Analysis of trade-offs between ecosystem services of provisioning and regulation, and plant biodiversity for better management strategies of agroforestry systems in Central America

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Credits

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Content

1. Introduction

There is a close relationship between agroecosystems, plant biodiversity and ecosystem services. In Central America, agroecosystems with arboreal components, such as coffee and cocoa provide a number of ecosystem services such as provisioning of products, carbon sequestration, improvement of soil fertility, food sources for wild animals, shelter, water, erosion reduction, etc. There are also other production systems which are common in Central America such as grain systems, pastures and homegardens, that are capable to provide ecosystem services as well. Each of these agroecosystems have particular characteristics of design, structure and management, and therefore their performance in providing ecosystem services can be different. Furthermore, each of them can present different types of trade-offs between several services, or between services and plant biodiversity. Such trade-offs should be balanced and reduced in order to offer two or more benefits for smallholder famers´ families simultaneously in a sustainable way.

The project Forests, Trees and Agroforestry (FTA) has proposed conducting a study on the relationships between plant biodiversity and ecosystem services provided by the most common agroecosystems in tropical productive landscapes of the Central American region. It is expected that the knowledge generated with this study reveals trade-offs either at systems level or at a general level. Analyzing the relationships between ecosystem services would identify which are the most critical trade-offs and the possible management strategies to balance them. The results will be a contribution to the knowledge about the services that agroecosystems with an arboreal component can provide in productive landscapes and the necessary actions to improve their design and management.

Thus, the main objective of this study was to analyze relationships between provisioning and regulating ecosystem services, and between such services and plant biodiversity in the most common agroecosystems with arboreal components in Central America, by using several statistical techniques, and with the aim to suggest management strategies to balance possible trade-offs. For that purpose, we analyzed data of two important projects developed in the region, which collected data of ecosystem services, management, and structure of agroecosystems of coffee, cocoa, grains, pastures and homegardens. All of this systems have woody perennial species (trees, palms and shrubs) and other plants (such as musaceas) among their components, and although they can have contrasting differences in spatial arrangements and densities, all of them can be considered as agroforestry systems.

This study offers recommendations for better design and management per land use. This type of recommendations can be useful for decision makers (policy briefs) and for farmers and their organizations. The expected impact of the application of such recommendations in the medium and long-term are: i) the reduction of trade-offs between ecosystem services in productive landscapes, and consequently the improvement of crop yields and incomes for farmers, as well as the improvement of regulating services aimed to conserve natural resources of farms; and ii) given that farmers increase their benefits from several current land uses of their farms, the pressure of deforestation of near forests to obtain goods or to establish more agricultural systems, could be reduced.

2. Materials and methods

For this study we used data sets of two projects in countries of Central America. One project with data of 114 cocoa agroforestry systems (cocoa AF) of four countries; and other project with data of coffee agroforestry systems (coffee AF), cocoa AF, pasture systems, basic grains systems, and homegardens of the Sentinel Landscape in Nicaragua (Table 1). These projects, among others, generated data of provisioning services and regulating services. We used data of crop yields, cash flow, value of domestic consumption and family benefit as indicators of provisioning services; data of carbon sequestration in aboveground biomass, and soil pH and soil nitrogen as indicators of regulating services; plant species richness and Shannon index as representatives of plant biodiversity; density and basal areas of plants/trees as descriptors of the structure of the shade canopies; and, data of cropping practices as representatives of the management of the systems.

Table 1. Data used of two projects for the analysis of trade-offs in this study

Projects	Countries	Crops	n	Crop yields	Economic indicators	Carbon sequestration	Soil fertility	Biodiversity	Structure	Management
Central America Cocoa Project	Panama, Costa Rica, Nicaragua, Guatemala	Cocoa	114	X	X	X	X	X	X	X
Sentinel Landscape	Nicaragua	Cocoa	31		X	X				
		Coffee	41		X	X		X	X	
		Grains	63		X	X		X	X	
		Pastures	61		X	X		X	X	
		Homegardens	75		X	X		X	X	

a. Data of shade canopies and indicators of ecosystem services

Data of the structure and plant biodiversity were obtained through field inventories. In all projects the individuals present in the systems were identified at species level and basic measurements such as trunk diameter were taken, which allowed to calculate densities and basal areas.

We calculated a management index with data of the Central America Cocoa Project in order to reflect the intensity of practices and inputs applied to the system. This type of index was already used for studies in similar agroforestry systems like coffee (Mas and Dietch, 2003; Philpott *et al.*, 2006; Cerda *et al.*, 2017). The higher the index, the higher the management intensity. The calculation was as following:

First, for each cropping practice, the number of times per year that this practice was applied was transformed to a value *IH* between 0 to 1 reflecting the practice intensity, the higher the value, the higher the intensity:

$$IH = \frac{value\ \ - minimum}{maximum - minimum}$$

where IH is the transformed value for cropping practices for which a higher number of applications denotes a higher management intensity (e.g. number of weedings, application of fertilizers, etc.); value was the annual number of applications of a given cropping practice for a given syatem; and minimum and maximum were the minimum and maximum values registered for that cropping practice in the data set, respectively. Then, the transformed values obtained for all cropping practices were summed to obtain the management intensity index of each system; the higher the index, the higher the management intensity.

The economic indicators (cash flow, value of domestic consumption and family benefit) reflect the overall contribution of the systems to the families. They include the incomes provided by the main crops as well as other products such as bananas, other fruits and timber. Data of prices of the products, cultural practices and inputs applied to the system, and incomes and costs (labor and inputs) were obtained through interviews. We calculated the economic indicators as suggested in a study which documented the overall contributions of cocoa agroforestry systems (Cerda *et al.*, 2014):

- GI = AS x MP
- CF = GI – CC
- VDC = ADC x MP
- FB = CF + VDC

Where: GI = gross income from sale of agroforestry products; AS = amount of agroforestry products for sales; MP = market price; CC = cash costs; CF = cash flow; FB = family benefit; VDC = value of domestic consumption; ADC = amount of agroforestry products for domestic consumption. Results were expressed in United State dollars as USD.

Carbon sequestration in the shade canopy (aboveground) was estimated through inventories of trees and use of allometric equations. The methodology is described in a study of carbon sequestration in agroforestry systems in countries of Central America (Somarriba *et al.*, 2013).

Variables of soil were obtained as done traditionally. Subsamples of soil were taken in the systems, a composite sample was obtained and then sent to laboratory for chemical analysis.

b. Analysis of trade-offs between ecosystem services, biodiversity, and management

There are several ways to analyze and identify possible trade-offs between indicators of ecosystem services, from different kind of relationships, indexes, to modelling. We reviewed the most recent and relevant papers on this topic: (Cheatham *et al.*, 2009; Bradford and D'Amato, 2012; Häger, 2012; Boreux *et al.*, 2013; Felipe-Lucia *et al.*, 2014; Howe *et al.*, 2014; Kragt and Robertson, 2014; Lu *et al.*, 2014; Railsback and Johnson, 2014; Grossman, 2015; Jopke *et al.*, 2015; Rapidel *et al.*, 2015; Rodriguez-Loinaz *et al.*, 2015; Corrigan and Nieuwenhuis, 2016; Kuyah *et al.*, 2016; Mora *et al.*, 2016; Rahman *et al.*, 2016; Tamburini *et al.*, 2016; Cerda *et al.*, 2017). For the purposes of this study, we performed:

- Principal component analysis among indicators of ecosystem services, structure and biodiversity of shade canopies and management practices, in order to explore the overall relationships among characteristics of shade canopies of the systems and among ecosystem services.

- Analysis of correlation of spearman between pairs of indicators of ecosystem services (Felipe-Lucia *et al.*, 2014; Tamburini *et al.*, 2016) and also between ecosystem services and characteristics of shade canopy. This analysis provides a first insight of positive or negative relationships between two variables. Negative correlations would be denoting trade-offs.

- Analysis of linear relationships (and plot) between original values of pairs of indicators of ecosystem services, and also between ecosystem services and characteristics of shade canopy (Rapidel *et al.*, 2015; Cerda *et al.*, 2017).

- Standardization of indicators of ecosystem services to values between 0-1 to analyze also relationships (plots) between pairs of indicators, and then calculate the root mean square deviation (RMSD) as representatives of the magnitudes of the trade-offs (Bradford and D'Amato, 2012; Lu *et al.*, 2014). With this approach there is an interesting way to visualize trade-offs, in the plot of the indicators the line 1:1 represents the ideal relationship which denotes no trade-offs (on the contrary denotes synergies), and the authors establish that the higher distance from points to the 1:1 line, the higher the trade-off.

  The standardization (0-1) for each observation of indicators of ecosystem services was done as following (Lu *et al.*, 2014):

ESstd = (ESobs –Esmin)/(ES max – Esmin)

where ESstd is the standardized value of any ES, ESobs is an observed value, and ESmin and ESmax are the minimum and maximum observed values.

The root mean square deviation (RMSD) was calculated as following (Lu *et al.*, 2014):

$$\mathrm{RMSD} = \sqrt{\frac{1}{n-1} \cdot \sum_{i=1}^{n} (\mathrm{ES}_i - \hat{\mathrm{ES}})^2}$$

where ESi is the standardized value of ESi and ES^ is the expected value of the i number of ESs. RMSD quantifies the average difference between an individual ESstd and the mean ESstd. In a two dimensional plot, ES^ is on the 1:1 ESs (Figure 1).

