



The spatial distribution and height of associated crops influence cocoa tree productivity in complex agroforestry systems

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Abstract

Knowledge is lacking on the effects of associated crops on cocoa productivity in complex cocoa-based agroforestry systems. Through a generalized linear mixed model, we analyzed the influence of (i) the density and (ii) the height of associated species on cocoa tree productivity along a distance gradient of 0 to 5 m between cocoa trees and associated plants. We mapped 34 mature agroforestry systems in farmers' plots to locate the position of different crop species in relation to each other. The production of each plant was monitored at fortnightly intervals over one year. The main results showed that cocoa tree productivity increased in the presence of *Fabaceae*, even when at a short distance (< 3 m), and to a lesser extent in the presence of timber trees. All the other species, i.e., food-producing trees, had a negative effect on cocoa productivity, which diminished with increasing distance up to a distance ranging from 3 to 5 m depending on the species. The height of associated plants also had a significantly negative effect on cocoa productivity at a distance of less than 3 m, beyond which the negative effect decreased. To our knowledge, it is the first study that finely analyzes the effect of associated crops on cocoa productivity according to farmers' use and for short distances. These results are of particular interest for the structural redesign of agroforestry systems, in order to optimize their agro-economic performance, and can be used to recommend the distance to be respected between cocoa trees and associated plants as well as the height of the different crops or forest trees.

Keywords Cocoa production · Spatial organization · Crop diversity · Tree height · Agroforestry system design

1 Introduction

Tropical agroforestry systems (AFS) are generally organized around a cash crop such as coffee, rubber, or cocoa that is often adapted to grow under shade (Seghieri and Harmand 2019). The associated crop species are usually varied and

are planted at lower densities (Deheuvels et al. 2012; Schneider et al. 2017; Jagoret et al. 2018). The diversity of the associated crop species provides a wide variety of products including food (Fig. 1), energy, construction materials, and medicinal products (Daily et al. 1997) that are grown by farm households either for self-consumption or for sale (Graefe et al. 2017; Jagoret et al. 2014; Rigal et al. 2018; Stroesser et al. 2018). Under certain density conditions and types of production, this diversity can insure the food safety of farming households (Mbow et al. 2014; Saj et al. 2017a). It also enables resilience in the face of climate hazards, such as hurricanes or severe drought, or economic events such as a sudden drop in the price of the main cash crop (Altieri et al. 2015; Jagoret et al. 2018; Lehébel-Péron et al. 2011; Saj et al. 2017b).

Yields of cash and associated crops vary widely between plots (Abdulai et al. 2018; Cerda et al. 2014), even though the structure of AFS itself does not vary much (Notaro et al. 2020). Likewise, at the within-plot scale, the productivity of neighboring cocoa trees can vary enormously (Fig. 1), from

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Fig. 1 Agroforestry system (upper photograph) showing the diversity and complexity of the systems, with banana trees in the lower stratum, cocoa trees in the middle stratum, and a mango tree in the upper stratum. Cocoa tree (lower photograph) in the foreground with many pods, while the cocoa trees in the background seem to have few pods.

zero to several dozen pods per cocoa tree per year (Wibaux et al. 2018). The same variability has also been reported for fruit crops associated with cocoa trees in AFS (Notaro et al. 2019) and may be due to variations in (i) plant material (genetic variability), (ii) soil or microclimatic conditions, or (iii) interactions between individual plants including allelopathic effects. Interactions between individuals can have a positive effect on their productivity (synergy effect) or a negative effect (competitive effect). They can be explained by the functional traits of crop species, defined as “morphological, physiological or phenological features measurable at the individual level, from the cell to the whole-organism level, without reference to the environment or any other level of organization” (Violle et al. 2007). For example, the vegetative height of the cultivated species influences the overall functioning of the system in relation to the canopy closure of the different species and the access of light to the plants in the lower strata (Garnier and Navas 2012). The tallest trees are much more competitive for light than species below (Coomes and Allen 2007). Indeed, the taller the trees, the larger the crown area (Tiralla et al. 2013), and the larger the crown area, the more shade is provided below (Asante et al. 2021). The intensity of

the effect of the trait on the functioning of the system is hypothesized to depend on the spatial arrangement of the individuals, i.e., on the distance between them (Damour et al. 2018; de Bello et al. 2010).

To our knowledge, yield variations in complex AFS linked to inter-species interactions at the within-plot scale have not yet been studied. A better understanding of these short distance responses would be useful (Fichtner et al. 2017), particularly to optimize the design of AFS (Simon et al. 2017) by choosing to associate certain species rather than others and by respecting the recommended distances between selected species to improve the agro-economic performance of AFS cocoa trees.

Our starting hypotheses are that each cultivated species in agroforestry systems positively or negatively affects the productivity of cocoa trees according to (i) the species or group of species and their specific functional traits, in our case the height of the trees and (ii) the distance between individuals. To test these hypotheses, we analyzed a wide range of spatial distributions of cocoa trees and associated species in AFS in farmers’ plots in the Dominican Republic.

We tested a mixed, functional, and spatialized approach to predicting the performance of AFS cocoa trees, in our case their production expressed in kilograms of fresh beans per tree. This allowed us to identify trade-offs between the agro-economic performance of the cocoa trees and the other cultivated species as a function of the proportion of each species in terms of plantation density. This mixed approach showed that respecting specific distances between individuals and maintaining a particular height of individuals of different species optimized the productions of complex AFS cocoa trees.

2 Material and methods

2.1 Location

The productivity of AFS cocoa trees in the Dominican Republic is estimated to be only half of their potential, on average 747 kg of dry bean ha⁻¹ (Berlan and Bergés 2011). The present study focused on a population of organic cocoa farmers belonging to two producer organizations, partners of the Cacao Forest project of which our research work was part of: the CONACADO cooperative and the FUNDOPO farmers’ association. Two areas with contrasting AFS structures (Notaro et al. 2020) were chosen: the province of San Cristobal, where AFS have a higher diversity of associated crops and a higher associated plants/cocoa trees ratio than in the province of Duarte. The province of San Cristobal accounts for only 1.7% of national production with an average yield of 557 kg dry bean ha⁻¹, while the province of Duarte accounts for 36.5% and an average yield of 681 kg dry bean ha⁻¹ (Deheuvels 2015; Berlan and Bergés 2011). The study

plots selected in the two areas therefore highlight the variability of species diversity of AFS, which was relevant for our study.

2.2 Experimental plots

The experimental plots were selected using purposive sampling (Ritchie et al. 2003) among reliable volunteer farmers, recommended by the two local partner organizations. In each of the two regions, 17 experimental plots with a surface area of 1000 m² (50 m × 20 m) were delineated in farmers' fields giving a total of 34 experimental plots monitored. An AFS belonging to each farmer was chosen, where the cocoa trees were considered to be “in full production” (generally between 7 and 10 years after plantation) with a relatively constant yield from 1 year to the next and that was easy to access (based on the farmer's knowledge). The experimental plots were located in an area considered to be representative of the selected AFS in terms of density and species diversity, preferably in the center of the AFS field to avoid edge effects. The experimental plots were representative of the diversity of Dominican AFS since they covered the entire typology of Dominican AFS (Notaro et al. 2020). The origin of the cocoa trees included in our study was as follows: 56% planted by the producer, 34% bought in nurseries, 9% spontaneous, and less than 0.3% whose sprout had been grafted with specific plant material (clone). The plots were managed without the use of chemical inputs, thus without fertilizers or pesticides. Cocoa trees were pruned once a year in July and August, after the main harvest period. The associated trees were generally not pruned, on the contrary.

2.3 Measurements in the experimental plots

The geospatial, morphological, agronomic, and economic variables of each plant in each experimental plot were measured

(Table 1). In each plot, the position of each plant was measured using a Cartesian coordinate system [X;Y] where X ranged from 0 to 50 m and Y ranged from 0 to 20 m. The positions were measured using 50-m and 20-m tape measures positioned on each side of the experimental plot. Orthogonal projections (with the eye) were made for each plant to determine its X and Y coordinates, requiring the work of three people: the first one designating the plant, the second one giving the X position, and the third giving the Y position. These coordinates made it possible to calculate the distance between two plants *i* and *j* according to the Pythagorean theorem:

$$Dist_{ij} = \sqrt{(X_i - X_j)^2 + (Y_i - Y_j)^2}$$

Plant height was estimated visually. With the agreement of each farmer, every 2 weeks from March 2018 to February 2019, we harvested the cocoa trees, and as far as possible also the associated plants in the experimental plots. The production of each individual tree was weighed or assessed for timber trees. Harvesting products other than cocoa was often complicated due to logistical problems: not having the appropriate equipment or simply because the product was sold to professionals, intermediaries for urban markets, who harvested it themselves. On each visit to the experimental plot, we asked the farmer if other products than cocoa had been harvested and, if so, the quantity harvested from each plant.

