Agroforest Syst
https://doi.org/10.1007/s10457-021-00657-z

Preliminary estimation of above-ground carbon storage in cocoa agroforests of Bengamisa-Yangambi forest landscape (Democratic Republic of Congo)

Germain Batsi · Denis Jean Sonwa · Lisette Mangaza · Jérôme Ebuy · Jean-Marie Kahindo

Received: 25 June 2020 / Accepted: 25 June 2021
© The Author(s), under exclusive licence to Springer Nature B.V. 2021

Abstract In the perspective of using cocoa as a response to climate change, a preliminary carbon stock assessment was conducted in cocoa agroforests of the Bengamisa-Yangambi forest landscape in the northeast of Democratic Republic of Congo (DRC). Data were collected in 25 plots of 2500 m^2 each, spread over 16 villages. Above-ground carbon stock assessment on cocoa trees and their associated plants revealed that cocoa agroforests store on average 44.48 Mg ha^{-1} of above-ground carbon of which, cocoa-associated plants represent 83.68%. The diversity (species richness) of cocoa associated plants determine the level of above-ground carbon stored in cocoa agroforests. Trees less than 50 cm in diameter stored a larger amount of above-ground carbon. Cocoa agroforests with associated plants dominated by forest species (Model F) store 1.76 and 1.72 times more carbon, respectively, than those where associated plants are dominated by oil palm (Model P) and a mixture of plant types (forest species mixed with oil palm plants, or Model FP). Associated plants inside cocoa agroforests also play additional roles to support livelihoods such as health care, household consumption and timber. Therefore, beyond carbon storage, cocoa agroforest is an important reservoir of some local species and thus useful for biodiversity conservation and local livelihoods. As cocoa agroforests in DRC are recognized as one of the main responses to climate change, this study constitutes an early contribution to the process of reducing emissions from deforestation and forest degradation (REDD +) in forest landscapes in this country of the Congo Basin.

Keywords Democratic Republic of Congo (DRC) · Bengamisa-Yangambi forest landscape · Cocoa agroforests · Carbon stock · REDD + · Congo Basin

G. Batsi (✉) · J. Ebuy
Faculty of Renewable Natural Resources Management, The University of Kisangani, Avenue Kitima, 5110400, PO Box 2012, Kisangani, Democratic Republic of Congo
e-mail: germainbatsi@gmail.com

J. Ebuy
e-mail: jebuyalip5@gmail.com

D. J. Sonwa
Center for International Forestry Research (CIFOR), PO Box 2008 Messa, Yaoundé, Cameroon
e-mail: d.sonwa@cgiar.org

L. Mangaza
Faculty of Science, University of Goma, Avenue de la Paix, 6110103, PO Box 204, Goma, Democratic Republic of Congo
e-mail: lisemangaza@gmail.com

J.-M. Kahindo
Faculty of Science, University of Kisangani, Avenue Kitima, 5110400, PO Box 2012, Kisangani, Democratic Republic of Congo
e-mail: jkahindo2@yahoo.fr

Published online: 16 July 2021

Introduction

Today, agroforestry systems have become a well-established approach to integrated land management, not only for renewable resource production but also for ecological and environmental considerations (Dhyani et al. 2020). Agroforestry systems have large potential across a wide range of production, climate, ecosystem services and diversity metrics as a strategy for climate-smart, sustainable agriculture (Blaser et al. 2018). Therefore, agroforestry has become a strategy for conserving natural resources in the tropics (Götz et al. 2004) and is implemented across large parts of Africa, Asia and South America (Blaser et al. 2018).

Globally, agroforests have high potential as a climate change mitigation strategy (Lasco et al. 2014) to store carbon (Verchot et al. 2007; Toppo and Raj 2018) due to their high levels of underground and aerial biomass (Cerda et al. 2014; Sonwa et al. 2018). The carbon storage potential of agroforestry systems has been successfully established (Albrecht and Kandji 2003; Dhyani et al. 2020).

However, the effectiveness of agroforestry systems in storage carbon depends on the environmental and socio-economic factors of each area (Mutuo et al. 2005). In addition, the total carbon amount stored greatly depends on region, type of system (nature of components and age of trees), site quality and previous land use (Dhyani et al. 2020). Agroforestry trees also improve land cover in agricultural fields, in addition to providing carbon inputs (root biomass, litter and pruning) to the soil, which reduce soil erosion (a crucial process in soil carbon dynamics) (Albrecht and Kandji 2003). Agroforestry systems with a mixture of diverse tree species provide more functions, both for the environment and the daily needs of local people, including income generation (Sari et al. 2020). Trees in agroforestry are not only relevant for carbon storage but also support soil carbon storage (Gusli et al. 2020). In addition, greater tree diversity (combinations of fruit and timber trees) in complex agroforestry slightly improve soil organic carbon at topsoil but do not affect deeper soil layers (Saputra et al. 2020).

Cocoa (*Theobroma cacao* L.), one of the major world cash crops (Hosseini-Bai et al. 2019), is traditionally grown in agroforestry systems (Sari et al. 2020). The carbon storage potential of these systems should be studied (Lojka et al. 2017) for several reasons. First, their management intensity directly affects stand composition and structural complexity (Deheuvels et al. 2014). Second, since the density of conserved trees is positively related to the density of cocoa trees (Saj et al. 2013), the diverse mixture and diversity of cocoa-associated trees with medium to high wood density help maintain carbon stock in cocoa agroforests systems (Sari et al. 2020). Therefore, carbon stocks in cocoa farms with dense tree canopy cover will be more similar to those in the original native forest than in farms with lower canopy (Dawoe et al. 2016).

Many cocoa-producing countries in Africa, including those of West and Central Africa, have already assessed the carbon stock of cocoa farms under different managements (Sonwa et al. 2017a).

In Democratic Republic of Congo (DRC), there is insufficient data on initiatives in the cocoa sector (Kroeger et al. 2017). Indeed, cocoa is generally cultivated by small farmers, most often alongside other crops (Downie 2018). In Tshopo province, cocoa has been promoted since the colonial era (Jassogne et al. 2014).

According to Batsi et al. (2020), in Bengamisa-Yangambi landscape, the distance between the main city and the intensity of forest degradation greatly impact the density and diversity of cocoa-associated plants. Therefore, as noticed by many authors (Saj et al. 2013; Deheuvels et al. 2014), there is a strong link between the density and diversity of cocoa-associated plants with landscape management, and secondarily, with carbon stock. Thus, the possible relationships between cocoa-associated plant density, diversity and carbon stock must be clarified in cocoa agroforestry systems (Vroh Bi Tra et al. 2010) in the Bengamisa-Yangambi landscape.

In this study, we explore the impact of forest degradation intensity, density and diversity of plants (species richness) and main uses of cocoa-associated plants on above-ground carbon in the Bengamisa-Yangambi landscape. We address the following research questions: (1) What forest degradation intensity from Zone A (most degraded) to Zone D (least degraded) affect above-ground carbon? (2) What main typologies (models) of cocoa agroforests affect the above-ground carbon? (3) Did the cocoa agroforest's structure (stem density, plant diversity and basal area) affect the above-ground carbon? In response to these three questions, we hypothesize that (1) above-ground carbon stock follows the forest degradation gradient; (2) cocoa agroforests main typology are due to farmer management (Sari et al. 2020); and (3) the cocoa agroforest's structure (diversity, density and basal area) and above-ground carbon are positively correlated.