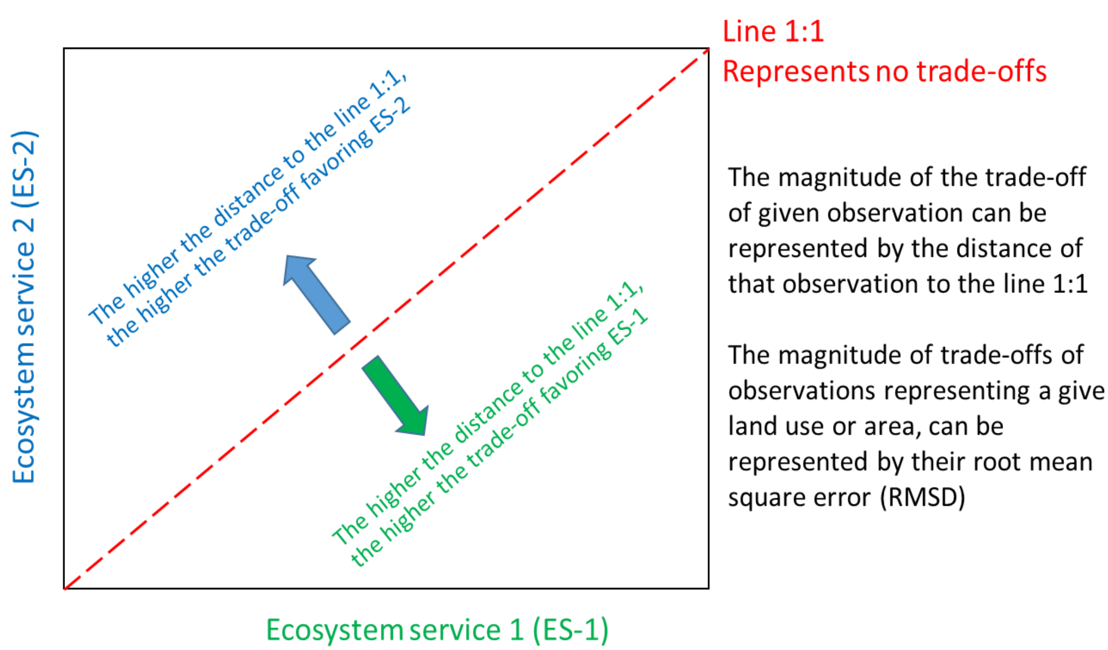


Figure modified from Bradford and D'Amato (2012) and Lu et al. (2014)

Figure 1. Explanation of trade-off analysis between two indicators of ecosystem services by standardization of ecosystem services values and use of root mean square deviation (RMSD)

Thus, we aimed to identify all possible trade-offs between pairs of ecosystem services, and between ecosystem services, biodiversity and management through different techniques. The integral analyzes of all results and discussion, permits to deduce recommendations to improve the balance and technical advices (on design and management) to balance possible trade-offs in each of the land uses studied and also at farm level.

We present results for each project, because of some differences in the methods of sampling and inventories of plants and trees in the systems. For the Cocoa Central America project, we present results differentiated per countries, and for the Sentinel Landscape we present results per each land use.

3. Results

a. Cocoa agroforestry systems in Central America

i. Structure and plant biodiversity of cocoa agroforestry systems

Cocoa AF of Costa Rica and Panamá can be considered the most complex systems according to their high densities and basal areas of all plants and trees in the shade canopy compared to other countries. Cocoa AF of Guatemala would be the ones with less diversity, based on their species richness and Shannon index. Cocoa AF of Nicaragua had similar diversity than the ones in Costa Rica and Panama, but with lower densities of woody perennials such as timber trees (Table 2 and Figure 2).

Table 2. Structure characteristics of the shade canopy of cocoa agroforestry systems in Central America

Characteristics		Costa Rica		Guatemala		Nicaragua		Panama	
	Units	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Area	ha	1.0	1.0	0.5	0.8	1.0	0.7	2.2	1.8
Age of cocoa plantation	years	23.7	14.1	17.5	8.7	21.7	4.3	27.2	5.5
Density of cocoa plants	ind/ha	606.2	214.3	601.7	126.4	528.8	106.8	599.1	216.7
Density of palms		39.7	47.5	1.4	5.5	10.8	26.1	23.9	36.0
Density of fruit trees		87.7	62.5	15.7	23.8	83.3	63.6	42.1	57.1
Density of timber trees		113.2	81.9	171.1	90.4	43.3	53.5	141.8	77.1
Density of service trees		35.3	39.6	36.3	43.1	28.3	28.2	13.3	21.0
Density of musacea plants		186.5	259.6	1.4	5.5	172.7	192.4	232.4	161.1
Density of woody perennials		275.9	110.7	224.6	100.0	165.8	103.3	221.2	121.5
Density of shade canopy		462.4	265.6	226.0	100.2	338.5	247.0	453.6	199.0
Total density of the plantation		1068.5	249.3	827.7	157.9	867.3	226.1	1052.7	305.7
Basal area of cocoa plants	m^2/ha	10.4	4.4	14.1	4.7	9.8	5.8	8.5	4.0
Basal area of palms		0.8	1.2	0.4	1.6	0.3	0.7	0.6	1.0
Basal area of fruit trees		2.0	1.7	0.5	1.0	3.0	2.2	1.2	1.6
Basal area of timber trees		7.9	5.5	7.3	3.5	2.1	3.0	7.7	5.0
Basal area of service trees		0.5	0.8	1.1	1.6	1.4	1.5	0.9	1.4
Basal area of musacea plants		3.3	4.6	0.0	0.1	3.1	3.4	4.1	2.9

Basal area of woody perennials		11.3	5.1	9.3	4.4	6.7	4.1	10.4	5.3
Basal area of shade canopy		14.6	6.1	9.3	4.4	9.8	5.1	14.5	5.5
Total Basal area of the plantation		24.9	5.6	23.4	7.0	19.6	4.2	23.0	5.3
Total species richness		20.7	8.1	8.3	9.3	17.2	8.3	25.9	9.5
Shannon index		2.2	0.5	0.7	0.5	2.0	0.4	1.9	0.5

SD: standard deviation; ind: individuals

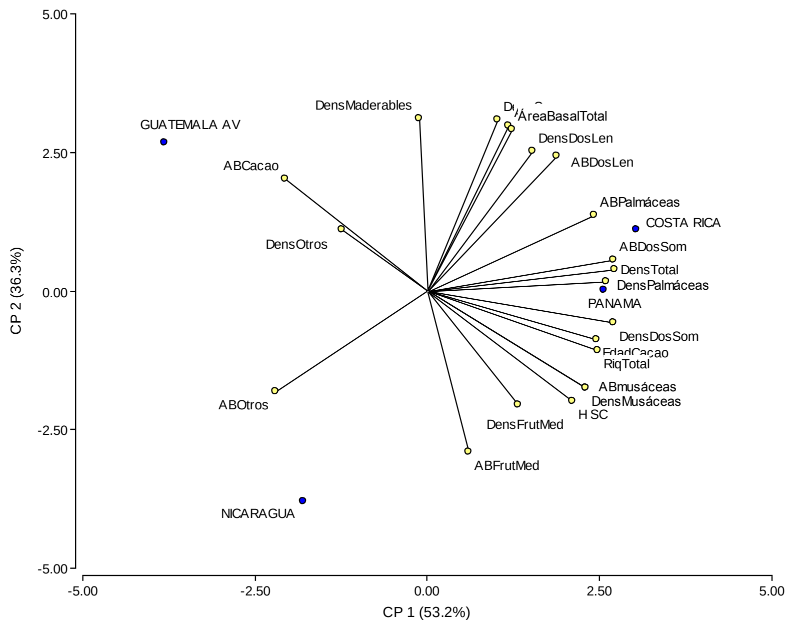


Figure 2. Principal component analysis. Exploratory relationships among structure characteristic of the shade canopies of cocoa agroforestry systems in Central America

3.1.2 Management characteristics of cocoa agroforestry systems

The main differences in management can be seen in the fertilization and phytosanitary prunings. Fertilization were registered only in cocoa AF of Nicaragua. Phytosanitary prunings were more frequent in Nicaragua and Panama. The cut of chupons was more frequent in Costa Rica and Panama. Cocoa AF of Nicaragua can be considered the ones with higher management intensity (more practices applied) according its relation with the management index (Table 3, Figure 3).

Table 3. Management characteristics (number of application of each practice per year) of cocoa agroforestry systems in Central America

Practices	Costa Rica		Guatemala		Nicaragua		Panama	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Manual weedings	3.3	1.8	2.3	1.5	2.8	1.7	2.9	0.8
Cut of chupons	3.4	3.7	1.4	1.0	2.8	1.9	3.3	3.6
Cut of musácea leaves	2.9	4.9	0.3	1.1	0.0	0.0	11.4	16.3
Fertilization	0.0	0.0	0.0	0.0	1.1	1.0	0.0	0.0
Pruning of maintenance	0.9	0.3	0.7	0.4	1.1	0.3	1.1	0.3
Pruning phitosanitary	0.9	0.4	0.7	0.8	2.6	1.4	3.4	1.7

SD: standard deviation

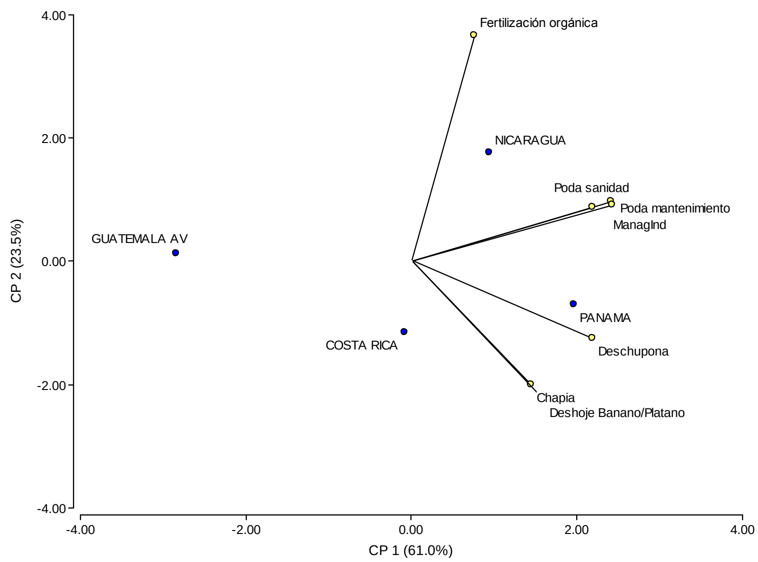


Figure 3. Principal component analysis. Exploratory relationships among management characteristics of the shade canopies of cocoa agroforestry systems in Central America

3.1.3 Ecosystem services provided by cocoa agroforestry systems

Ecosystem services of provisioning were higher in cocoa AF of Nicaragua. Cocoa AF of Nicaragua registered higher cocoa yields than other countries and consequently higher cash flow as well, furthermore they had high value of domestic consumption and therefore their contribution to family benefit was also remarkable. Carbon sequestration as regulation service was higher in cocoa AF of Costa Rica and Panama. In summary, cocoa AF of Nicaragua were more related to provisioning services, and cocoa AF of Costa Rica and Panama to services related to mitigation. Cocoa AF of Guatemala showed only a slight relation with soil pH (Table 4, Figure 4).

