Carbon stocks, tree diversity, and the role of organic certification in different cocoa production systems in Alto Beni, Bolivia

Johanna Jacobi · Christian Andres ·
Monika Schneider · Maria Pillco ·
Patricia Calizaya · Stephan Rist

Abstract This study compares aboveground and belowground carbon stocks and tree diversity in different cocoa cultivation systems in Bolivia: monoculture, simple agroforestry, and successional agroforestry, as well as fallow as a control. Since diversified, agroforestry-based cultivation systems are often considered important for sustainable development, we also evaluated the links between carbon stocks and tree diversity, as well as the role of organic certification in transitioning from monoculture to agroforestry. Biomass, tree diversity, and soil physiochemical parameters were sampled in 15 plots measuring 48×48 m. Semi-structured interviews with 52 cocoa farmers were used to evaluate the role of organic certification and farmers' organizations (e.g., cocoa cooperatives) in promoting tree diversity. Total carbon stocks in simple agroforestry systems (128.4 ± 20 Mg ha^{-1}) were similar to those on fallow plots (125.2 ± 10 Mg ha^{-1}). Successional agroforestry systems had the highest carbon stocks (143.7 ± 5.3 Mg ha^{-1}). Monocultures stored significantly less carbon than all other systems (86.3 ± 4.0 Mg ha^{-1}, posterior probability P(Diff > 0) of 0.000–0.006). Among shade tree species, *Schizolobium amazonicum*, *Centrolobium ochroxylum*, and *Anadenanthera* sp. accumulated the most biomass. High-value timber species (*S. amazonicum*, *C. ochroxylum*, *Amburana cearensis,* and *Swietenia macrophylla*) accounted for 22.0 % of shade tree biomass. The Shannon index and tree species richness were highest in successional agroforestry systems. Cocoa plots on certified organic farms displayed significantly higher tree species richness than plots on non-certified farms. Thus, expanding the coverage of organic farmers' organizations may be an effective strategy for fostering transitions from monoculture to agroforestry systems.

Keywords Successional agroforestry · *Theobroma cacao* · Agrobiodiversity · Biomass · Carbon stocks · Organic agriculture · Bolivia

J. Jacobi (✉) · S. Rist
Centre for Development and Environment (CDE),
University of Bern, Hallerstrasse 10, 3012 Bern,
Switzerland
e-mail: johanna.jacobi@cde.unibe.ch

C. Andres · M. Schneider
Research Institute of Organic Agriculture (FiBL),
Ackerstrasse 21, 5070 Frick, Switzerland

M. Pillco
Facultad de Agronomía, Universidad Mayor de San
Andrés (UMSA), Héroes del Acre N° 1850, La Paz,
Bolivia

P. Calizaya
Fundación PIAF - El Ceibo, Sapecho, Alto Beni, La Paz,
Bolivia

Introduction

Agriculture in the humid tropics is both highly vulnerable to climate change and contributes to it,

since the related clearing of rainforests releases high amounts of greenhouse gases (FAO 2011; IPCC 2007). Shortening cycles of slash-and-burn-based cultivation with annual crops in monoculture are changing natural ecosystems, rendering some areas unsuitable for agriculture. Consequently, the agricultural frontier is advancing as land users look for new areas to cultivate. Studies have revealed that deforestation and conversion of forest to agriculture contribute 17.4 % of global greenhouse gas emissions (IPCC 2007). Many observers see agroforestry systems as presenting a promising alternative to common-practice agriculture in the tropics because they can serve as carbon sinks and biodiversity pools and may play a significant role in mitigating or adapting to climate change (Tscharntke et al. 2011; Soto-Pinto et al. 2010; Nair et al. 2009a, b). Similarly, organic agriculture (IFOAM 2005) is perceived as a promising approach (FAO 2011; Leifeld and Fuhrer 2010; Mueller-Lindenlauf 2009; Niggli et al. 2007). Organic agriculture practices in general and agroforestry in particular are frequently seen as having greater carbon sequestration potential than common-practice agriculture; they are also frequently viewed as making positive contributions to agrobiodiversity and natural biodiversity (FAO 2011). Thus, combining organic certification and practices with agroforestry in the tropics would appear to be a promising strategy for reducing emissions, sequestering carbon, and increasing productivity (Scialabba and Mueller-Lindenlauf 2010; Niggli et al. 2007). A literature review by Nair et al. (2009a) indicated high potential for carbon sequestration in agroforestry systems, especially in the humid tropics. However, agroforestry's capacity for carbon sequestration remains underappreciated and underexploited because of a lack of consistent assessments and comparable data on carbon stocks and carbon cycles (Nair et al. 2009a).

At the same time, there have been many studies on the environmental benefits of agroforestry systems in the tropics (Clough et al. 2011; Tscharntke et al. 2011; Soto-Pinto et al. 2010). By comparison, studies of the effects and challenges of organic agriculture in tropical areas are scarce (FAO 2011; cf. Scialabba and Mueller-Lindenlauf 2010; Leifeld and Fuhrer 2010; Koepke 2008). One study of organic and conventional shaded and full-sun coffee plantations in Costa Rica and Nicaragua indicated that low-external-input organic cultivation supports agroecosystem services such as

biomass inputs and increases soil fertility (Haggar et al. 2011). A meta-analysis of 74 studies comparing organic and non-organic farming systems from all over the world found significantly higher soil organic carbon (SOC) stocks in soils under organic management (Gattinger et al. 2012). Two recent literature reviews—by Mueller-Lindenlauf (2009), FAO (2011) respectively—indicated significantly higher SOC concentrations in organic farming systems when compared with non-organic farming systems. However, the studies assessed by Mueller-Lindenlauf (2009) were all from temperate regions, and FAO (2011) specified that studies from Africa and South America were unavailable, highlighting the lack of data on organic farming in tropical regions.

Many farmers in the region of Alto Beni, Bolivia, have long-standing experience with different forms of agroforestry systems. Still others in the region continue to practice cocoa monocultures. This long-running diversity of local farming systems makes it possible to compare differently managed cocoa cultivation systems. The present study sought to compare carbon stocks and tree diversity in different cocoa cultivation systems: cocoa monoculture, simple agroforestry systems, and successional agroforestry systems. Fallow plots were also included as a control.

The umbrella organization of cocoa cooperatives El Ceibo active in Alto Beni provides farmers with access to organic certification and related extension services, in an effort to obtain higher cocoa prices, to increase cocoa yields, and to foster more sustainable management of natural resources (Ortiz and Somarriba 2005). However, the question of whether and to what extent such activities have increased the adoption of agroforestry practices among farmers has yet to be answered. As such, the present study also included an analysis of the effect of organic certification and membership in farmers' organizations on the diversity of agroecosystems.

