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Influence of tree cover on diversity, carbon sequestration and productivity of cocoa systems in the Ecuadorian Amazon

Photo 1.
Cocoa agroforestry system "chakra" one of the most important traditional agricultural systems in the Sumaco Biosphere Reserve (SBR).
Photograph O. Jadán, 2011.

RÉSUMÉ

INFLUENCE DU COUVERT FORESTIER SUR LA DIVERSITÉ, LES STOCKS DE CARBONE ET LA PRODUCTIVITÉ DES CACAOYÈRES DANS LA RÉGION AMAZONIENNE DE L'ÉQUATEUR

La production de cacao dans la région amazonienne de l'Équateur représente une source de revenus importante pour la population locale. Les systèmes de production de cacao varient entre forêt primaire enrichie, systèmes agroforestiers traditionnels et monoculture. Cette étude vise à évaluer la relation entre diversité spécifique, stocks de carbone, productivité agricole et utilisations potentielles des ressources forestières pour trois modes d'utilisation des terres dans la région amazonienne de l'Équateur : agroforesterie à dominante cacaoyère (AF Cacao), monoculture de cacao (Monoculture) et forêt primaire (FP). La connaissance et la quantification des meilleurs compromis entre les différents services écosystémiques liés à la culture du cacao permettent de contribuer à la conservation des forêts primaires et d'optimiser les revenus des populations locales. La richesse spécifique, la diversité bêta, les stocks de carbone (biomasse aérienne et souterraine, nécromasse et sols) et la production de cacao et de bois ont été déterminés pour chaque système de culture sur des parcelles de 1 600 m² (n = 28). Nos résultats montrent que la diversité bêta, la richesse spécifique et les stocks de carbone sont significativement plus élevés dans les systèmes FP et AF Cacao, tandis que la production du cacao est 1,5 fois plus élevée en Monoculture que sur les parcelles en AF Cacao. Pour ces deux systèmes, la richesse spécifique, la diversité bêta et les stocks de carbone totaux sont corrélés négativement avec la productivité de cacao. Alors que nos résultats montrent que la monoculture de cacao est plus rentable pour les agriculteurs que l'AF Cacao, un système de rémunération monétaire de la déforestation évitée, basé sur les crédits carbone, pourrait représenter une stratégie viable pour encourager la mise en œuvre de systèmes AF Cacao, lesquels contribueraient aux efforts de conservation et d'atténuation des effets du changement climatique tout en permettant de maintenir une production commerciale de cacao dans la région.

Mots-clés : cacao, systèmes agroforestiers, forêts primaires, Chakra, monoculture, Sumaco, carbone.

ABSTRACT

INFLUENCE OF TREE COVER ON DIVERSITY, CARBON SEQUESTRATION AND PRODUCTIVITY OF COCOA SYSTEMS IN THE ECUADORIAN AMAZON

Cocoa production in the Ecuadorian Amazon is an important source of income for the local population. There is a wide variety of cocoa production systems, from enriched primary forests to traditional agroforestry systems and monoculture. This study assesses the relationship between tree diversity, carbon stocks, agricultural productivity and forest use potential under three land use systems in the Ecuadorian Amazon: cocoa-based agroforestry (Cocoa AFS), cocoa monoculture (Monoculture) and primary forest (PF). Understanding and quantifying the tradeoffs between different ecosystem services related to cocoa production systems can contribute to the conservation of primary forests and help to optimize income for local people. Species richness, beta-diversity, carbon stocks (above- and below-ground biomass, necromass and soil), and cocoa and timber production were determined for each system in 1,600 m² study plots (n=28). The results show that beta diversity, species richness and carbon stocks were significantly higher in PF and Cocoa AFS, whereas cocoa production was 1.5 times higher in the Monoculture than in Cocoa AFS. In both cocoa systems, species richness, beta diversity and total C were negatively correlated with cocoa productivity. Although our results show that cocoa monoculture was more profitable than Cocoa AFS for the farmers, a monetary payment based on carbon credits for avoided deforestation could be a viable strategy to support the implementation of Cocoa AFS, which would help conservation efforts and climate change mitigation while sustaining commercial cocoa production in the area.

Keywords: cocoa, agroforestry systems, primary forests, Chakra, monoculture, Sumaco, carbon.

RESUMEN

INFLUENCIA DE LA CUBIERTA FORESTAL EN LA DIVERSIDAD, ALMACENAMIENTO DE CARBONO Y PRODUCTIVIDAD DE SISTEMAS DE CACAO EN LA AMAZONÍA ECUATORIANA

La producción de cacao en la Amazonía ecuatoriana constituye una importante fuente de ingresos para la población local. Los sistemas de producción de cacao son variados y engloban bosques primarios enriquecidos, sistemas agroforestales tradicionales y monocultivos. El objetivo de este estudio es evaluar la relación entre diversidad específica, reservas de carbono, productividad agrícola y usos potenciales de los recursos forestales en tres sistemas de uso de la tierra de la Amazonía ecuatoriana: agroforestería con predominio de cacao (AF Cacao), monocultivo de cacao (Monocultivo) y bosque primario (BP). La comprensión y cuantificación de las compensaciones recíprocas entre los diferentes servicios ecosistémicos relacionados con el cultivo de cacao puede contribuir a la conservación de los bosques primarios y optimizar los ingresos de la población local. En cada sistema de cultivo, en parcelas de 1 600 m² (n=28), se determinó la riqueza específica, diversidad beta, reservas de carbono (biomasa aérea y subterránea, necromasa y suelo) y la producción de cacao y madera. Nuestros resultados muestran que la diversidad beta, la riqueza específica y las reservas de carbono son significativamente mayores en los sistemas BP y AF Cacao, mientras que la producción de cacao es 1.5 veces mayor en Monocultivo que en las parcelas AF Cacao. En estos dos sistemas, la riqueza específica, la diversidad beta y las reservas de carbono totales están negativamente correlacionadas con la productividad de cacao. Aunque nuestros resultados muestran que el monocultivo de cacao es más rentable para los agricultores que la AF Cacao, se podría aplicar una retribución monetaria por deforestación evitada basada en los bonos de carbono. Esto podría ser una estrategia viable para favorecer la implantación de sistemas AF Cacao, que contribuirían a los esfuerzos de conservación y mitigación de los efectos del cambio climático, permitiendo al mismo tiempo mantener una producción comercial de cacao en la región.