Table 4. Ecosystem services provided by cocoa agroforestry systems in Central America

Ecosystem services	Costa Rica		Guatemala		Nicaragua		Panama	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Cocoa yield (kg/ha)	140.9	97.5	295.3	150.7	558.3	295.4	162.5	113.0
Cash Flow (USD/ha)	325.6	252.6	996.7	718.6	1288.1	938.9	275.6	384.1
VDC (USD/ha)	191.0	161.3	255.2	403.6	1423.3	1000.0	717.9	634.5
Family Benefit (USD/ha)	516.6	253.2	1251.9	956.0	2711.4	1202.9	993.5	878.2
Carbon SC (tons/ha)	41.6	16.7	30.6	17.0	20.1	14.8	38.2	28.3
pH	5.4	0.5	6.0	0.4	5.9	0.4	5.0	0.5
Soil N (%)	0.3	0.1	0.2	0.0	0.3	0.1	0.3	0.1
Organic matter (%)	5.9	1.7	5.0	1.0	6.1	1.2	4.9	1.3

SD: standard deviation; Carbon SC: carbon in the shade canopy; VDC: value of domestic consumption

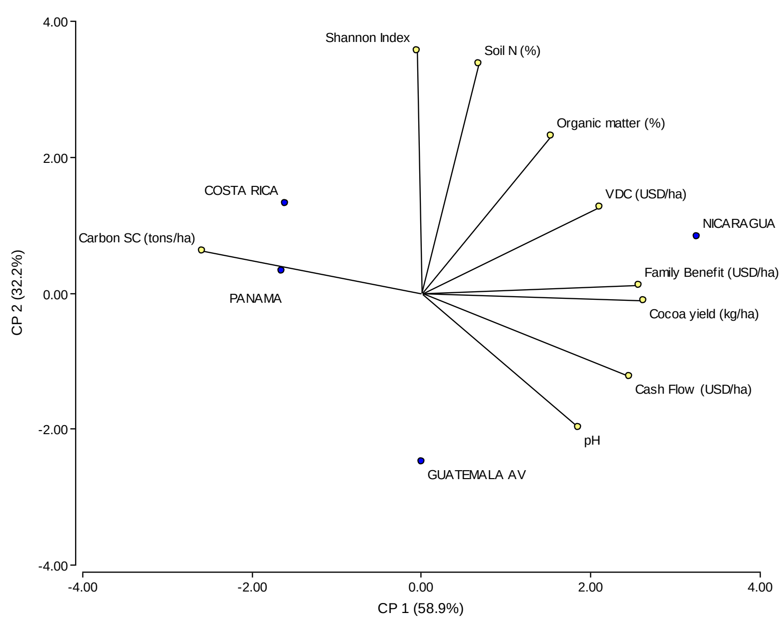


Figure 4. Principal component analysis. Exploratory relationships among indicators of ecosystem services provided by cocoa agroforestry systems in Central America

3.1.4 Trade-offs between ecosystem services, biodiversity, and management

Correlations Spearman

Most of significant relationships between indicators of ecosystem services were positive and only few were negatives. Cocoa yield and cash flow presented negative relationships with carbon in aboveground biomass, although the significances were at 10% of confidence and with a low coefficient, they indicate at least slight trade-offs (Table 5).

Table 5. Correlations (Spearman) between indicators of ecosystem services

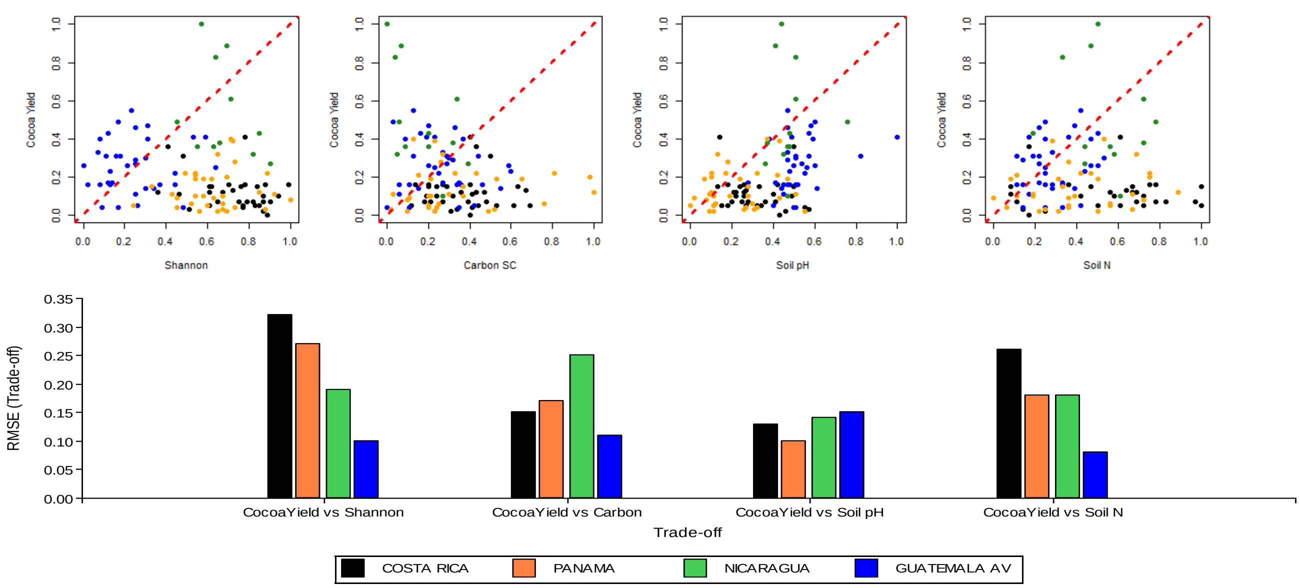
	Cocoa yield		Cash Flow		VDC		Family Benefit	
	Coef.	p-value	Coef.	p-value	Coef.	p-value	Coef.	p-value
Cash Flow	0.83	<0.0001						
VDC	0.19	0.0436	0.03	0.721				
Family Benefit	0.77	<0.0001	0.79	<0.0001	0.54	<0.0001		
Carbon SC	-0.16	0.0922	-0.16	0.0877	-0.13	0.1757	-0.14	0.1243
pH	0.41	<0.0001	0.48	<0.0001	-0.2	0.0309	0.26	0.0049
Soil N	-0.02	0.8471	-0.1	0.2727	0.19	0.0484	0.03	0.769
Organic matter	0.08	0.3981	0.02	0.8428	0.07	0.4508	0.07	0.4717

Carbon SC: carbon in the shade canopy; VDC: value of domestic consumption

Magnitude of trade-offs

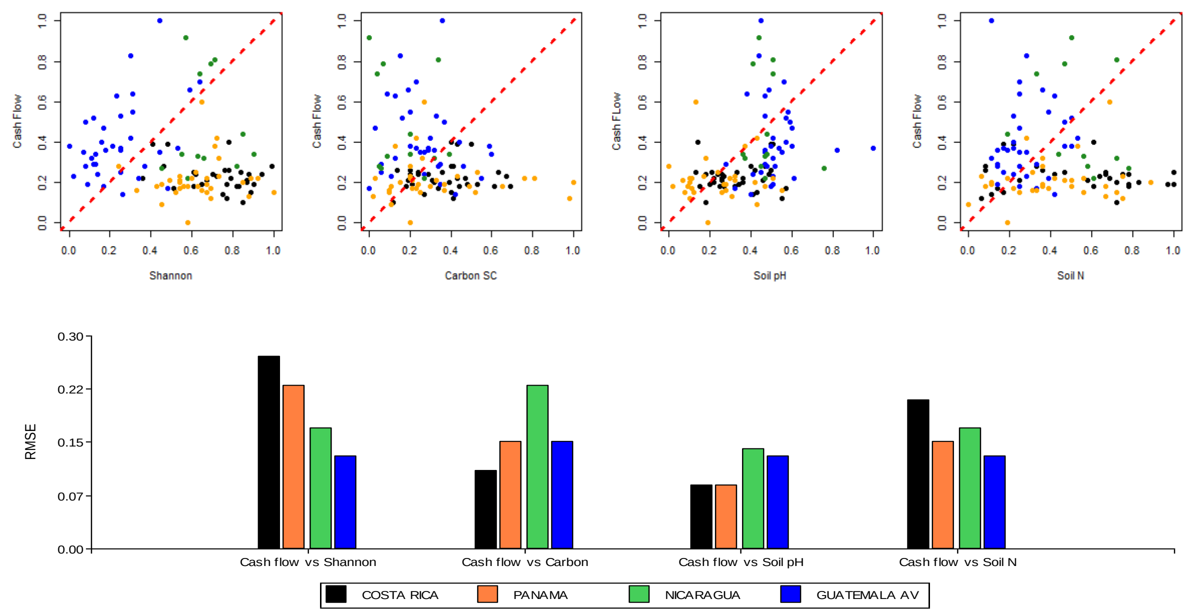
The analysis of relationships using standardized indicators of ecosystem services and RMSD revealed contrasting trade-offs among cocoa AF of different countries. Most of cocoa AF of Costa Rica and Panama favored biodiversity, carbon sequestration and soil fertility over cocoa yield and cash flow, while cocoa AF of Nicaragua and Guatemala had no clear tendency (Figures 5 and 6). Most of cocoa AF of all countries in general favored more biodiversity and regulating services than value of domestic consumption, only cocoa AF of Nicaragua favored more such consumption over carbon sequestration (Figure 7). All cocoa AF of Costa Rica and most of Panama favored biodiversity and regulating services more than family benefit, on the contrary cocoa AF of Nicaragua tended to favor more family benefit, and the tendency was not clear with cocoa AF of Guatemala (Figure 8). The magnitude of trade-offs (reflected by RMSD) were higher for cocoa AF favoring biodiversity and regulating services, and for cocoa AF of Nicaragua favoring provisioning services, in comparison with the other countries (Figures 5 to 8).

Contrary to what we logically expected, we did not find clear relationships between indicators of provisioning and management intensity. Specially in the cases of cocoa AF of Costa Rica and Panama, we found that they had more management intensity than other countries but with lower benefits, which also represents important unexpected trade-offs, possibly because farmers were applying a series of practices but not adequately. In the cases of cocoa AF of Nicaragua and Guatemala, they showed to favor more cocoa yield, cash flow and family benefit even with lower management intensity than the other countries, indicating that practices were somehow applied with more efficiency (Figure 9).