Materials and methods

The study site: Alto Beni, Bolivia

Cocoa cultivation is one of the most important income sources in the study area, located in Alto Beni, between $15°20'$ to $15°55'$S and $66°55'$ to

Fig. 1 Different cultivation systems: **1** full-sun monoculture (Mono), **2** simple agroforestry system (AFS), **3** successional agroforestry system (SAFS), **4** fallow (Fallow)

67°33′W, in the foothills of the Andes (Ortiz and Somarriba 2005). Classification of land use/land cover in the study area—based on a WorldView-2 image (10 August 2010)—revealed cocoa to be one of the most abundant crops, accounting for up to 25 % of all agricultural land (including fallow land) in the study area (Pinto 2011). The region is composed of valleys featuring wide alluvial terraces and steep hills ranging from 350 to 1,600 m a.s.l. Annual precipitation varies from 1,300 to 1,500 mm, occurring mostly in the rainy season from November to March (Somarriba and Trujillo 2005). The annual mean temperature is about 26 °C, but minima drop as low as 9 °C in winter. Soils on the alluvial terrace are mainly classified as Chromic Cambisols and Haplic Lixisols of medium to high fertility; soils on the slopes are primarily classified as Haplic Acrisols and Dystric Cambisols of low fertility (Somarriba and Trujillo 2005). Cocoa is cultivated on the alluvial terraces and slopes as high as 600 m a.s.l., in plantations measuring around 2.3 ha per family (Somarriba and Trujillo 2005). In the 1960s, Aymaras and Quechuas from the Andean highlands began settling in the region and cultivating cocoa, with support from the Bolivian government. They were given land titles and seedlings, and cocoa was mostly cultivated in monocultures. In the 1980s, agroforestry projects and organic initiatives were launched in the region. By the time data were collected for the present study, ∼1,500 farming families were associated with one of the 49 locally active El Ceibo cocoa cooperatives and/or different farmers' organizations supporting organic certification and cocoa cultivation in the region (El Ceibo 2012, pers. comm.). Nevertheless, half or more of the local cocoa producers in Alto Beni had no or very few shade trees on their cocoa plots (Ortiz and Somarriba 2005).

Different cultivation systems studied

Biomass, biodiversity, and soil data were sampled in three different cocoa cultivation systems, and in fallow plots (Fig. 1). The systems were: (1) Full-sun cocoa monoculture (hereafter Mono), (2) simple cocoa agroforestry system (hereafter AFS), (3) successional agroforestry system (hereafter SAFS), and (4) agricultural plot under recovery, previously monoculture (hereafter Fallow).

(1) *Mono* Full-sun monoculture is the most common method of cocoa (*Theobroma cacao*) cultivation in the study area. Young cocoa plants are planted alongside *Musaceae*, which initially provide protective shade. Almost no agrochemicals are used in cocoa cultivation in the study area. Cocoa trees are usually pruned once a year, following the main harvest. Cocoa is normally planted at a distance of 4 × 4 m, resulting in 625 plants per hectare (in monoculture and in agroforestry). Weeding is a constant activity and soil cover crops are uncommon. Individual fruit trees are occasionally scattered around the cocoa plot.

(2) *AFS* Simple agroforestry systems may feature leguminous shade trees such as *Inga* spp. and *Erythrina poeppigiana*; associated fruit trees such as *Rheedia* spp., *Nephelium lappaceum*, *Theobroma grandiflorum*, and *Persea americana*; and timber trees such as *Swietenia macrophylla*, *Hymenaea courbaril*, *Centrolobium ochroxylum*, *Cedrela odorata*, and *Amburana cearensis*. Cocoa trees and shade trees are

usually pruned once a year to induce flowering of cocoa and to regulate shade. The need for weeding depends on shade intensity and whether soil cover crops are present.

(3) *SAFS* Successional agroforestry systems feature multi-purpose agroforestry shade trees, natural regeneration trees, and many crops. They are based on understanding and application of natural succession dynamics. The plant species occurring in the process of natural succession may be grouped as pioneers, secondary or primary forest species, depending on their life cycle. These species can be replaced by similarly grouped agricultural crops. The aim is to form a composition of species in which all stories (spatial) and all phases (temporal) are occupied by specific species, maximizing density and diversity. In SAFS in which cocoa is the main crop, the process is often initiated with maize and rice in combination with manioc (*Manihot esculenta*) and pigeon pea (*Cajanus cajan)*, quickly followed by banana (*Musaceae*) and papaya (*Carica papaya*), then pineapple (*Ananas comosus*) and *Inga* sp., which provide shade that enables more slowly growing primary forest species such as cocoa and *S. macrophylla* to thrive. The latter species will dominate the system after 10–15 years. The overall process benefits farmers by enabling them to obtain harvests from the first year on thanks to crops in the pioneer and secondary forest species categories. Furthermore, the system's high diversity provides a number of environmental services, such as soil preservation and regeneration (Vieira et al. 2009), accumulation of organic matter, and pest control (Milz 2010). Management of SAFS is knowledge and labor intensive. It requires regular pruning and selective weeding that depend greatly on farmers' understanding of the system and its underlying dynamics. Pest and weed pressures are considered indicators of incorrect management. Optimal implementation of SAFS can result in high yields from a range of crops with minimal use of external inputs (Schulz 2011; Milz 2010; Vieira et al. 2009; Yana and Weinert 2001; Schulz et al. 1994).

(4) *Fallow* These are plots featuring naturally regenerating pioneer vegetation and secondary forest, occasionally complemented by leguminous trees. Farming families sometimes fetch firewood and harvest wild fruit or medicinal plants from such plots. Fallow was included in this analysis to compare the data from Mono, AFS, and SAFS with data from plots left to naturally regenerate (for soil recovery), and because fallow is an integral part of the local land use cycle.

The previous land use of most SAFS and AFS plots studied was fallow (followed by 1–2 years of rice, *Oryza sativa*, and/or corn, *Zea mays*, before planting cocoa) or cocoa monoculture. Mono plots were installed in riparian vegetation or monocultures of other crops. Previous land use of fallow plots was cocoa, citrus, or papaya monocultures (Table 1). There were no input-intensive organic or conventional cultivation systems as described by Noponen et al. (2012). Cocoa pod husks from harvested cocoa beans were the only fertilizer used (applied in all cocoa systems). Thus, all of the cocoa cultivation systems in the study area could be considered low- or even zero-external-input systems.