Materials and methods

Study area

This study was conducted between June and July 2018 in 16 villages and recorded above-ground carbon of cocoa agroforest in four zones of 15 km each. These are defined along the main road, from Kisangani city to Yangambi forest reserve landscape, via Bengamisa village (Fig. 1). This area is located between the city of Kisangani (N00°31′; E25°11′) (Moloba et al. 2019) and the Yangambi Biosphere Reserve (N00°48′; E24°29′) (Kearsley et al. 2017) in Banalia territory, Tshopo province, DRC. Kisangani, founded in 1883, is the capital of Tshopo province and its main city. Its population is estimated at about 1 million (around 20% of the 5,032,472 inhabitants of the province) (Moonen et al. 2016; Moloba et al. 2019). In the Bengamisa-Yangambi forest landscape, Kisangani is the main city with its urbanization impacting the forest landscape between the city and the Yangambi Biosphere Reserve. In this region, which has excellent agricultural and climatic conditions, cocoa cultivation has been encouraged since colonial times. In 1979, the African Development Bank financed the development of 1750 ha of small peasant and commercial plantations in Bengamisa called CABEN (Cacaoyères de Bengambisa) to increase congolese cocoa production. CABEN did not achieve its objectives and most of these plantations were abandoned (Jassogne et al. 2014). In Bengamisa-Yangambi landscape, small farmers have cultivated cash crops such as oil palm and cocoa for several decades (Béguin 1974; Jassogne et al. 2014).

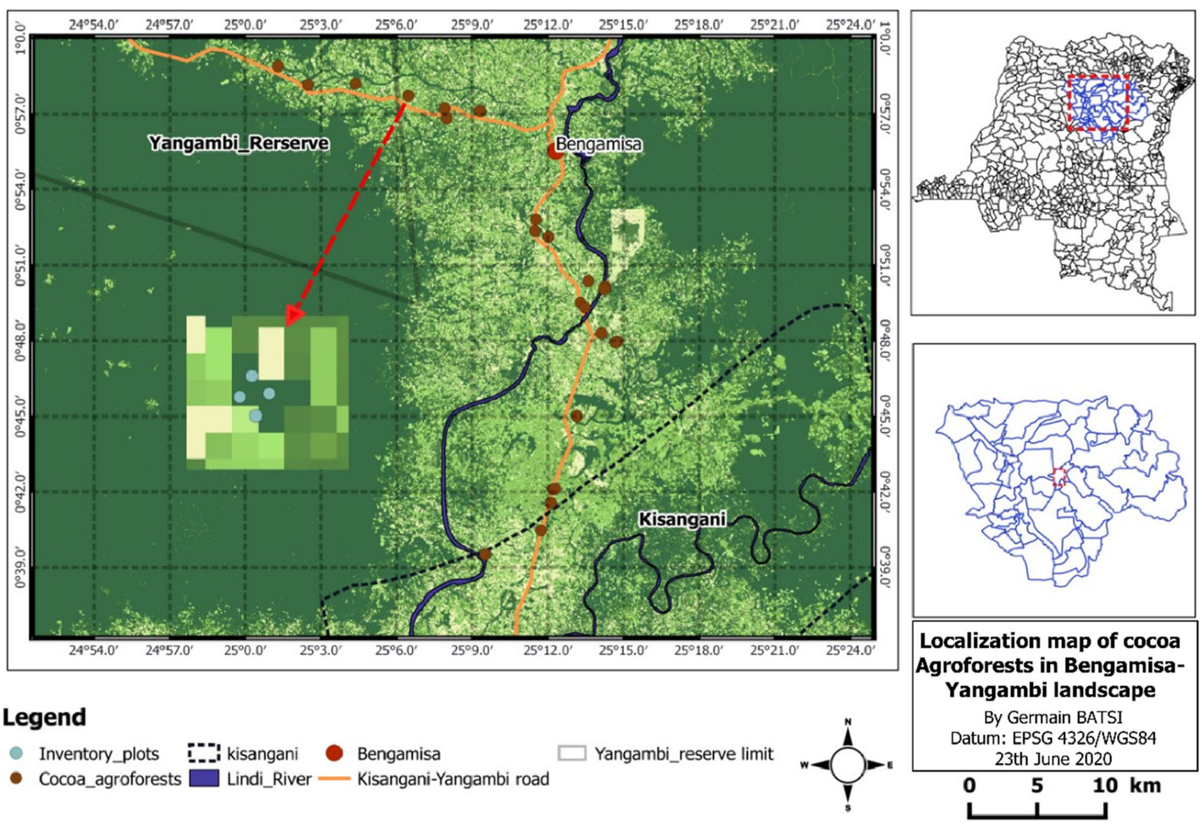

Fig. 1 Localization map of the cocoa agroforests and inventory plots in Bengamisa-Yangambi landscape

Methods

Data collection

Four zones of 15 km each (Fig. 1) were defined along the main road, including Zone A (18–33 km from Kisangani city), Zone B (34–49 km from Kisangani city), Zone C (50–65 km from Kisangani city) and Zone D (66–81 km from Kisangani city). These zones are arranged from the highly degraded area nearest Kisangani city (Zone A) to the least degraded area in the forest zone (Zone D) (Fig. 1).

Twenty-five cocoa agroforests of at least 0.5 ha were selected (Torres et al. 2014). Four plots of 25 m × 25 m (i.e. 625 m^2 for each plot), corresponding to an area of 2500 m^2, were established within each cocoa agroforest to assess carbon stocks of plants. In small plantations, the plots were installed successively, spaced 3–5 m apart. In large plantations, the plots were arranged on a diagonal to represent the diversity of the cocoa farm. On each cocoa tree the diameter was measured at 30 cm from the ground and at 1.30 m on the cocoa-associated plants (Zapfack et al. 2002).

The following equations were used to estimate carbon stock: allometric Eq. (7) developed by Chave et al. (2014): $AGB = \exp(-2.024 - 0.896E + 0.920\log(WD) + 2.795\log(D^2))$ for the cocoa-associated trees, where AGB = above-ground biomass in Mg, WD = wood density in g.cm^{-3}, D = diameter in cm and E = environmental variable integrating temperature and precipitation variability. We used the BIOMASS package developed by Réjou-Méchain et al. (2017) to calculate the biomass. We used the equation of Andrade et al. (2008): $Bt = 10^{(-1.625+2.63\log(d30))}$ for cocoa trees, where d30 = stem diameter at 30 cm from the soil, Bt = biomass in kg. Finally, we used the allometric equation $Y(kg) = 4.5 + 7.7H$, of Frangi and Lugo (1985) for oil palms, where H = height of the palm tree in m and Y = above-ground biomass in kg. The conversion factor of 0.47 was used to transform biomass to carbon stock (Thomas and Martin 2012). Wood densities of different species were taken from the global wood density database of Zanne et al. (2009) and wood density database of ICRAF.

Data analysis

Preliminary analysis of cocoa agroforests helps identify the three following models defined by Batsi et al. (2020): *Cocoa agroforests in which companion plants (associated with cocoa trees) were composed primarily of forest/native species* (Residual species from the previous natural forest or from regeneration of these species or regeneration of species from the adjacent forest), named **Model F**; *cocoa agroforests in which companion plants were split equally between forest/native species and oil palms,* named **Model FP**; lastly, *cocoa agroforests in which companion plants were composed primarily of oil palms*, named **Model P**.