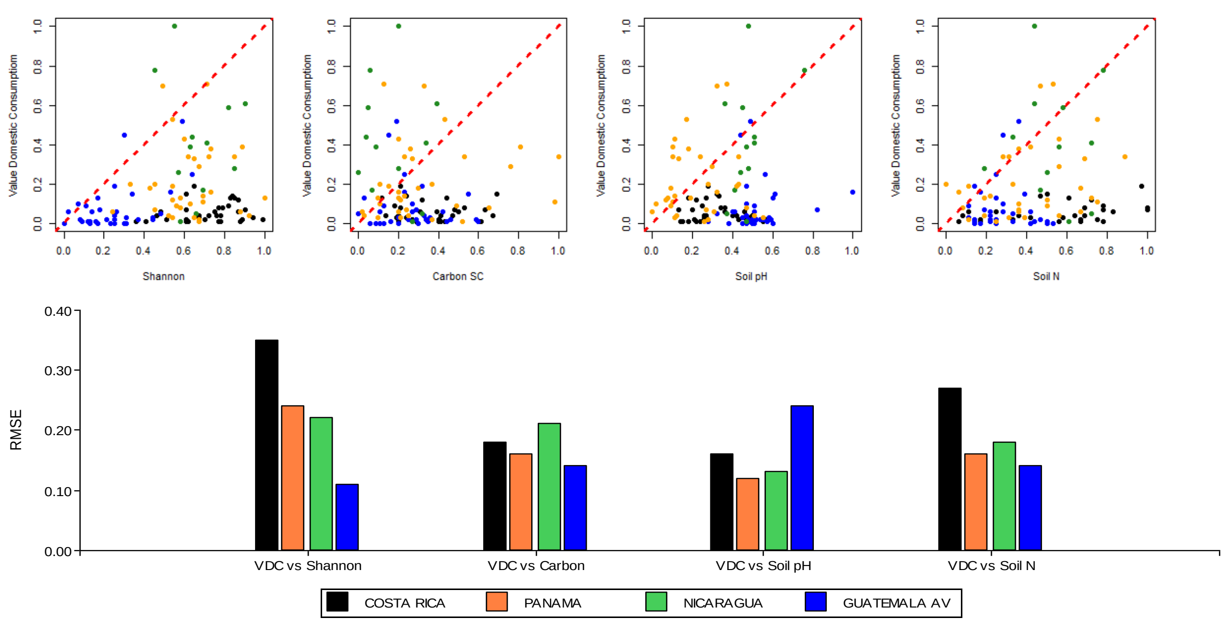
Red line is the 1:1 line, which represents no trade-offs.
Black dots: cocoa agroforestry systems of Costa Rica; blue dots: Guatemala; green dots: Nicaragua; orange dots: Panama
Figure 5. Analysis of trade-offs between cocoa yield and indicators of biodiversity (represented by Shannon index) and of regulating ecosystem services in cocoa agroforestry systems of Central

America. Magnitude of trade-offs are represented by the Root Mean Square Deviation (RMSD): the higher the RMSD, the higher the trade-off



Red line is the 1:1 line, which represents no trade-offs.
Black dots: cocoa agroforestry systems of Costa Rica; blue dots: Guatemala; green dots: Nicaragua; orange dots: Panama

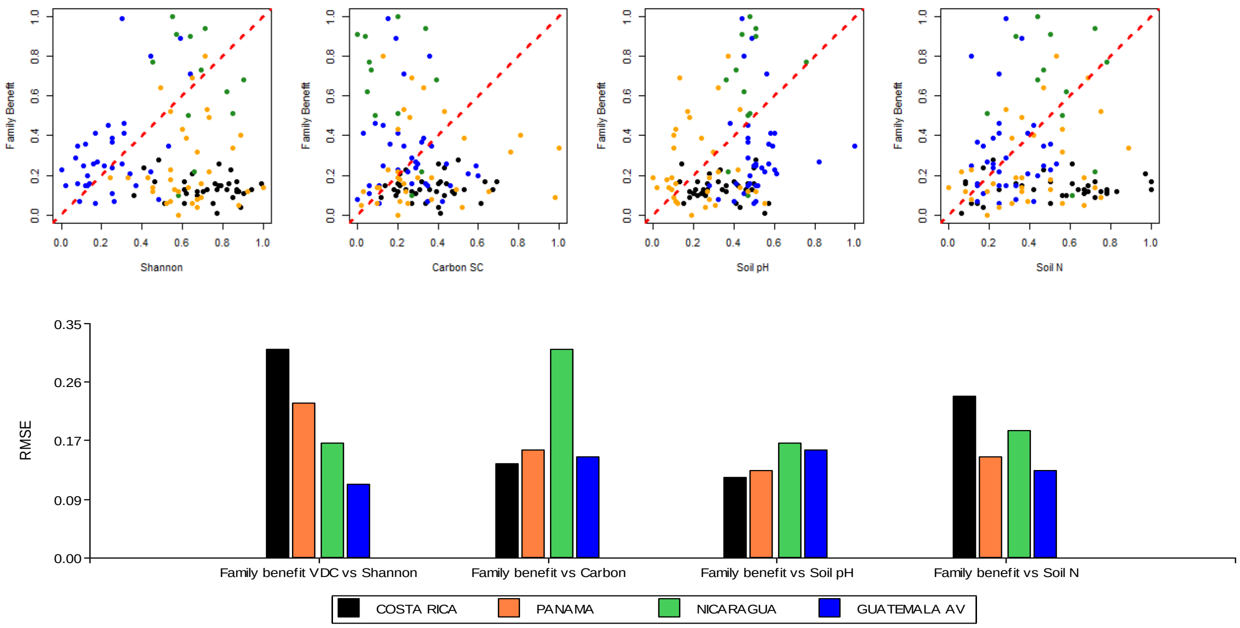
Figure 6. Analysis of trade-offs between cash flow and indicators of biodiversity (represented by Shannon index) and of regulating ecosystem services in cocoa agroforestry systems of Central America. Magnitude of trade-offs are represented by the Root Mean Square Deviation (RMSD): the higher the RMSD, the higher the trade-off



Red line is the 1:1 line, which represents no trade-offs.
Black dots: cocoa agroforestry systems of Costa Rica; blue dots: Guatemala; green dots: Nicaragua; orange dots: Panama

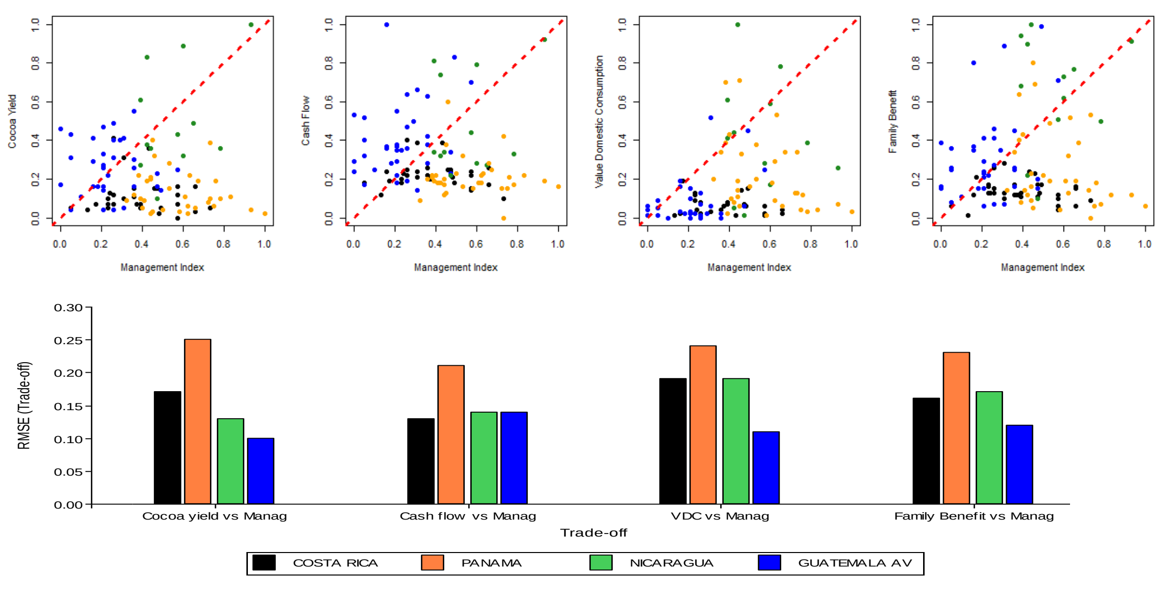
Figure 7. Analysis of trade-offs between value of domestic consumption and indicators of biodiversity (represented by Shannon index) and of regulating ecosystem services in cocoa agroforestry systems

of Central America. Magnitude of trade-offs are represented by the Root Mean Square Deviation (RMSD): the higher the RMSD, the higher the trade-off



Red line is the 1:1 line, which represents no trade-offs.
Black dots: cocoa agroforestry systems of Costa Rica; blue dots: Guatemala; green dots: Nicaragua; orange dots: Panama

Figure 8. Analysis of trade-offs between family benefit and indicators of biodiversity (represented by Shannon index) and of regulating ecosystem services in cocoa agroforestry systems of Central America. Magnitude of trade-offs are represented by the Root Mean Square Deviation (RMSD): the higher the RMSD, the higher the trade-off



Red line is the 1:1 line, which represents no trade-offs.
Black dots: cocoa agroforestry systems of Costa Rica; blue dots: Guatemala; green dots: Nicaragua; orange dots: Panama

Figure 9. Analysis of trade-offs between indicators of provisioning ecosystem services and management intensity (represented by a management index) in cocoa agroforestry systems of Central America. Magnitude of trade-offs are represented by the Root Mean Square Deviation (RMSD): the higher the RMSD, the higher the trade-off