Farm selection, plot design, and sampling

Representative cocoa farms for the systems SAFS, AFS, and Mono were selected in collaboration with local agricultural consultants, taking into account environmental conditions and plantation age (Table 1). The farms were distributed between three spatial clusters (population centers) along the river Alto Beni (Fig. 2). Organic certification was not a selection criterion. Certification was mainly organized by cooperatives belonging to El Ceibo. Cocoa farms obtained organic certification after a three-year transition period, and were inspected annually. Since import countries' organic certification standards do not explicitly require cultivation of cocoa in agroforestry systems, there are also cocoa monocultures in Alto Beni that are certified organic. However, the Monos in our study were not certified. By contrast, all SAFS and all but one AFS in the present study were certified organic.

Sampling plots measuring 48×48 m (based on the cocoa planting distance of 4×4 m) were installed on every farm ($n = 12$); the sampling plots were further divided into four sub-plots measuring 24×24 m (ICRAF 2005; Pearson et al. 2005). Four sampling

Table 1 Location, physical, and environmental conditions of the sampling plots; *Mono* cocoa monoculture, *AFS* simple agroforestry system, *SAFS* successional agroforestry system

	Coordinates	Elevation (m.a.s.l.)	Slope (°)	Distance to river (km)	Mean annual temp. (°C)[a]	Mean annual precipitation (mm)[a]	Age of plantation (y)	Previous land use
Mono 1	15°26′31″S 67°28′11″W	360	0	0.4	N. a.	1,293	5	Riverine vegetation
Mono 2	15°40′2.9″S 67°10′20″W	465	1.5	2.5	24.9	1,540	8	Plantain monoculture
Mono 3	15°45′34″S 67°3′1″W	493	0	0.6	24.6	1,372	5	Papaya monoculture
Mono 4	15°48′43″S 66°59′2″W	515	0	1.6	24.6	1,372	20	Riverine vegetation
AFS 1	15°29′12″S 67°24′14″W	476	0	2.3	N. a.	1,293	17	Cocoa monoculture
AFS 2	15°38′7″S 67°12′7″W	448	1.5	0.9	24.9	1,540	8	Fallow
AFS 3	15°45′8″S 67°1′41″W	483	0	0.7	24.6	1,372	17	Fallow
AFS 4	15°30′44″S 67°25′57″W	365	0	0.3	N. a.	1,293	10	N. a.
SAFS 1	15°29′56″S 67°24′34″W	510	0	1.7	N. a.	1,293	16	Fallow
SAFS 2	15°37′20″S 67°10′7″W	441	2	1.6	24.9	1,540	13	Cocoa monoculture
SAFS 3	15°44′20″S 67°5′59″W	503	0.5	2.3	24.6	1,372	14	Pasture
SAFS 4	15°45′50″S 67°0′7″W	510	0	0.8	24.6	1,372	14	N. a.
Fallow 1	15°26′41″S 67°28′4″W	360	0	0.6	N. a.	1,293	15	Papaya monoculture
Fallow 2	15°38′6″S 67°12′7″W	446	0	2	24.6	1,540	8	Cocoa monoculture
Fallow 3	15°44′9″S 67°5′5″W	512	0	2.1	24.9	1,372	15	Cocoa monoculture

[a] *Source* Elbers (2002)

plots were installed per cultivation system—SAFS, AFS, and Mono. Additionally, one fallow sampling plot was installed per cluster on a cocoa farm where one SAFS, AFS, or Mono sampling plot had already been installed. This resulted in three fallow sampling plots in total. One or two replications of each cultivation system were sampled in each spatial cluster, depending on availability; this resulted in four replications per cultivation system in total (Fig. 2). All

data were sampled between April and November 2010 (dryer season).

Biomass and carbon assessment

We assessed aboveground biomass (AGB) and belowground biomass (BGB) using both destructive and non-destructive methods. To determine AGB, we measured the following components: tree diameter at
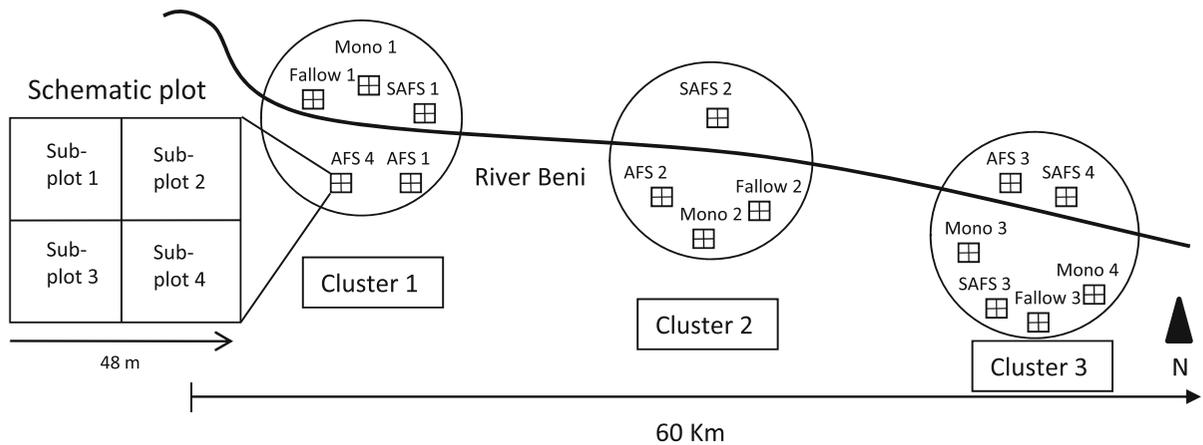
Fig. 2 Schematic map of the research design

Table 2 Allometric equations used for biomass estimation

	Formula	R^2	Source
Shade trees	$AGB = 0.0509 * \rho * D^2 * H$	0.96	Chave et al. (2005)
Palm trees	$AGB = 10.0 + 6.4 * H$	0.96	Brown (1997)
Theobroma cacao	$AGB = 10^{(-1.625+2.63*\log(D_{30}))}$	0.98	Andrade et al. (2008)
Coffea arabica	$AGB = 10^{(-1.18+1.19*\log(D_{15}))}$	0.93	Andrade et al. (2008)
Musaceae	$AGB = 0.030 * DBH^{2.13}$	0.99	Pearson et al. (2005)

AGB aboveground biomass per kg dry matter, ρ wood density in g cm^{-3}, *D* diameter in cm, *H* height in m

breast height (130 cm, hereafter DBH); and tree height (of trees with DBH ≥5 cm) using a clinometer (Chave et al. 2005; Santos et al. 2004). The species was categorized and annotated. The formula we used to calculate the biomass of shade trees (moist forest stands, Chave et al. 2005) is more conservative than the formula used by Brown (1997) and recommended by UNFCCC (2009). To calculate biomass using allometric formulas (Table 2), we subdivided trees and crops into different classes: shade trees, palm trees, cocoa, coffee (*Coffea arabica*), and banana/plantains (*Musaceae*).