The fruit tree production (in kg tree⁻¹) and the number of boards in the case of timber tree were recorded, along with the economic value associated with the sale or self-consumption of these products (Table 1). The “global economic value” (GEV) is the economic value of the entire production of the plant, and therefore, it is the sum of the quantities sold, self-consumed, and lost for each plant. To calculate the cocoa income (CI), the average sale price for the year 2018 was used

Table 1 Variables measured for all plants in the 34 experimental plots.

Category	Variable	Abbreviation	Unit
Geospatial	X-axis coordinates	X	m
	Y-axis coordinates	Y	m
	Distance between plants <i>i</i> and <i>j</i>	Dist _{ij}	m
Morphology	Height	H	m
Agronomy	Production	Prod	kg tree ⁻¹ (fruit trees), board number tree ⁻¹ (timber tree)
	Stand density	d	Plant ha ⁻¹
	Economy	Global economic value	GEV
	Cocoa income	CI	US\$ ha ⁻¹
	Value of other products than cocoa	VOP	US\$ ha ⁻¹

(Ministerio de Agricultura 2019). For the estimation of the economic value of other products (VOP), we used the average values of farm gate prices in 2017 provided by the Ministry of Agriculture (Ministerio de Agricultura 2019). Quantities lost, i.e., fruit that had ripened and then rotted on the ground, were also recorded to estimate production losses. We measured economic performance per hectare (CI, VOP) for each of the thirty-four experimental plots, as in the following equations:

$$CI = \frac{a}{b} * \sum^i Prod\ cocoa\ tree_i \quad (1)$$

$$VOP = \frac{\sum^j (price_j * \sum^k Prod\ associated\ crop_{jk})}{b} \quad (2)$$

With:

- Parameter a is the average sale cocoa price in 2018, equal to 0.66 US\$ kg fresh bean⁻¹
- Parameter b is a factor allowing to switch from data measured on 1000m² to hectare, equal to 0.1
- i is the number of the cocoa tree
- j is an associated crop
- k the number of the plant from the associated crop j

2.4 Classification of crop species found in AFS

Groups belonging to different strata in the AFS were formed to facilitate further analysis. The groups were distinguished by the services provided and the functional traits of each. The size of each group had to be sufficient for statistical analysis. Seven groups were distinguished according to whether they are ligneous or not (Table 2): (i) among the ligneous plants, those that produce cocoa (COCOA), citrus fruits (CITRUS), and other fruits (FRUIT), those that fix atmospheric nitrogen (N-FIX), and those that provide timber (TIMBER) and (ii) among the non-woody plants, food plants (STAPLE) and *Musaceae* (BANANA). Each group contains species, and in the cocoa tree group (COCOA) even varieties, with similar morphological traits. As the morphological traits of all the citrus group (CITRUS) are very similar, they were put in a separate group from the other fruit trees (FRUIT); separation was also possible because the sample of citrus was big enough for statistical analysis.

2.5 Statistical analyses

2.5.1 Descriptive statistical analyses

To characterize Dominican AFS and their average agro-economic performance, descriptive statistical analyses were performed of the diversity and density of crop species, their

spatial distribution in the experimental plots, the production obtained from each, the quantities sold, self-consumed or lost, and the resulting global economic value (GEV) in each group (Parts 1 and 2 of the Results section).

2.5.2 Influence of the density and height of associated crops on cocoa productivity

The production of the cocoa trees was studied using two mixed models (GLMM) in version R 4.0.2 (R Core Team 2020). The first model accounts for the number of plants of each group growing in the 0–5-m vicinity of the cocoa trees (horizontal analysis model). The second model accounts for the cumulative height of the plants present in the 0–5-m vicinity, irrespective of the group (vertical analysis model). These two models are written as follows:

- (1) $Prod_{COCOA\ r} \sim (n_{COCOA} + n_{TIMBER} + n_{CITRUS} + n_{FRUIT} + n_{N-FIX} + n_{STAPLE} + n_{BANANA})_r + (1|plot)$
- (2) $Prod_{COCOA\ r} \sim (\sum_{i=0}^j H_i)_r + (1|plot)$

where n is the number of plants (counted for each group), H is the height of the plant, r is the concentric circle around the cocoa tree whose production is being analyzed (0 to 1 m, 1 to 2 m, 2 to 3 m, 3 to 4m, 4 to 5 m), j is the number of plants in the concentric circle r , and $1|plot$ is the plot-related random effect.

This approach makes it possible to identify positive or negative effects on the cocoa production with different groups of plants, depending on their number and height, and on their distance from the cocoa tree (Fig. 2). The correlations between plant production and the other variables measured were analyzed using the “corrplot” package (Wei and Simko 2013). The mixed model explaining cocoa production as a function of distance from other groups of species, and the height of these species, was studied using the “lmer” package (Bates et al. 2015).

3 Results

3.1 Diversity, density, and spatial arrangement of crop plants in AFS

Average crop density was 1223 plants ha⁻¹ (Table 2). Cocoa trees are the main plants in the Dominican agroforestry systems with an average of 860 cocoa trees ha⁻¹, i.e., 70% of total plant density. Next come non-ligneous plants (NLP) with an average of 202 plants ha⁻¹, of which 124 plants ha⁻¹ are food crops such as yam, pineapple, or taro (STAPLE) and 78 plants ha⁻¹ are *Musaceae* (BANANA). The average density of associated trees (AT) was 161 trees ha⁻¹, of which 50 trees ha⁻¹ were citrus (CITRUS), 60 trees ha⁻¹ were other fruit trees

Table 2 Total number of individuals in the study, heights and densities of cocoa trees and associated crops, distributed in three strata and seven crop groups in all 34 experimental plots in the regions of Duarte and San Cristobal.

Stratum	Group	Species	Common name	Total number of individuals	Mean height H in m (\pm SD)	Mean density plants ha ⁻¹ (\pm SD)
Cocoa Main cash crop	COCOA	<i>Theobroma cacao</i>	Cocoa	2926	5.1 (\pm 2.5)	860 (\pm 102)
AT (Associated Trees) Stratum of plants most taller than cocoa trees	N-FIX Nitrogen-fixing plants	<i>Erythrina poeppigiana</i> <i>Gliricidia sepium</i> <i>Acacia mangium</i> <i>Tamarindus indica</i> <i>Cassia fistula</i>	Erythrina Gliricidia Acacia Tamarind Golden shower	48 33 1 1 1	23.7 (\pm 13.7)	25 (\pm 25)
	TIMBER	<i>Roystonea hispaniolana</i> <i>Colubrina arborescens</i> <i>Cedrela odorata</i> <i>Nectandra hihua</i> <i>Simarouba glauca</i> <i>Hura crepitans</i> <i>Swietenia macrophylla</i> <i>Spiroteca rubriflora</i> <i>Guazuma tomentosa</i> <i>Cupania americana</i> <i>Swietenia mahagoni</i> <i>Ocotea floribunda</i> <i>Karwinskia caloneura</i> <i>Chrysophyllum argenteum</i>	Royal palm Greenheart Cuban cedar Cigua Paradise-tree Possumwood Mahogany Capá Guacimo Guara Cuban mahogany Laurel espada Cuerno de buey Caimito de mono	40 11 9 9 4 3 2 2 2 2 1 1 1 1	17 (\pm 9.2)	26 (\pm 14)
	CITRUS	<i>Citrus sinensis</i> <i>Citrus aurantium</i> <i>Citrus paradisi</i> <i>Citrus reticulata</i> <i>Citrus latifolia</i>	Sweet orange Bitter orange Grapefruit Tangerine Lime	98 44 14 11 1	6.3 (\pm 2.7)	50 (\pm 26)
AT (Associated Trees) Stratum of plants most taller than cocoa trees	FRUIT Non-citrus fruit trees	<i>Persea americana</i> <i>Coffea arabica</i> <i>Pouteria sapota</i> <i>Artocarpus altilis</i> <i>Annona muricata</i> <i>Bixa orellana</i> <i>Mangifera indica</i> <i>Carica papaya</i> <i>Cocos nucifera</i> <i>Artocarpus communis</i> <i>Anacardium occidentale</i> <i>Psidium guajava</i> <i>Spondias mombin</i> <i>Pimenta racemosa</i> <i>Annona reticulata</i> <i>Genipa americana</i> <i>Blighia sapida</i> <i>Annona cherimola</i> <i>Malpighia emarginata</i> <i>Chrysophyllum cainito</i> <i>Crescentia cujete</i> <i>Melicoccus bijugatus</i> <i>Spondias cytherea</i> <i>Moringa oleifera</i>	Avocado Coffee Sapotilla Breadfruit Soursop Achiote Mango Papaya Coconut Breadnut Cashew Guava Yellow mombin Bay rum tree Anona Genip Ackee Cherimoya Acerola cherry Caimito Calabash Quenepa Ambarella Moringa	40 30 27 17 11 11 10 9 8 8 6 5 5 3 3 2 2 2 1 1 1 1 1	11.8 (\pm 9.0)	60 (\pm 47)

