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Carbon storage and density dynamics of associated trees in three contrasting *Theobroma cacao* agroforests of Central Cameroon

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Abstract In Central Cameroon cocoa is mainly produced by household farming systems based on complex associations between cocoa and companion trees. Setup either on native/remnant forest or savannah, these agroforestry systems (AFS) are managed according their geographical position and local pedoclimatic conditions. In this paper, we investigated the effects of local management strategies on carbon (C) storage of live trees in three different cocoa production zones of Central Cameroon. In the 58 fields studied, 8,996 cocoa trees and 1,258 companions were surveyed. Tree sampling was non-destructive and to estimate C storage we used allometric models for above- and belowground biomasses. We measured abundance, height, diameter at breast height and determined species of companion trees. We distinguished between four cocoa plantation age categories (immature, young, mature and senescent) and three preceding systems (forest, forest gallery and savannah). We surveyed farmers' use of each associated tree, allocated it to a functional category and asked if it had been introduced or conserved. Total C content of live trees was on average close to 70 t ha^{-1}. We found that it mostly relied on associated trees—cocoa trees contribution being ac. 2–12 % of live trees total C. The level of contribution to C storage of companions from different use categories differed between sites—trees producing food had contributed most in Bokito and Obala while trees used for shading or fertility contributed most in Ngomedzap. Dynamics of C storage in live trees was found to be independent from cocoa trees growth and age. When aging, AFS continuously lost companion trees and especially conserved ones putatively because of farmers' selective logging. Yet, AFS apparently maintained equivalent C storage abilities with time. Hence, even if cocoa do not contribute significantly to C storage in our study, the systems into which they are included are able to significantly store C and may also contribute to other ecological services such as conservation.

Keywords Allometry · Agricultural practices · Associated trees · Biomass · Cocoa · Conservation · Household farming

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Introduction

Land-use systems such as agroforests are long recognized good candidates for carbon (C) storage and climate-change mitigation (Jose 2009; Kumar and Nair 2011). In Northern countries, they are therefore often promoted by stakeholders and take part to the so-called "green revolution" of agriculture (Mosquera-Losada et al. 2012). Yet, for many of those countries the process of conversion from native habitat to agriculture has largely run its course. Consequently, setting-up new agroforestry systems (AFS) generally improve agroecological services provided. In Southern countries, environmental conditions are completely different: AFS are much more diverse and still regularly set-up on native habitats (Miles et al. 2006). As a result, they can also be perceived as a threat to these habitats and their associated ecological services (Brown 2006; Kotto-Same et al. 1997). This is particularly the case of Central Africa where, for instance, international policy agenda try to slow down forest degradation and improve conservation via the REDD + initiative (Reducing Emissions from Deforestation and forest Degradation) or the establishment of conservation areas. Unfortunately, these are extremely demanding tasks since most terrestrial biodiversity hotspots and significant forests lie alongside rapidly growing and impoverished human populations (Fisher and Christopher 2007).

Cocoa is commonly cultivated within AFS in the administrative district of Central Cameroon which gathers approximately 70 % of the national production (ONCC 2012). These household systems comprise a restricted area (ac. 1–3 ha), use limited inputs and are characterized by relatively low yields (up to 1 t ha^{-1}).

They were long considered "inefficient" by cocoa agronomists and buyers. Yet, they often produce cocoa and other goods for several decades, seem to sustain high biological (and sociological) diversity and preserve partly native tree species when established on forests (Gockowski and Sonwa 2011; Sonwa et al. 2007; Zapfack et al. 2002). Nowadays, these practices are more likely to be classified as "wildlife-friendly" (Green et al. 2005) and are thought to be sustainable in the long-term (Clough et al. 2011; Gockowski et al. 2004; Perfecto and Vandermeer 2008). However, intensive production models tend to gain interest in Cameroon (Pédelahore 2012) as leading producing countries suffer a decline of production and chocolate consumers are more and more numerous (Gilmour 2012). This currently represents a threat to putatively sustainable cocoa AFS of Central Cameroon.

Hence, there is an urgent need to check for ecological services those agroforests currently provide in order to promote and support local "ecofriendly" agricultural practices detected. Unfortunately, data is scarce on this topic. Recent findings on biodiversity and dynamics within cocoa AFS of Central Cameroon showed that agricultural practices vary between production areas and affect production levels as well as live plant diversity (Bisseleua and Vidal 2007; Jagoret et al. 2011; Sonwa et al. 2007). This in turn could affect conditions for C storage in these systems. Yet, a handful of studies have assessed C content and dynamics of cameroonese AFS (Kotto-Same et al. 1997; Sonwa 2004; Njomgang et al. 2011). They mainly focused on total C dynamics after slash-and-burn on forest and its comparison to primary or secondary forest C stocks. These studies did not distinguish between AFS' different tree components and their relative contribution to C dynamics. As such they can't be used to check for agricultural practices that govern conditions of C storage of live trees in those AFS.

This study aims at characterizing the relative contribution to C levels and dynamics of different tree components in cocoa AFS. It was conducted in three distinct production areas of Central Cameroon—each area being characterized by contrasting ecological and socio-economical contexts. Herein, we assessed (1) the contribution of cocoa and associated trees to live tree C content and (2) the long-term dynamics of these contributions. We also studied (3) the relationships between cocoa and associated trees distinguishing between (a) the functions associated trees were given by farmers, (b) introduced and conserved communities and (c) system's complexity.