Depending on the tree/crop, we measured stem diameters at the following heights: cocoa at a height of 30 cm (Andrade et al. 2008); coffee at a height of 15 cm (Andrade et al. 2008; Segura et al. 2006); and shade trees, palm trees, and *Musaceae* at a height of 130 cm.

Wood densities were obtained from the list by Brown (1997) as well as the World Agroforestry Centre's Wood Density Database (ICRAF 2011). If a species was not listed, we used a mean wood density of 0.6 g cm^{-3} as suggested by Brown (1997).

Litter, as well as herbs and shrubs with DBH <5 cm were sampled five times per sampling plot, from a square measuring 50 × 50 cm (Andrade and Ibrahim 2003; Hairiah et al. 2001), and air-dried to constant weight.

We assessed biomass from dead wood using the line-intersect method (Pearson et al. 2005). The dry weight of dead wood was calculated using the following formula:

$$W = \left(S\frac{\pi^2}{8L} \right) \sum d^2$$

where W = dry weight in g cm^{-3}, S = wood density, and L = length of the sample line. Twigs and dead wood with diameter ≥0.5 cm were thus not included in the litter fraction. For dead wood density, we assumed a default value of 0.5 g cm^{-3} (Hairiah et al. 2001).

The biomass from coarse roots was calculated using the formula of Cairns et al. (1997), also recommended by Pearson et al. (2005):

BGB from coarse roots $= \exp^{(-1.085+0.926*\ln(AGB))}$

We sampled fine roots ≤ 5 mm at three depths (0–10, 10–20, and 20–30 cm) twice at the center of each sub-plot (Roncal-García et al. 2008). We washed and air-dried the samples to constant weight at the Experimental Station of the Faculty of Agronomy, University of La Paz (UMSA). To calculate carbon stocks from total biomass (AGB + BGB), we applied the factor 0.5 (IPCC 2003).

To assess SOC and the soil parameters clay content, pH, total N, available P, exchangeable K, and CEC, soil was sampled at two soil depths (0–25 and 25–50 cm) using a soil auger every 5 m in a grid. We mixed the samples at the sub-plot level, so that two soil samples—one topsoil and one subsoil sample—were obtained per sub-plot, resulting in eight soil samples (four topsoil; four subsoil) per replication/farm (cf. Schroth and Sinclair 2003). The bulk density of topsoil and subsoil was sampled with metal cylinders at the center of each sub-plot, according to the method described by Schroth and Sinclair (2003), resulting in eight bulk-density samples (four topsoil; four subsoil) per replication/farm. SOC was determined following the Walkley–Black method as described by van Reeuwijk (2002). All soil parameters were determined according to ISRIC standards (van Reeuwijk 2002). The depth of the Ah horizon was also measured at the center of each sub-plot.

When comparing carbon stocks calculated from carbon concentrations in different land use systems, differing soil mass at the same sampling depth—due to differing bulk density—can lead to errors (Nair 2011; Don et al. 2011). Without soil mass corrections, the influence of different land use systems on SOC is likely to be underestimated (Don et al. 2011; Schroth and Sinclair 2003). Thus, in line with de Moraes et al. (1996), we calculated SOC with an equivalent soil mass (mean soil mass of all sub-plots), carbon concentration in %, bulk density in g cm^{-3}, and sampling depth in cm.

Belowground carbon was then calculated as the sum of SOC and biomass from coarse roots * 0.5 and fine roots * 0.5 (IPCC 2003).

Quantification of tree and crop diversity

Tree species were identified with the help of staff from El Ceibo's forest seed bank. To identify and compare

Table 3 Coefficients of the first three PCs based on age, location, and soil fertility parameters of 15 cocoa farms in Alto Beni, Bolivia

Parameters	PC 1 Eigenvectors	PC 2 Eigenvectors	PC 3 Eigenvectors
Age	−0.392	0.647	0.346
Distance to river	0.303	0.768	−0.263
Depth Ah horizon			0.919
Clay content	0.934	0.153	
pH	0.205	−0.648	
Total N	0.736	−0.142	0.339
Available P	0.666	−0.315	−0.355
Exchangeable K	0.926	−0.152	
CEC	0.948	−0.131	−0.108
Eigenvalue	4.08	1.48	1.24
Cumulative variance (%)	43.3	61.3	75.6

the diversity of trees and crops in the different cultivation systems, we calculated the Shannon diversity index (H_S) (ICRAF 2005; Shannon and Weaver 1949):

$$H_S = -\sum_{i=1}^{S} p_i \ \ln p_i,$$

where S = number of categories in a habitat, p_i = share from one category in the total number of categories. The maximum possible value $H_{max}\left(-\ln\frac{1}{t}\right)$ and evenness (H_S/H_{max}) are also displayed to give an impression of the distribution of species.

Organic certification and affiliation with a farmers' organization

To investigate the role of organic certification and the influence of local farmers' organizations—such as cooperatives—on the type of cocoa cultivation system practiced by farmers, we conducted 52 semi-structured interviews. We interviewed 30 certified-organic cocoa producers and 22 non-certified cocoa producers. They were asked questions such as the number of tree species in their main cocoa plots and what they perceived as key potentials and constraints of the three different cocoa cultivation systems. Producers were also asked about their motivation to join a cooperative or other farmers' organization, and the implications of membership for organic certification. The information from the

Table 4 Overview of biomass and carbon stocks in Mg ha^{-1} in three different cocoa cultivation systems and Fallow with standard error of means; *Mono* cocoa monoculture, *AFS* simple agroforestry system, *SAFS* successional agroforestry system; four replications for SAFS, AFS, and Mono; three replications for Fallow

	Shade trees	Palm trees	Cocoa	Coffee	Banana	Understorey and litter	Dead wood	Coarse roots	Fine roots	Total biomass	SOC stocks	Total C*
Mono	2.4 ± 1.5	0	25.1 ± 11.7	0.1 ± 0.0	6.5 ± 0.0	9.3 ± 1.3	3.1 ± 2.0	10.8 ± 2.5	4.9 ± 0.9b	62.2 ± 12c	55.2 ± 2.4a	86.3 ± 4.0b
AFS	35.1 ± 13	6.1 ± 2.5	30.3 ± 9.5	0.1 ± 0.0	1.8 ± 0.9	14.4 ± 2.8	9.0 ± 5.0	23.0 ± 6.9	10.2 ± 2.2a	130.0 ± 21b	59.8 ± 3.8a	128.4 ± 20a
SAFS	89.6 ± 7.0	16.8 ± 9.5	11.7 ± 1.8	0	5.2 ± 4.4	11.8 ± 0.9	7.8 ± 2.3	33.3 ± 6.2	10.6 ± 1.2a	186.8 ± 10a	50.8 ± 2.7a	143.7 ± 5.3a
Fallow	64.2 ± 12.5	8.4 ± 7.2	0	0	0	11.1 ± 2.8	10.3 ± 3.6	22.9 ± 4.7	8.3 ± 2.3a	125.2 ± 17b	64.8 ± 9.5a	125.2 ± 10a

[a,b,c] No significant difference for numbers sharing the same letter; α = 0.05

* Total C = (AGB + BGB)/2 + SOC

interviews was analyzed qualitatively following Patton (2002).