We estimated the above-ground carbon stock of cocoa agroforests in the Bengamisa-Yangambi forest landscape by: (i) zones of distance and cocoa agroforests model; (ii) pools of above-ground carbon; (iii) floristic composition of cocoa-associated plants; (iv) local usefulness of cocoa-associated plants, (v) diameter classes of cocoa-associated plants; and (vi) relationship between structure (plant density and species richness) and above-ground carbon.

We used statistical analysis to compare zones [Zone A (18–33 km from Kisangani), Zone B (34–49 km from Kisangani), Zone C (50–65 km from Kisangani) and Zone D (66–81 km from Kisangani)] and cocoa agroforest typologies (Model F, Model FP and Model P). We first applied one-way analysis of variance (ANOVA) with Tukey's test in order to check for significant differences among zones and cocoa agroforest's typologies. When, ANOVA test residuals do not follow a normal distribution (tested by Shapiro's test), Kruskal test was used and the differences among groups were estimated with a post-hoc Duncan test. A probability of 0.05 was used as limit for significance. All these analyses were performed by the R software version 4.0.3 (R Core Team 2019) under its R studio interface.

Results

Above-ground carbon of cocoa-associated plants and cocoa trees

Cocoa agroforests in the Bengamisa-Yangambi forest landscape stored an average of 44.18 Mg ha^{-1} of

Table 1 Above-ground carbon (Mg ha^{-1}) of cocoa agroforests by zone (differentiated by distance from Kisangani city)

Agroforest components	Zone A 18–33 km (n = 6 agroforests)	Zone B 34–49 km (n = 11 agroforests)	Zone C 50–65 km (n = 3 agroforests)	Zone D 66–81 km (n = 5 agroforests)	Whole region (n = 25 agroforests)	*P*
Associated plants	15.58 ± 7.65a	50.07 ± 30.36b	43.97 ± 4.84ab	29.6 ± 17.19ab	36.97 ± 25.65	0.0407
Cocoa trees	8.18 ± 2.26	6.54 ± 1.69	6.6 ± 1.71	7.9 ± 4.06	7.21 ± 2.42	0.516
Whole zones	23.77 ± 7.41a	56.6 ± 30.19b	50.57 ± 3.21ab	37.5 ± 13.73ab	44.18 ± 24.75	0.0474

We provided ANOVA test's *p* value or Kruskal–Wallis test's *p* value when the condition of ANOVA was not satisfied; we added the same letter in row when the difference between two groups is not significant (a) and different letters when it is significant (a, b, ab); (n) is number of cocoa agroforests and (km) is kilometer

carbon (Table 1). The carbon stock averages vary significantly between zones depending on the distance from Kisangani city. Thus, Zone B (34–49 km from Kisangani city) recorded the highest average (56.6 Mg ha^{-1}) followed by Zone C (50–65 km from Kisangani city) (50.57 Mg ha^{-1}) and and Zone A (18–33 km from Kisangani city) with stored the lowest value amount of carbon (23.77 Mg ha^{-1}). The above-ground carbon sequestered by plants associated with cocoa trees (36.97 Mg ha^{-1}) is largely higher ($p < 0.001$) than that of cocoa trees (7.21 Mg ha^{-1}) and represents 83.68% of the total above-ground carbon recorded in the study area.

Looking at the different cocoa agroforest' models recorded in the above-mentioned landscape (Table 2), it is absolutely clear that the model F (agroforests in which companion plants [associated with cocoa trees] are dominated by forest species) store significantly more carbon (59,43 Mg ha^{-1}) than the other models. On the other hand, the smallest amount of carbon (33,78 Mg ha^{-1}) is stored by the model P (cocoa agroforests in which companion plants are dominated by oil palms). However, the model FP (cocoa agroforests in which companion plants are split equally between forest species and oil palms) have a value (34,48 Mg ha^{-1}) between the two previous models, hence its statistical similar with them.

Carbon storage by main plant species

Turning to the five cocoa-associated species with respect to highest rated carbon storage (Table 3), *Elaeis guineensis* JACQ. storing 4.08 Mg ha^{-1} (or 8.12% of above-ground carbon of plant associated with cocoa) is classified at the top of all species of study area. When considering each zone specifically, species classified at the top are for *Elaeis guineensis* (5.65 Mg ha^{-1} or 20.87%) in Zone A (18–33 km from Kisangani city); *Zanthoxylum gilletii* (DE WILD.) P.G. WATERMAN (5.26 or 8.59%) in Zone B

Table 2 Above-ground carbon (Mg ha^{-1}) of cocoa associated plants and cocoa trees by type/model of cocoa agroforests

Agroforest components	Model F (n = 10 agroforests)	Model FP (n = 5 agroforests)	Model P (n = 10 agroforests)	Whole region (n = 25 agroforests)	*P*
Associated plants	52.48 ± 25.67a	27.24 ± 15.05ab	26.31 ± 23.43b	36.97 ± 25.65	0.0396
Cocoa trees	6.95 ± 1.8	7.24 ± 3.85	7.47 ± 2.37	7.21 ± 2.42	0.899
Whole zones	59.43 ± 25.06a	34.48 ± 12.37ab	33.78 ± 22.52b	44.18 ± 24.75	0.0345

Model F (agroforests in which companion plants [associated with cocoa trees] are dominated by forest species); Model FP (cocoa agroforests in which companion plants [associated with cocoa trees] are split equally between forest species and oil palms); and Model P (cocoa agroforests in which companion plants [associated with cocoa trees] are dominated by oil palms); we provided ANOVA test's *p* value or Kruskal–Wallis test's *p* value when the condition of ANOVA was not satisfied; we added the same letter in row when the difference between two groups is not significant (a) and different letters when it is significant (a, b, ab) and (n) is number of cocoa agroforests

Table 3 Five cocoa associated species impacting the above-ground carbon (Mg ha^{-1}) of cocoa agroforests by zone (differentiated by distance from Kisangani city)

Species	Zone A 18–33 km (n = 6 agroforests)	Zone B 34–49 km (n = 11 agroforests)	Zone C 50–65 km (n = 3 agroforests)	Zone D 66–81 km (n = 5 agroforests)	Whole region (n = 25 agroforests)
Elaeis guineensis JACQ	5.65 (20.87%)	4.3 (8.03%)	5.01 (8.08%)	1.17 (3.72%)	4.08 (8.12%)
Musanga cecropioides R. BR	–	–	3.55 (7.32%)	10.51 (8.36%)	3 (7.67%)
Zanthoxylum gilletii (DE WILD.) P.G.WATERMAN	–	5.26 (8.59%)	2.96 (6.44%)	–	2.84 (7.29%)
Trilepisium madagascariense DC	–	–	14.13 (11.4%)	–	2.7 (6.62%)
Ficus exasperata VAHL	0.83 (4.24%)	3.78 (6.71%)	–	2.48 (4.77%)	2.45 (5.45%)
Persea americana MILLER	3.25 (10.66%)	–	–	1.41 (3.94%)	–
Dacryodes edulis (D. DON) H.J. LAM	1.66 (7.9%)	–	–	–	–
Alstonia boonei DE WILD	1.23 (5.32%)	–	–	–	–
Pycnanthus angolensis(WELW.) EXELL	–	4.02 (7.55%)	–	–	–
Pseudospondias microcarpa (A. RICH.) ENGLER	–	3.36 (6.59%)	–	–	–
Petersianthus macrocarpus (P. BEAUV.) LIBEN	–	–	3.22 (6.74%)	–	–
Pterocarpus soyauxii TAUB	–	–	–	1.1 (3.66%)	–
Total of the top 5 plant	12.62 (81%)	20.72 (41.39%)	28.87 (65.67%)	16.66 (56.29%)	15.06 (40.75%)
Total of whole zone	15.58 (100%)	50.07 (100%)	43.96 (100%)	29.6(100%)	36.97 (100%)