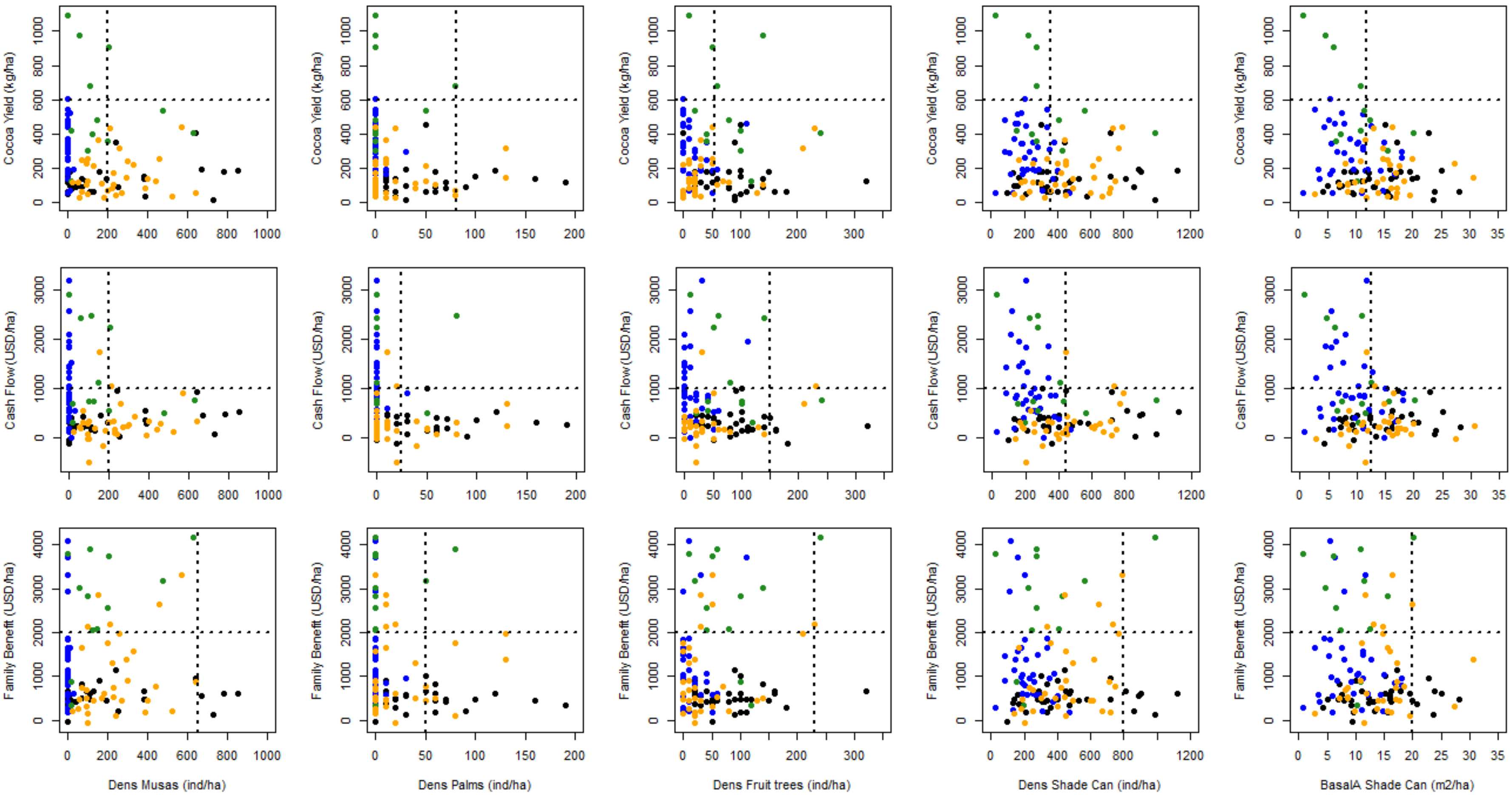
Relationships between ecosystem services and structure of shade canopies of cocoa AF

With the analysis of correlations (Spearman) we found several negative relationships between ecosystem services and characteristics of the shade canopy, denoting trade-offs. We can highlight that indicators of provisioning and of soil had negative relationships with the area and the age of cocoa AF; the densities and basal areas of palms, fruit trees and musaceas had negative relationships with cocoa yield, cash flow and soil pH; species richness and Shannon index (as indicators of biodiversity) even reported negative relationships with Family Benefit. Although musaceas, fruit trees and biodiversity did report positive relationships with Value of Domestic Consumption, the fact that their relationship with family benefit is compromised, indicates that high densities of such trees and high biodiversity could compromise the overall contribution of the system, and also the soil fertility. These and other relationships can be seen in Table 6.

In Figure 10, we show the performance of provisioning indicators in function of densities of different plants and trees of the cocoa AF. We considered that cocoa yields should be at least above 500 dry kg/ha, cash flows above 1000 USD/ha and family benefits above 2000 USD/ha to represent attractive levels for cocoa farmers´ families according to their objectives. Based on that, we could determine the acceptable densities in the shade canopies for obtaining such values. For instance, most of the few cocoa AF that surpassed 500 dry kg/ha and 1000 USD/ha of cash flow, had densities of musaceas between 0 and 220 plants/ha; therefore, for cocoa farmers that have the main objective of only good yields and incomes by selling cocoa beans, an acceptable density of musaceas should not surpass 220 plants/ha. However, the adequate density can change if the objective of the farmer is different, for example, if the objective is to obtain overall benefits from several products of the system, then the densities of musaceas could be around 600 plants/ha. That way, adequate densities of different plants and trees in the shade canopy can be visualized in Figure 10. It was interesting to note that total basal area of the shade canopy for obtaining good cocoa yields and cash flow should not surpass 12 m2/ha, but for obtaining good overall family benefit could reach 20 m2/ha.

Table 6. Correlations (Spearman) between indicators of ecosystem services and characteristics of cocoa agroforestry systems

	Cocoa yield		Cash Flow		VDC		Family Benefit		Carbon SC		pH		Soil N		Organic matter	
	Coef.	p-valor	Coef.	p-valor	Coef.	p-valor	Coef.	p-valor	Coef.	p-valor	Coef.	p-valor	Coef.	p-valor	Coef.	p-valor
Area	-0.36	0.0001	-0.38	<0.0001	0.14	0.1308	-0.25	0.0068	-0.14	0.1357	-0.33	0.0003	-0.1	0.2863	-0.28	0.0029
Age of cocoa plantation	-0.17	0.0744	-0.28	0.0021	0.24	0.0098	-0.12	0.1929	-0.04	0.6593	-0.17	0.0755	-0.1	0.2877	-0.23	0.0158
Density of cocoa plants	-0.17	0.0728	-0.04	0.6806	-0.15	0.1102	-0.08	0.3728	-0.11	0.2404	-0.01	0.8808	0.06	0.52	0.05	0.5743
Density of palms	-0.31	0.0008	-0.36	0.0001	0.15	0.1058	-0.19	0.0396	0.3	0.0011	-0.39	<0.0001	0.35	0.0001	0.25	0.0072
Density of fruit trees	-0.14	0.1294	-0.19	0.0394	0.11	0.2434	-0.15	0.1231	0.12	0.2138	-0.24	0.0107	0.34	0.0003	0.27	0.0037
Density of timber trees	0.04	0.6679	0.03	0.7824	-0.22	0.0211	-0.07	0.4799	0.18	0.0588	-0.01	0.8794	-0.19	0.0419	-0.16	0.0899
Density of service trees	0.11	0.2649	0.15	0.1132	-0.02	0.8364	0.07	0.43	0.09	0.3566	0.08	0.4192	0.07	0.4389	0.12	0.2149
Density of musácea plants	-0.18	0.0554	-0.28	0.0025	0.42	<0.0001	0.01	0.8894	0.02	0.8136	-0.29	0.002	0.03	0.7348	-0.16	0.089
Density of woody perennials	-0.1	0.2936	-0.12	0.1991	-0.1	0.269	-0.17	0.0762	0.26	0.0057	-0.2	0.036	0.14	0.1396	0.12	0.199
Density of shade canopy	-0.17	0.0638	-0.24	0.0118	0.2	0.0363	-0.07	0.4699	0.11	0.2644	-0.21	0.0247	-0.01	0.8817	-0.15	0.1063
Total density of the plantation	-0.25	0.0085	-0.2	0.0372	0.03	0.7768	-0.12	0.2214	0.02	0.8008	-0.16	0.0885	0.03	0.7498	-0.1	0.2787
Basal area of cocoa plants	-0.03	0.7164	0.11	0.2602	-0.23	0.0146	-0.01	0.8952	-0.13	0.179	0.35	0.0002	-0.17	0.0717	-0.03	0.7678
Basal area of palms	-0.28	0.0023	-0.34	0.0002	0.17	0.0729	-0.16	0.0815	0.31	0.0007	-0.35	0.0001	0.33	0.0004	0.23	0.0121
Basal area of fruit trees	-0.07	0.4824	-0.1	0.2798	0.1	0.2797	-0.09	0.3574	0.15	0.1109	-0.11	0.2347	0.24	0.0108	0.17	0.0751
Basal area of timber trees	-0.13	0.1712	-0.13	0.1624	-0.19	0.0462	-0.14	0.1281	0.75	<0.0001	-0.18	0.0546	1.30E-03	0.9889	-0.01	0.9239
Basal area of service trees	0.16	0.0917	0.15	0.1008	0.11	0.2411	0.19	0.0479	0.19	0.0404	0.1	0.3111	0.08	0.3761	0.13	0.1727
Basal area of musácea plants	-0.18	0.0554	-0.28	0.0025	0.42	<0.0001	0.01	0.8894	0.02	0.8136	-0.29	0.002	0.03	0.7348	-0.16	0.089
Basal area of woody perennials	-0.13	0.1796	-0.16	0.0954	-0.14	0.1352	-0.16	0.0895	0.93	<0.0001	-0.19	0.0387	0.12	0.1891	0.09	0.3238
Basal area of shade canopy	-0.18	0.0548	-0.23	0.0153	0.06	0.5555	-0.11	0.2297	0.74	<0.0001	-0.22	0.0164	0.05	0.5846	-0.06	0.4995
Total Basal area of the plantation	-0.17	0.0752	-0.12	0.203	-0.18	0.0559	-0.13	0.1762	0.58	<0.0001	0.13	0.1681	-0.09	0.3523	-0.07	0.4851
Total species richness	-0.34	0.0002	-0.37	<0.0001	0.3	0.0012	-0.2	0.0319	-0.02	0.8452	-0.46	<0.0001	0.17	0.0688	0.02	0.7952
Shannon index	-0.28	0.0023	-0.31	0.0007	0.29	0.0016	-0.16	0.0805	0.05	0.604	-0.41	<0.0001	0.35	0.0001	0.2	0.0337



Black dots: cocoa agroforestry systems of Costa Rica; blue dots: Guatemala; green dots: Nicaragua; orange dots: Panama
Horizontal black lines indicate the acceptable values of provisioning services considered in this study
Vertical black lines indicate the most adequate densities that should be managed in order to at least achieve the acceptable values of provisioning services

Figure 10. Relationships between indicators of provisioning ecosystem services and densities of different types of plants and trees in the shade canopies of cocoa agroforestry systems of Central America

3.1.5 Recommendations for management strategies of cocoa agroforestry systems

Based on the analysis of trade-offs and relationships of indicators of ecosystem services, we derive the following recommendations for cocoa AF in four countries of Central America:

- Trade-offs between indicators of provisioning and regulating ecosystem services in cocoa AF need to be balanced. Specially in the case of cocoa AF of Costa Rica and Panama, which favor regulating services but with low cocoa yields and incomes. Trade-offs in cocoa AF of Nicaragua and Guatemala are less critical, but deserves attention in the cases where high provisioning benefits are obtained but with low contribution to carbon sequestration or biodiversity.

- The major part of cocoa AF of all countries in general, tend to benefit more the soil fertility (pH and N) than provisioning services. This can be seen as a trade-off if we interpret that increasing soil fertility would decrease incomes for the families, but actually this should be interpreted as an opportunity to improve the overall benefits from the system. This means that the agroforestry production can be increased by taking advantage of the soil fertility that currently is well maintained in this systems.