Palabras clave: cacao, sistemas agroforestales, bosques primarios, chacra, monocultivo, Sumaco, carbono.

Introduction

Deforestation to expand conventional farming systems is the major cause for the continuing loss of tropical ecosystems (Seufert *et al.*, 2012). Over the last decade, such land use changes have been responsible for around 10% of global CO_2 emissions (Le Quéré *et al.*, 2013). In the Ecuadorian Amazon, loss of natural ecosystems is particularly evident in areas of high biodiversity. For instance, in the Sumaco Biosphere Reserve (SBR), between 2008 and 2013, the deforestation rate was 3.34%, mainly due to anthropogenic processes such land use changes for livestock and agricultural production (Ministerio del Ambiente del Ecuador and Deutsche Gesellschaft für Internationale Zusammenarbeit, 2013).

In that region, conventional agricultural production systems are mostly based on monocultures with typically low long-term productivity (Price and Norsworthy, 2013). In contrast, it is also possible to find traditional and originally organic farming production systems, mainly practiced by indigenous groups (Porro *et al.*, 2012). Locally known as "Chakra" (photo 1), they consist of small plots within the rainforest that are used to plant subsistence crops (photo 2); a traditional practice carried out over centuries by the local Kichwa population (Whitten and Whitten, 2008). Over time, the cultivation of staple food such as manioc, *Manihot sculenta*, peach palm, *Bactris gasipaes*, and banana, *Musa paradisiaca*, were integrated with other commercially valuable species such as cocoa, *Theobroma cacao* (Torres *et al.*, 2014). Aside from its economic importance, the "Chakra" also provides social and cultural goods to the farmers (Selesi, 2013). Interestingly, the "Chakra" cacao system is one of the most important land use systems in the SBR, after native forests and livestock farming (Selesi, 2013), with about 12,000 farmers practicing this production system (75% of whom are indigenous farmers) in over 14,000 hectares (Torres *et al.*, 2014).

The presence of timber species within cocoa plantations, such as in the "Chakra" system, provides an added value to the production of cocoa and improves profitability in

Photo 2.
Chakra subsistence contributes to food security for population in Biosphere Reserve Sumaco.
Photograph O. Jadán, 2011.

the long run (Ramirez *et al.*, 2001). Thus, cocoa-based agroforestry systems (cocoa AFS) maintain productivity, functionality and economic efficiency of crops while showing a yet to be determined climate change mitigation potential (Verchot *et al.*, 2007). To the best of our knowledge, this is the first study in which a complete assessment of the potential of cocoa AFS for climate change mitigation is reported. The objective of this project was to determine the influence of tree cover on richness and floristic diversity, carbon stocks, ecosystem services, agricultural productivity and silvicultural utilization potential under three land use systems (LUS) and to determine the relation of these variables with the agricultural management under organic and conventional practices in the Ecuadorian Amazon. Cocoa Monoculture and cocoa AFS were compared with each other and against Primary forest (PF) (photo 3).

Methods

Study sites

The study sites were located in the lower part of the SBR in the cantons of Archidona and Tena, Napo Province, Ecuador (figure 1). The SBR comprises 88,000 hectares at elevations under 700 m. The climate is typical of Holdridge's Tropical Wet Forest life zone (Holdridge, 1967), with mean annual temperature of 23°C, mean annual precipitation of 3,500 mm, and distinct wet (April-May) and dry (October-December) seasons (Inamhi, 2014).

Participating farms were selected among the members of the Napo-Kallari cocoa growers association. The criteria for the initial farm selection were: a) crop area ≥ 0.5 ha, b) tree crown cover ≥ 10% in cocoa AFS and < 10% in cocoa Monoculture, determined with a densiometer as in Guilherme (2000), c) cultivation in cocoa AFS must be organic, and d) all study sites had to be planted with the same, "national", cocoa variety. A total of 300 farms meeting these characteristics were identified (195 AFS and 105 Monoculture), from which 23 were selected randomly (15 AFS and 8 Monoculture, 8% of initially selected farms) and based on the willingness of the farmers to participate in the study. In each farm, one 1,600 m circular plot was installed. For comparison to the cocoa systems, five similar study plots were installed in a primary forest located at the Jatun Sacha Biological Station (JSBS), thus totaling 28 study plots distributed among the three land use types.