Table 2 (continued)

Stratum	Group	Species	Common name	Total number of individuals	Mean height H in m (\pm SD)	Mean density plants ha ⁻¹ (\pm SD)
NLP (Non-ligneous plants) <i>Stratum of plants most shorter than cocoa trees</i>	BANANA	<i>Musa acuminata</i> AAA	Dessert banana	166	2.5 (\pm 1.7)	78 (\pm 38)
		<i>Musa acuminata</i> X	banana	65		
		<i>balbisiana</i> AAB	Plantain	33		
		<i>Musa acuminata</i> X	banana			
	STAPLE	<i>balbisiana</i> ABB	Rulo			
		<i>Xanthosoma sagittifolium</i>	American taro	313	0.5 (\pm 0.2)	124 (\pm 85)
		<i>Ananas comosus</i>	Pineapple	76		
		<i>Dioscorea alata</i>	Pineapple	28		
		<i>Manihot esculenta</i>	Yam	2		
		<i>Zingiber officinale</i>	Cassava	1		
<i>Cucurbita maxima</i>	Ginger	1				
		Squash				

(FRUIT), 26 trees ha⁻¹ were timber trees (TIMBER), and 25 trees ha⁻¹ were from Fabaceae family (N-FIX). The variability of the density of each group of associated species in the 34 experimental plots is presented in Fig. 3. A very high variability is observed especially for the groups with a food production value.

There is a great variability in the diversity of the associated crops and the spatial arrangements of these species among the 34 plots monitored (Supplementary material S1). For example, in the last plot in the second row of the supplementary material S1, there is a strong association of fruit trees (FRUIT), while more nitrogen-fixing trees (N-FIX) are observed in the second plot in the third row, and more citrus trees (CITRUS) in the last plot in the fourth row. Some plots contained different staple crops (STAPLE) planted in rows

between the cocoa trees like in the fourth plot in the third row, while in others there was a relatively large space between cocoa trees and—for example—timber trees (TIMBER) like in the last plot in the third row. *Musaceae* (BANANA) are sometimes grouped together in the same part of the plot as can be seen in the third plot in the fourth row.

3.2 Varying inter-species and inter-group agro-economic performances

The average annual productions per plant of the different AFS species varied greatly (Fig. 4A and B). The cocoa trees produced an average of 2.08 kg of fresh cocoa beans per tree per year, i.e., just over 17 pods, but with very high variations (SD of \pm 2.75 kg fresh cocoa bean per tree and \pm 23 pods tree⁻¹).

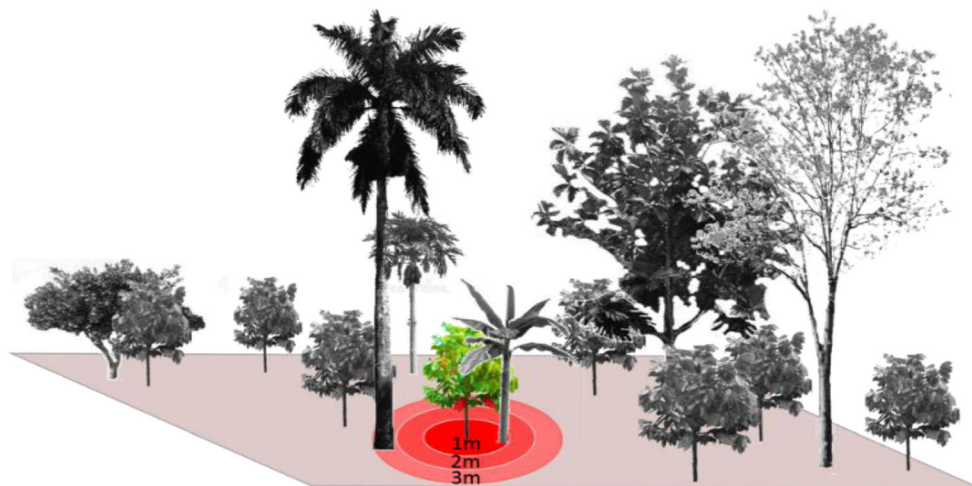


Fig. 2 Representative diagram of a portion of an experimental plot to help visualize the analysis performed with mixed models to explain cocoa yield as a function of distance from neighboring plants. If the lower edge of the diagram corresponds to the edge of the experimental plot, then the yield of the colored cocoa tree can only be used in the model

for the concentric circles with a radius r of 0 to 1 m, 1 to 2 m, and 2 to 3 m. Within a radius of 1 m only, *Musaceae* (BANANA) is integrated in the model; in the following concentric circle (1 to 2 m), no plant is integrated in the model; in the following concentric circle (2 to 3 m), the palm tree is integrated in the model.

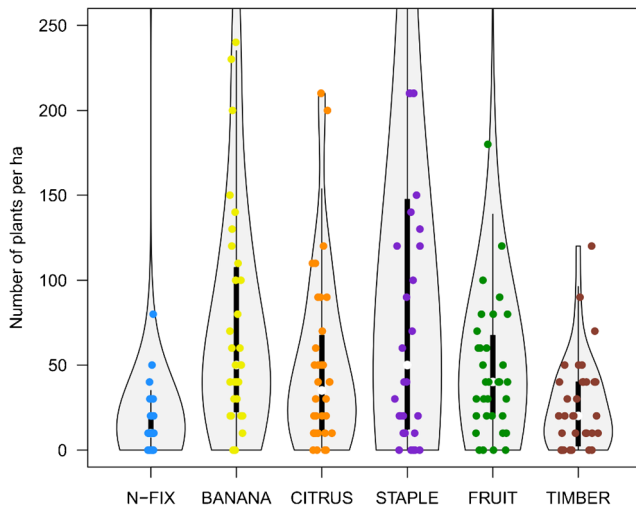


Fig. 3 Distribution of the density of associated plants in each studied plot.

The entire production of cocoa is sold, which is not usually the case of associated crops.

Large fruit trees, sometimes several dozen meters tall, such as the mango (H_{\max} around 25 m), breadfruit and breadnut (H_{\max} around 30 m) produce relatively large quantities of fruit, ranging from 30 to 140 kg tree⁻¹ y⁻¹. Smaller ligneous and staple crops produce smaller productions of between 0.5 and 2 kg plant⁻¹ y⁻¹. Citrus trees and *Musaceae* produce on average between 2 and 7 kg.plant⁻¹ y⁻¹.

Useable production, consumed directly by the farmer and his family or sold, was not the same among the species. Mango, breadfruit, breadnut, quenepa, coconut, tangerine, grapefruit, lime, and yam provide products that are highly valued in the diet of the producer and his family. There are markets for specific species such as breadfruit, genip, coconut, avocado, orange (bitter and sweet) and banana.

Production losses of associated plants were high and accounted for 41% of total production (kg), but only 20% of total potential global economic value (GEV0 (US\$ ha⁻¹)) (data not shown). Indeed, quantitative losses of mango, breadnut, quenepa, mombin, and ambarella are important but are of low economic value due to their low sales prices.

COCOA, CITRUS, FRUIT, BANANA, STAPLE provide food services, TIMBER trees produce construction or craft materials, N-FIX fixes nitrogen. All species in the CITRUS and BANANA groups were productive, which was not the case for the TIMBER, STAPLE, and FRUIT groups, where 12.5%, 50%, and 68% of the species were productive, respectively (Table 3). The majority of associated plants and 19% of the cocoa trees produced no products.

The group with the highest proportion (81%) of productive plants was COCOA. The average GEV generated by productive cocoa trees was US\$1.7 tree⁻¹ y⁻¹ (Table 3). The proportion of productive citrus (CITRUS) and other fruit trees (FRUIT) were 41% and 43%, respectively, higher than the