Statistical analysis

To explore differences in age, location, and soil fertility between the farms, we performed a principal component analysis (PCA). The PCA included the following parameters: age of plantation; distance to river; depth of Ah horizon; clay content; pH; total N; available P; exchangeable K; and CEC. The resulting principal components (PC) were checked for their eigenvalues, and the PCA was recomputed using only PC with eigenvalues >1 (first three PC). Together, these three PC accounted for 75.6 % of the variance in the data across all farms. We calculated the PC using the library "psych" (Revelle 2012) and rotated the axis with the varimax function from the library "GPArotation" (Bernaards and Jennrich 2012). The PCA results are shown in Table 3.

The data at sub-plot level were analyzed with linear mixed-effect models. We began with a model with cultivation system, pc1, pc2, and pc3 defined as fixed effects, and plot and cluster as random intercepts. For each dependent variable (total biomass, SOC stocks, total C, aboveground C, belowground C, and fine roots), we then compiled the best model via backward selection of model parameters using likelihood-ratio tests including only main effects with $P < 0.05$. We checked model assumptions graphically (normal Q–Q, Tukey–Anscombe, and Jitter plots). To compare the means of the different cultivation systems, we used a multilevel-modeling approach (Gelman et al. 2012). We defined cultivation system as a random factor in the best model, and the shrinked group mean estimate was used to do post hoc comparisons. Using the package "arm", we simulated ($n = 4,000$) a random sample of the joint posterior distribution of the model parameters and calculated the differences between the group means; this generates a random sample from the posterior distribution of the between-group differences. From these posterior distributions, we extracted the probabilities of the hypothesis that the difference is bigger than zero $P(\text{Diff} > 0)$. We defined a difference to be significant if $P(\text{Diff} > 0) < 0.025$ or >0.975 (equal to $P < 0.05$ in general linear models).

The effect of organic certification and membership in farmers' organizations on tree diversity in cocoa plots was tested using Kruskal–Wallis rank-sum tests. Correlation

Table 5 Overview of biodiversity and selected soil parameters in three different cultivation systems, and in Fallow, with standard error of means; *Mono* cocoa monoculture, *AFS* simple agroforestry system, *SAFS* successional agroforestry system; four replications for SAFS, AFS, and Mono; three replications for Fallow

	Cocoa stem density (ha⁻¹)	Tree stem density (ha⁻¹)	Mean tree height (m)	Mean DBH (cm)	Depth of Ah horizon (cm)	Shade tree species	Shannon index	SOC (%)	Bulk density (g cm⁻³)	Clay content (%)
Mono	625	23.9 ± 14.8	4.8 ± 2.9	7.6 ± 4.4	5.9 ± 0.4	1.6 ± 0.3	0.34 ± 0.2	1.2 ± 0.0	1.2 ± 0.1	40.8 ± 10.3
AFS	625	296 ± 71.2	10.0 ± 0.8	18.5 ± 1	12.1 ± 0.4	10.2 ± 2.2	1.7 ± 0.2	1.6 ± 0.0	0.9 ± 0.1	45.7 ± 14.6
SAFS	625	699 ± 114	13.5 ± 1.1	15.9 ± 0.7	10.3 ± 1.1	14.6 ± 1.3	2.3 ± 0.1	1.3 ± 0.1	1.0 ± 0.0	41.8 ± 5.9
Fallow	–	1374 ± 437	9.9 ± 1.6	13.5 ± 2.5	6.8 ± 1.9	12.2 ± 2.0	2.0 ± 0.5	1.7 ± 0.3	1.0 ± 0.1	52.7 ± 18.0

between Ah horizon and bulk density was tested using Pearson's product-moment correlation. All statistical computing was done in R, version 2.15.2 (R Development Core Team 2012).

Results

Biomass and carbon assessment

Total biomass ranged from 62.2 ± 12 Mg ha⁻¹ in Mono to 186.8 ± 10 Mg ha⁻¹ in SAFS. Post-hoc tests showed that the system Mono was significantly different from all other systems (Posterior probability $P(\text{Diff} > 0) = 0.000$ or 1.000 for all). SAFS was also significantly different from all other systems (posterior probability $P(\text{Diff} > 0) = 0.000$ or 1.000 for all). AFS and Fallow did not differ significantly from each other, displaying total biomass between Mono and SAFS (Posterior probability $P(\text{Diff} > 0) = 0.412$, Table 4).

Fine roots ranged from 4.9 ± 0.9 Mg ha⁻¹ in Mono to 10.6 ± 1.2 Mg ha⁻¹ in SAFS. Post-hoc tests showed that Mono was significantly different from all other systems (posterior probability $P(\text{Diff} > 0)$ between 0.003 and 0.000). Fallow did not differ significantly from AFS ($P(\text{Diff} > 0) = 0.074$) and was almost significantly different from SAFS ($P(\text{Diff} > 0) = 0.973$). AFS and SAFS were not significantly different from each other ($P(\text{Diff} > 0) = 0.687$, Table 4).

SOC stocks ranged from 50.8 ± 2.7 Mg ha⁻¹ in SAFS to 64.8 ± 9.5 Mg ha⁻¹ in Fallow, and accounted for 47.7 % of total carbon stocks. In SAFS, SOC had a share of 35.5 % of total carbon; in AFS, its share was 46.6 %; in Fallow, its share was 51.8 %; and in Mono, SOC's share was 64.0 % of total carbon. Post-hoc tests showed that no system differed significantly from the others ($P(\text{Diff} > 0)$) between 0.498 and 0.596, Table 4).