Materials and methods

Sites characteristics

The study was carried at three different sites of Central Cameroon, namely: Bokito, Ngomedzap and Obala. Central Cameroon is located between 2.1° and 5.8°N and 10.5° and 16.2°E, at 600–800 m elevation, with a hot and humid climate and an average annual temperature of 25 °C (Santoir and Bopta 1995). The weather is characterized by a bimodal rainfall regime comprising two distinct wet and dry seasons that vary in duration from north to south (Fig. 1). The main dry season lasts 3 months in Bokito (mid-November–mid-February) and 5 months in Obala and Ngomedzap (mid-November–mid-April). The average total annual rainfall is around 1,400 mm in Bokito, 1,600 mm in Obala, and 1,800 mm in Ngomedzap. Bokito is located in a forest–savannah transition zone with low land pressure, characterized by a patchwork of forest galleries and herbaceous and sedge savannahs on rejuvenated slightly desaturated soils (Ultisol). Obala is in a forest zone with substantial human activity, where the vegetation is influenced by forest clearing and tree cropping on moderately desaturated ferralitic soils (Oxisol). Ngomedzap is in a forest zone with low land pressure, where the prevailing vegetation is dense evergreen forest on highly desaturated ferralitic soils (Oxisol) (Santoir and Bopta 1995). The three zones are also characterized by differing socio-ethnic group compositions (muturzikin.com 2007; Pédelahore 2012), mean population density (Fig. 1; Jagoret 2011) and by their distance to the nearest town of importance. Bokito is located at 25 km from Bafia (~70,000 inhabitants), Obala is at 40 km from Yaoundé (the capital, ~2,000,000 inhabitants) and Ngomedzap is at 60 km from Mbalmayo (~65,000 inhabitants). Bokito and Obala are situated on the main road between Yaoundé and Baffoussam (the third town of the country).

Sampling methodology

We worked on 0.1 ha (30.3 × 30.3 m^2) homogeneous plots—defined as being a portion of an area where cocoa tree stands have a uniform age and structure. In 2008, we sampled 20, 21 and 17 plots in Bokito, Ngmomedzap and Obala respectively. Those plots were considered representative of local AFS based on cocoa. Cocoa densities, associated trees species and densities, height (H), and diameter at breast height (DBH) were directly measured or estimated in 2007–2008. A total of 8,996 cocoa trees and 1,258 associated trees were studied. We couldn't allocate to a particular species 7.3 % of the associated individuals while we registered 97 species in the study.

Concomitantly, four cocoa plantation age categories were defined as in Jagoret (2011): immature plantations under 8 years old; young plantations: 9–20, mature plantations: 21–40 years; and senescent plantations: 41 and older. Unfortunately we couldn't sample the same number of plots in each age category, which varied from 3 to 7. We surveyed local farmer's field practices (establishment of cocoa, cocoa type, use of associated trees, inputs use, weeding strategy; see Jagoret (2011) for more information) and considered the type of ecosystem formerly present (savannah, forest or forest gallery).