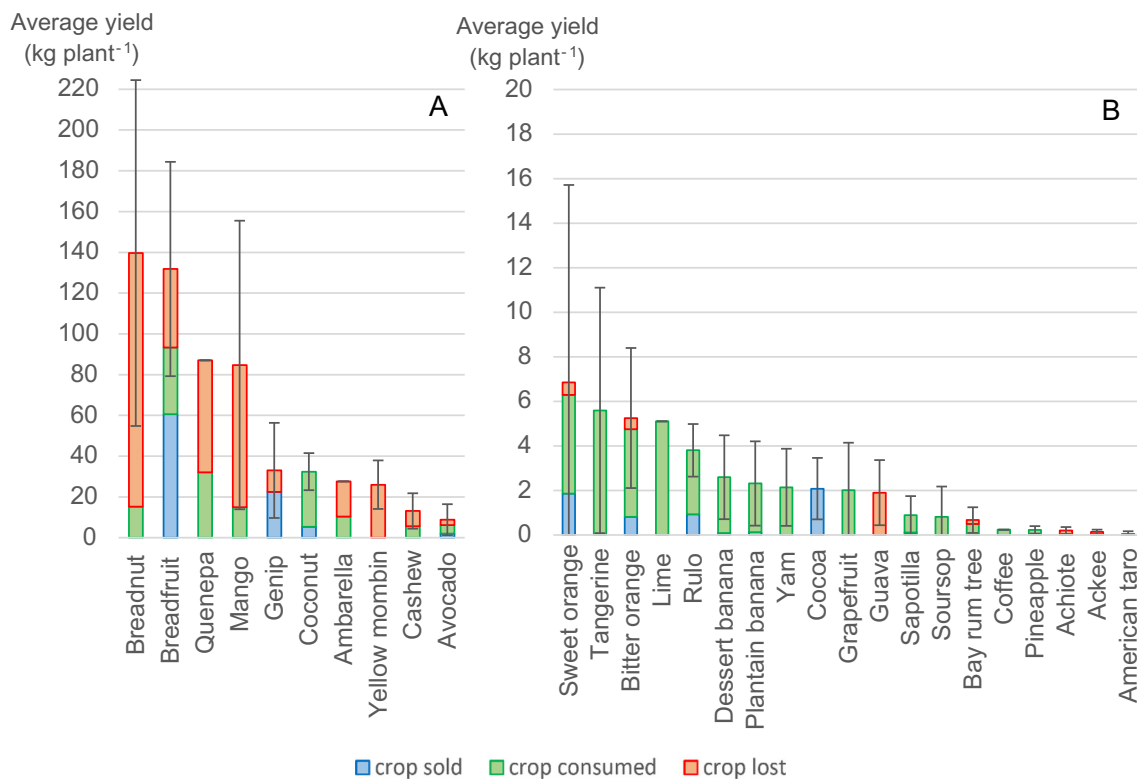


Fig. 4 Average annual yield per species, measured or estimated across all experimental plots, ranked in decreasing order: graph A for crops with a yield > 10 kg plant⁻¹ and graph B for crop with a yield < 10 kg.plant⁻¹.

The absence of error bars means the measurement was taken on a single plant. For timber trees, as we did not know the yield per unit weight, timber trees are not included.

Table 3 Number of species and individual plants as a function of their total number and the number of productive individuals as well as average annual global economic value (GEV) for each of the seven groups.

Group	Total number of species	Number of productive species	Total number of plants	Number of productive plants	Proportion of productive plants	Average GEV per productive plant per year
COCOA	1	1	2,926	2,375	81%	1.7 US\$ tree ⁻¹ y ⁻¹
CITRUS	5	5	168	69	41%	5.9 US\$ tree ⁻¹ y ⁻¹
N-FIX	4	0	83	0	0%	-
FRUIT	25	17	206	88	43%	5.3 US\$ tree ⁻¹ y ⁻¹
TIMBER	16	2	89	7	8%	20 US\$ tree ⁻¹ y ⁻¹
BANANA	3	3	264	71	27%	2.2 US\$ plant ⁻¹ y ⁻¹
STAPLE	6	3	421	47	11%	1.1 US\$ plant ⁻¹ y ⁻¹

proportion of productive non-ligneous plants (BANANA and STAPLE), which were 27% and 11%, respectively. Over the year, 8% of timber trees (TIMBER) were cut. Timber trees have the highest GEV per unit compared to the other crops. The average value of the production of citrus and other fruit trees were US\$5.9 and 5.3 tree⁻¹ y⁻¹, respectively, while the GEV of the non-ligneous plants in the lower stratum was between US\$1.1 and US\$2.2 plant⁻¹ y⁻¹.

3.3 Determinants of agro-economic performance

The densities of plants in the different strata (dNLP, dCOCOA, and dAT) did not influence the economic performances of cocoa or associated crop products in the same way:

- dNLP did not influence either the cocoa Income (CI) or the value of other products (VOP) (Fig. 5A).
- dCOCOA did not really influence the CI, but had a negative influence on the VOP, although the correlation was weak (Fig. 5B).
- dAT implies a trade-off, as it had a positive impact on the VOP but a negative impact on the CI (Fig. 5C);

The trade-off between cocoa trees and associated trees is further illustrated by considering the CI and VOP as a function of the proportion of cocoa trees among the ligneous plants (Fig. 5D). This suggests there may be competition related to the distance between plants, since by increasing the density, the average distance between plants decreases. It is this important trade-off that led us to examine more closely the effect of the density and height of plants associated very closely (< 5 m) with cocoa trees on their productivity.

There were two categories of associated species groups: the first had a positive effect on cocoa productivity (N-FIX and TIMBER groups), while the second had a negative or no effect (STAPLE, COCOA, BANANA, CITRUS, and FRUIT groups), within a radius of 5 m (Fig. 6A). Except for the TIMBER group in the 0–1-m radius (p value = 0.697), all

predictors were highly significant (p value < 0.001) (except STAPLE group in 1–2-m radius with p value = 0.025). With the exception of the TIMBER group where the positive effects on cocoa productivity were apparent at greater distances between cocoa trees and timber trees, there was generally a gradual reduction in the positive and negative effects with increasing distance between the cocoa tree and the associated plants. At < 1-m distance from the cocoa tree, the presence of a tree in the N-FIX group led to an increase of + 0.33kg plant⁻¹ y⁻¹ in cocoa production. At a distance of 4 to 5 m, the positive effect was + 0.13kg plant⁻¹ y⁻¹. On the other hand, citrus trees had a strongly depressing effect on cocoa production when planted < 1 m from the cocoa tree causing a decrease of - 0.5kg plant⁻¹ y⁻¹, but the effect decreased with distance to - 0.08 kg plant⁻¹ y⁻¹ at 4- and 5-m distance.

The result of the cumulative height effect model was not significant within 1-m distance from the cocoa trees with a p value of 0.43 (dashed line in Fig. 6B). At larger distance (1 to 3 m), cumulative height of associated crops had significant negative effects on the cocoa production per tree, and then, this effect decreased (3 to 5 m). For example, with no tree taller than the cocoa tree in the 1- to 2-m concentric circle, the production of the cocoa tree was 2.1 kg plant⁻¹ y⁻¹. However, if trees in the same space were taller than the cocoa tree and the cumulative height above the cocoa tree reached 10 m, the cocoa production decreased by about 33% to only 1.4 kg plant⁻¹ y⁻¹.

4 Discussion

4.1 Significant variability in productions and uses between groups of species

The low proportion of the non-ligneous crops that was productive can be explained by (i) plants that were unable to complete their production cycle because they were not suitable for the plot environment (soil properties, luminosity); (ii) injuries caused by animals, such as taro stems pecked by

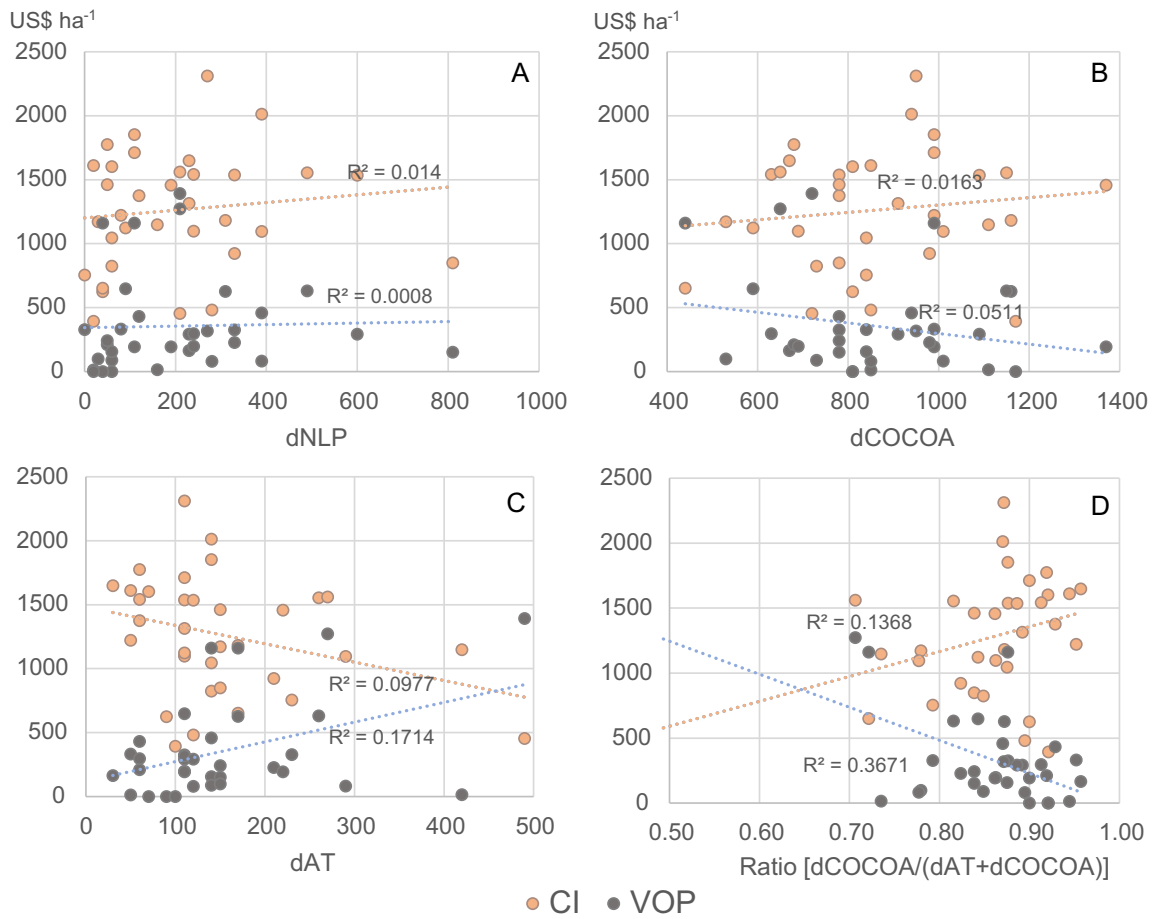


Fig. 5 Relationship between cocoa income (CI, in orange) and the economic value of other products' income (VOP, in gray) with (i) density of non-ligneous plants dNLP (A), (ii) density of cocoa trees