Total C ranged from 86.3 ± 4.0 Mg ha⁻¹ in Mono to 143.7 ± 5.3 Mg ha⁻¹ in SAFS (Table 4). Figure 3 shows aboveground carbon stocks according to components, indicating that shade trees were the main component of aboveground-biomass-based carbon stocks across all systems (constituting 50.3 % of aboveground carbon stocks and 19.7 % of total carbon stocks). Figure 4 shows belowground carbon stocks, indicating that SOC stocks were the main component of total carbon stocks across all systems. Post-hoc tests
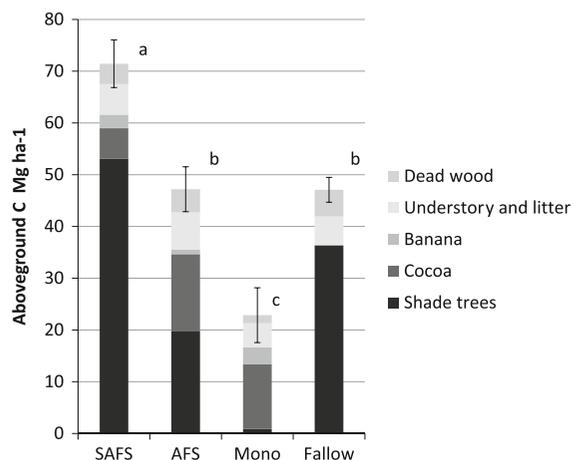
Fig. 3 Aboveground carbon stocks according to components with standard error of means; *SAFS* successional agroforestry system, *AFS* simple agroforestry system, *Mono* cocoa monoculture; shade trees include palm trees; *a*, *b*, *c* No significant difference for *bars* sharing the same letter
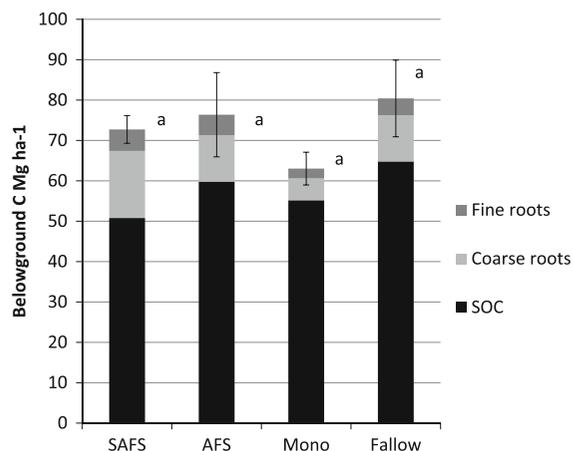

Fig. 4 Belowground carbon stocks (0–50 cm) according to components with standard error of means; *SAFS* successional agroforestry system, *AFS* simple agroforestry system, *Mono* cocoa monoculture; *a* No significant difference for *bars* sharing the same letter

for total C showed that Mono was significantly different from AFS (posterior probability $P(\text{Diff} > 0) = 0.002$), Fallow (posterior probability $P(\text{Diff} > 0) = 0.006$), and SAFS (posterior probability $P(\text{Diff} > 0) = 1.000$). The remaining systems did not differ significantly from each other ($P(\text{Diff} > 0)$ between 0.417 and 0.923). Comparison of aboveground carbon stocks alone revealed all systems to be significantly different from each other except Fallow

and AFS (Fig. 3, posterior probability $P(\text{Diff} > 0) = 0.000$ or 1.000 for all). In regards to belowground carbon stocks alone, post hoc tests showed that no system differed significantly from the others ($P(\text{Diff} > 0)$ between 0.217 and 0.644).

Depth of Ah horizon in SAFS and AFS was higher than in Fallow and in Mono (Table 5). Ah horizon was negatively correlated with bulk density ($r^2 = -0.64$, $P < 0.05$, Pearson's product-moment correlation).

Diversity of trees and crops

Altogether, 105 tree species belonging to 38 families were identified in the sampling plots, 96 species in cocoa agroforestry systems (AFS and SAFS), and four species in Mono. Eight species could not be identified (two in SAFS, one in AFS, and five in Fallow). The richest family was *Fabaceae* with 18 species, followed by *Rutaceae* (eight species), *Moraceae* (six species), and *Bombacaceae* (five species). The majority of plant families (27) were only represented by one or two species.

Stem density of woody perennials without cocoa was highest in Fallow ($1,374 \pm 437$) and more than double in SAFS (699 ± 114) compared to AFS (296 ± 71.2, Table 5). The Shannon index for SAFS ($HS = 2.3 \pm 0.1$, $H_{max} = 4.3$, Evenness = 0.53) was higher than all other systems, including Fallow ($HS = 2.0 \pm 0.5$, $H_{max} = 3.85$, Evenness = 0.52). However, Fallow displayed a higher Shannon index than AFS ($HS = 1.7 \pm 0.2$, $H_{max} = 3.99$, Evenness = 0.42). As expected, Mono displayed the lowest Shannon index ($HS = 0.3 \pm 0.2$, $H_{max} = 1.38$, Evenness = 0.25).

The most abundant shade tree species were *Leucaena leucocephala* (N-fixing species, used for improved fallows), *Piper angustifolium* (natural succession), *A. cearensis* (timber), *Attalea phalerata* (natural succession, fruit, and other plant material used, e.g., for construction or medicinal purposes), *Inga* sp. (fruit tree, N-fixing, and biomass accumulating species), and *S. macrophylla* (timber). These species constituted 45.2 % of total shade tree species abundance. In regards to overall species composition, natural succession species constituted 22.8 % of the total; the rest was composed of intentionally planted trees such as fruit, timber, medicinal, ornamental trees, or trees/palm trees that provide construction material. With regard to carbon accumulation, natural

Fig. 5 The 15 most important shade tree species according to biomass in %. The remaining 90 species constituted 39.9 % of biomass (column not included in the graph)
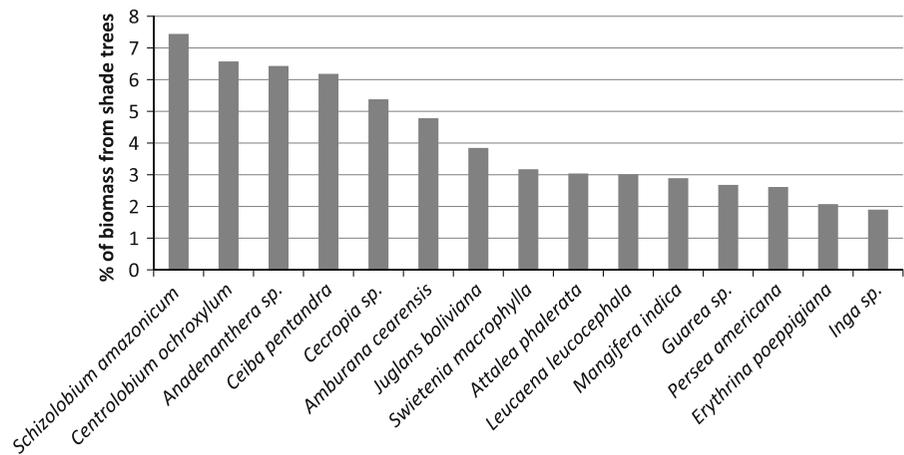
succession species constituted 25.9 % of total shade tree biomass. In Fallow, 29.4 % of tree biomass was composed of intentionally planted tree species (e.g., *L. leucocephala*). High-value timber tree species (*Schizolobium amazonicum, C. ochroxylum, A. cearensis*, and *S. macrophylla*) comprised 22.0 % of total shade tree biomass. Figure 5 shows which species contributed most to shade tree biomass. The list of species abundance differed from the list of species contributing to biomass accumulation, since larger trees contributed most to biomass and carbon stocks. For instance, the numerous *L. leucocephala* stems (23.6 % of total shade tree species abundance) had small diameters and thus did not contribute much biomass (only 3.0 % of total shade tree biomass).