- The mentioned trade-offs can be one of the reasons which cause that most of cocoa AF of all countries do not even reach the acceptable (modest) values proposed for indicators of provisioning services. For balancing the trade-offs we suggest the following management strategies:

    - If the objective is to reach at least the acceptable values of cocoa yields (600 kg/ha) and cash flow (1000 USD/ha) from both cocoa and other agroforestry products, then the densities of musaceas should be around 200 plants/ha, palms less than 20 plants/ha, fruit trees around 50 trees/ha, and total density of the shade canopy no more than 400 individuals/ha, which means that 100 trees/ha could be distributed in service trees and/or timber trees. And the total basal area of plants and trees in the shade canopy must not surpass 12 m^2/ha.
    - If the objective is to reach at least the acceptable value of family benefit (1000 USD/ha) from all agroforestry products, then the densities of musaceas could be around 600 plants/ha, palms up to 50 plants/ha, fruit trees up to 140 trees/ha, and total density of the shade canopy up to 800 individuals/ha. And the total basal area of plants and trees in the shade canopy could reach 20 m^2/ha.
    - In both of the two objectives, use species in the shade canopy which give a tangible benefit for the family. For instance, if leguminous service trees are used for improving soil fertility, try to choose a leguminous tree that also can offer fruits or firewood.
    - In order to achieve positive relationships between provisioning indicators and management intensity, farmers should be trained to apply efficiently cropping practices with better

techniques and/or tools and inputs. Thus, less cropping practices would be required to obtain the same benefits, or even better, the investment in better practices would yield higher benefits.

3.2 Production systems in the Sentinel Landscape of Nicaragua

3.2.1 Structure and plant biodiversity in the systems

The five land uses of this Sentinel Landscape were notably contrasting in their characteristics. Pastures represented the largest systems in area, followed by grain systems, cocoa AF and coffee AF with 2 ha in average, and the homegardens as the smallest systems with less than a quarter of hectare in average. Homegardens can be considered the most complex systems according to their high density, dominated by fruit trees. The next systems in complexity were the agroforestry systems with perennial crops, where coffee AF registered higher densities of trees than cocoa AF, and the highest basal areas compared to all other systems. Grain systems and pastures had similar characteristics in most types of trees, although grain systems could be considered as the ones with the lowest complexity according to their total densities, basal area and diversity (Table 7 and Figure 11).

Table 7. Structure characteristics of the shade canopy of production systems in the Sentinel Landscape, Nicaragua

Characteristics		Cocoa AF		Coffee AF		Grains		Pastures		Homegardens	
	Units	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Area of the system	ha	1.9	2.5	1.8	1.8	2.0	2.2	8.3	13.5	0.2	0.2
Density of service trees	ind/ha	33.2	28.9	43.6	24.8	8.5	9.5	14.8	11.9	41.7	41.7
Density of posts trees		1.5	3.3	4.5	7.8	0.8	2.0	1.0	2.2	1.8	4.6
Density of fruit trees		35.2	49.0	51.5	55.2	4.8	7.3	6.7	9.8	109.6	88.2
Density of timber trees		38.7	36.1	55.1	45.1	19.6	19.2	22.9	19.2	26.7	30.0
Total density of shade canopy		108.6	85.7	154.7	86.4	33.6	30.1	45.4	29.7	180.1	111.8
Basal area of service trees	m^2/ha	1.7	1.2	2.0	0.9	0.4	0.4	0.7	0.5	1.7	2.2
Basal area of posts trees		0.2	0.4	1.1	3.3	0.1	0.3	0.1	0.3	0.1	0.6
Basal area of fruit trees		1.0	1.6	1.3	1.6	0.2	0.3	0.2	0.3	3.2	3.2
Basal area of timber trees		2.7	2.0	3.8	2.8	1.2	1.7	1.2	0.9	1.4	2.1
Total Basal area of shade canopy		5.5	3.4	8.2	4.1	1.9	2.1	2.1	1.4	6.5	4.7
Total species richness		26.4	15.5	31.5	12.2	12.4	6.8	29.6	20.9	12.9	8.5
Shannon index		2.5	0.6	2.7	0.4	1.9	0.6	2.3	0.8	2.0	0.7

SD: standard deviation; ind: individuals

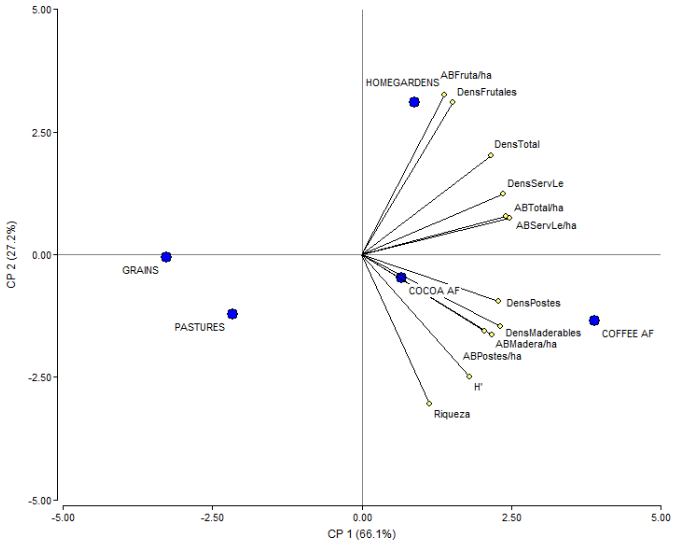


Figure 11. Principal component analysis. Exploratory relationships among structure characteristic of the shade canopies of production systems in the Sentinel landscape, Nicaragua

3.2.2 Ecosystem services provided by production systems

We found important differences in both provisioning indicators and carbon sequestration among the production systems. Homegardens contributed the most to the overall family benefit, but thanks only to their high domestic consumption because their cash flow was negative in average, which means that the major or almost entire part of the products of these systems are consumed in the very family and farm. Coffee and cocoa AF registered higher contributions to cash flow than the other systems, and also higher value of standing timber, which represents an important provisioning for families in the future. Grain systems, similar to homegardens, contributed more to the value of domestic consumption than to the cash flow. And pastures can be considered as the systems with the lowest indicators of provisioning in general. Carbon sequestration was higher in the shade canopies of coffee AF, followed by cocoa AF and homegardens, and finally pastures and grain systems with the lower carbon stocks (Table 8, Figure 12).

Table 8. Ecosystem services provided by production systems in production systems of the Sentinel Landscape, Nicaragua

Ecosystem services	Cocoa AF		Coffee AF		Grains		Pastures		Homegardens	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Cash Flow (USD/ha)	426	776	796	953	126	567	226	400	-753	1521
VDC (USD/ha)	529	753	555	663	745	551	223	245	2978	3042
Family Benefit (USD/ha)	955	1035	1351	1123	871	708	449	479	2225	2564
Value standing timber (USD/ha)	4857	3833	6564	5189	2001	2723	1896	1688	2163	3294
Carbon SC (tons/ha)	20	16	36	32	6	5	9	5	22	17

SD: standard deviation; Carbon SC: carbon in the shade canopy; VDC: value of domestic consumption

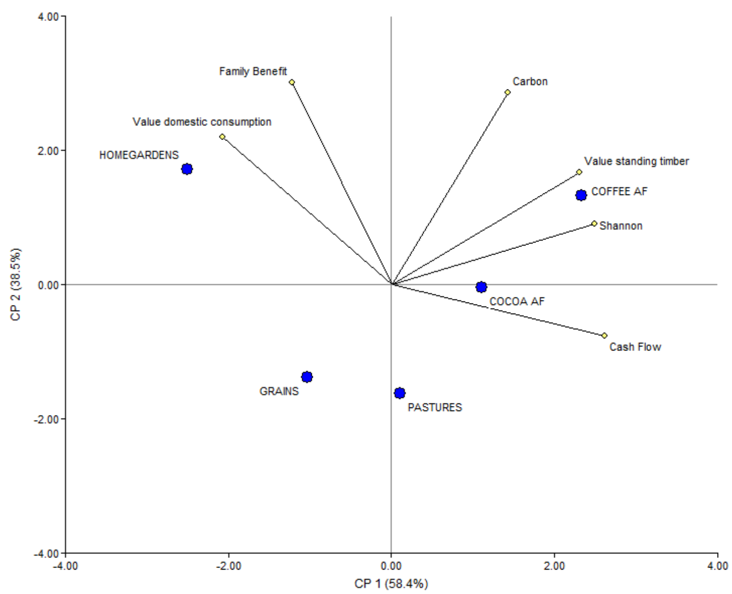


Figure 12. Principal component analysis. Exploratory relationships among indicators of ecosystem services provided by production systems in the Sentinel Landscape, Nicaragua

3.2.3 Trade-offs between ecosystem services, and biodiversity

Correlation spearman

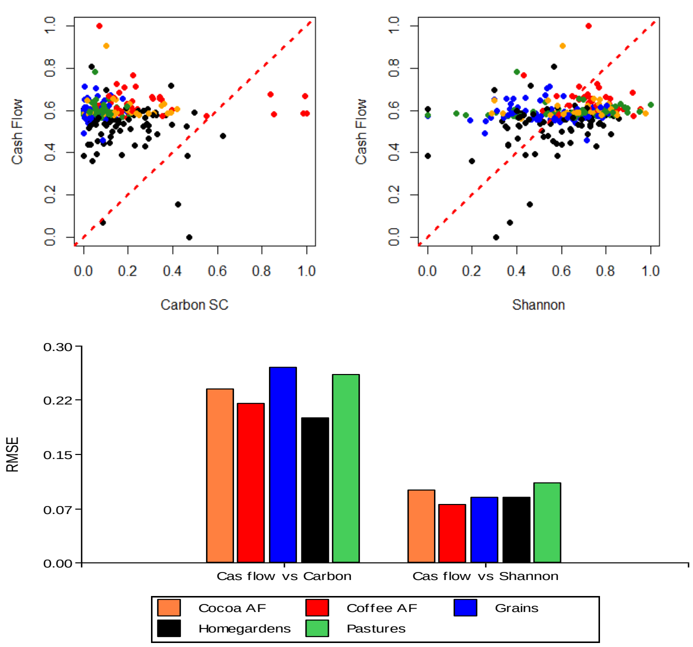
We found only two significant relationships denoting trade-offs. The value of domestic consumption had negative relationships with cash flow and with the value of standing timber. In the first case, it is a trade-off caused by the decision (and necessity) to consume the products for the family alimentation (or feeding domestic animals, or use materials in the farm) instead of selling the products. In the second case, it could be related to the fact that the timber trees are currently growing, occupying and space in the system that for the moment is not contributing to the family consumption (Table 9).