dCOCOA (B), and (iii) density of associated trees dAT (C) and (iv) proportion of cocoa trees among all ligneous plants (D).

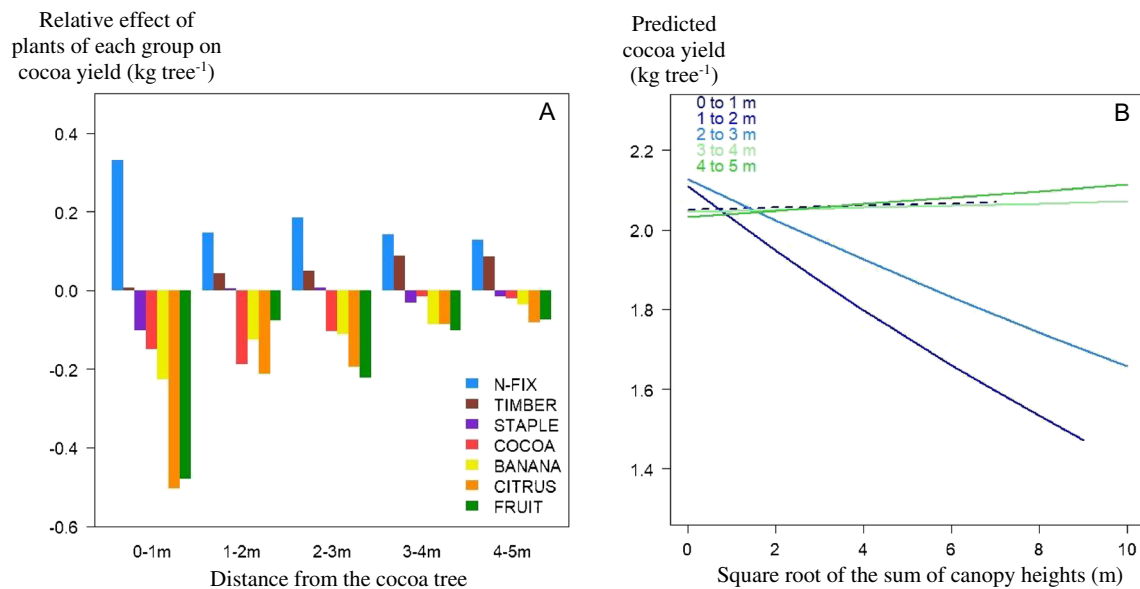


Fig. 6 Effect on the productivity of cocoa trees at concentric radius distances of 1 to 5 m of A species groups and B cumulative height of associated plants. The dashed line means that the effect of height is not significant in a radius of 0 to 1m.

chicken that roam freely in the plots (personal communication from producers); or (iii) unsuitable management practices. In addition, the lack of connection to markets for products other than cocoa does not necessarily lead farmers to replace certain low-yielding plants, as long as they provide sufficient quantities to feed the farming family.

A higher production rate, on average 42%, was observed for the FRUIT and CITRUS groups, but more than half of these trees were not productive. Possible explanations are that these trees are either not suitable for the environmental conditions, or are diseased and/or ageing; however, a biennial alternation factor, where the tree produces fruit every other year due to physiological regulation processes (Sharma et al. 2019), cannot be excluded. Indeed, some farmers told us that whereas no fruit was harvested in our study year, some trees had been very productive in the previous year, particularly avocado, citrus, and mango trees (Boulay and Mainié 1966; Monselise and Goldschmidt 2011). Moreover, although the proportion of productive fruit trees was half as high as the proportion of productive cocoa trees, these trees still provided on average the best plant economic value. One might think it would be advantageous to plant more citrus or other fruit trees to replace cocoa trees, but (i) the difficulty and time required to harvest these trees and (ii) the greater space requirement of these species compared to cocoa trees have to be taken into account. In addition, the sale of some fruit crops (e.g. breadnut, quenepa, mango, ambarella, mombin among others) is sometimes not possible due to lack of commercial contacts. Farmers consume a part of the fruit they produce themselves but are sometimes unable to market what they do not consume. These products then end up rotting in plots, which reduced the economic value of these associated species for farm households (Leakey et al. 2005; Lombard and Leakey 2010). It would be interesting to analyze the role these fruits and their rotting in the field play in ecosystem functioning. It is likely that they increase biodiversity, particularly that of certain decomposers, probably improving certain ecosystem functions, e.g., soil fertility through the supply of organic matter.

For timber trees, the fact that 8% were logged in our study is a bonus. Even though timber generally has much higher added value than fruit production (Cerdea et al. 2014), it can be seen here that the profit per cut tree corresponds to only four years of average production of a productive fruit tree. This is not much, but can be explained by the fact that the wood cut was intended for relatives of the farmers who owned the trees and was therefore sold at a much lower price than if it had been marketed to a timber company (Somarriba et al. 2014).

4.2 Cocoa production influenced by neighboring plants

The greater the distance between a cocoa tree and its neighboring plant (cocoa tree or other), the higher its cocoa production. The model simulating the influence of a given group of

species on cocoa production according to the distance between plants allowed us to refine the analysis. The food production groups (FRUIT, CITRUS, COCOA, BANANA, STAPLE) were seen to be responsible for the positive relationship between the distance to the cocoa tree and cocoa production. This suggests competitive phenomena between plants when they are located close together either for access to water and soil nutrients (Niether et al. 2019), for access to light (Charbonnier et al. 2013) or of crowding of the space between crowns (e.g., between cocoa and citrus trees) which is possible given the higher average height of FRUIT and to a lesser extent, of CITRUS compared to the CACAO group. The N-FIX and TIMBER groups had a positive effect on cocoa production, as already suggested by Bos et al. (2007), and demonstrated by Somarriba and Beer (2011), probably because the functional traits of these two groups of species are particularly dissimilar to those of the cocoa tree (Sauvadet et al. 2020). This effect was particularly strong when the legume grew close to the cocoa tree. This result suggests the possibility of (i) facilitation, via the supply of nitrogen made assimilable to the cocoa tree roots by N-FIX from leaf litter fall and root turnover mineralization (Kaba et al. 2019; Nygren and Leblanc 2015); or (ii) niche complementarity (Yang et al. 2020; Duchene et al. 2017; Rowe et al. 2001; Willey 1990), e.g., in the exploration of different soil horizons by TIMBER and COCOA roots; or (iii) reverse or non-concurrent phenology (Roupsard et al. 1999), e.g., the erythrin (N-FIX tree) loses its leaves when cocoa trees need light to limit the appearance of brown rot fungus during growth and maturation of pods from December to April.

Above a certain threshold of intensity and covering, the shading provided by the associated trees has a considerable impact on the cocoa tree yield (Vanhove et al. 2016; Middendorp et al. 2018). Of course, this shading is partly a function of the height of the trees, as presented in the introductory section. However, beyond this morphological characteristic, functional traits related to the foliage will influence the quality of the shading (Kyereh 2017), as leaf area index or specific leaf area for example. Therefore, further studies on the impact of groups of shade trees sharing similar foliar functional traits on the shade provided to cocoa trees and their yields, rather than “use” groups, would be particularly valuable.

Finally, neither the agronomic and morphological characteristics nor the competition or facilitation of plant communities in the neighborhood of the cocoa tree are enough to explain all the variations in cocoa production. These variations are also linked to genetic factors, with certain genes involved in the formation of cocoa production (Fernandes et al. 2020), that are more or less active depending on soil and climate conditions. Indeed, within the same plot, we observed significant differences in productivity between cocoa trees of the same origin, whether directly sown using beans from own pods or cocoa clones produced in the nursery.