The influence of organic certification on diversification of cocoa plots

Organic certification had a significant effect on shade tree diversity in cocoa plots ($P = 0.0008837$, Kruskal–Wallis rank-sum test); affiliation with a farmers' organization also had a significant effect on shade tree diversity ($P = 0.0089$, Kruskal–Wallis rank-sum test). The two variables (organic certification and affiliation with a farmers' organization) are associated, as 27 of 30 certified-organic farmers interviewed were affiliated with a farmers' organization, and 15 of 22 non-certified farmers interviewed were not affiliated with a farmers' organization. Organic cocoa producers mentioned that joining an El Ceibo cooperative to obtain organic certification offered the prospect of better prices for their product. All members of cooperatives

had obtained organic certification or were in the process of transitioning to meet organic requirements. Nevertheless, farmers in the area need not be affiliated with an El Ceibo cooperative to obtain organic certification, since other organizations also facilitate organic certification in the region. The cocoa plots on such farms were also highly diversified, indicating that other organizations—not only El Ceibo cooperatives—can play a significant role in enhancing the diversity of crops and plants on farms (cf. Abruzzese et al. 2005). With regard to cocoa yields (which was part of another study on the same plots and three more Monos), SAFS displayed the highest annual yields (510 kg dry beans ha^{-1}) and Mono the lowest (350 kg ha^{-1}), with AFS falling in between the two (423 kg ha^{-1}). AFS in general and SAFS in particular were more systematically managed than Mono, as indicated by a survey on management activities such as pruning and pest and plant-disease control (Jacobi et al. 2013).

The positive relationship between organic certification and shade tree diversity suggests that cocoa farmers who are affiliated with an El Ceibo cooperative or another organization that supports organic production are more likely to practice agroforestry. However, despite general awareness of the advantages of agroforestry among farmers practicing monoculture, the implementation of agroforestry systems does not appear to be expanding at present. Out of 52 farmers interviewed, 40 cited lack of knowledge of specific agricultural practices as a factor constraining their installation of agroforestry systems. At the same time, nearly all interviewees (48 of 52 farmers) displayed a high level of

Table 6 Potentials and constraints of three different cocoa cultivation systems according to coca farmers ($n = 52$), number of citations in brackets; *SAFS* successional agroforestry system, *AFS* simple agroforestry system, *Mono* cocoa monoculture

	Potentials	Constraints
Mono	High yields in the short term (2)	More susceptible to droughts (17)
	Less labor input (5)	More susceptible to pests and diseases (15)
		Soil erosion and degradation (11)
AFS	Income from timber (19, same for SAFS)	More labor input for pruning of trees (23, same for SAFS)
	Shade is better for cocoa trees and working conditions (10, same for SAFS)	Lack of equipment to prune the trees (9)
	Better water retention capacity (7, same for SAFS)	Lower cocoa yields (4, same for SAFS)
SAFS	Diversified products (7)	More labor input to manage the different crops (12)
	Soil restoration (5)	Lack of knowledge and extension services (40)
	Less susceptible to pests and diseases (3)	

interest in extension services. Table 6 shows the most frequently mentioned potentials and constraints of the three different cocoa-cultivation systems.

Discussion

As the largest component of total biomass (see Fig. 3), shade trees are crucial to carbon stocks in the cocoa cultivation systems of Alto Beni. Of the cultivation systems analyzed in the current study, successional agroforestry systems displayed the most biomass and the highest total carbon stocks. Our results for total carbon stocks are comparable to the findings of other authors, e.g., Haeger (2012) who found stocks ranging from 76.1 to 109.1 Mg ha^{-1}. Andrade et al. (2008) found 115.5 Mg ha^{-1} of carbon stocks in cocoa agroforestry—close to our findings—as well as SOC stocks ranging from 41.9 to 66.8 Mg ha^{-1}. In comparison with Somarriba et al. (2008), our findings for total carbon stocks are medium for AFS and high for SAFS. We found considerable differences in carbon stocks and shade tree diversity between AFS and

SAFS—the latter system displaying different stories or strata that are filled with plants. Our finding of higher carbon stocks in SAFS compared with Fallow is also particularly interesting, as fallows reflect natural regeneration. One explanation for the lower carbon stocks found in Fallow could be that most fallow plots in the study area were 5–15 years old, which is not enough time for all stories to completely re-establish themselves naturally. Indeed, the fallow plots sampled in this study displayed less biomass and fewer total carbon stocks than SAFS, a cultivation system that is designed to mimic and accelerate the natural succession and structure of plant growth with multiple-use species (cf. Schulz et al. 1994). Ah horizon was deeper in SAFS and AFS than in Mono. This and the results for bulk density indicate that soils were less compacted in both successional and simple agroforestry systems. Our finding that SAFS had the highest amount of fine roots underscores the potential of this system for carbon sequestration in soils, as fine roots are considered a major contributor to soil organic matter (Nair et al. 2009a). We did not find evidence for significant differences in SOC stocks between the different cultivation systems. However, we cannot rule out that SOC was determined more by the initial conditions of plots than by the cultivation systems themselves, due to our lack of baseline data regarding the plots' SOC stocks prior to the current cultivation system (cf. FAO 2011). One other shortcoming of our research design was the difference in ages of the cultivation systems: Mono was the youngest system, and SAFS the oldest (Table 1). This occurred because various selection criteria had to be taken into account which made it impossible to find representative plots of the same age. Based on our finding that SAFS had the highest carbon stocks, we conclude that this cultivation system bears special potential in regards to climate change mitigation. According to interviews with cocoa farmers, two of the SAFS were begun in nutrient-poor soils, one in a pasture and the other in a cocoa monoculture (SAFS 2 and SAFS 3, Table 1). Vieira et al. (2009) have recommended combining the principles of forest restoration and successional agroforestry in order to accelerate restoration of soil fertility while improving farmers' food security. In this way, farmers can actively take charge of restoration efforts, and conflicts between the interests of soil restoration and agricultural production may be reduced (Vieira et al. 2009).