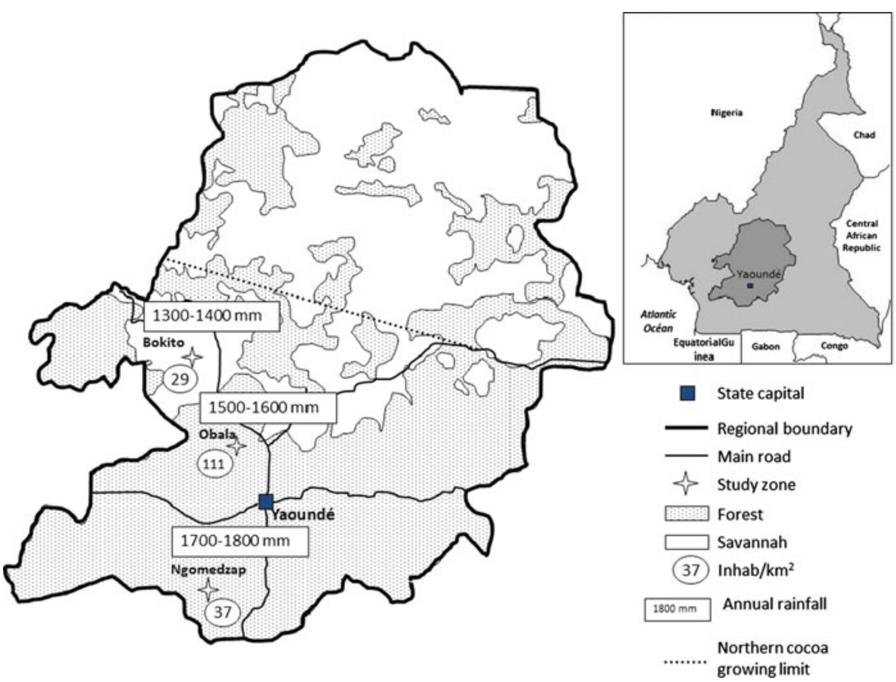

Fig. 1 Location and characteristics of the three study sites in Central Cameroon

As regards to associated trees, we surveyed age and uses. Each time an associated tree was said to be introduced, we asked the farmer when he had sown/transplanted it—which gave us the approximate age of the tree. On one hand, we distinguished three major categories of services provided by associated trees according to farmers point of view: useful for wood (category W: timber, firewood, tool manufacture), useful for cocoa growing (category U: shade, improving fertility, managing water retention), edible food production or useful for food production (which is either self-consumed or sold, category F). The other services mentioned by the farmers (such as medicine, religion or belief, field boundary, none) were gathered into the fourth category: "other uses" (category O). On the other hand, we distinguished between introduced (category "Int") and native (category "Cons") individuals. Further, we calculated Holdridge's complexity index (C_{HCI}) for associated trees populations (Holdridge 1967; Holdridge et al. 1971) as modified by Lugo et al. (1978) to include stems with a DBH $\geq$ 5 cm:

$$C_{HCI} = HGDS/1000,$$

where H is mean canopy height (m), G is basal area ($m^2\ ha^{-1}$), D is the number of stems, and S is species density (number of species per 0.1 ha).

Estimation of carbon stocks in live tree biomass

The total amount of carbon (C) stored in living tree biomass was estimated by non-destructive sampling of all (cocoa + associated) trees with a DBH $\geq$5 cm within each 1,000 m^2 plot. We estimated living tree aboveground biomass using Chave et al. (2005)'s allometric model for both cocoa and associated trees. Model calculations were made according annual rainfall ranges—with formula (1a) for Bokito and (1b) for Ngomedzap and Obala.

$$\begin{aligned} AGB_i &= \exp\left[-2.187 + 0.916 \ln\left(W_i \times \left(DBH_i^2\right) \times H_i\right)\right] \\ &= 0.112 \times \left(W_i \times \left(DBH_i^2\right) \times H_i\right)0.916 \qquad (1a) \end{aligned}$$

$$\begin{aligned} AGB_i &= \exp\left[-2.977 + 0.94 \ln\left(W_i \times \left(DBH_i^2\right) \times H_i\right)\right] \\ &= 0.0509 \times \left(W_i \times \left(DBH_i^2\right) \times H_i\right). \qquad (1b) \end{aligned}$$

In these equations AGB_i represents aboveground biomass of an individual tree, H_i individual tree height and W_i specific gravity of the tree. AGB is expressed in kilogram (kg), DBH in centimeter (cm), H in meter (m) and W in g cm^{-3} dry weight. Chave et al. (2005) model is based on trees harvested from dry and moist tropical forest sites around the world and requires data on DBH, height (H) and wood specific gravity (W) for each tree.

To proceed to the calculations, we purposely determined each tree DBH, height (H) and specific gravity (W). We usually measured the DBH at 1.3 m above ground level (using callipers). Yet, we followed the recommendations of Weyerhaeuser and Tennigkeit (2000) when the shape of the tree did not allow such measurement. Tree height was estimated with a rule when $\leq$6 m and an infrared clinometer if >6 m (TruPulse 360, LaserTechnology Inc.) also according to Weyerhaeuser and Tennigkeit (2000). Associated trees wood specific gravity was usually chosen after Zanne et al. (2009). If not, we used data from World Agroforestry Centre (Carsan et al. 2012), Brown (1997) or Vivien and Faure (2012). To be coherent with the model used, we chose a cocoa specific gravity of 0.42 g cm^{-3} (Chave et al. 2006). Further, for associated trees where no record on species-specific wood gravity was found ($\sim$19.3 % of associated trees total number) we used the mean gravity of all species from the same genus found in the literature search (as suggested by Chave et al. 2006). This accounted for 8.2 % of associated trees total count. Finally, for associated trees that couldn't be determined or for which no data on genus/species specific gravity data were found, we used the mean gravity of all other sampled individuals (unless cocoa trees, 0.526 g cm^{-3}). This accounted for 11.1 % of associated trees total count.

Root biomass was estimated indirectly from aboveground biomass after Cairns et al. (1997) using the following equation:

$$BGB_i = \exp(-1.0587 + 0.8836 \times \ln(AGB_i)), \qquad (2)$$

where BGB_i and AGB_i represent respectively belowground and aboveground biomass of an individual tree i. This equation is comparable to that of Mokany et al. (2006)—also used in the same context—when the AGB is estimated to be under 125 t ha^{-1} and slightly more conservative when AGB per ha is higher.

Carbon stocks are often estimated to represent 50 % of total tree biomass. Yet, recently Martin and Thomas (2011) considered that it surestimates actual C content in live biomass. On the other hand, Kotto-Same et al. (1997) and Njomgang et al. (2011) used a 45 % value in Cameroonese agroforests. Therefore, we used the value of 47.5 % which corresponds to the mean of conventionally used value (Hairiah et al.

2011) and the value used on Cameroonese sites. It is close to the 47.4 % found by Martin and Thomas (2011) in their study.