4.3 An interesting starting point for AFS structural design

Given the much higher proportion of productive cocoa trees compared to other associated species across all other groups (81% vs. 23%), monospecific cocoa cropping systems could be envisaged. However, many studies have demonstrated the value of maintaining plant biodiversity in cropping systems (Santos et al. 2019). The increase in biodiversity in AFS favors, for example, the provision of pest control services (Loguercio et al. 2009; Medeiros et al. 2010), or supporting services such as recycling of soil nutrients (Rousseau et al. 2012; Schwendenmann et al. 2010; Torralba et al. 2016). Biodiversity also makes it possible to increase global production services, or agro-economic performance, compared to monoculture or less diversified systems (Schneider et al. 2017; Salazar-Díaz and Tixier 2019). More simply, to improve the production of these systems, remove trees that are currently unproductive and replant them with plants that are better able to grow and produce in this environment. Alternatively, rehabilitation of some trees may be envisaged, through rejuvenation pruning or grafting of adapted and productive genetic material on shoots or branches (Djuideu et al. 2021).

The results of our study offer decision rules for the design of spatially optimized AFS, (i) horizontally, with distances to be respected between individuals, and (ii) vertically, with maximum heights to be respected, depending on the distance from the cocoa tree. We arbitrarily set a threshold of negative effect lower than $-0.1\text{kg plant}^{-1}\text{y}^{-1}$ on cocoa production to determine the plot spacing between a cocoa tree and associated species (according to its group). Other analyses suggest a minimum distance of 6.5 m between cocoa trees and orange or avocado trees, corresponding to the inflection point of the logistic functions tested (Koko et al. 2013).

In the same way, we recommend pruning to limit the height of associated trees, as already suggested by Tschamtké et al. (2011), growing less than three meters from a cocoa tree. Strong pruning of trees growing a distance of less than 2 m so the cocoa trees are not under the shade of neighboring trees, a little less pruning between 2 and 3 m, as the model showed a weaker effect at this distance (Fig. 6B). This involves rigorous inter-species spatial arrangements at planting or during rehabilitation of the AFS. Then, when the AFS is developing, pruning should maintain the species at the specified height, especially N-FIX and TIMBER, if planted within 3 m of a cocoa tree. From a practical point of view, if timber trees have a commercial use, a certain spatial configuration should be considered. A slightly wider row should be left for timber trees only to facilitate the logging and extraction of timber for commercial purposes. Indeed, when a timber tree is logged, if it is growing within a short distance of the cocoa tree, the cocoa tree will inevitably be damaged. However, Ryan et al.

(2009) demonstrated that the selling price of the timber can offset the cocoa production losses caused by damaged cocoa trees.

These agroforestry systems are complex and host a significant diversity of crop species that provide most of the basic products required by the farm household (Mbow et al. 2014; Cerda et al. 2014; Kiptot et al. 2014). Although FRUIT, CITRUS, and BANANA have a negative effect on cocoa tree productivity when planted too close, their production can to some extent provide economic compensation for the loss of cocoa (Armengot et al. 2016). In our study, the highest overall incomes (CI+VOP) were observed when the density of the associated trees was 100 to 300 ha^{-1} and the density of the cocoa trees was 600 to 1000 ha^{-1} , i.e., the proportion of cocoa trees ranged from 70 to 90% (data not shown), as we demonstrated in a previous study that combined interviews and field surveys (Notaro et al. 2020).

If the effect of the groups of species on cocoa productivity was additive, then cocoa systems with high densities of N-FIX and TIMBER could be designed as they positively influence cocoa productivity. However, from a practical point of view, this is impossible since unless they are pruned regularly, these trees are voluminous. Also, above a certain density of association, competition probably replaces facilitation. In any case, this is what Canham et al. (2004) showed with other types of indicators of neighbor competition in temperate forests, where density has a more negative impact on growth performance than shade.

Forming groups of species enabled us to perform robust statistical analyses, but it is important to note that our groups contained a variety of species with sometimes very different characteristics, particularly within the FRUIT, TIMBER, and N-FIX groups. Indeed, the choice of species to be associated with cocoa trees should be systemic to favor species that are not competitive but rather facilitator (Hombegowda et al. 2020), and preferably that provide useful products for farm households. Analyses of groups comprising only functional species, with the species in each group sharing several common traits, leading to a larger sample than in our study would make it possible to considerably refine these results. Not only for the analysis on cocoa productivity, but also for the other groups, making it possible to recommend more reliable spacing distances between species.

5 Conclusion

The structural and functional diversity of Dominican AFS, linked to the species diversity and the spatial arrangement of the different crops, results in significant differences in production between associated crops. The scientific literature largely demonstrates the relevance from an economic point of view of the association of species in agroforestry systems. Our research brings novelty in the way that we show that certain

species are to be favored more than others in the direct vicinity of cocoa trees. Competition, which has a negative influence on cocoa tree productivity, was particularly marked in species whose production is intended for food (FRUIT, CITRUS, COCOA, and BANANA) when they are planted less than 3–4 m from the cocoa tree. However, some trees (N-FIX, TIMBER) have a favorable influence on cocoa trees even at less than 3 m. Within this distance, it is preferable to prune at least the species with a production purpose so that they do not grow taller than the cocoa trees to avoid heavy shading that negatively affects cocoa production. These results offer good prospects for the design of innovative AFS at a spatial scale, both in the horizontal dimension—with the choice and arrangement of the cultivated species in relation to each other—and in the vertical dimension, with the use of pruning for some crop species. The temporal scale is also an essential aspect in the functioning of these complex AFS that mix very diverse species, ligneous or herbaceous, perennial or annual, fast or slow growing, and voluminous or not as recently proposed by Schwarz et al. (2021) as a conceptual framework. Additional studies of the temporal scale would complete our work on the spatial scale and make it possible to suggest specific techniques for the dynamic management of AFS.

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Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Code availability Not applicable.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethics approval Not applicable.

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Consent for publication Not applicable.

References

- Abdulai I, Jassogne L, Graefe S, Asare R, Van Asten P, Läderach P, Vaast P (2018) Characterization of cocoa production, income diversification and shade tree management along a climate gradient in Ghana. *PLoS One* 13(4):e0195777. <https://doi.org/10.1371/journal.pone.0195777>
- Altieri MA, Nicholls CI, Henao A, Lana MA (2015) Agroecology and the design of climate change-resilient farming systems. *Agron Sustain Dev* 35(3):869–890. <https://doi.org/10.1007/s13593-015-0285-2>
- Armengot L, Barbieri P, Andres C, Milz J, Schneider M (2016) Cacao agroforestry systems have higher return on labor compared to full-sun monocultures. *Agron Sustain Dev* 36(4):70. <https://doi.org/10.1007/s13593-016-0406-6>
- Asante WA, Ahoma G, Gyampoh BA, Kyereh B, Asare R (2021) Upper canopy tree crown architecture and its implications for shade in cocoa agroforestry systems in the Western Region of Ghana. *Trees, Forests and People* 5:100100. <https://doi.org/10.1016/j.tfp.2021.100100>
- Bates D, Maechler M, Bolker B, Walker S (2015) lme4: linear mixed-effects models using Eigen and S4. R package version 1.1-8, <http://CRAN.R-project.org/package=lme4>
- Berlan A, Bergés AR (2011) Cocoa production in the Dominican Republic: sustainability, challenges and opportunities. University of Manchester. 150 p
- Bos MM, Steffan-Dewenter I, Tscharnkte T (2007) Shade tree management affects fruit abortion, insect pests and pathogens of cacao. *Agric Ecosyst Environ* 120(2):201–205. <https://doi.org/10.1016/j.agee.2006.09.004>
- Boulay H, Mainié P (1966) Arboriculture et production fruitière. FeniXX
- Canham CD, LePage PT, Coates KD (2004) A neighborhood analysis of canopy tree competition: effects of shading versus crowding. *Can J For Res* 34(4):778–787. <https://doi.org/10.1139/x03-232>
- Cerda R, Deheuvels O, Calvache D, Niehaus L, Saenz Y, Kent J, Vilchez S, Villota A, Martinez C, Somarriba E (2014) Contribution of cocoa agroforestry systems to family income and domestic consumption: looking toward intensification. *Agrofor Syst* 88:957–981. <https://doi.org/10.1007/s10457-014-9691-8>
- Charbonnier F, le Maire G, Dreyer E, Casanoves F, Christina M, Dauzat J, Eitel JUH, Vaast P, Vierling LA, Rouspard O (2013) Competition for light in heterogeneous canopies: application of MAESTRA to a coffee (*Coffea arabica* L.) agroforestry system. *Agric For Meteorol* 181:152–169. <https://doi.org/10.1016/j.agrformet.2013.07.010>
- Coomes DA, Allen RB (2007) Effects of size, competition and altitude on tree growth. *J Ecol* 95(5):1084–1097. <https://doi.org/10.1111/j.1365-2745.2007.01280.x>
- Core Team R (2020) R: A language and environment for statistical computing. R foundation for Statistical Computing, Vienna
- Daily G, Postel S, Bawa K, Kaufman L (1997) Nature's services: societal dependence on natural ecosystems. Bibliovault OAI Repository, the University of Chicago Press
- Damour G, Navas ML, Garnier E (2018) A revised trait-based framework for agroecosystems including decision rules. *J Appl Ecol* 55(1):12–24. <https://doi.org/10.1111/1365-2664.12986>
- de Bello F, Lavorel S, Díaz S, Harrington R, Cornelissen JHC, Bardgett RD, Berg MP, Cipriotti P, Feld CK, Hering D, Martins da Silva P, Potts SG, Sandin L, Sousa JP, Storkey J, Wardle DA, Harrison PA