Richness and floristic diversity

Within each study plot, diameter and commercial height of all trees and palms with a diameter at breast height (dbh)

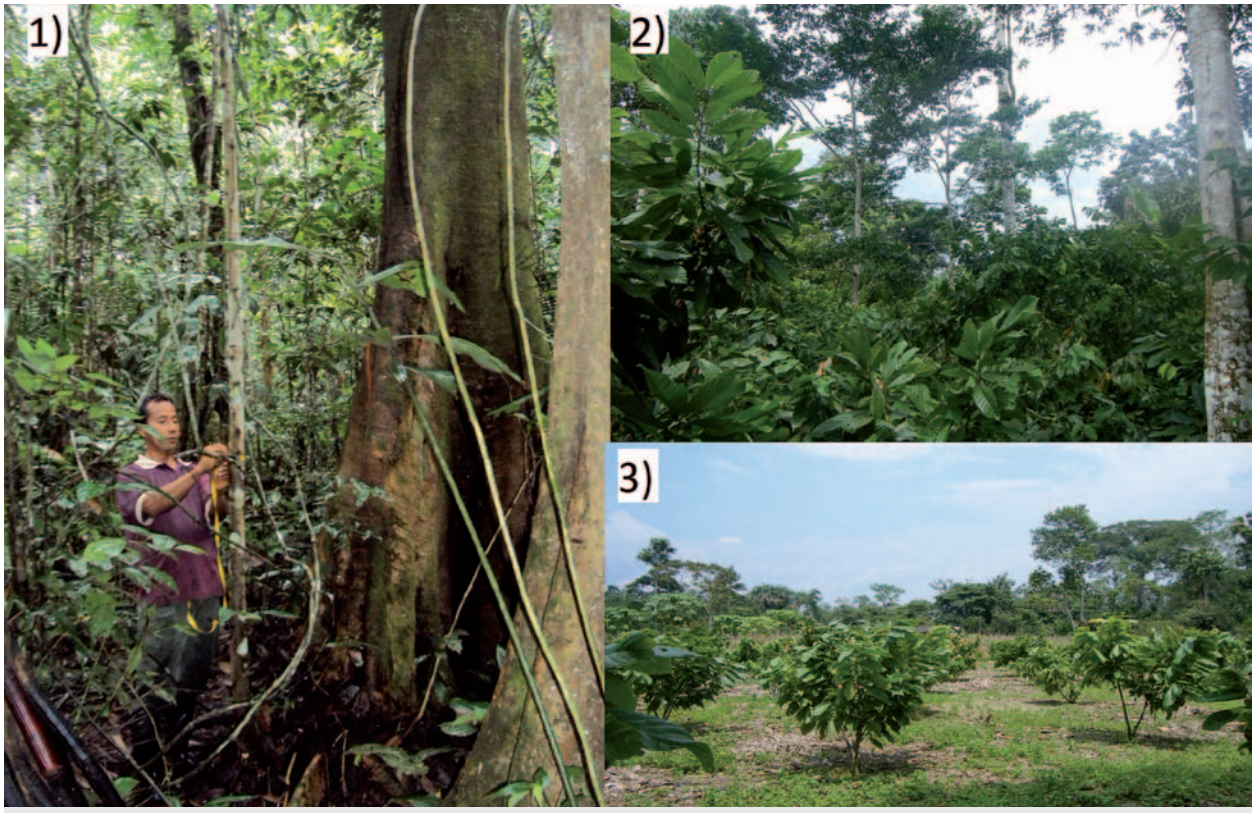


Photo 3.
Systems of land use evaluated: 1) primary forest, 2) cocoa AFS and 3) monoculture.
Photograph O. Jadán, 2011.

≥ 10 cm were measured and their species identified. EstimateS v.5.0.1 (Colwell, 2011) was used to calculate density of individuals per hectare, dominance, species richness and beta diversity. Beta diversity was calculated using an analysis of similarities (ANOSIM) and non-metric multidimensional scaling (NMS) using Bray Curtis as dissimilarity measure in species composition.

Carbon storage and accumulation rate

Biomass was divided into five storage components; aboveground biomass, belowground biomass (roots), litter (branches < 10 cm in diameter and leaves), necromass (> 10 cm diameter) and soil. Aboveground biomass was classified according to the physiognomy of its components: cocoa trees, timber trees, fruit trees, Musaceae and palms. Above and below ground biomass for these were estimated using allometric equations (table I). Litter samples were taken from four 1 m² subsamples per plot and dried to constant mass. Necromass (> 10 cm diameter) was measured along two 23 m-long transects, laid out perpendicularly to each other and bisecting the study plot (Penman *et al.*, 2003). Composite soil samples from four randomly located points per plot were taken to estimate soil C at two depths (0-10 cm and 10-30 cm).

Total soil C was determined by dry combustion (Macdicken, 1997). Carbon (C) was estimated as 0.5 of the biomass (Penman *et al.*, 2003) and total carbon (TC) as the sum of all storage components. Carbon equivalence (CO_{2e}) was calculated by multiplying C values by the molecular equivalence factor 3.67. We used an annual C accumulation rate of 0.45 Mg/ha/yr for PF (Lewis *et al.*, 2009) and of 1.3 Mg/ha/yr

