield per tree and the density of cocoa trees was expected as it is well known in monocropping systems. As described in Section 3.1, the high Musa density cluster had the lowest density of cocoa trees of all the clusters and its very dense canopy stratum included mainly Musaceae (60%). In this case, each individual cocoa tree produced almost twice as much as cocoa trees in other clusters. In this region, water is not a limiting factor. We can expect that two main factors may explain these results. First, the competition for nutrients between cocoa trees and between cocoa trees and associated plants is probably low. We can assume these plants do not compete for nutrients with cocoa as much as other plants, as they have no deep rooting system. Second, light availability for cocoa trees was probably higher in these systems as compared with complex AFS, as Musaceae and cocoa occupied almost the same stratum and the overstorey shade was light. The type of plant associated with cocoa trees in low density situations could play a mitigating role in the effect of density on cocoa yield per tree. Interactions between cocoa tree density and the proportion of Musaceae require further investigation to identify the exact effects Musaceae have on cocoa yield per tree.

The complex and low density canopy AFS cluster includes foothill cocoa agroforests that arevery similar to the high cocoa density AFS cluster in terms of bio-physical context, even if they are located slightly lower on the slopes. These AFS are slightly bigger than the high cocoa density AFS but are still small (0.25–1.25 ha) and are located on steep slopes (10–35°) at altitudes between 220 and 310 m above sea level. In terms of management, they differ from complex and high density canopy AFS and high cocoa density AFS because the cocoa trees are pruned twice a year. With an average of two sanitary harvests and four weed cuttings per year, agroforests belonging to this cluster are similar to those of complex and high density canopy AFS and high cocoa density AFS for these criteria.

Finally, the four clusters based on vegetation structure parameters can be compared for their average cocoa yield per tree using the cocoa density criteria as a vegetation structure indicator (Fig. 3). The arrow represents the potential for low yield per tree categories to shift to high yield per tree situations without affecting its overall productivity, possibly by spatially organizing and managing vegetal biodiversity associated with the cocoa trees.

5. Conclusions

Our study showed that cocoa agroforests within a restricted area can be separated into significantly different structural groups. These groups differ in a number of variables concerning the ground, cocoa and canopy strata. In spite of these differences, neither cocoa yield per ha, nor estimated aboveground fresh plant volume of the system were affected by this variability. This result highlights the different farmers' strategies that can be found in the same cocoa producing area. Farmers choose the mix of species they want to associate with cocoa trees according to their strategies and their choice does not affect the overall productivity of the system. Further investigations are needed to understand these farmers' strategies in which management of shade species plays a central role, and to link these strategies with ongoing investigations on shade management. Existing cocoa-based AFS in Central America need to be investigated to identify those that have a high density of cocoa trees and a high yield per tree. Identification of the factors involved in increasing cocoa yield per tree in AFS with a high density of cocoa trees is a key issue for the intensification of these systems.

Our results also throw a positive light on proposals to increase (rather than simplify) the vegetative complexity of cocoa AFS and to provide larger amounts of habitat for forest species without affecting the productivity of the main crop. Further efforts are needed to assess the effects of different botanical compositions of cocoa AFS when the density of cocoa trees remains stable. How structure can affect the impact of pests and diseases on cocoa productivity under different farmers' management strategies is still poorly known. The impact of frosty pod rot disease (*M. roreri)* on cocoa productivity could also vary with the degree of shade, the height of the cocoa trees, or even the botanical composition of the canopy layer.

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