- (2010) Towards an assessment of multiple ecosystem processes and services via functional traits. *Biodivers Conserv* 19(10):2873–2893. <https://doi.org/10.1007/s10531-010-9850-9>
- Dehevels O (2015) Rapport d'expertise. Caractérisation des systèmes de culture du cacao de République Dominicaine dans les provinces de Duarte, Hato Mayor et El Seibo
- Dehevels O, Avelino J, Somarriba E, Malezieux E (2012) Vegetation structure and productivity in cocoa-based agroforestry systems in Talamanca, Costa Rica. *Agric Ecosyst Environ* 149:181–188. <https://doi.org/10.1016/j.agee.2011.03.003>
- Djuideu CTL, Bisseleua HDB, Kekeunou S, Ambele FC (2021) Rehabilitation practices in cocoa agroforestry systems mitigate outbreaks of termites and support cocoa tree development and yield. *Agric Ecosyst Environ* 311:107324. <https://doi.org/10.1016/j.agee.2021.107324>
- Duchene O, Vian J-F, Celette F (2017) Intercropping with legume for agroecological cropping systems: complementarity and facilitation processes and the importance of soil microorganisms. A review *Agric Ecosyst Environ* 240:148–161. <https://doi.org/10.1016/j.agee.2017.02.019>
- Fernandes LS, Correa FM, Ingram KT, de Almeida A-AF, Royaert S (2020) QTL mapping and identification of SNP-haplotypes affecting yield components of *Theobroma cacao* L. *Hortic Res* 7(1):26. <https://doi.org/10.1038/s41438-020-0250-3>
- Fichtner A, Härdtle W, Li Y, Bruelheide H, Kunz M, von Oheimb G (2017) From competition to facilitation: how tree species respond to neighbourhood diversity. *Ecol Lett* 20(7):892–900. <https://doi.org/10.1111/ele.12786>
- Garnier E, Navas M-L (2012) A trait-based approach to comparative functional plant ecology: concepts, methods and applications for agroecology. A review *Agron Sustainable Dev* 32(2):365–399. <https://doi.org/10.1007/s13593-011-0036-y>
- Graefe S, Meyer-Sand LF, Chauvette K, Abdulai I, Jassogne L, Vaast P, Asare R (2017) Evaluating Farmers' Knowledge of Shade Trees in Different Cocoa Agro-Ecological Zones in Ghana. *Hum Ecol* 45(3): 321–332. <https://doi.org/10.1007/s10745-017-9899-0>
- Hombegowda HC, Köhler M, Röhl A, Hölscher D (2020) Tree species and size influence soil water partitioning in coffee agroforestry. *Agrofor Syst* 94(1):137–149. <https://doi.org/10.1007/s10457-019-00375-7>
- Jagoret P, Kwesseu J, Messie C, Michel-Dounias I, Malézieux E (2014) Farmers' assessment of the use value of agrobiodiversity in complex cocoa agroforestry systems in central Cameroon. *Agrofor Syst* 88(6):983–1000. <https://doi.org/10.1007/s10457-014-9698-1>
- Jagoret P, Nngogue H, Malézieux E, Isabelle M (2018) Trajectories of cocoa agroforests and their drivers over time: lessons from the Cameroonian experience. *Eur J Agron* 101:183–192. <https://doi.org/10.1016/j.eja.2018.09.007>
- Kaba JS, Zerbe S, Agnolucci M, Scandellari F, Abunyewa AA, Giovannetti M, Tagliavini M (2019) Atmospheric nitrogen fixation by gliricidia trees (*Gliricidia sepium* (Jacq.) Kunth ex Walp.) intercropped with cocoa (*Theobroma cacao* L.). *Plant Soil* 435(1): 323–336. <https://doi.org/10.1007/s11104-018-3897-x>
- Kiptot E, Franzel S, Degrande A (2014) Gender, agroforestry and food security in Africa. *Curr Opin Environ Sustain* 6:104–109. <https://doi.org/10.1016/j.cosust.2013.10.019>
- Koko LK, Snoeck D, Lekadou TT, Assiri AA (2013) Cocoa-fruit tree intercropping effects on cocoa yield, plant vigour and light interception in Côte d'Ivoire. *Agrofor Syst* 87(5):1043–1052. <https://doi.org/10.1007/s10457-013-9619-8>
- Kyereh D (2017) Shade trees in cocoa agroforestry systems in Ghana: influence on water and light availability in dry seasons. *J Agric Ecol Res Int* 10:1–7. <https://doi.org/10.9734/JAERI/2017/31227>
- Leakey RRB, Tchoundjeu Z, Schreckenber K, Shackleton SE, Shackleton CM (2005) Agroforestry tree products (AFTPs): targeting poverty reduction and enhanced livelihoods. *Int J Agric Sustain* 3(1):1–23. <https://doi.org/10.1080/14735903.2005.9684741>
- Lehélbel-Péron A, Feintrenie L, Levang P (2011) RUBber agroforests' profitability, the importance of secondary products. *For, Trees Livelihoods* 20:69–84
- Loguercio LL, Santos LS, Niella GR, Miranda RAC, De Souza JT, Collins RT, Pomella AWV (2009) Canopy-microclimate effects on the antagonism between *Trichoderma stromaticum* and *Moniliophthora perniciosa* in shaded cacao. *Plant Pathol* 58(6): 1104–1115. <https://doi.org/10.1111/j.1365-3059.2009.02152.x>
- Lombard C, Leakey RRB (2010) Protecting the rights of farmers and communities while securing long term market access for producers of non-timber forest products: experience in southern africa. *For, Trees Livelihoods* 19(3):235–249. <https://doi.org/10.1080/14728028.2010.9752669>
- Mbow C, Van Noordwijk M, Luedeling E, Neufeldt H, Minang PA, Kowero G (2014) Agroforestry solutions to address food security and climate change challenges in Africa. *Curr Opin Environ Sustain* 6:61–67. <https://doi.org/10.1016/j.cosust.2013.10.014>
- Medeiros FHV, Pomella AWV, de Souza JT, Niella GR, Valle R, Bateman RP, Fravel D, Vinyard B, Hebbar PK (2010) A novel, integrated method for management of witches' broom disease in Cacao in Bahia, Brazil. *Crop Prot* 29(7):704–711. <https://doi.org/10.1016/j.cropro.2010.02.006>
- Middendorp RS, Vanacker V, Lambin EF (2018) Impacts of shaded agroforestry management on carbon sequestration, biodiversity and farmers income in cocoa production landscapes. *Landsc Ecol* 33(11):1953–1974. <https://doi.org/10.1007/s10980-018-0714-0>
- Ministerio de Agricultura (2019) Datos de transparencia. <https://agricultura.gob.do/transparencia/index.php/estadisticas/estadisticas-agropecuarias/category/981-precios-delproductor>. Accessed 12 June 2019.
- Monselise SP, Goldschmidt E (2011) Alternate Bearing in Fruit Trees. *Hortic Rev* 4:128–173. <https://doi.org/10.1002/9781118060773.ch5>
- Niether W, Schneidewind U, Fuchs M, Schneider M, Armengot L (2019) Below- and aboveground production in cocoa monocultures and agroforestry systems. *Sci Total Environ* 657:558–567. <https://doi.org/10.1016/j.scitotenv.2018.12.050>
- Notaro M, Gary C, Dehevels O (2019) Mapping plant diversity in cocoa-based agroforestry systems to improve overall productivity. In: 4th World Congress on Agroforestry. Book of abstracts. Dupraz Christian (ed.), Gosme Marie (ed.), Lawson Gerry (ed.). CIRAD, INRA, World Agroforestry, Agropolis International, MUSE. Montpellier : CIRAD-INRA, Résumé, p. 580. World Congress on Agroforestry. 4, Montpellier, France, 20 Mai 2019/22 Mai 2019
- Notaro M, Gary C, Dehevels O (2020) Plant diversity and density in cocoa-based agroforestry systems: how farmers' income is affected in the Dominican Republic. *Agrofor Syst* 94(3):1071–1084. <https://doi.org/10.1007/s10457-019-00472-7>
- Nygren P, Leblanc HA (2015) Dinitrogen fixation by legume shade trees and direct transfer of fixed N to associated cacao in a tropical agroforestry system. *Tree Physiol* 35(2):134–147. <https://doi.org/10.1093/treephys/tpu116>
- Rigal C, Vaast P, Xu J (2018) Using farmers' local knowledge of tree provision of ecosystem services to strengthen the emergence of coffee-agroforestry landscapes in southwest China. *PLoS One* 13(9):e0204046. <https://doi.org/10.1371/journal.pone.0204046>
- Ritchie J, Lewis J, Elam G (2003) Designing and selecting samples. In: Lewis J (ed) Ritchie J. Qualitative research practice. Sage Publications, London
- Roupsard O, Ferhi A, Granier A, Pallo F, Depommier D, Mallet B, Joly HI, Dreyer E (1999) Reverse phenology and dry-season water uptake by *Faidherbia albida* (Del.) A. Chev. in an agroforestry parkland of Sudanese west Africa. *Funct Ecol* 13(4):460–472. <https://doi.org/10.1046/j.1365-2435.1999.00345.x>