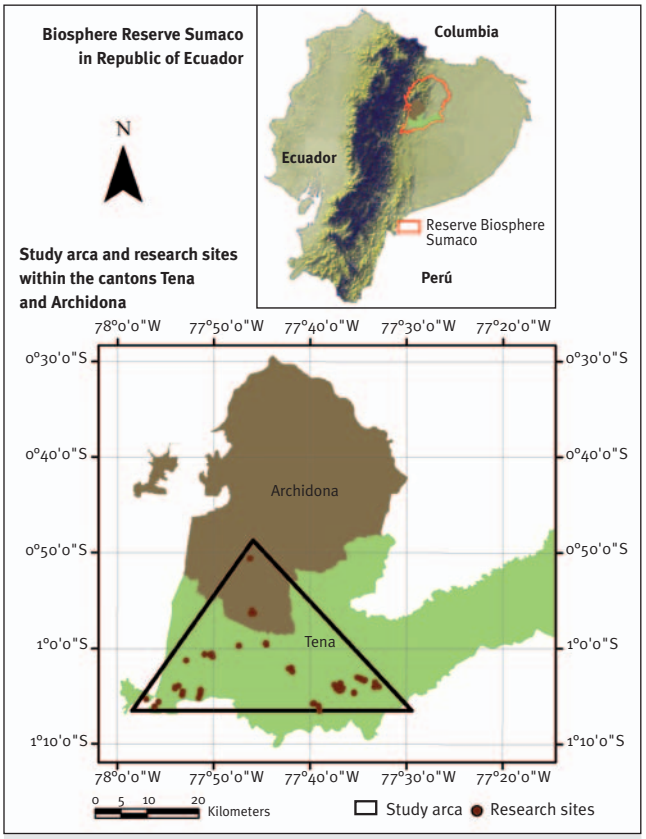


Figure 1.
Study area in Sumaco Biosphere Reserve, Napo Province, Ecuador.

Table I.
Allometric equations for biomass estimation, calculating C accumulation rate, productivity and income for three land use systems evaluated in the Sumaco Biosphere Reserve, Ecuador.

Ecosystem or species	Equation	Range DBH (cm)	R^2	Author
Tropical forests	Ln (Bt)= -1.864+2.608 × Ln (dap) + Ln (d)	5 - 150	0.99	(Chave *et al.*, 2005)
Bactris gasipaes	Bt = 0.74 × h2		0.95	(Szott *et al.*, 1993)
Cocoa	Bt = 1.0408 expo.0736 × (d30)		0.97	(Torres *et al.*, 2014)
Saplings	Bt = 10(-1.27+2.2 × Log (dap))	0.3 - 9.3	0.88	(Andrade *et al.*, 2008)
Musaceae	Bt = (185.1209 + 881.9471 × (Log(ht)/ ht2))/1000			(Villavicencio, 2009)
Palms	Bt =7.7 × ht + 4.5		0.90	(Frangi and Lugo, 1985)
Roots	Br = exp (-1.0587 + 0.8836 × Ln Bt)		0.84	(Penman *et al.*, 2003)
Accumulation rate	$IAt = CBT / e$			(Equation 1)
Cocoa productivity	$Pc = Nfl \times 0.136\ kg \times \frac{10{,}000}{Sm}$			(Equation 2)
Net revenue cocoa	$IN = ITp - Cp$			(Equation 3)

Notes: R^2: adjusted R^2; Bt: total aboveground biomass (kg/tree); Br: belowground biomass; DBH: diameter at breast height (cm); d: basic wood density; d30: diameter at 30 cm height ; ht: total height (m); exp: power base e ; Ln: natural logarithm (base e); IAt: annual increment of each plant type (Mg C/ha/yr); CBT: carbon stored in the total biomass of each plant (Mg C/ha/yr), e: estimated age of each plant; Pc: productivity cocoa (kg/ha); Nfl: total number of pods per plot; Sm: sampling surface; IN: net revenue; ITp: total income per production cocoa; Cp: production costs cocoa.

for soils across all LUS (Silver *et al.*, 2000). To estimate the C accumulation rate for trees and palms in LUS with cocoa cultivation, the DBH was used to estimate the age, assuming a growth of 1 cm/yr (Korning and Balslev, 1994 ; Calero, 2008). In farming systems the rate of accumulation was calculated using Equation 1 (table I).

Agricultural and forest productivity

Cocoa productivity was calculated counting all fruits in the study plots during the wet (April-May) and dry seasons (October-November). All fruits were counted disregarding phytosanitary status or maturity stage and avoiding double counting. Wet pulp weight (the product typically sold by the Kichwa population) was measured on 50 mature fruits at each sampling time (photo 4). Potential cocoa productivity was then calculated using Equation 2 (table I). Off-season productivity was considered negligible, based on local interviews and direct observations. Timber production was calculated with the commercial volume information obtained from the floristic inventory.

Costs, revenue and valuation

Agricultural production costs

Production costs were calculated in each agricultural system during one year. For cocoa, we considered fertilization (conventional and organic), weed control (manual weeding), phytosanitary control, shade regulation, pruning and harvesting costs.

Total net revenue

The sale price of wet cocoa pulp was 1.21 USD/kg, which is the local "fair market" price paid to the local Napo-Kallari cocoa growers association. This value was used to calculate the total income from cocoa production (ITp). Net cocoa revenue was calculated with Equation 3 (table I). The commercial timber volume was based upon a net income of 8 USD/m^3 for softwoods and 45 USD/m^3 for hardwoods (Gatter and Romero, 2005). The total monetary value of timber was divided according to rotation periods defined in the national forest regulations (Ministerio del Ambiente del Ecuador, 2010). Potential revenue from CO_{2e} sales was estimated using a price of 5 USD for CO_2/ha and financial scenarios between forest C stocks and crops were compared within the REDD+ context (Peters-Stanley and Gonzalez, 2014).

Photo 4.
Fruit harvesting for calculating productivity in the cocoa SAF.
Photograph O. Jadán, 2011.

Statistical analysis

LUS variables and differences were analyzed using ANOVA, Fisher LSD test and Pearson's correlation coefficient at a 95% confidence level.

Results

Richness and floristic diversity

We found more species per area and more sampled individuals in PF than in Cocoa AFS and in Monoculture ($p < 0.05$; figure 2). According to these curves, a one-hectare forest was estimated to have 225 species, compared to 35 species.ha^{-1} in Cocoa AFS and only 10 species/ha in the Monoculture.

Species richness, density of individuals per hectare (Ind/ha), basal area (m^2/ha) and canopy cover (%) were higher in PF than in both cocoa AFS and Monoculture ($p < 0.009$). Cocoa AFS shared the greatest number of species (19) with PF (table II).