Table 9. Correlations (spearman) between indicators of ecosystem services of production systems of the Sentinel Landscape, Nicaragua

	Cash Flow		Value domestic consumption		Family Benefit		Value standing timber	
	Coef	p-value	Coef	p-value	Coef	p-value	Coef	p-value
Value domestic consumption	-0.41	1.20E-12						
Family Benefit	0.16	0.01	0.74	0				
Value standing timber	0.35	2.30E-09	-0.12	0.04	0.06	0.35		
Carbono SC	0.1	0.12	0.09	0.14	0.24	5.60E-05	0.52	0

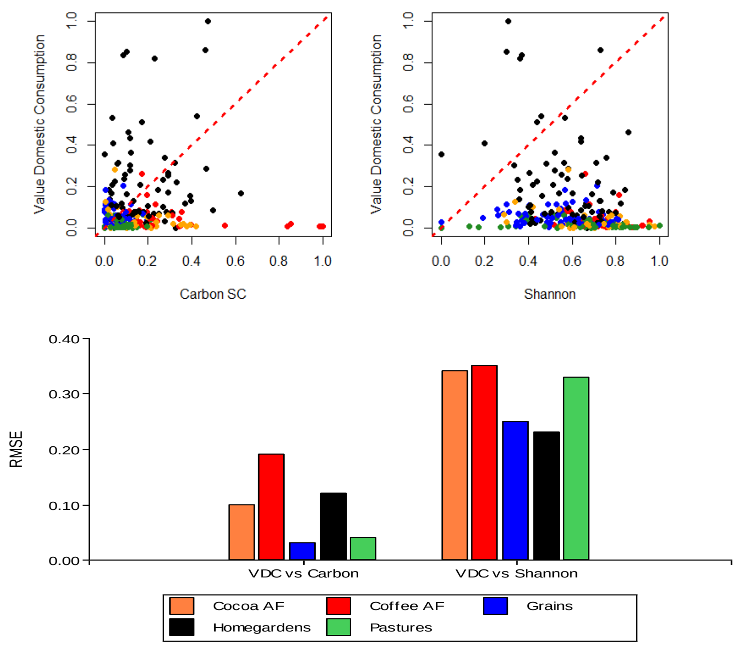
Magnitude of trade-offs

The analysis of relationships using standardized indicators and RMSD revealed trade-offs between provisioning services and biodiversity, and carbon sequestration. Only in the case of cash flow, most of the systems of all land uses favored more the cash flow than the carbon in shade canopy; while in the relationships between cash flow and biodiversity the tendency was not clear, approximately half of the systems of land uses favored one service and half the other service (Figure 13). In the cases of value of domestic consumption and family benefit, the relationships with carbon sequestration and biodiversity were similar: more systems of homegardens benefited more the indicators of provisioning than carbon sequestration; and it was interesting to note that practically all systems of coffee AF, cocoa AF and grains benefited more the biodiversity than the provisioning indicators (Figures 14 and 15). This latter indicates that the plant diversity of the systems is not benefiting the provisioning as it would be desired. In the case of relationships with value of standing timber something similar occurred, indicating that most of the plant diversity is not dedicated to the timber production (Figure 16). The magnitude of trade-offs (reflected by RMSD) were higher for coffee AF, cocoa AF and pastures than grain systems and homegardens in general (Figures 13 to 16).



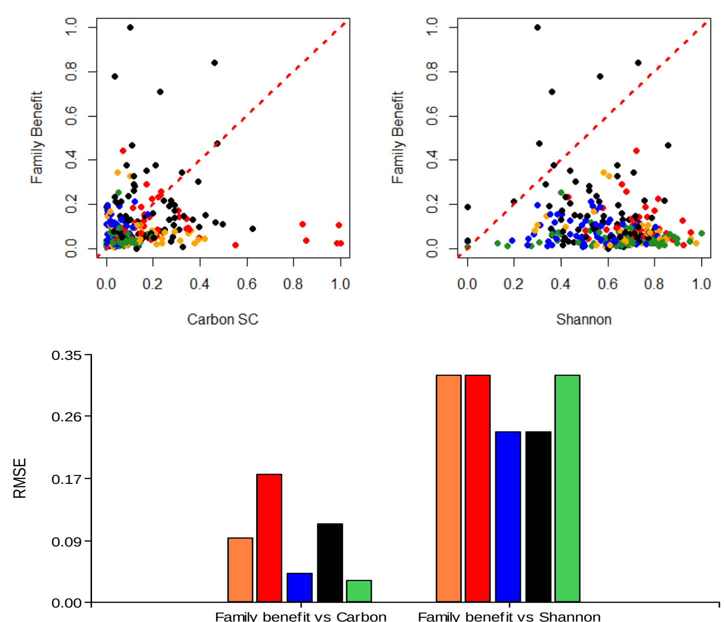
Red line is the 1:1 line, which represents no trade-offs.
Black dots: homegardens; blue dots: grain systems; green dots: pastures; red dots: coffee agroforestry systems; orange dots: cocoa agroforestry systems
Magnitude of trade-offs are represented by the Root Mean Square Deviation (RMSD): the higher the RMSD, the higher the trade-off

Figure 13. Analysis of trade-offs between cash flow and carbon, and biodiversity (represented by Shannon index) of production systems of the Sentinel Landscape, Nicaragua



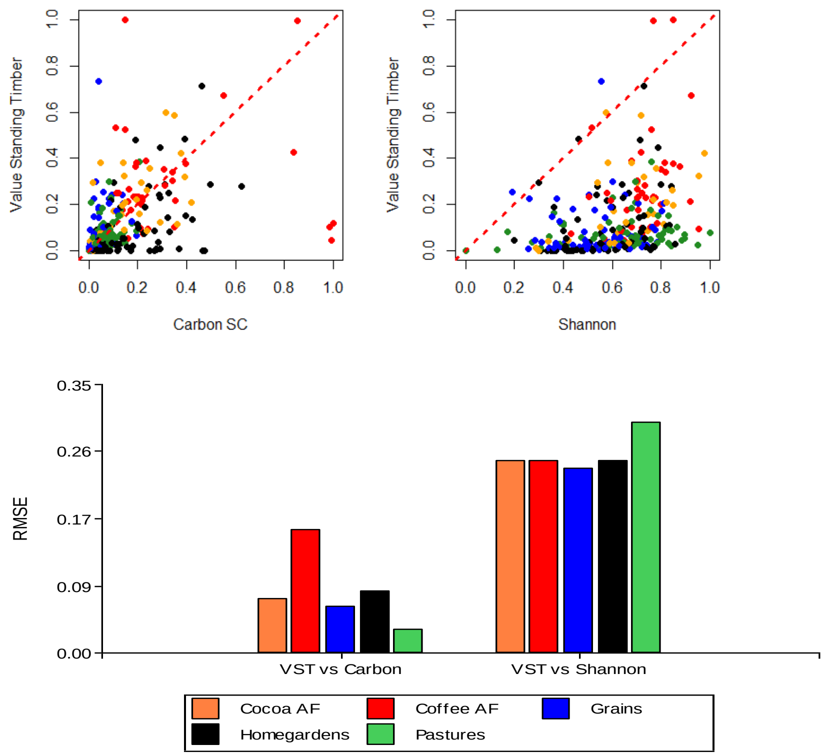
Red line is the 1:1 line, which represents no trade-offs. Black dots: homegardens; blue dots: grain systems; green dots: pastures; red dots: coffee agroforestry systems; orange dots: cocoa agroforestry systems.
Magnitude of trade-offs are represented by the Root Mean Square Deviation (RMSD): the higher the RMSD, the higher the trade-off

Figure 14. Analysis of trade-offs between value of domestic consumption and carbon, and biodiversity (represented by Shannon index) of production systems in the Sentinel Landscape, Nicaragua



Red line is the 1:1 line, which represents no trade-offs. Black dots: homegardens; blue dots: grain systems; green dots: pastures; red dots: coffee agroforestry systems; orange dots: cocoa agroforestry systems
Magnitude of trade-offs are represented by the Root Mean Square Deviation (RMSD): the higher the RMSD, the higher the trade-off

Figure 15. Analysis of trade-offs between family benefit and carbon, and biodiversity (represented by Shannon index) of production systems of the Sentinel Landscape, Nicaragua



Red line is the 1:1 line, which represents no trade-offs. Black dots: homegardens; blue dots: grain systems; green dots: pastures; red dots: coffee agroforestry systems; orange dots: cocoa agroforestry systems
Magnitude of trade-offs are represented by the Root Mean Square Deviation (RMSD): the higher the RMSD, the higher the trade-off

Figure 16. Analysis of trade-offs between value of standing timber and carbon, and biodiversity (represented by Shannon index) of production systems of the Sentinel Landscape, Nicaragua

Relationships between ecosystem services and structure of shade canopies of production systems