Statistical analysis

Data were first analyzed by three-way ANOVA (site × previous system × plantation age category) in a factorial model including all possible interactions to test the results. Site (Bokito, Ngomedzap, Obala), previous system (forest, forest gallery, savannah) and plantation age category (under 8 years old, between 9 and 20 years old, between 21 and 40 years old and over 41 years old) were treated as qualitative variables. In some cases data were log-transformed to fulfill criteria of variance-homogeneity. Following ANOVA, Student-Neuwman-Keuls test was used to find the statistically significant differences between the different types of treatments. When interactions were observed, one- or two-way ANOVA was carried out separately by freezing one of the factors. If the variance was not sufficiently homogeneous even after logarithmic transformation, the data was analyzed using the non-parametric Kruskal–Wallis test in combination with an appropriate post hoc test. Statistical significance was set at $p < 0.05$ and the analyses were performed using SPSS 17.0 (IBM, 2008).

Further, overall patterns in the C contents, tree densities per hectare, relative proportions of associated trees and Holdridge index were investigated using an overlay in principal component analysis (PCA) graph. Site, type of previous system, age of cocoa plantation, total C content per area and mean C content (cocoa and associated) of trees were added as supplementary data.

Finally, regression analysis was performed between Holridge index scores, total C content and mean C content of cocoa trees. PCA and regression calculations were performed using XLSTAT (Addinsoft XLSTAT, version 2011) and were based on correlation matrices in order to standardize variables of varying scales and magnitudes.

Results

Effect of site

Carbon (C) content of cocoa trees was significantly affected by the site where they were growing in. It was higher in Bokito and Obala and lower in Ngomedzap (Table 1; Fig. 2). Interactions with cocoa plantation age were detected for cocoa trees density and mean C content of cocoa trees (Table 1).

Within the associated trees community, the proportions of (U) and (F) use categories were as well affected by site. C content of associated trees of category (F) were nearly affected by site. The latter was higher, intermediate and lower in Bokito, Obala and Ngomedzap respectively (Table 1; Fig. 2). (U) trees were proportionally more numerous in Ngomedzap. C content of associated trees of category (U) was higher in Ngomedzap and lower in Bokito and Obala (Table 1; Fig. 2). Conserved trees (Cons.) were also much more numerous in Ngomedzap and Obala than in Bokito. Finally, an interaction with cocoa plantation age was detected for mean C content of associated trees (Table 1).

Effect of previous system

The mean C content of cocoa trees was found to be higher after forest gallery, intermediate after savannah and lowest after forest (Table 1). Associated trees densities were significantly affected by the system previously in place. It was higher after savannah than after forest or forest gallery (Table 1; Fig. 3). The number of conserved (Cons.) trees in the cocoa plantation was nearly significantly higher in Ngomedzap than in Bokito and in Obala (Table 1; Fig. 3). The number of introduced (Int.) trees in the cocoa plantation was nearly significantly higher in Bokito than in Ngomedzap and Obala (Table 1; Fig. 3). Interactions with cocoa plantation age were detected for the proportion of (U) trees. Considering this variable, only the proportion of trees from the category (U) was affected when the cocoa plantation had been setup on forest. The latter were proportionally more numerous in Ngomedzap than in Obala (data not shown).

Long-term dynamics of cocoa agroforests

C content of cocoa trees were highly affected by cocoa plantation age (Table 1), it was highest for mature and senescent plantations, intermediate for young plantations and lowest for immature plantations. Associated tree density and conserved tree densities were found to be decreasing with plantation age. Densities were higher for immature plantations, intermediate for

Table 1 Results of the 3-way ANOVA analysis and mean values of non-transformed variables per factor studied

	Site				Previous system				Plantation age				
	F/H	Bokito	Ngomed.	Obala	*F/H*	Forest	Forest gallery	Savannah	*F/H*	Immature	Young	Mature	Senescent
Densities (ind.ha^{-1})													
Cocoa	*chr**	1,214	1,828	1,734	*0.37*	1,782	1,120	1,342	*site**	1,728	1,783	1,527	1,303
Associated	*1.36*	244	233	194	*4.03#*	214b	181b	330a	*5.27***	328a	258ab	188b	147b
Conserved	*6.40**	45c	150a	99b	*0.19*	125	49	40	*3.09**	160a	102bc	77c	65c
Introduced	*0.17*	198a	83b	95b	*3.41#*	89b	132b	290a	*1.26*	168	155	112.0	81
Proportions (%)													
Useful for wood	*0.08*	3.4	21.5	23.0	*0.03*	22.2	4.8	1.5	*0.03*	15.6	16.7	16.3	13.8
Useful for cocoa cultivation	*14.23****	29.9b	41.5a	21.8b	*chr**	31.9	31.7	27.5	*syst**	38.2	28.3	29.38	31.4
Edible production	*8.13***	65.2a	30.7c	50.5b	*0.00*	40.4	62.0	69.6	*1.57*	43.8	52.3	48.1	49.8
Other	*0.22*	1.47	6.25	4.66	*0.01*	5.5	1.6	1.3	*0.79*	2.4	2.7	5.1	6.2
Tree live C content (t ha^{-1})													
Cocoa	*3.20*$^{\#}$	7.0a	3.3c	5.3b	*0.20*	4.3	8.1	5.4	*21.3****	1.3c	4.5b	7.3a	7.0a
Mean C content per cocoa tree (kg)	*chr**	6.0	2.0	3.8	*4.52**	2.9c	7.3a	4.3b	*site**	0.9	3.0	5.6	5.8
Associated	*0.03*	40.5	73	70.6	*0.11*	71.9	38.7	43.0	*0.35*	47.8	66.0	62.3	62.5
Total	*0.10*	47.5	76.3	75.9	*0.15*	76.1	46.8	48.4	*0.54*	49.1	70.5	69.6	69.5
Useful for wood	*0.16*	1.6	18.8	16.8	*0.03*	17.8	2.5	0.3	*0.13*	8.6	11.0	12.4	15.5
Useful for cocoa cultivation	*8.56***	14.6b	29.6a	15.1b	*1.24*	22.6	17.2	11.1	*1.00*	18.6	18.3	21.3	21.1
Edible production	*3.20*$^{\#}$	24ab	20.3b	33.7a	*1.67*	26.8	18.8	31.3	*1.08*	19.4	34.4	24.1	21.9
Other	*0.10*	0.3	4.3	5.0	*0.00*	4.6	0.3	0.3	*0.02*	1.3	2.3	4.5	3.9
Conserved	*0.06*	29.5	63.7	62.5	*0.27*	63.1	30.9	27.6	*0.22*	41.9	57.2	48.4	53.2
Introduced	*0.98*	11.0	9.3	8.1	*0.21*	8.7	7.8	15.4	*1.41*	5.9	8.9	13.9	9.2
Holdridge Index	*1.33*	27.7	79.1	53.2	*0.00*	67.5	23.9	33.3	*0.05*	53.6	58.6	58.9	43.0