Beta diversity showed significant differences in species composition between the three land uses ($R^2 = 0.70$, $p = 0.001$). The results of the NMS and ANOSIM (figure 3) for the species composition was significantly higher in PF than in Cocoa AFS ($p = 0.001$) and in Monoculture ($p = 0.012$). The species composition between cocoa farming types was statistically different ($p = 0.009$).

Carbon storage and accumulation

Aboveground and belowground C and total C were 4 to 36 times greater in PF than in Cocoa AFS and Monoculture systems ($p < 0.009$). There were no significant differences ($p = 0.6917$) of C in necromas and soil ($p = 0.6917$) among the LUS. The annual increment of total C was significantly higher ($p = 0.0001$) in Cocoa AFS than in the Monoculture and PF (table III).

Production and potential revenue

Cocoa production was 1.5 times higher ($p = 0.0522$) in Monoculture than in Cocoa AFS. Consequently, net cash income from cocoa productivity was similarly higher in the monoculture than in cocoa AFS ($p = 0.0587$). Although

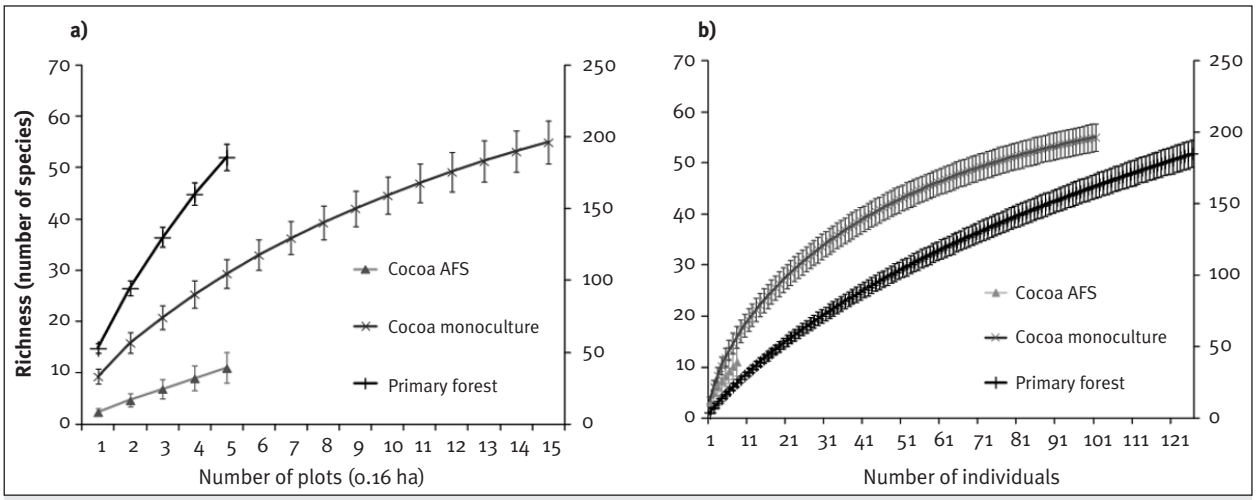


Figure 2.
Species accumulation curves (± standard deviation) in relation to sample area (a) and individuals (b) of trees and palms with DBH ≥ 10 cm. The secondary axis (right side) shows the values of the primary forest.

Table II.
Mean ± standard error of species richness, diversity and structure of three land use systems in the Sumaco Biosphere Reserve, Ecuador.

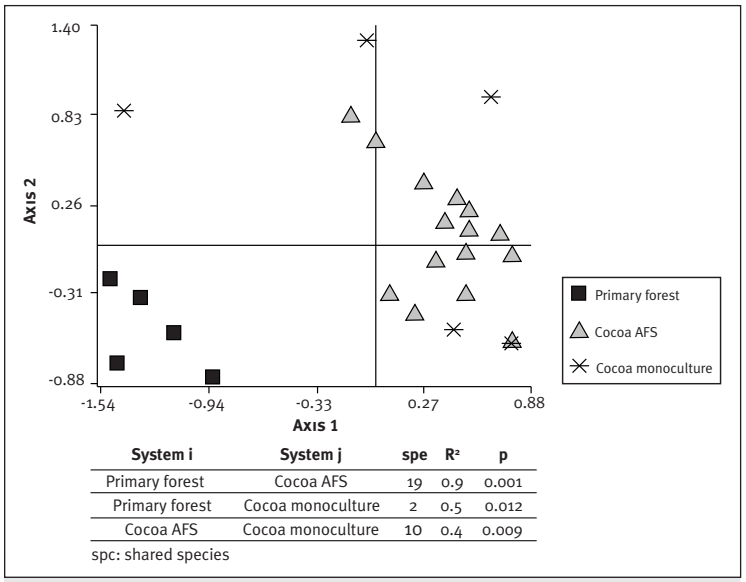
Variable	Primary forest	Cocoa AFS	Cocoa monoculture
Species (richness)	53 ± 4.5 a	9.3 ± 1.3 b	1.5 ± 0.8 c
Shared species with forest and Sorensen index	-	19 - 0.158	2 - 0.02
Abundance (Ind/ha)	633.8 ± 65.4 a	169.6 ± 19.7 b	25 ± 10.5 c
Basal area (m^2/ha)	37.7 ± 4.1 a	10.1 ± 1.2 b	1 ± 0.5 c
% Canopy cover	95.1 ± 16.9 a	40.9 ± 3 b	4.6 ± 1.9 c

ANDEVA Fisher $p < 0.05$; different letters indicate statistically different values.

timber production potential was 1.6 times higher in PF than in Cocoa AFS (p = 0.5075; table IV-a), higher revenue would come from a possible sale of C (table IV- b).