(n) is number of cocoa agroforests and (km) is kilometer

(34–49 km from Kisangani city); *Trilepisium madagascariense DC.* (14.13 Mg ha^{-1} or 11.4%) in Zone C (50–65 km from Kisangani city); and *Musanga cecropioides* R. BR. (10.51 Mg ha^{-1} or 8.36%) in Zone D (66–81 km from Kisangani city). Furthermore, in Zone A (18–33 km from Kisangani city), edible plant species such as *Elaies guineensis, Persea americana* MILLER and *Dacryodes edulis* (D. DON) H.J. LAM are classified at the top.

Above-ground carbon of cocoa associated plants by diameter classes and the linkage between above-ground carbon and cocoa associated plants' diversity

Figure 2 illustrates the distribution of carbon stocks by diameter classes. It indicates that trees with diameters less than 50 cm store the largest proportion of above-ground carbon. This contrasts to the forest where larger diameter trees store the most carbon. In the Bengamisa-Yangambi forest landscape in general, diameter classes between 20 and 50 store significantly more carbon than others ($p < 0.0001$). Species richness is significantly correlated with above-ground carbon in cocoa agroforests (r = 0.65; $p < 0.001$) (Fig. 3). However, plant density has not significantly influence above-ground carbon storage (r = 0.38, $p > 0.05$).

Above-ground carbon storage by useful local cocoa associated plants

As shown in Table 4, carbon storage by useful plants for the local community differs significantly ($p < 0.05$) by zones. Thus, the large contribution of medicinal plants (13.68 Mg ha^{-1}) in carbon storage should be highlighted, particularly in Zone C (50–65 km from Kisangani city) (22.61 Mg ha^{-1}). On the other hand, edible caterpillar-host plants (Host_Cat) stored a small amount of carbon (3.27 Mg ha^{-1}). Furthermore, although timber did not store as much carbon as other categories, it is the

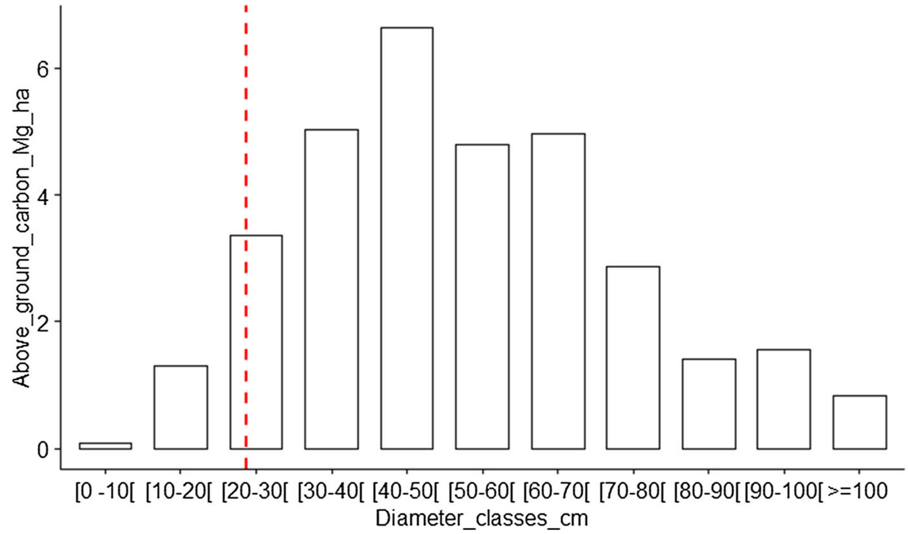

Fig. 2 Above-ground carbon (Mg ha^{-1}) average by diameter classes of cocoa agroforest in Bengamisa-Yangambi forest landscape (Democratic Republic of Congo) *Legend:* ( ) is the median of above-ground carbon

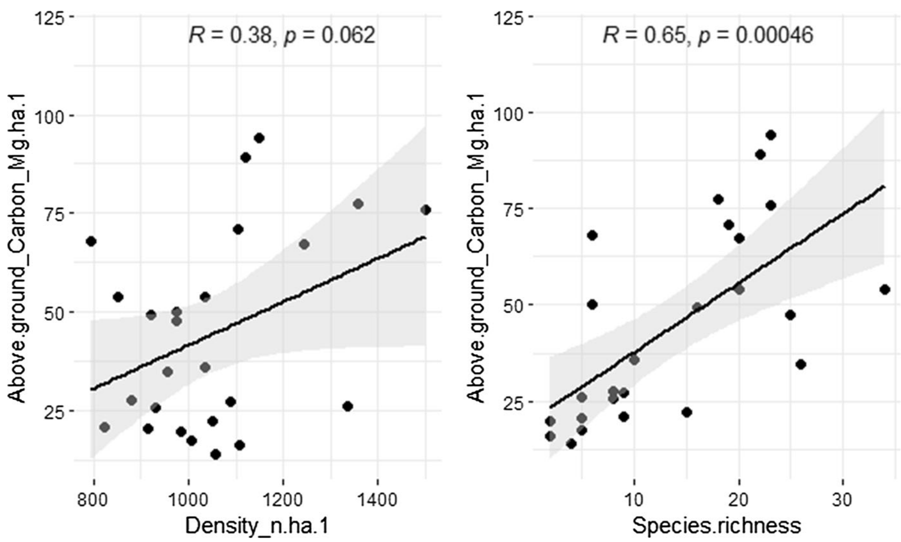

Fig. 3 Correlation between plant density, species richness and above-ground carbon (Mg·ha^{-1}) in cocoa agroforests of Bengamisa-Yangambi landscape

only one whose carbon storage amount increases significantly ($p < 0.05$) with distance from Kisangani city—from Zone A (18–33 km from Kisangani city) to Zone D (66–81 km from Kisangani city).