In regards to tree diversity, SAFS plots displayed the highest Shannon index on average as well as the highest species richness of the cultivation systems assessed. Agrobiodiversity has been suggested as an important feature of agroecological systems in terms of their ability to adapt to climate change (e.g., Ifejika Speranza 2010; Henry et al. 2009; Niggli et al. 2007)—SAFS may be considered promising in this context. The eastern foothills of the Andes belong to a hotspot of biodiversity (Myers et al. 2000); agroforestry systems in general and successional agroforestry systems in particular may serve as important buffer ecosystems here (cf. Rice and Greenberg 2000). The region of Alto Beni connects two national parks (Isibore Seguré and Madidi), and its agroforestry systems could play an important role on behalf of gene exchange. Selective logging has nearly eliminated certain tree species—such as *S. macrophylla*—that were frequently found in the region's primary forests. Several authors have argued that agroforestry provides an opportunity to protect such tree species in areas where overexploitation could lead to their extinction (Bhagwat et al. 2008; Orozco and Somarriba 2005). Indeed, *S. macrophylla* was frequently found in the agroforestry systems examined in the present study; farmers stated that they were planting timber trees for the future (Table 6). Many farmers claimed planting such trees would enable their children to study at a university. Indeed, authors have argued elsewhere that plantations of such high-value timber trees serve as a bank account for farming families (Tscharntke et al. 2011; Somarriba and Beer 2011). Similarly, ways should be found of incentivizing diversified agroforestry systems that provide various environmental benefits (Soto-Pinto et al. 2010). Organic certification may be one way of incentivizing agroforestry, but may not yet be sufficient because current certification standards—for example, European Union organic regulation (2008)—do not explicitly require agroforestry systems (e.g., IFOAM basic standards, IFOAM 2005). Thus, additional incentives are needed to foster cultivation of diverse—even successional—agroforestry systems, considering the high carbon stocks found in these systems and their potential to restore degraded soils (Vieira et al. 2009). When evaluating our sampling plots according to the criteria of two key coffee-certification mechanisms—Bird-Friendly and Rainforest Alliance (Philpott et al. 2007)—we found that all four SAFS plots would likely pass the "Bird-Friendly" criteria, however the AFS plots would not due to insufficient shade stratification (three strata required, 40 % shade cover, at least 10 tree species representing 1 % or more of the total, <60 % comprised of *Inga* spp.). Nevertheless, according to our assessment, two of the four AFS plots would pass the Rainforest Alliance's ecological requirements for certification (two strata of shade, buffer zone, 40 % shade cover, more than 12 tree species among others, Philpott et al. 2007). In particular, both agroforestry systems exceeded these certification organizations' species-richness requirements. At present, however, these particular certification mechanisms—and their benefits—remain unavailable to Alto Beni's cocoa producers.

When discussing the positive aspects of diversified agroforestry systems, it is important to note that these systems can never match all the benefits of natural forests. Since agroforestry systems cannot develop over decades or centuries, primary species are rare and pioneer and secondary species are abundant (Asare 2006; Rice and Greenberg 2000). Furthermore, these systems do not feature understory development as is found in natural forests. Thus, protected areas, in which natural processes may occur free of direct intervention, are and will remain indispensable (cf. Clough et al. 2011). Nevertheless, agroforestry provides a good means of sequestering carbon since it supports density and diversity—key elements of carbon sequestration (Somarriba et al. 2008). In addition, various studies have shown that agroforestry—even successional agroforestry—does not necessarily reduce cost effectiveness when compared with other management practices (e.g., Haggar et al. 2011; Ramirez and Somarriba 2000; Schulz et al. 1994).

Aside from fallow, the most common land use practice in the study area is slash-and-burn cultivation of annual crops for 1–2 years. Following slash-and-burn preparation of a plot, perennial crops are planted or the plot is left fallow again for soil recovery. These techniques were also practiced in the plots sampled in the present study. However, there are other promising approaches in the study area, such as slash-and-*mulch* rather than slash-and-burn (for annual and perennial crops); widespread use of such techniques could significantly reduce greenhouse gas emissions from forest clearing and enhance organic material in soils. At present, however, techniques such as slash-and-mulch are only practiced by a handful of farmers in the

region—in particular those who receive support from a local organization—as these techniques require specific knowledge and labor-force availability. Our findings of a statistically significant relationship between farmers' membership in a cooperative/ organic certification and the (higher) number of shade tree species on their cocoa plots are consistent with the findings of Orozco and Somarriba (2005): Comparing tree density and diversity in the same region, these authors found that members of an organic cooperative had a higher number of shade trees on their cocoa plots and a greater commercial volume from their cocoa plantations than non-members. According to their study, members of organic cooperatives also receive more capacity building and technical assistance (Orozco and Somarriba 2005); this may provide one explanation for the higher cocoa yields we found in AFS and, in particular, SAFS compared with Mono, when we evaluated the same plots in a second study (Jacobi et al. 2013). Indeed, our data reinforce the idea that knowledge (in this case supported by cooperatives and other farmers' organizations) is crucial to successful implementation of cocoa agroforestry systems, particularly successional agroforestry systems (Table 6). This adds to a growing body of evidence including studies by Quelca et al. (2005), Orozco and Somarriba (2005), Ortiz and Somarriba (2005), and Miranda and Somarriba (2005). In the present study, cocoa producers who were affiliated with El Ceibo and underwent the organic-certification process were given access to shade tree seedlings as well as technical assistance in planting and management of such trees on their cocoa plots—incentives that clearly encourage the practice of agroforestry (Miranda and Somarriba 2005; Abruzzese et al. 2005).

Conclusion

Our study compared biomass and carbon stocks in cocoa cultivation systems of varying agroecological complexity. Biomass, carbon stocks, and species richness were highest in successional agroforestry systems—even when compared with fallow plots of a similar age. The results of the study indicate that diversified cocoa cultivation was enhanced by local farmers' organizations that promoted organic production. These organizations recommended diversification and supported it through courses and extension services emphasizing agroforestry. Certified-organic farms were found to have higher shade tree diversity. Indeed, farming families who maintained certified-organic plots were more likely to practice agroforestry, whereas non-certified farmers tended to practice full-sun monoculture (more common in the region). Based on this, we conclude that enhancement of carbon stocks and increased conservation of tree diversity are not likely to occur if individual farming families are left on their own; rather, these developments depend on increasing farmers' social capital, for example by bringing farming families together in cooperatives, or linking them to specific service providers such as certifying organizations. Further, we conclude that expanding access to organic certification increases the likelihood that cocoa farmers will implement diversified agroforestry. Nevertheless, the current organic-certification standards in place do not obligate cocoa farmers to transition from monoculture to agroforestry-based cultivation systems. Fostering a more widespread transition to agroforestry will require close collaboration between producers, their cooperatives, and certifying organizations. Finding ways of systematically supporting such collaboration is therefore key to fostering growth of more sustainable cocoa-growing systems.

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