Relationship between species richness, diversity of tree species, carbon and productivity indicators

In PF, production and the resulting income were negatively correlated with species richness (r = -0.95 and r = -0.98; table V-a). In the Cocoa AFS, productivity was negatively correlated with tree species richness (r = -0.53). Forest density was positively correlated (r = 0.63) and basal area negatively correlated (r = -0.55) with species richness (table V-b). In contrast, in the Cocoa AFS, tree density and percentage of tree cover were positively correlated with species richness. Cocoa productivity was negatively correlated with the percentage of tree cover. In both cocoa systems basal area was correlated with species richness (r = 0.64 and r = 0.77).



System i	System j	spe	R^2	p
Primary forest	Cocoa AFS	19	0.9	0.001
Primary forest	Cocoa monoculture	2	0.5	0.012
Cocoa AFS	Cocoa monoculture	10	0.4	0.009

spc: shared species

Figure 3.
Non-metrical multidimensional scaling analysis (Bray-Curtis) and ANOSIM. Figure shows species richness, which was shown to be significantly different among systems.

Table III.
Mean ± standard error of stored C (Mg/ha) annual carbon accumulation rate (Mg C/ha/yr) of the three LUS evaluated in the Sumaco Biosphere Reserve, Ecuador.

Variable	Primary forest	Cocoa AFS	Cocoa monoculture	p
Carbon in aboveground biomass (Mg C/ha)	206.2 ± 32.4 a	52.7 ± 7.8 b	5.7 ± 2.6 c	0.0001
Carbon in belowground biomass (Mg C/ha)	58 ± 8 a	15.3 ± 2 b	1.8 ± 0.8 c	0.0001
Soil carbon (Mg C/ha)	65.9 ± 8.9 a	69.2 ± 5 a	74.9 ± 6.8 a	0.6917
Carbon in necromass (Mg C/ha)	4 ± 0.8 ab	4.1 ± 0.4 a	2.8 ± 0.6 ab	0.2540
Total Carbon (CT) (Mg C/ha)	334.2 ± 47.1 a	141.4 ± 11 b	85.2 ± 8.9 c	0.0001
Accumulation rate of * CT (Mg C/ha/yr)	0.45 ± 0.01 c	4.9 ± 0.5 a	1.9 ± 0.1 b	0.0001
T accumulation rate* of CO_{2e} for CT (Mg CO^{2e}/ha/yr)	1.7 ± 0.02 c	17.9 ± 1.8 a	7.4 ± 0.4 b	0.0001

ANOVA Fisher $p < 0.05$; different letters indicate statistically different values. Transformation factor of carbon stock C to its equivalent in $CO_2 = C \times 3.67$. *Estimation average based on the assumption of an increment of 1 cm/ha according to data reported by Korning and Balslev (1994) and Calero (2008).

Table IV.
Mean ± standard error of: a) agricultural and forestry productivity; b) income from agricultural activity, forestry and potential carbon sale prices in three LUS in the lower Sumaco Biosphere Reserve, Ecuador.

Variable	Primary forest	Cocoa AFS	Cocoa monoculture	p
a)				
Productivity of cocoa-wet (kg/ha/yr)	-	1,719.5 ± 227.3 a (≡ 573 kg/ha/yr, cocoa-dry; relation 3:1)	2,515.1 ± 317.9 a	0.0522
Productivity of trees (m^3/ha/yr)	34.2 ± 16 a	21.7 ± 9.2 a	-	0.5075
b)				
ITA CO_{2e} (USD/ha/yr)	8.3 ± 0.15 c	89.7 ± 9.9 a	35.4± 0.2 b	0.0001
NI-wet cocoa (USD/ha/yr)	-	1,687.1 ± 274.9 a	2,686.8 ± 417.7 a	0.0587
NI-harvestable timber (USD/ha/yr)	70 ± 51.2 a	83.8 ± 29.6 a	-	0.8174

NI: net income; ITA: Income from accumulation rates.

Discussion

Management aspects of cocoa systems

In the lower part of the SBR cocoa production is particularly relevant given the high demand of the product and its contribution to the economy of local families. Management in cocoa AFS is closely related with typical organic practices, whereas in monocultures, management is more related with conventional practices. Both systems have a long history of use within the region. While monoculture systems are aimed at maximizing production, cocoa AFS represent an instance of the traditional agroforestry systems practiced by the Kichwas from Ecuador (Whitten and Whitten, 2008). In the latter systems, in addition to cocoa, other tree species are included that increase the tree cover of the cocoa plantation above levels observed under cocoa monoculture (Selesi, 2013). In the Sumaco region, cocoa monoculture has been subject to intense efforts for improvement through domestication and design of better production practices (Ramírez, 2006).

In regard to ecosystem services, cocoa monoculture maximizes provision services through cocoa production at the expense of carbon sequestration, biodiversity conservation and cultural identity (Seufert *et al.*, 2012). The latter are discussed more in detail in the following subsections.

Table V.
Pearson correlation coefficients (r) for relationships among a) productivity and monetary incomes and species richness; b) between structural parameters abundance, basal area and canopy cover and C total, productivity and species richness in the three LUS evaluated in the Sumaco Biosphere Reserve, Ecuador.