Different letters following mean values show significant differences after post hoc

*chr**: significant interaction with plantation age, *site**: significant interaction with site; *syst**: significant interaction with previous system

$^{\#}$ $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

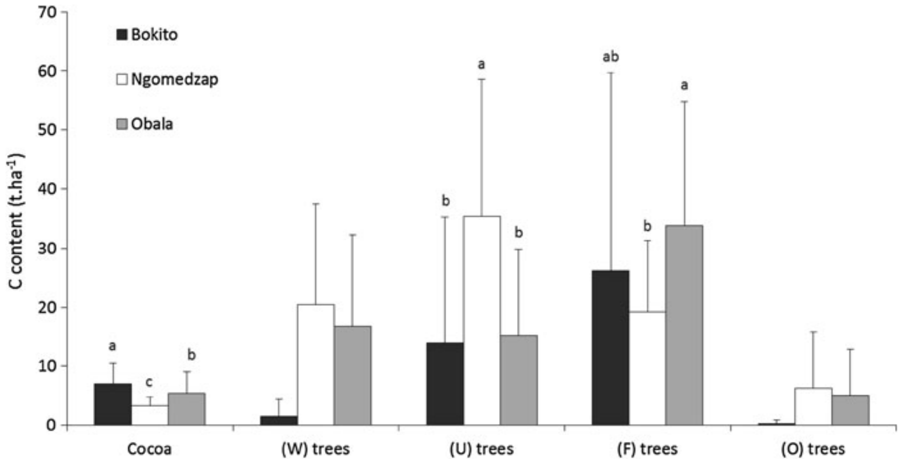

Fig. 2 Carbon content of live trees from different categories in the three zones studied (mean + 1 SE). Different letters show significant differences between sites. *W* useful for wood (timber, firewood, tool manufacture), *U* useful for cocoa growing (shade, improving fertility, managing water retention), *F* edible food production or useful for food production, *O* other uses (medicine, religion or belief, field boundary, none)

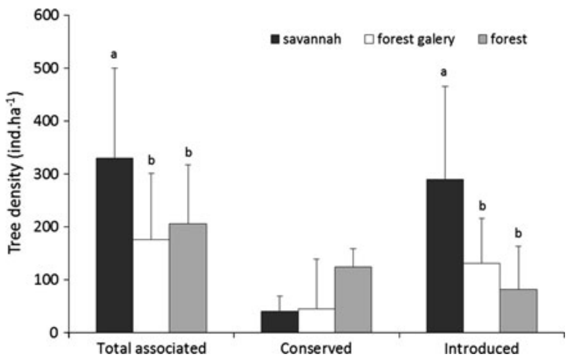

Fig. 3 Total associated, conserved and introduced trees densities for the previous systems tested (mean + 1 SE). Different letters show significant differences between sites

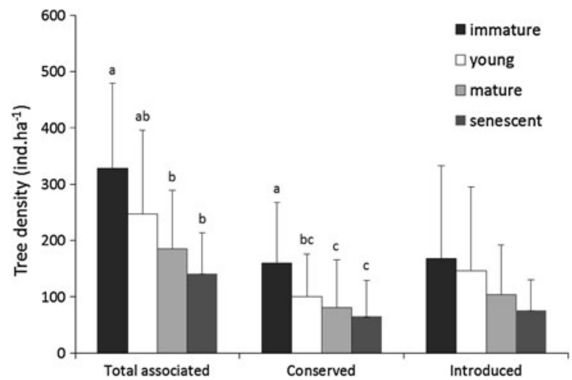

Fig. 4 Total associated, conserved and introduced trees densities in the four plantation age categories studied (mean + 1 SE). Immature plantations: ≤ 8 yo; young plantations: 9–20 yo, mature plantations: 21–40 yo; and senescent plantations: ≥ 41 yo

young plantations and lowest for older plantations (Table 1; Fig. 4).