When we compare carbon storage by main uses of cocoa-associated plants in three models/types of cocoa agroforests (MF, MFP and MP) identified in Bengamisa-Yangambi landscape (Table 5), the amounts of above-ground carbon of these models/types are significantly different ($p < 0.05$). Medicinal plants contributed more in carbon storage (13.68 Mg ha^{-1}), especially in Model F (agroforests in which companion plants [associated with cocoa trees] are dominated by forest species (Model F) (with a value of 20.29 Mg ha^{-1}). The amount of carbon stored by timber (5.83 Mg ha^{-1}) ($p < 0.01$) and plants with

Table 4 Above-ground carbon storage in cocoa associated plants main utility by zones (differentiated by distance from Kisangani city)

Plant main utility	Zone A 18–33 km (n = 6 agroforests)	Zone B 34–49 km (n = 11 agroforests)	Zone C 50–65 km (n = 3 agroforests)	Zone D 66–81 km (n = 5 agroforests)	Whole region (n = 25 agroforests)	*P*
Edible	11.47 ± 7.69	8.13 ± 3.79	5.56 ± 6.43	3.73 ± 5.9	7.75 ± 5.92	0.16
Host_Cat	0.21 ± 0.51	5.96 ± 6.37	3.22 ± 2.65	1.07 ± 0.77	3.27 ± 4.93	0.08284
Medicinal	3.27 ± 5.03	20.05 ± 15.65	22.61 ± 3.92	6.8 ± 11.06	13.68 ± 13.95	0.1211
Timber	0.37 ± 0.87a	4.85 ± 6.57ab	7.52 ± 6.56ab	13.51 ± 12.15b	5.83 ± 8.18	0.02623
Others	0.26 ± 0.41	11.06 ± 12.67	5.05 ± 7.23	4.5 ± 3.41	6.44 ± 9.67	0.2238
Whole zones	15.58 ± 7.65a	50.07 ± 30.36b	43.96 ± 4.84ab	29.6 ± 17.19ab	36.97 ± 25.65	0.0407

(Host_Cat) is edible caterpillar-host plants; We provided ANOVA test's *p* value or Kruskal–Wallis test's *p* value when the condition of ANOVA was not satisfied; we added the same letter in row when the difference between two groups is not significant (a) and different letters when it is significant (a, b, ab); (n) is number of cocoa agroforests and (km) is kilometer

Table 5 Above-ground carbon storage capacity by cocoa associated plants main utility by cocoa agroforests type/model

Plant main utility	Model F (n = 10 agroforests)	Model FP (n = 5 agroforests)	Model P (n = 10 agroforests)	Whole region (n = 25 agroforests)	*P*
Edible	5.95 ± 4.83	11.06 ± 9.63	7.89 ± 4.38	7.75 ± 5.92	0.299
Host_Cat	3.82 ± 4.15	1.84 ± 2.06	3.45 ± 6.65	3.27 ± 4.93	0.2973
Medicinal	20.29 ± 15.33	7.14 ± 11.28	10.34 ± 11.94	13.68 ± 13.95	0.141
Timber	12.04 ± 9.74a	2.71 ± 3.38b	1.18 ± 2.46b	5.83 ± 8.18	0.004807
Others	10.39 ± 9.74	4.48 ± 5.31	3.45 ± 10.62	6.44 ± 9.67	0.01536
Whole zones	52.48 ± 25.67a	27.24 ± 15.05ab	26.31 ± 23.43b	36.97 ± 25.65	0.0396

Model F (agroforests in which companion plants [associated with cocoa trees] are dominated by forest species); Model FP (cocoa agroforests in which companion plants [associated with cocoa trees] are split equally between forest species and oil palms); and Model P (cocoa agroforests in which companion plants [associated with cocoa trees] are dominated by oil palms). We provided ANOVA test's *p* value or Kruskal–Wallis test's *p* value when the condition of ANOVA was not satisfied; we added the same letter in row when the difference between two groups is not significant (a) and different letters when it is significant (a, b, ab); (n) is number of cocoa agroforests and (km) is kilometer

secondary or unknown use (Others) (6.44 Mg ha^{-1}) ($p < 0.05$) vary significantly between typologies. Agroforests in which companion plants [associated with cocoa trees] are dominated by forest species (Model F) has the best performance.

Discussion

Above-ground carbon of shade trees and cocoa trees

Cocoa agroforests in the Bengamisa-Yangambi forest landscape stored an average of 44.18 Mg ha^{-1} of above-ground carbon. This average is lower than the range of 50–75 Mg ha^{-1} defined by Verchot et al. (2007) for agroforestry systems in the tropics. In addition, numerous similar studies in several tropical countries have revealed higher averages than ours: Madountsap et al. (2018) in Cameroon (136.1 Mg ha^{-1}); Santhyami et al. (2018) in Indonesia (99.23 Mg ha^{-1}); Schroth et al. (2013) in Brazil (87 Mg ha^{-1}); Madountsap et al. (2017) in Cameroon (100.01 Mg ha^{-1}) and Saj et al. (2013) in Cameroon (70 Mg ha^{-1}). However, this last one is close to the 49 Mg ha^{-1} obtained by Somarriba et al. (2013) in Central America and the 52.7 Mg ha^{-1} obtained by Jadán et al. (2015) in the Ecuadorian Amazon. The difference in carbon storage among the different agroforest's site could be attributed to the ages of agroforest that ranged from immature to mature (Besar et al. 2020).

Nevertheless, when we compare our average of cocoa agroforests with those of other land-use types in the same study area, we find that cocoa agroforests stored lower amounts of carbon than the semi-deciduous forests of the Yoko (191 Mg ha^{-1}) and Yangambi Reserve (163 Mg ha^{-1}) obtained by Doetterl et al. (2015) and lower amounts of carbon than Yangambi old-growth forest (162 $\pm$ 20 Mg ha^{-1}) obtained by Kearsley et al. (2013). However, carbon storage average of cocoa agroforests is high to 58.4 Mg ha^{-1} of Above-ground biomass, corresponding to 27.4 Mg ha^{-1} of Above-ground carbon stock obtained by Moonen et al. (2019) in the fallow areas of Tshopo province.

Plants associated with cocoa trees store about six times more carbon than cocoa trees and represent the major proportion (83.68%) of carbon stock in the study area. Thus, associated plants are crucial to carbon stocks in the cacao agroforests (Dawoe et al. 2016). Indeed, many authors have confirmed this supremacy of associated plants on cocoa trees in other countries: Sonwa et al. (2017b) and Madountsap et al. (2018) in Cameroon; and Somarriba et al. (2013) in Central America. This difference in carbon storage between cocoa trees and cocoa companion plants is explained by the presence of large trees storing the large proportion of estimated carbon (Loubota et al. 2018).

Agroforests store less carbon than natural forests. However, cocoa agroforests provide better opportunities for carbon storage (Saj et al. 2013; Obeng and Aguilar 2015). Moreover, they have the potential for generating non-carbon and sustainable development benefits that might also include the simultaneous enhancement of climate change adaptation and mitigation in multiple ways (Minang et al. 2014).

In fact, above-ground carbon stocks increase in cocoa agroforests with the increase of associated plant diversity (Bisseleua and Vidal 2008; Rajab et al. 2016). This explains the low amount of carbon recorded under Model P compared to Model F. In cocoa agroforests, above-ground carbon is strongly related to the diversity and density of associated plants (Mortimer et al. 2017) and the presence of large trees (Schroth et al. 2013). Consequently, the change (shade level) at cocoa agroforest plot level affects biomass accumulation at the landscape scale and establishes the role of agrosystems as a tool to mitigate climate change in the landscape (Middendorp et al. 2018).

Relationship between cocoa-associated plants composition, structure (density, species richness, diameter class) and above-ground carbon

Turning to the five cocoa-associated plants storing more carbon, generally *Elaies guineensis* (4.08 Mg ha^{-1}) is the strongest, constituting 8.12% of the global amount of above-ground carbon in the study area. The area around Kisangani city (Zone A) is particularly important since edible plants such as *Elaies guineensis, Persea americana* and *Dacryodes edulis* have a considerable influence on the carbon stock. This is probably because they are the most important and common planted species in cocoa agroforestry systems for livelihoods in Africa (Sonwa et al. 2014; Alemagi et al. 2015). But the presence of some species such as *Elaies guineensis* (the main palm oil provider) and *Zanthoxylum gilletii* (the best-known medicinal species in traditional medicine) within the first five species that stored more above-ground carbon is also important. It demonstrates the strong implication of farmers' willingness to plant and protect the species (Asigbaase et al. 2020) and farmers' local management strategies and functional use of associated plants (Saj et al. 2013) on carbon storage in the cocoa agroforests of the above-mentioned landscape.