- Rousseau GX, Deheuvels O, Rodriguez Arias I, Somarriba E (2012) Indicating soil quality in cacao-based agroforestry systems and old-growth forests: the potential of soil macrofauna assemblage. *Ecol Indic* 23:535–543. <https://doi.org/10.1016/j.ecolind.2012.05.008>
- Rowe EC, van Noordwijk M, Suprayogo D, Hairiah K, Giller KE, Cadisch G (2001) Root distributions partially explain 15N uptake patterns in *Gliricidia* and *Peltophorum* hedgerow intercropping systems. *Plant Soil* 235(2):167–179. <https://doi.org/10.1023/A:1011961409353>
- Ryan D, Bright GA, Somarriba E (2009) Damage and yield change in cocoa crops due to harvesting of timber shade trees in Talamanca, Costa Rica. *Agrofor Syst* 77(2):97–106. <https://doi.org/10.1007/s10457-009-9222-1>
- Saj S, Jagoret P, Etoa LE, Eteckji Fonkeng E, Tarla JN, Essobo Nieboukaho J-D, Mvondo Sakouma K (2017a) Lessons learned from the long-term analysis of cacao yield and stand structure in central Cameroonian agroforestry systems. *Agric Syst* 156:95–104. <https://doi.org/10.1016/j.agry.2017.06.002>
- Saj S, Torquebiau E, Hainzelin E, Pages J, Maraux F (2017b) The way forward: An agroecological perspective for Climate-Smart Agriculture. *Agric Ecosyst Environ* 250:20–24. <https://doi.org/10.1016/j.agee.2017.09.003>
- Salazar-Díaz R, Tixier P (2019) Effect of plant diversity on income generated by agroforestry systems in Talamanca, Costa Rica. *Agrofor Syst* 93(2):571–580. <https://doi.org/10.1007/s10457-017-0151-0>
- Santos PZF, Cruzeilles R, Sansevero JBB (2019) Can agroforestry systems enhance biodiversity and ecosystem service provision in agricultural landscapes? A meta-analysis for the Brazilian Atlantic Forest. *For Ecol Manag* 433:140–145. <https://doi.org/10.1016/j.foreco.2018.10.064>
- Sauvadet M, Saj S, Freschet GT, Essobo J-D, Enock S, Becquer T, Tixier P, Harmand J-M (2020) Cocoa agroforest multifunctionality and soil fertility explained by shade tree litter traits. *J Appl Ecol* 57(3):476–487. <https://doi.org/10.1111/1365-2664.13560>
- Schneider M, Andres C, Trujillo G, Alcon F, Amurrio P, Perez E, Weibel F, Milz J (2017) Cocoa and total system yields of organic and conventional agroforestry vs. monoculture systems in a long-term field trial in Bolivia. *Exp Agric* 53(3):351–374. <https://doi.org/10.1017/S0014479716000417>
- Schwarz J, Schnabel F, Bauhus J (2021) A conceptual framework and experimental design for analysing the relationship between biodiversity and ecosystem functioning (BEF) in agroforestry systems. *Basic Appl Ecol*. <https://doi.org/10.1016/j.baae.2021.05.002>
- Schwendenmann L, Veldkamp E, Moser G, Hölscher D, Köhler M, Clough Y, Anas I, Djajakirana G, Erasmi S, Hertel D, Leitner D, Leuschner C, Michalzik B, Propastin P, Tjoa A, Tscharntke T, van Straaten O (2010) Effects of an experimental drought on the functioning of a cacao agroforestry system, Sulawesi, Indonesia. *Glob Chang Biol* 16(5):1515–1530. <https://doi.org/10.1111/j.1365-2486.2009.02034.x>
- Seghieri J, Harmand J-M (2019) Agroforesterie et services écosystémiques en zone tropicale : Recherche de compromis entre services d'approvisionnement et autres services écosystémiques. Versailles (ed) Quae, 252 p
- Sharma N, Singh SK, Mahato AK, Ravishankar H, Dubey AK, Singh NK (2019) Physiological and molecular basis of alternate bearing in perennial fruit crops. *Sci Hortic* 243:214–225. <https://doi.org/10.1016/j.scienta.2018.08.021>
- Simon S, Lesueur-Jannoyer M, Plénet D, Lauri P-É, Le Bellec F (2017) Methodology to design agroecological orchards: Learnings from on-station and on-farm experiences. *Eur J Agron* 82:320–330. <https://doi.org/10.1016/j.eja.2016.09.004>
- Somarriba E, Beer J (2011) Productivity of *Theobroma cacao* agroforestry systems with timber or legume service shade trees. *Agrofor Syst* 81(2):109–121. <https://doi.org/10.1007/s10457-010-9364-1>
- Somarriba E, Suárez-Islas A, Calero-Borge W, Villota A, Castillo C, Vélchez S, Deheuvels O, Cerda R (2014) Cocoa–timber agroforestry systems: *Theobroma cacao*–*Cordia alliodora* in Central America. *Agrofor Syst* 88(6):1001–1019. <https://doi.org/10.1007/s10457-014-9692-7>
- Stroesser L, Penot E, Michel I, Tongkaemkaew U, Chambon B (2018) Income diversification for rubber farmers through agroforestry practices. How to Withstand Rubber Price Volatility in Phatthalung Province, Thailand (Income diversification for rubber farmers through agroforestry practices). *Rev Int Études Dév* 235(3):117–145. <https://doi.org/10.3917/ried.235.0117>
- Tiralla N, Panferov O, Knohl A (2013) Allometric relationships of frequently used shade tree species in cacao agroforestry systems in Sulawesi, Indonesia. *Agrofor Syst* 87(4):857–870. <https://doi.org/10.1007/s10457-013-9602-4>
- Torralba M, Fagerholm N, Burgess PJ, Moreno G, Plieninger T (2016) Do European agroforestry systems enhance biodiversity and ecosystem services? A meta-analysis. *Agric Ecosyst Environ* 230:150–161. <https://doi.org/10.1016/j.agee.2016.06.002>
- Tscharntke T, Clough Y, Bhagwat SA, Buchori D, Faust H, Hertel D, Hölscher D, Juhbandt J, Kessler M, Perfecto I, Scherber C, Schroth G, Veldkamp E, Wanger TC (2011) Multifunctional shade-tree management in tropical agroforestry landscapes – a review. *J Appl Ecol* 48(3):619–629. <https://doi.org/10.1111/j.1365-2664.2010.01939.x>
- Vanhove W, Vanhoudt N, Van Damme P (2016) Effect of shade tree planting and soil management on rehabilitation success of a 22-year-old degraded cocoa (*Theobroma cacao* L.) plantation. *Agric Ecosyst Environ* 219:14–25. <https://doi.org/10.1016/j.agee.2015.12.005>
- Violle C, Navas ML, Vile D, Kazakou E, Fortunel C, Hummel I, Garnier E (2007) Let the concept of trait be functional! *Oikos* 116(5):882–892
- Wei T, Simko V (2013) corplot: Visualization of a correlation matrix. R package version 0.73 230 (231), 11
- Wibaux T, Konan D-C, Snoeck D, Jagoret P, Bastide P (2018) Study of tree-to-tree yield variability among seedling-based cacao populations in an industrial plantation in côte d'ivoire. *Exp Agric* 54(5):719–730. <https://doi.org/10.1017/S0014479717000345>
- Willey RW (1990) Resource use in intercropping systems. *Agric Water Manag* 17(1):215–231. [https://doi.org/10.1016/0378-3774\(90\)90069-B](https://doi.org/10.1016/0378-3774(90)90069-B)
- Yang B, Meng X, Singh AK, Wang P, Song L, Zakari S, Liu W (2020) Intercrops improve surface water availability in rubber-based agroforestry systems. *Agric Ecosyst Environ* 298:106937. <https://doi.org/10.1016/j.agee.2020.106937>

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