Considering variables affected by an interaction between plantation age and site, mean C content per cocoa tree was found to be regularly increasing with plantation age in Bokito (Table 2). In Ngomedzap, mean C content per cocoa tree calculated was found to be highest for senescent plantations, intermediate for young and mature plantations, and lowest for immature ones(Table 2). In Obala, mean C content per cocoa tree calculated, was found to be highest for mature plantations followed by senescent, young and immature plantations, respectively (Table 2). Cocoa tree density was not found to be varying with time in any of the three sites studied (data not shown).

Table 2 Significant results of one-way ANOVA on mean C content per cocoa tree when interaction had been detected between site and plantation age

	F	Mean C content per cocoa tree (kg)			
		Immature	Young	Mature	Senescent
Bokito	*3.7**	1.9c	4.4cb	7.6ab	8.8a
Ngomedzap	*3.27**	0.6b	2.0ab	1.9ab	3.1a
Obala	*31.8****	0.3d	2.8c	7.3a	5.6b

Different letters following mean values show significant differences after post hoc

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Relationships between studied variables (associated tree density, total associated trees C content and cocoa trees C content)

The first and second axes of the PCA explained respectively 32.82 and 17.20 % of the total variance of tree communities studied (Fig. 5). Total associated trees C content, category (W) C content, category (U) C content, category (Cons) C content and the proportion of category (F) were the main contributors to the first axis. Associated tree density, cocoa trees C content and category (Int) density were the main contributors to the second axis. The projection showed that total C content of live trees is positively related to the C content of associated trees of functional categories (U), (W) (O) and to C content of category (Cons) trees. It appeared that C content of cocoa trees was independent from associated trees C content. Further, cocoa C content was oppositely related to cocoa and associated trees densities, category (U) and (Cons) proportions, category (Cons) C content as well as Holdridge index. On the contrary, it was positively related to the proportion of category (F) trees. The ACP well discriminated between the sites (and their respective previous system) on the first axis (Fig. 5)—Obala appeared to be in an intermediate position between Bokito and Ngomedzap. On the other hand, the second axis discriminated between the different cocoa plantation classes of age (Fig. 5).

Regression analyses of HCI against C storage in live tree biomass and mean C of cocoa trees showed opposite patterns (Fig. 6). C storage increased with HCI ($R^2 = 0.51$) while it decreased with mean C content of cocoa trees ($R^2 = 0.40$).

Discussion

Contributions of cocoa and associated trees to live tree C storage

In our study, the main drivers of C storage are associated trees. Cocoa share in C stock remains low and represent on average 10 % of total C stock in live trees, despite cocoa trees being at least 10 times more numerous than companions. Unexpectedly, total C storage in live trees did not differ between sites, previous systems or plantation ages and appeared relatively independent from some categories of live trees density. This may be partly due to the higher diversity of situations encountered on the field in comparison to previous studies that focused on sites close or only South from Yaoundé. Yet, these results could also show that Chave et al. (2005)'s more conservative allometric equations may appropriately moderate C stocks high estimates that were found in several AFS of Central Cameroon (Kotto-Same et al. 1997; Sonwa, 2004; Njomgang et al. 2011). For instance, we found that live trees of old cocoa plantations stored about 70 t ha^{-1}—which is about 30 % less than the values found by Kotto-Same et al. (1997), Sonwa (2004) or Njomgang et al. (2011).

Moreover, C stocks of cocoa trees, of trees considered useful for cocoa cultivation (shade essentially: category U) and producing food (category F) differed between sites—notably because of differing proportions within each sampled field. These factors are directly controlled by farmers when setting up and then managing their plantation. Bokito and Obala are characterized by higher (F) trees densities and C content. This could show the resilience of farmers and adaptation to economic problems encountered during the 1980–1990s in Cameroon: diversification of household revenue by increasing activity in food crop production and intensification of AFS with the introduction of fruit tree species and/or palm oil (Aulong 1998; Gockowski and Dury 1999). This could also support the hypothesis that the edible production from these systems can be easily sold locally (Aulong 1998; Gockowski and Dury 1999). Inversely, in Ngomedzap the local needs for edible products are low due to low population density and high distance to an economical important town. There, (U) trees are far more numerous and contain much more C. We could hypothesize that because there is little issue on other perennials than cocoa, Ngomedzap's farmers manage more extensively their fields and let grow trees that would have been removed or replaced in Bokito or Obala. Despite being positive for C storage, this impairs cocoa yields since (i) mean and total C content of cocoa trees and (ii) potential yields (calculated on the same samples by Jagoret 2011) are lower in Ngomedzap when compared to Bokito and Obala.