In general, medicinal plants stored a large amount (13.68 Mg ha^{-1}) of above-ground carbon and edible caterpillar-host plants (Host_Cat) stored a small amount of carbon (3.27 Mg ha^{-1}). However, Sonwa et al. (2017a) in Cameroon and Asigbaase et al. (2020) in Ghana found that high-value timbers stored more carbon than other main uses. Indeed, farmers' preference for plant species to be associated with cocoa is guided by economic importance and compatibility with cocoa trees (Sonwa et al. 2014).

The storage and renewal of above-ground carbon in the cocoa agroforests of the Bengamisa-Yangambi landscape is still found to be determined by trees less than 50 cm in diameter, with a peak between 40 and 50 cm. This is contrary to the forest where larger diameter trees store the most carbon. This result largely explains the positive correlation observed between above-ground carbon and stem density and above-ground carbon and species richness. Therefore, stem density and species richness are the key factors determining the level of carbon stored in cocoa agroforests in the above-mentioned landscape. Indeed, the changes in composition of plant species of the cocoa plantation result in variations in the amount of carbon stored (Dawoe et al. 2016; Mortimer et al. 2017; Tesfaye et al. 2019; Mustari et al. 2020).

Cocoa agroforest and REDD + process and other forest conservation initiatives in DRC

Demonstrating the role of cocoa agroforests in carbon storage, our study shows the importance of these systems in REDD + (Reducing Emissions from Deforestation and forest Degradation) process. It focuses on the role of associated plants and the cocoa agroforests models (management practices-dependent) adopted by farmers.

Some agroforestry systems or trees outside forests may not fall within the forest definition proposed by countries in the current REDD + process. However, some countries, including DRC, expressed interest in monitoring agroforestry in future evolutions of their REDD + Monitoring Reporting and Verification systems (Rosenstock et al. 2018a). Recognizing that investments in cocoa can generate multiple social, economic and environmental benefits, Côte d'Ivoire (2015), Cameroon (2016) and Ghana (2017) have prioritized sustainable cocoa programs in their REDD + strategies, especially for emission reduction programs (Carodenuto 2019). Indeed, Ghana has proposed large-scale subnational programs focusing on the main cocoa-producing regions through the REDD + Cocoa Forest Programme (GCFRP) that would link to national MRV systems (Rosenstock et al. 2018b). Similar programs have been found in the Republic of Congo (World Bank 2017). Large cocoa industry actors such as Olam, Cargill and Barry Callebaut all have sustainability programs whose activities may likely be the same as what is required for zero deforestation efforts. However, the joint Action Frameworks recently released for zero deforestation cocoa have yet to be operationalized (Carodenuto 2019).

In DRC, the national communications include agroforestry in the inventory section, where the mitigation analysis includes agroforestry (Rosenstock et al. 2018a). At the national level, DRC plans to launch an "Agriculture: Sustainable Cocoa" program. This would support development of a sustainable cocoa crop that has a reduced impact on the forest and offsets farmers' income from food production. This program will make it possible to monitor the impact of sustainable cocoa cultivation on the forest by monitoring and evaluating the impact of the program's activities on deforestation. The proposed sites are the intervention areas of the integrated programs: Mambasa-Irumu/Ituri site, Gemena-Lisala-Bumba/Equateur site, Kisangani-Bengamisa/Tshopo site and Mai-Ndombe site (DRC Government, 2015). Thus, our study on above-ground carbon stock of cocoa agroforests is important at the scale of Tshopo province and DRC within the MRV framework to properly generate the local emission factor. However, the cocoa agroforestry model that uses local forest trees as shade for cocoa trees stores the most carbon, making them spaces to conserve local biodiversity.

Conclusion

In the Bengamisa-Yangambi landscape, cocoa agroforests store significantly lower amounts of above-ground carbon than natural forests. The large proportion of global carbon stock (83.68%) was drained by associated cocoa plants, which store six times more carbon than cocoa trees. The carbon stock follows the forest degradation gradient (zones) and the typologies of cocoa agroforests (models). Thus, Model F (agroforests in which companion plants [associated with cocoa trees] are dominated by forest species) is more diversified and more complex, stores more carbon and can be recommended in REDD + strategies to increase the level of carbon stock in Tshopo province. Model P is less diversified, has a low carbon level and is therefore not recommended. Above-ground carbon stock variation corresponds strongly to diversity (species richness) of plants associated with cocoa trees, but corresponds less to cocoa-associated plant density. In contrast to the natural forest, the largest proportion of carbon in the Bengamisa-Yangambi forest landscape was found in trees lower than 50 cm of diameter. Regarding the main use of associated plants, medicinal plants retain the most amount of carbon, while caterpillar-host plants retain only small amounts of carbon. The top five species for storing carbon are, in descending order, *Elaeis guineensis*, *Musanga cecropioides*, *Zanthoxylum gilletii*, *Trilepisium madagascariense* and *Ficus exasperata.* Thus, cocoa agroforests are great opportunities that DRC must exploit not only to increase the level of carbon stocks in degraded forest and non-forest landscapes, but also to preserve its immense biodiversity and raise the socio-economic level of rural populations.

Acknowledgements The authors would like to thank the European Union (EU) and CIFOR for funding through the Training and Research in Tshopo (FORETS: Formation, Recherche, Environment dans la Tshopo) project. We also thank the Resources & Synergies Development design office for its logistical support. We thank all cocoa farmers in the Bengamisa-Yangambi landscape for their support during the data collection period. Finally, we would like to thank all those who accompanied us in the field during this period (guides and botanical identifiers). This research was carried out to partially complete the requirements of a master's degree, but also as part of the CIFOR GCS-REDD+ project funded by the Norwegian Agency for Development Cooperation (NORAD).

Author Contributions D.S. conceptualized and supervised the study with J.-M.K. and J.E.; G.B. collected the data with the assistance of L.M. All authors have read and agreed to the published version of the manuscript.

Funding This research was funded by EU (Contrat FED/2016/381-145) and NORAD Grant agreement code No: NOR114.

Declrations

Conflicts of interest The authors declare no conflict of interest.