Variable A	Variable B	Primary forest		Cocoa AFS		Cocoa monoculture	
		n	r	n	r	n	r
a)							
Cocoa productivity (kg/ha/yr)	Species richness	5	0	15	-0.53*	8	-0.45
Timber potential (m³/ha)	Species richness	5	-0.95*	15	-0.01	8	0
NI-cocoa (USD/ha/yr)	Species richness	5	0	15	-0.48	8	-0.48
NI-timber (USD/ha/yr)	Species richness	5	-0.98***	15	-0.05	8	0
b)							
Density (Ind/ha)	Total C (Mg/ha)	5	0.03	15	0.41	8	0.58
Density (Ind/ha)	Cocoa productivity (kg/ha/year)	5	0	15	-0.30	8	-0.05
Density (Ind/ha)	Species richness	5	0.63***	15	0.77***	8	0.66
% Tree cover	Total C (Mg/ha)	5	0.13	15	0.3	8	0.39
% Tree cover	Cocoa productivity (kg/ha/year)	5	0	15	-0.65*	8	-0.93***
% Tree cover	Species richness	5	0.35	15	0.83***	8	0.58
Basal area (m²/ha)	C total (Mg/ha)	5	0.96	15	0.9***	8	0.57
Basal area (m²/ha)	Cocoa productivity (kg/ha/year)	5	0	15	-0.17	8	-0.47
Basal area (m²/ha)	Species richness	5	-0.55***	15	0.64*	8	0.77*

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; C: Carbon; NI: Net income.

Ecosystem services: Tree diversity and carbon sequestration and relation with agricultural management

Cocoa AFS had higher species richness than Monoculture (photo 5) because of shared native tree species with the PF (e.g. *Oenocarpus bataua, Solanum sycophanta, Iriartea deltoidea* and *Wettinia maynensis*) and a wide variety of planted trees with commercial value (e.g. *Cedrela odorata*, *Cedrelinga cateniformis*, *Cordia alliodora*, *Terminalia amazonia*, and *Myroxilum balsamun*) and others able to provide food security to the local farmers (e.g. *Bactris gasipaes*, *Carica papaya*, *Caryodendron orinocense*, *Inga edulis*, *Inga ilta*, *Persea americana*, *Pouoruma bicolor* and *Pouruma cecropifolia*). Some of these species, such as *C. alliodora, C. odorata, C. cateniformis, B. gasipaes* and *I. deltoidea*, are managed under traditional indigenous systems in different tropical contexts, forming an essential part in the structure and richness of Cocoa AFS (Suatunce *et al.*, 2003). Cocoa AFS also contain several tree species such as *Clarisia racemosa, Acacia glomerosa* and *Vochysia braceliniae*, that provide food and shelter for wildlife. In the Monoculture, intensification results in few remnant trees in the plots, lowering biodiversity and reducing ecological functions and potential provision of ecosystem services when compared with Cocoa AFS and PF (Ramirez *et al.*, 2001; Torres *et al.*, 2014) .

Our results confirm that species composition differs significantly between primary forest and cocoa systems, which coincides with findings from a study in Costa Rica (Deheuvels *et al.*, 2014). Besides these expected findings, there are also important differences between cacao systems. First, agricultural management practices by farmers determine these differences. In cocoa AFS, the tree component and its species richness is traditionally part of the productive system, which is closely related to the uses that people give most plants (Selesi, 2013). For example, mean values of species richness in the cocoa AFS (9 species) is more than double than those reported by Suatunce *et al.* (2003) in Costa Rica, in a system of cocoa trees and *Musa* spp., but similar to those found in other indigenous multi-layered cocoa system in that same study. The latter is due to the traditional type of management practiced by indigenous farmers in the two sites; they tend to favor the presence of

Photo 5.
Existence of trees, which determine greater richness of species in the cocoa SAF, opposite of monoculture.
Photograph O. Jadán, 2011.

many different species from which they can obtain multiple benefits. Second, the supply of domestic and international markets for cocoa enhances the creation of conventional production systems with low species richness, but accepted and practiced by their management efficiency and profitability (Ramirez *et al.*, 2001).

Thus, we assume that the difference between management practices is a result of cultural heritage and traditional knowledge related to the "Chakra" concept on the one side, while monocultures on the other side are more related to optimization of crop productivity. Further studies are necessary to show compatibility of cocoa productivity and long term effects on cultural identity. It is also unclear whether species composition in traditional cocoa AFS might provide adequate synergies for enhanced productivity in cocoa cultivation (Somarriba *et al.*, 2001), or if the relationship depends heavily on shade management only, as discussed previously.

The total C stored in PF and cocoa AFS is higher than under cocoa monoculture. C values recorded in PF are similar to those reported by several authors for Latin America Cifuentes-Jara (2008). Likewise, total C in cocoa AFS is similar to that measured in similar systems in Central America at elevations < 1,000 m (Somarriba *et al.*, 2013). Average C accumulation rates derived from literature are higher for trees in cocoa systems than for PF because the former do not exceed 25 years of age and are in a more dynamic growth phase. The degree to which these estimates are representative of individual trees (especially remnant ones) is yet to be validated, as long-term repeated measurements would be needed.

Potential payments for carbon sequestration

Net income from cocoa productivity in cocoa Monoculture and AFS are, respectively, 76 and 18 times higher than those yielded by the potential sale of C. Therefore, the payment for this ecosystem service does not seem competitive in comparison to cocoa production (Gilroy *et al.*, 2014), negatively affecting the promotion of tree cover on farms or conventional crops. However, considering C offsets only does not take into account additional environmental benefits provided by cocoa AFS in terms of adaptation to climate change, food security for local residents (Torres *et al.*, 2014) and the provision of other ecosystem services. A broader economic valuation of the extra benefits of traditional and conventional systems would be necessary to reach a conclusion about the financial feasibility of promoting compensation schemes for environmental services in these systems.