Associated trees management and conservation

Total associated trees density did not significantly differ between sites and ranged from 40 to 620 t ha^{-1}

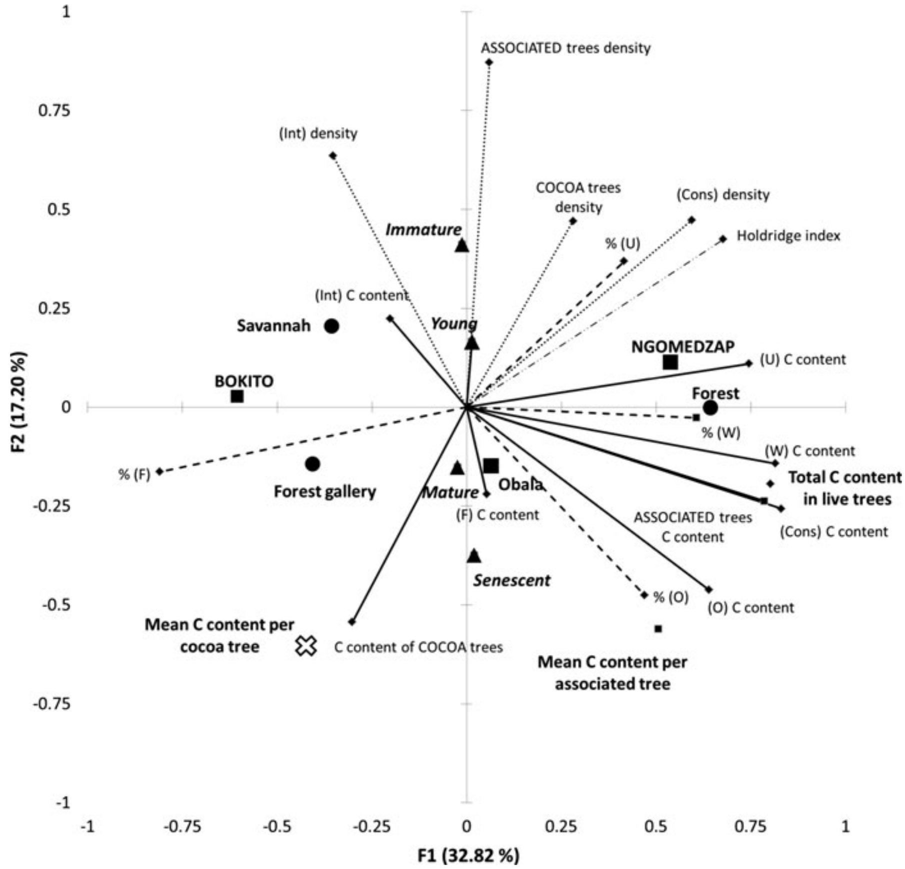

Fig. 5 PCA of carbon content, density and relative proportions of live trees per category. Site, previous system type, plantation age, total C content of live trees, mean C contents are projected data that did not account for PCA analysis. Categories: *W* useful for wood (timber, firewood, tool manufacture), *U* useful for cocoa growing (shade, improving fertility, managing water retention), *F* edible food production or useful for food production, *O* other uses (medicine, religion or belief, field boundary, none), *Cons* conserved, *Int* introduced. C content in t ha^{-1}, densities $ind.ha^{-1}$

(50 % having between 120 and 260 t ha^{-1}). These scores are in line with those measured in cocoa-based AFS found recently by Sonwa et al. (2007) or Bisseleua and Vidal (2007) but show much more diverse situations than the latter. This is probably because we included systems that were setup on savannah and forest gallery, which, to our knowledge, has not been done previously. Shares of introduced and conserved trees were contrasted. Introduced trees density was influenced both by site and previous system while conserved trees depended on site. Introduced trees density followed on a North–South gradient and inversely for conserved trees. Among conserved trees none were considered at threat or close to extinction (Cheek and Onana 2011). Yet, we found in Ngomedzap two individuals of *Guibourtia tessmanni* that Cameroon is willing to classify in CITES list of endangered species (personal communication, Ministry of Forestry and Fauna of Cameroon). Interestingly, one individual had been conserved from preceding forest (old plantation), one had been introduced by the farmer (in a young plantation). Most of the systems studied had an HCI below 100, yet a handful showed a higher HCI—which could be considered comparable to those of late successional forests (Kalacska et al. 2004). Within those, even fewer were able to maintain as well mean C content of cocoa trees above the regression curve. If we are to recommend structural changes and management practices to promote both complexity and C storage while maintaining cocoa production potential, the study of this short number of systems may help to select and test factors that would be promising for both conservation and C storage.

Further, conserved trees density was found to be positively related to cocoa trees density. We did not found any studies that checked for such relationships and it is therefore difficult to interpret or explain such a result. Yet, we could at least suggest two partial but complementary hypotheses, coming from informal discussions with farmers:

(1) In Ngomedzap—where no other goods could be consumed or sold at marketable scale—farmers try to