References

Albrecht A, Kandji ST (2003) Carbon sequestration in tropical agroforestry systems. Agric Ecosyst Environ 99:15–27. https://doi.org/10.1016/S0167-8809(03)00138-5

Alemagi D, Duguma L, Minang PA et al (2015) Intensification of cocoa agroforestry systems as a REDD+ strategy in Cameroon: hurdles, motivations, and challenges. Int J Agric Sustain 13:187–203. https://doi.org/10.1080/14735903.2014.940705

Andrade H, Segura M, Somarriba E, Villalobos M (2008) Valoración biofísica y financiera de la fijación de carbono por uso del suelo en fincas cacaoteras indígenas de Talamanca , CATIE, Turrialba, Costa Rica. Agroforestería en las Américas 46:45–50

Asigbaase M, Dawoe E, Lomax BH, Sjogersten S (2020) Biomass and carbon stocks of organic and conventional cocoa agroforests. Ghana Agric Ecosyst Environ. https://doi.org/10.1016/j.agee.2020.107192

Batsi G, Sonwa DJ, Mangaza L et al (2020) Biodiversity of the cocoa agroforests of the bengamisa-yangambi forest landscape in the democratic republic of the congo (Drc). Forests 11:1–21. https://doi.org/10.3390/f11101096

Béguin (1974) Densité de population, productivité et développement agricole. In: Doin (ed) Espace géographique, tome 3, no4, Paris, pp 267–272. https://doi.org/10.3406/spgeo.1974.1498

Besar NA, Suardi H, Phua MH et al (2020) Carbon stock and sequestration potential of an agroforestry system in Sabah, Malaysia. Forests 11:1–16. https://doi.org/10.3390/f11020210

Bisseleua H, Vidal S (2008) Plant biodiversity and vegetation structure in traditional cocoa forest gardens in southern Cameroon under different management. Biodivers Conserv 17:1821–1835. https://doi.org/10.1007/s10531-007-9276-1

Blaser WJ, Oppong J, Hart SP et al (2018) Climate-smart sustainable agriculture in low-to-intermediate shade agroforests. Nat Sustain 1:234–239. https://doi.org/10.1038/s41893-018-0062-8

Carodenuto S (2019) Governance of zero deforestation cocoa in West Africa: neEw forms of public–private interaction. Environ Policy Gov 29:55–66. https://doi.org/10.1002/eet.1841

Cerda R, Deheuvels O, Calvache D et al (2014) Contribution of cocoa agroforestry systems to family income and domestic consumption: looking toward intensification. Agrofor Syst 88:957–981. https://doi.org/10.1007/s10457-014-9691-8

Chave J, Réjou-Méchain M, Búrquez A et al (2014) Improved allometric models to estimate the aboveground biomass of tropical trees. Glob Change Biol 20:3177–3190. https://doi.org/10.1111/gcb.12629

Dawoe E, Asante W, Acheampong E, Bosu P (2016) Shade tree diversity and aboveground carbon stocks in Theobroma cacao agroforestry systems: implications for REDD+ implementation in a West African cacao landscape. Carbon Balance Manag 11:1–13. https://doi.org/10.1186/s13021-016-0061-x

Deheuvels O, Rousseau GX, Soto Quiroga G et al (2014) Biodiversity is affected by changes in management intensity of cocoa-based agroforests. Agrofor Syst 88:1081–1099. https://doi.org/10.1007/s10457-014-9710-9

Dhyani SK, Ram A, Newaj R et al (2020) Agroforestry for carbon sequestration in tropical India. In: Ghosh PK, Kumar S et al (eds) Carbon management in tropical and sub-tropical terrestrial systems. Springer Nature Singapore, Singapore, pp 313–331

Doetterl S, Kearsley E, Bauters M et al (2015) Aboveground vs. belowground carbon stocks in African tropical lowland rainforest: drivers and implications. PLoS One 10:1–14. https://doi.org/10.1371/journal.pone.0143209

Downie R (2018) Assessing the growth potential of Eastern Congo's coffee and cocoa sectors. Center for Strategic and International Studies (CSIS), Washington, DC

Frangi JL, Lugo AE (1985) Ecosystem dynamics of a subtropical floodplain forest published by: ecological society of America ecosystem dynamics of a subtropical. Ecol Monogr 55:351–369

Götz S, Harvey CA, Grégoire V (2004) Agroforestry and biodiversity conservation in tropical landscapes. In: Schroth

G, da Fonseca GAB, Harvey CA, Gascon C, Vasconcelos HL (eds) Agroforestry and biodiversity conservation in tropical landscapes. ISLAND PRE, Washington, Covelo, London, pp 227–260

Gusli S, Sumeni S, Sabodin R et al (2020) Soil organic matter, mitigation of and adaptation to climate change in cocoa-based agroforestry systems. Land 9:1–18. https://doi.org/10.3390/LAND9090323

Hosseini-Bai S, Trueman SJ, Nevenimo T et al (2019) The effects of tree spacing regime and tree species composition on mineral nutrient composition of cocoa beans and canarium nuts in 8-year-old cocoa plantations. Environ Sci Pollut Res 26:22021–22029. https://doi.org/10.1007/s11356-019-05519-x

Jadán O, Cifuentes M, Bolier T et al (2015) Influence of tree cover on diversity, carbon sequestration and productivity of cocoa systems in the Ecuadorian Amazon. Bois for Des Trop 325:35–47

Jassogne L, van Asten P, De Beule H (2014) Cocoa: driver of deforestation in the Democratic Republic of the Congo? CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), Working Paper No. 65

Kearsley E, De Haulleville T, Hufkens K et al (2013) Conventional tree height-diameter relationships significantly overestimate aboveground carbon stocks in the Central Congo Basin. Nat Commun 4:1–8. https://doi.org/10.1038/ncomms3269

Kearsley E, Verbeeck H, Hufkens K et al (2017) Functional community structure of African monodominant Gilbertiodendron dewevrei forest influenced by local environmental filtering. Ecol Evol 7:295–304. https://doi.org/10.1002/ece3.2589

Kroeger A, Bakhtary H, Haupt F, Streck C (2017) Eliminating deforestation from the cocoa supply chain. The World Bank Group, Washington, DC

Lasco RD, Delfino RJP, Espaldon MLO (2014) Agroforestry systems: Helping smallholders adapt to climate risks while mitigating climate change. Wiley Interdiscip Rev Clim Chang 5:825–833. https://doi.org/10.1002/wcc.301

Lojka B, Pawera L, Kalousová M et al (2017) Multistrata systems: potentials and challenges of cocoa-based agroforests in the humid tropics. Agroforestry. Springer, Singapore, pp 587–628

Loubota G, Fayolle A, Feldpausch TR et al (2018) Forest ecology and management what controls local-scale aboveground biomass variation in central Africa? Testing structural, composition and architectural attributes. For Ecol Manage 429:570–578. https://doi.org/10.1016/j.foreco.2018.07.056

Madountsap N, Zapfack L, Chimi C et al (2017) Biodiversity and carbon stock in the SODECAO agroforestry system of center region of cameroon: case of talba locality. Am J Agric for 5:121. https://doi.org/10.11648/j.ajaf.20170504.16

Madountsap N, Zapfack L, Chimi C et al (2018) Carbon storage potential of cacao agroforestry systems of different age and management intensity. Clim Dev 11:543–554. https://doi.org/10.1080/17565529.2018.1456895

Middendorp RS, Vanacker V, Lambin EF (2018) Impacts of shaded agroforestry management on carbon sequestration, biodiversity and farmers income in cocoa production landscapes. Landsc Ecol. https://doi.org/10.1007/s10980-018-0714-0

Minang PA, Duguma LA, Bernard F et al (2014) Prospects for agroforestry in REDD+ landscapes in Africa. Curr Opin Environ Sustain 6:78–82. https://doi.org/10.1016/j.cosust.2013.10.015

Moloba Y, Mobula V, Ntoto R, Mahungu M (2019) Dynamique socio-économique de l'adoption des variétés améliorées du manioc en république démocratique du congo (RDC): cas des provinces de kongo central et la tshopo. Eur Sci J 15:346–362. https://doi.org/10.19044/esj.2019.v15n15p346