To increase C stocks, tree richness could be increased by introducing productive trees as has been done in other production scenarios in Ecuador (Castro *et al.*, 2013) and Central America (Somarriba *et al.*, 2013). However, according to our results, these changes could decrease the productivity of the cocoa Monoculture about 1.5 times, thus decreasing revenue by 999 USD/ha/yr. Converting cocoa monoculture to cocoa AFS would increase stocks by about 56 Mg C/ha (table II) or 206 Mg CO_{2e}/ha of C stored and 3 Mg C/ha/yr or 11 Mg CO_{2e}/ha/yr of C fixed. Hence, to compensate for the loss in cocoa revenue, each unit of stored CO_{2e} would have to be paid at 4.85 USD (999 USD/ha/yr i.e. 206 Mg CO_{2e}/ha). Because the price of C in international markets is currently uncertain a final determination about whether or not to recommend changes to conventional production systems cannot be made. However, we note this price for Mg CO_{2e} is not an overestimate by any means (Peters-Stanley and Gonzalez, 2014), opening the possibility of at least breaking even financially when potentially switching Monocultures to AFS.

Furthermore, the prevailing deforestation pressure makes remaining forests ideal candidates for avoided deforestation schemes included in the REDD+ mechanism (Bosetti and Frankel, 2011). To compensate the total revenue loss in cocoa, landowners require a theoretical price of 2.98 USD/Mg/CO_{2e} for avoided deforestation under monoculture, and 2.82 USD/Mg/CO_{2e} for avoided degradation of primary forests towards cocoa AFS. Both values are very close to the current market price of C for REDD+ activities, opening a favorable outlook to include Sumaco primary forests in compensation payment regimes for avoided deforestation. The lower SBR, specifically in the watersheds of the rivers Napo and Misahualli would be an excellent candidate for promoting avoided deforestation through this mechanism, because between 2008 and 2013, its deforestation rate was 3.34% (Ministerio del Ambiente del Ecuador and Deutsche Gesellschaft für Internationale Zusammenarbeit, 2013). Thus, at the landscape scale, there are considerable financially viable options to use the cocoa/forest production land matrix to avoid deforestation and provide some additional revenue to locals for conserving forests.

Productivity of cocoa systems and relation with agricultural management

A diverse tree canopy is an essential component in traditional Cocoa AFS systems. However, an excess of trees and their resulting shade limits yields compared to those obtained under Monoculture. In fact, there was a negative correlation between canopy cover and tree density on the productivity of cocoa and, therefore, on income in Cocoa AFS and Monoculture. Shade management is thus key in balancing cocoa productivity and carbon sequestration (Somarriba *et al.*, 2013). However, not all tree species are suitable for or chosen as shade components. In traditional systems, for example, we found more species related to PF, potentially remnants from former natural stands. This suggests that local farmers are making conscious decisions regarding which tree species are left standing in any given plot. The rationale for these choices is beyond the scope of our study, but we can speculate that criteria used relate to any real and perceived benefits any given species can provide in terms of amount and quality of shade, timber and building materials, food, traditional medicine, wildlife shelter or other cultural values they provide. To the best of our knowledge, no studies have systematically addressed the optimal levels of tree density and shade in these local cocoa production systems.

Cocoa productivity in Monoculture was similar to that recorded in Guatemala (Ministerio de Agricultura, 2007). This high productivity is associated with a high planting density (1,111 trees/ha) and direct light incidence on the crop (Zuidema *et al.*, 2005). In our study, the average dry cacao production is four times higher compared to that recorded in Costa Rica by Deheuvels *et al.* (2011); (573 kg/ha/yr vs. 135 kg/ha/yr). This result may be due in part to differences in how fruit harvesting was accounted for: in Costa Rica only healthy and ripe fruits in fruiting peaks were counted, while in SBR fruit were accounted for regardless of pod health and maturity stage. However, the results obtained in our study are within the average yields for Ecuador (500 kg/ha/yr) (Ramírez, 2006). Within cocoa systems, AFS production was 25% higher than in Monoculture. However, this difference may be compensated by higher resilience of cocoa AFS systems, increased C stocks, timber potential, more food security (fruit species) and benefits from other ecosystem services, some of which are discussed below.

Conclusions

The cocoa systems analyzed have lower richness, tree diversity and C storage than primary forest. There is also a negative correlation between the presence of trees, cocoa productivity and potential income from cacao production. In fact, potential income in cocoa AFS was 1.5 times lower than in cocoa monoculture systems. However, the tree component of natural forest and cacao AFS is the key to the provision of ecosystem services such as C storage and species conservation, which are not present in systems without trees and have not been studied locally.

Higher revenues from cacao productivity in systems without tree cover and the low amounts offered for conservation or sale of C do not promote increasing tree cover to significantly enhance C stocks. On the other hand, it is feasible that the economic losses due to the establishment of trees are largely offset by environmental benefits such as increased C sequestration and storage, improved food security, cultural identity compatibility and greater resilience of production systems. In addition, the areas of greatest deforestation have a high potential for inclusion in REDD+ strategies, even under scenarios of low market prices for C. For these reasons, the maintenance of carbon by avoided deforestation, combined with the promotion of sustainable cocoa production systems, would be a viable option to balance conservation, diversity and climate change mitigation at the landscape level in the Sumaco region of Ecuador. So far, studies have focused on products and services for potential or actual sale, but the intrinsic heritage value from these

cacao AFS, evolved from former traditional "chakras" combining food security and ancestral practices of Amazonian Kichwa, has not been properly and fully quantified. Future studies should focus on a thorough valuation of ecosystem services including cultural values and all other products of cocoa AFS in the study area to quantify the added value of fruit trees, medicinal plants, and other elements of cocoa AFS that the Kichwa culture has been using as part of their livelihoods.

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