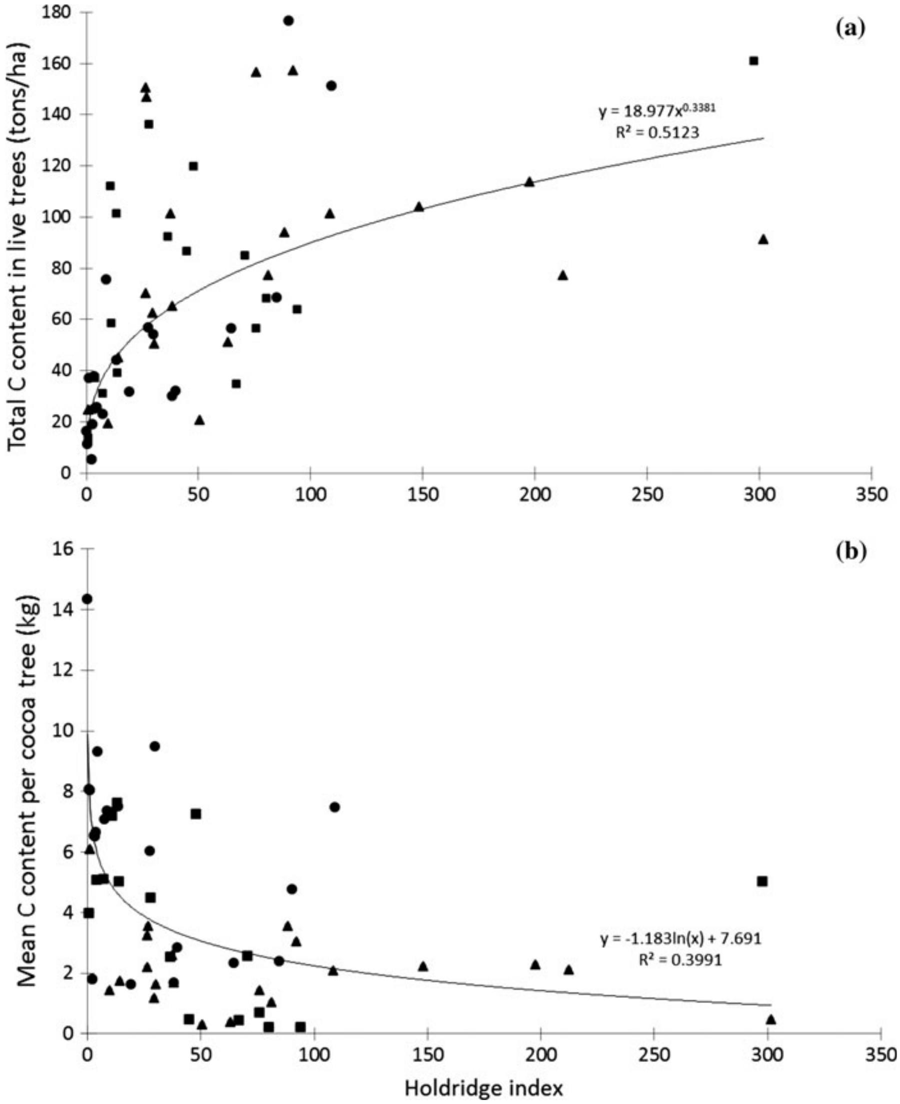

Fig. 6 **a** Regression curve between HCI and C stocks in live trees. **b** Regression curve between HCI and mean C content of cocoa trees. *black circle* Bokito plots, *black square*: Obala plots, *black triangle* Ngomedzap plots

produce more cocoa by increasing plantation density. Yet, they do it without clearing as much companion trees as in other sites. While being helpful for conservation purposes, this type of management is counterproductive for the farmer as shown by its lower productivity (Jagoret 2011).

(2) In Bokito, transformation of local pedoclimatic conditions by farmers when setting-up their system favors the spontaneous development of seeds already present in the soil or coming from neighboring forest galleries. Those trees are conserved when considered useful by farmers. This could partly explain why associated trees are found more numerous on systems setup on savannah—conserved trees being added to those that were already introduced. Again, in this case conservation purposes can meet farmers' objectives. And, interestingly, this could also show that such practices contribute—together with other factors—to the progression of forest-like ecosystems in the forest-savannah transition zone of Central Cameroon (Happi 1998; Jagoret et al. 2012).

Carbon and tree density dynamics of the systems studied

Unexpectedly, live tree C storage did not increase significantly with plantation age. Hence, despite a regular increase of their C content, cocoa trees did not significantly contribute to C storage when aging. Moreover, it seems that C storage dynamics of companions may be fast after plantation (<8 years) and then maintained at a certain level depending either on local pedoclimatic conditions and/or farmers management (clearing and pruning for instance). Unfortunately, we do not have much information to corroborate these assertions. Nevertheless, AFS consistently loose companion trees and especially conserved trees while aging. After discussion with farmers, we can hypothesize that the latter proceed to selective logging in order to regulate competition with cocoa and other introduced trees. We could also hypothesize that "natural" selection would be concomitant to farmers' work and eliminate the weakest individuals with time. Natural or anthropogenic, this selection would permit to slowly rearrange storage ability to cocoa or/and other remaining trees, depending on the position of eliminated trees in the field.

Conclusion

Among other ecological services, C storage in the AFS studied relies on farmers' local management strategies and functional use of trees. On one hand, cocoa trees do not contribute significantly to C storage. On the other hand, the level of contribution to C storage of companions from different use categories appears driven by geographical situation. Moreover, it seems that conservation aims and C storage enhancement can either meet or go against farmers' practices—and this within a same area. Dynamics of C storage was found to be independent from cocoa trees growth and age. When aging, AFS continuously loose associated trees whilst apparently maintaining equivalent C storage abilities. Farmers' selective logging during system's management may slowly move C storage potential from eliminated trees to cocoa.

Hence, even if cocoa trees do not contribute significantly to C storage, the systems into which they are included are able to significantly store C and may also contribute to other ecological services such as conservation. If we are to enhance sustainability of those AFS as a whole and obtain successful results, we shall (1) use fine-tuned (i.e., household scale) recommendations that take into account all (not only cocoa) farmers practices and uses of systems' trees, and (2), accept trade-offs on ecosystem services targeted.

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