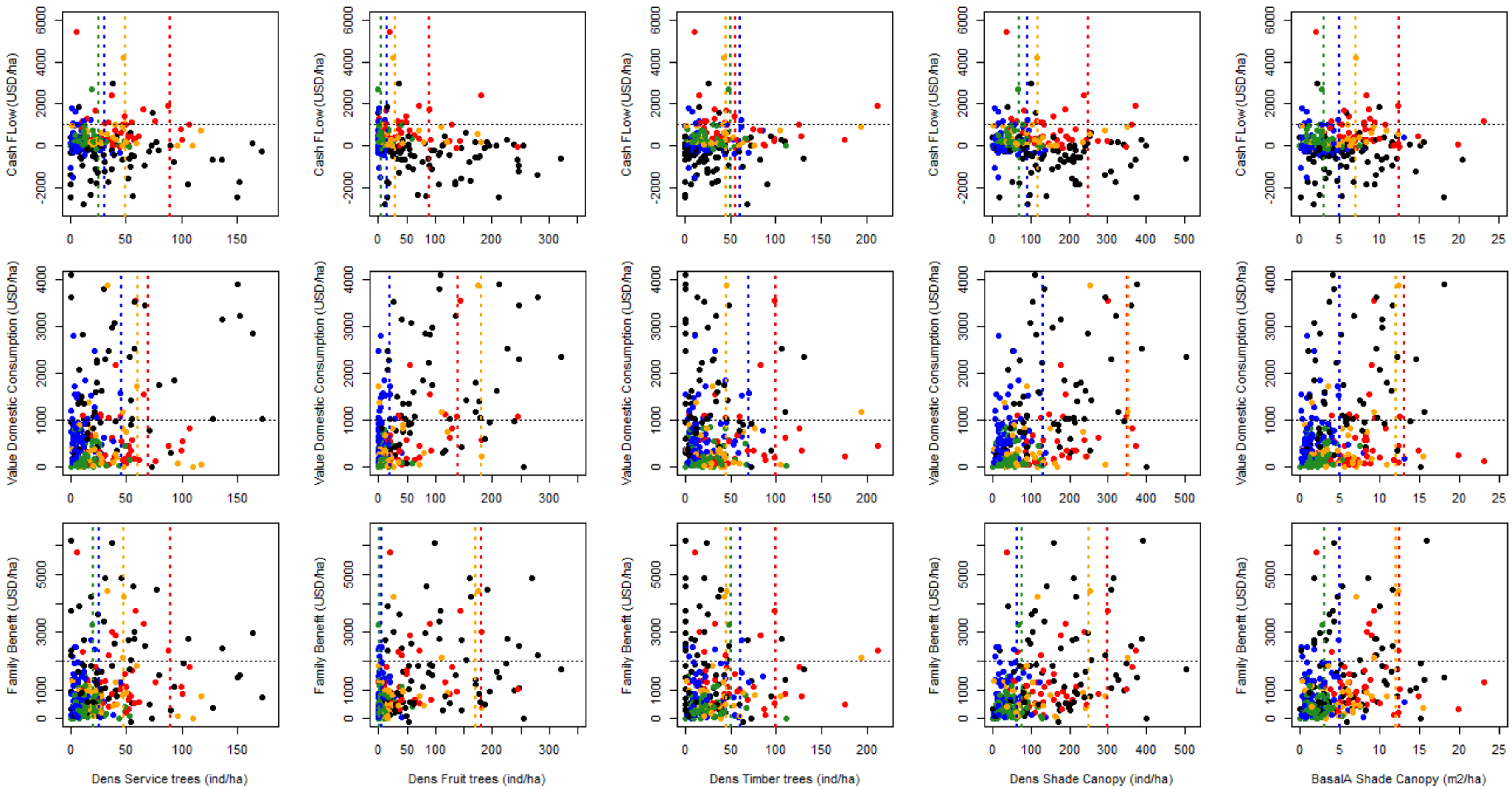
With the analysis of correlations (Spearman) we found few important significant negative relationships between provisioning services and characteristics of the shade canopy, denoting trade-offs. We can highlight the negative relationship between cash flow and densities and basal areas of fruit trees. There were also negative relationships of value of domestic consumption and family benefit with post trees, but actually this does not mean a considerable problem given that densities of such trees are low. Contrary to what was expected, the relationships of value of domestic consumption and family benefit with species richness and shannon index were negative (Table 10). This latter indicates that plant biodiversity in the systems of the Sentinel Landscape is incurring in trade-offs with the overall benefits expected for the families. In other words, there is good biodiversity but, on one hand farmers would not be taking advantage from it, or on the other hand most of the species do not offer products for the farmers. This is also supported by the results in Figures 14 and 15.

In Figure 17, we show the performance of provisioning indicators in function of densities of different trees of the production systems in the Sentinel Landscape. We considered that cash flows and value of domestic consumption should be at least above 1000 USD/ha and family benefits above 2000 USD/ha to represent attractive levels for farmers´ families according to their objectives. Based on that, we could determine the acceptable densities in the shade canopies for obtaining such values, using the same reasoning applied to the results for cocoa AF in Central America (see section 3.1.4, subtitle Relationships between ecosystem services and structure of shade canopies of cocoa AF). However, in the case of the Sentinel Landscape, it worth to differentiate the adequate densities for each type of land use. For instance, for obtaining the desired cash flow, in the case of coffee AF the densities of service trees should not surpass 80 trees/ha, but in the case of grain systems these trees should not surpass 40 trees/ha; another example, if the objective of farmers would be to take advantage of the overall contribution of the systems: the desired level (or higher levels) of family benefit could be reached with even 300 fruit trees/ha in homegardens, no more than 180 fruit trees/ha in coffee and cocoa AF, while in grains and pastures such family benefits would be possible with less than 10 fruit trees/ha. The same reasoning applies with basal areas, grains and pastures needs less m2 of trees/ha that the other land uses in order to achieve acceptable levels of provisioning services (Figure 17).

Table 10. Correlations (Spearman) between indicators of ecosystem services and characteristics of production systems of the Sentinel Landscape, Nicaragua

	Cash Flow		Value of domestic consumption		Family Benefit		Value of standing timber		Carbon SC	
	Coef	p-value	Coef	p-value	Coef	p-value	Coef	p-value	Coef	p-value
Density of service trees	0.04	0.5198	0.15	0.0131	0.23	0.0001	0.33	<0.0001	0.44	<0.0001
Density of posts trees	0.27	<0.0001	-0.28	<0.0001	-0.12	0.0465	0.21	0.0005	0.24	0.0001
Density of fruit trees	-0.2	0.0008	0.46	<0.0001	0.43	<0.0001	0.18	0.0038	0.53	<0.0001
Density of timber trees	0.22	0.0004	-0.03	0.5762	0.09	0.1623	0.79	<0.0001	0.4	<0.0001
Total density of shade canopy	-0.11	0.0674	0.38	<0.0001	0.4	<0.0001	0.39	<0.0001	0.6	<0.0001

Basal area of service trees	0.13	0.0391	0.06	0.3154	0.18	0.0028	0.45	<0.0001	0.58	<0.0001
Basal area of posts trees	0.21	0.0004	-0.2	0.0012	-0.07	0.2377	0.21	0.0004	0.26	<0.0001
Basal area of fruit trees	-0.16	0.0065	0.43	<0.0001	0.42	<0.0001	0.2	0.0008	0.62	<0.0001
Basal area of timber trees	0.34	<0.0001	-0.1	0.0955	0.07	0.2197	0.98	<0.0001	0.53	<0.0001
Total Basal area of shade canopy	0.06	0.3553	0.24	0.0001	0.34	<0.0001	0.65	<0.0001	0.82	<0.0001
Total species richness	0.37	<0.0001	-0.43	<0.0001	-0.19	0.0021	0.5	<0.0001	0.45	<0.0001
Shannon index	0.27	<0.0001	-0.32	<0.0001	-0.13	0.0397	0.44	<0.0001	0.44	<0.0001



Black dots: homegardens; blue dots: grain systems; green dots: pastures; red dots: coffee agroforestry systems; orange dots: cocoa agroforestry systems
Horizontal black lines indicate the acceptable values of provisioning services considered in this study
Vertical colored lines indicate the most adequate densities that should be managed (per each land use) in order to at least achieve the acceptable values of provisioning services

Figure 17. Relationships between indicators of provisioning ecosystem services and densities of different types of plants and trees in the shade canopies of production systems of the Sentinel Landscape, Nicaragua

3.2.4 Recommendations for management strategies of coffee AF, cocoa AF, grain systems, pastures and homegardens

Based on the analysis of trade-offs and relationships of indicators of ecosystem services, we derive the following recommendations for production systems in the Sentinel Landscape of Nicaragua:

- Trade-offs between indicators of provisioning and carbon sequestration need to be balanced. The systems with more variability showing extreme observations benefiting one or the other service were form coffee AF and homegardens. Such particular observations (systems) would need more interventions to reduce high trade-offs.

- Trade-offs between indicators of provisioning and biodiversity need to be balanced as well. The most critical trade-off was between the value of domestic consumption and biodiversity. This relationship was probably influenced by observations from homegardens, because of their high domestic consumption. Nevertheless, the other land uses must improve the offer of agroforestry products for self-consumption of families or for being used on farm (e.g. construction materials).

- In general, the systems which are offering the least values of provisioning and regulating services were the grain systems and pastures. Therefore, these land uses deserve more agroforestry interventions than the other systems in order to increase the overall contributions of the systems and reduce trade-offs between both provisioning and carbon sequestration, and provisioning and biodiversity.

- Homegardens provide a lot for the value of domestic consumption but not for cash flow (whose most values were negative), denoting a trade-off between those indicators. Therefore, especially in homegardens, efforts should be placed in promoting the sale of products or plant species which offer marketable products, if the farmers want to increase the incomes in cash from these systems.

- Contrary to homegardens, coffee and cocoa AF, would need to increase the offer of products for domestic consumption. Such improvement will produce a better balance between family benefit and carbon sequestration, and between family benefit and biodiversity.

- The mentioned trade-offs could be balanced with the improvement of densities of trees in the systems. However, given the particular characteristics of the main crops in each land use, the suggested densities of the different trees will be different for each land use. In Figure 17, the densities suggested for each of them are indicated with lines of colors.

- A general key recommendation for all land uses, as well as in cocoa AF of Central America, is the use species in the shade canopy which give a tangible benefit for the family. For instance, if leguminous service trees are used for improving soil fertility, try to choose a leguminous tree that also can offer fruits or firewood.

4 Preliminary conclusions

The statistical techniques that we used in this study were useful and complementary among them in order to identify and support the findings of trade-offs. The principal component analysis was useful to first explore overall relationships among structure characteristics of shade canopies, ecosystem services and the different agroecosystems studied. The simple correlations (Spearman) were useful to identify the main negative relationships, when they were significant, they were an important warning of the main trade-offs that should be taken into account. The approach of standardized indicators, scatter observations in plots and the RMSD were the most useful to identify the most critical trade-offs, and in which type of systems that trade-offs were occurring.

We identified trade-offs between indicators of provisioning and regulating services, and between ecosystem services and biodiversity, especially with the approach of standardizing indicators, paired plots and RMSD. In general, most of the observations of all agroecosystems (coffee AF, cocoa AF, grain systems, pastures and homegardens) favored more regulating services and plant biodiversity over provisioning services. The most critical trade-offs were found in grains systems and pastures because they offered the lowest provisioning services among the land uses evaluated in this study.

The integral analysis conducted to derive key management strategies for better balances among indicators of ecosystem services. The exploration of indicators of ecosystem services in function of densities of different types of plants and trees, after already know the main trade-offs, permitted to derive key suggestions on the densities and basal areas that should be maintained in the shade canopies of the production systems. The management applied to the systems should be also improved in order to be more effective and finally change its current negative relationships with provisioning services. Another key suggestion is to manage plant biodiversity that really contribute with a tangible benefit to the farmers, which is choose better the plant species that offer marketable products.

The recommendations and management strategies suggested in this study are important to reduce trade-offs between ecosystem services, and biodiversity, cropping practices and structure of shade canopies of production systems, and aim to maximize the overall benefits that agroecosystems can offer to smallholder farmers and their families. If the benefits are maximized in productive landscapes of Central America where coffee, cocoa, grains, pastures and homegardens are the most common agroecosystems, then the pressure of clearing secondary and primary forests in such landscapes could be reduced.

Despite very few systems achieved high levels of indicators of two indicators of ecosystem services at the same time, such systems are representatives that such benefits could be achieved. The most successful observations (specific systems) that reached the highest levels of services without or with low trade-offs, deserves to be described and studied in detail. Such systems can be models to follow in order to better balance trade-offs.

5 Literature

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