Moonen PCJ, Verbist B, Schaepherders J et al (2016) Actor-based identification of deforestation drivers paves the road to effective REDD+ in DR Congo. Land Use Policy 58:123–132. https://doi.org/10.1016/j.landusepol.2016.07.019

Moonen PCJ, Verbist B, Boyemba F et al (2019) Disentangling how management affects biomass stock and productivity of tropical secondary forests fallows. Sci Total Environ 659:101–114. https://doi.org/10.1016/j.scitotenv.2018.12.138

Mortimer R, Saj S, David C (2017) Supporting and regulating ecosystem services in cacao agroforestry systems. Agrofor Syst 92:1639–1657. https://doi.org/10.1007/s10457-017-0113-6

Mustari K, Asrul L, Kaimuddin FL (2020) Carbon stock analysis of some cocoa planting systems in South Sulawesi. IOP Conf Ser Earth Environ Sci. https://doi.org/10.1088/1755-1315/486/1/012085

Mutuo PK, Cadisch G, Albrecht A et al (2005) Potential of agroforestry for carbon sequestration and mitigation of greenhouse gas emissions from soils in the tropics. Nutr Cycl Agroecosyst 71:43–54. https://doi.org/10.1007/s10705-004-5285-6

Obeng EA, Aguilar FX (2015) Marginal effects on biodiversity, carbon sequestration and nutrient cycling of transitions from tropical forests to cacao farming systems. Agrofor Syst 89:19–35. https://doi.org/10.1007/s10457-014-9739-9

R Core Team (2019) R: a language and environment for statistical computing. R Found. Stat. Comput., Vienna, Austria. ISBN 3-900051-07-0. http://www.R-project.org

Rajab YA, Leuschner C, Barus H et al (2016) Cacao cultivation under diverse shade tree cover allows high carbon storage and sequestration without yield losses. PLoS One 11:1–22. https://doi.org/10.1371/journal.pone.0149949

Réjou-Méchain M, Tanguy A, Piponiot C et al (2017) biomass: an r package for estimating above-ground biomass and its uncertainty in tropical forests. Methods Ecol Evol 8:1163–1167. https://doi.org/10.1111/2041-210X.12753

Rosenstock T, Wilkes A, Jallo C et al (2018a) Making trees count: measurement, reporting and verification of agroforestry under the UNFCCC. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), Working Paper No. 240

Rosenstock T, Wilkes A, Jallo C et al (2018b) Faire compter les arbres en Afrique : Une meilleure stratégie de MRV de l'agroforesterie pour satisfaire aux ambitions de l'Afrique. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). Info Note. http://CCAFS.cgiar.org/donors

Saj S, Jagoret P, Todem Ngogue H (2013) Carbon storage and density dynamics of associated trees in three contrasting Theobroma cacao agroforests of Central Cameroon. Agrofor Syst 87:1309–1320. https://doi.org/10.1007/s10457-013-9639-4

Santhyami BA, Patria MP, Abdulhadi R (2018) The comparison of aboveground C-stock between cocoa-based agroforestry system and cocoa monoculture practice in West Sumatra, Indonesia. Biodiversitas 19:472–479. https://doi.org/10.13057/biodiv/d190214

Saputra DD, Sari RR, Hairiah K et al (2020) Can cocoa agroforestry restore degraded soil structure following conversion from forest to agricultural use? Agrofor Syst 94:2261–2276. https://doi.org/10.1007/s10457-020-00548-9

Sari RR, Saputra DD, Hairiah K et al (2020) Gendered species preferences link tree diversity and carbon stocks in Cacao agroforest in Southeast Sulawesi, Indonesia. Land 9:1–15. https://doi.org/10.3390/land9040108

Schroth G, Bede LC, Paiva AO et al (2013) Contribution of agroforests to landscape carbon storage. Mitig Adapt Strateg Glob Change 20:1175–1190. https://doi.org/10.1007/s11027-013-9530-7

Somarriba E, Cerda R, Orozco L et al (2013) Carbon stocks and cocoa yields in agroforestry systems of Central America. Agric Ecosyst Environ 173:46–57. https://doi.org/10.1016/j.agee.2013.04.013

Sonwa DJ, Weise SF, Schroth G et al (2014) Plant diversity management in cocoa agroforestry systems in West and Central Africa—effects of markets and household needs. Agrofor Syst 88:1021–1034. https://doi.org/10.1007/s10457-014-9714-5

Sonwa DJ, Weise SF, Nkongmeneck BA, Tchatat M, Janssens MJJ (2017a) Profiling carbon storage/stocks of cocoa agroforests in the forest landscape of Southern Cameroon. In: Dagar J, Tewari V (eds) Agroforestry. Springer, Singapore, pp 739–752. https://doi.org/10.1007/978-981-10-7650-3_30

Sonwa DJ, Weise SF, Nkongmeneck BA et al (2017b) Structure and composition of cocoa agroforests in the humid forest zone of Southern Cameroon. Agrofor Syst 91:451–470. https://doi.org/10.1007/s10457-016-9942-y

Sonwa DJ, Weise SF, Schroth G et al (2018) Structure of cocoa farming systems in West and Central Africa: a review. Agrofor Syst 93:2009–2025. https://doi.org/10.1007/s10457-018-0306-7

Tesfaye MA, Gardi O, Bekele T, Blaser J (2019) Temporal variation of ecosystem carbon pools along altitudinal gradient and slope: The case of Chilimo dry afromontane natural forest, Central Highlands of Ethiopia. J Ecol Environ 43:1–22. https://doi.org/10.1186/s41610-019-0112-9

Thomas C, Martin A (2012) Carbon content of tree tissues: a synthesis. Forests 3:332–352. https://doi.org/10.3390/f3020332

Toppo P, Raj A (2018) Role of agroforestry in climate change mitigation. J Pharmacogn Phytochem 7:241–243

Torres B, Maza OJ, Aguirred P et al (2014) Contribution of traditional agroforestry to climate change adaptation in the Ecuadorian Amazon: the chakra system bolier. Handb Clim Change Adapt. https://doi.org/10.1007/978-3-642-40455-9_102-1

Verchot LV, Van Noordwijk M, Kandji S et al (2007) Climate change: linking adaptation and mitigation through agroforestry. Mitig Adapt Strateg Glob Chang 12:901–918. https://doi.org/10.1007/s11027-007-9105-6

Vroh Bi Tra A, Adou Yao Y, Kouame D et al (2010) Diversités floristique et structurale sur le site d'une réserve naturelle volontaire à azaguié, sud-est de la Côte d'Ivoire. Eur J Sci Res 45:311–326. https://doi.org/10.4314/acsj.v23i4.2

World Bank (2017) Forest carbon partnership facility: annual report. Washington, DC. www.forestcarbonpartnership.org

Zanne A, Lopez-Gonzalez G, Coomes D, Ilic J, Jansen S, Lewis S, Miller R, Swenson N, Wiemann M, Chave J (2009) Data from: towards a worldwide wood economics spectrum. Dryad, Dataset. https://doi.org/10.5061/dryad.234

Zapfack L, Engwald S, Sonke B et al (2002) The impact of land conversion on plant biodiversity in the forest zone of Cameroon. Biodivers Conserv 11:2047–2061. https://doi.org/10.1023/A:1020861925294

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.