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Contribution of agroforests to landscape carbon storage

Götz Schroth · Lucio C. Bede · Artur O. Paiva · Camila R. Cassano · André M. Amorim · Deborah Faria · Eduardo Mariano-Neto · Adriana M. Z. Martini · Regina H. R. Sambuichi · Renato N. Lôbo

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Abstract While many studies have measured the carbon (C) stocks of traditional agroforests at the plot level, their contribution to overall landscape C storage has rarely been quantified. Here we demonstrate the significant contribution that traditional agroforests with shaded tree crops can make to landscape C storage, and thus climate change mitigation, focusing on the

G. Schroth
C.P. 513, 68109-971 Santarém, PA, Brazil

L. C. Bede
Instituto Terra Brasilis, 31010-060 Belo Horizonte, MG, Brazil

A. O. Paiva
WWF-Brazil, 71620-430 Brasília, DF, Brazil

C. R. Cassano · A. M. Amorim · D. Faria
Department of Biological Sciences, State University of Santa Cruz, 45662-900 Ilhéus, BA, Brazil

C. R. Cassano
Institute of Socio-Environmental Studies of Southern Bahia, Av. Itabuna 93, 45650-015 Ilhéus, BA, Brazil

A. M. Amorim
Herbarium CEPEC, CEPLAC, C.P. 07, 45600-970 Itabuna, BA, Brazil

E. Mariano-Neto
Institute of Biology, Federal University of Bahia, 40170-115 Salvador, BA, Brazil

A. M. Z. Martini
Institute of Biosciences, Department of Ecology, University of São Paulo, 05508-900 São Paulo, SP, Brazil

R. H. R. Sambuichi
Institute of Applied Economic Research, 70076-900 Brasília, DF, Brazil

R. N. Lôbo
Difusão Consulting Ltd., 70340-907 Brasília, DF, Brazil

Present Address:
G. Schroth (✉)
Rainforest Alliance, 6708 LT Wageningen, Netherlands
e-mail: Goetz.schroth@gmail.com

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cocoa (*Theobroma cacao*) agroforests (locally known as cabrucas) of southern Bahia, Brazil. Using published allometric relationships and tree inventories of 55 shaded cocoa farms, 6 mature forests, 8 disturbed forests and 7 fallows, we calculate average aboveground C stocks of 87 and 46 Mg ha^{-1} in traditional and intensified cocoa agroforests, respectively, 183 Mg ha^{-1} in old-growth forests, 102 Mg ha^{-1} in disturbed forests and 33 Mg ha^{-1} in fallows. Based on the most recent land cover data available, we estimate that cocoa agroforests hold 59 % of the total aboveground C stocks of the tree dominated vegetation in this landscape, while forests hold 32 % and fallows hold 9 %. Carbon stocks of intensified cocoa agroforestry systems were only little over one-half of those of traditional agroforests, indicating a threat to landscape C stocks from current land use trends. We show that in agroforests as in natural forests, C stocks are highly concentrated in the largest trees. This suggests that the intensification of traditional agroforests, which generally involves increasing the density of cocoa and other tree crops and reducing the density of shade trees, is possible without greatly affecting their C storage if large trees are conserved. In order to conserve the climate stabilizing effect of traditional agroforests and steer necessary intensification measures towards climate-friendly solutions, we suggest that biodiversity and C-rich traditional agroforests should be included in current discussions about Reducing Emissions from Deforestation and Forest Degradation (REDD+) and/or their owners be rewarded for their environmental services through other incentive mechanisms.

Keywords Atlantic forest biome · Brazil · Climate change mitigation · Cocoa · Land use intensification · *Theobroma cacao*

1 Introduction

Financial mechanisms to reward forest countries and forest dependent communities for reducing greenhouse gas (GHG) emissions from deforestation and forest degradation are receiving attention as a potentially cost-efficient way to mitigating global climate change (Evans et al. 2013). Carbon (C)-based incentives for conserving natural forests may offer simultaneous benefits for the conservation of biodiversity and other ecosystem services provided by forests, such as watershed functions (Zepeda et al. 2010). However, while this approach offers interesting development prospects for rural communities in regions with significant remaining forest areas, such as the Amazon or Congo river basins, it risks bypassing farming communities in consolidated agricultural landscapes where most natural forest has over the centuries been replaced with traditional agroforests. In such agroforestry landscapes, ecosystem processes that are commonly associated with natural forest, such as C sequestration and biodiversity conservation, depend to a significant extent on traditional agroforestry systems (Michon and de Foresta 1999; Schroth et al. 2004). Examples for landscapes shaped to a significant extent by high-biodiversity and high-C agroforests include large parts of Central America where coffee (*Coffea arabica*) and cocoa (*Theobroma cacao*) agroforests are a traditional land use (Somarriba et al. 2004, 2013), several million hectares covered by rubber (*Hevea brasiliensis*), resin, fruit, spice and timber agroforests in Indonesia (Michon 2005), homegarden landscapes across South Asia (Kumar and Nair 2004), landscapes dominated by traditional rubber agroforests in parts of the Brazilian Amazon (Schroth et al. 2003), and also the cocoa landscape of Southern Bahia in the Atlantic forest of Brazil that is the focus of this research (Schroth et al. 2011). Because agroforestry systems especially with tree crops offer simultaneous opportunities for commodity production and climate change mitigation, C sequestration in agroforests has received considerable attention recently (Kumar and Nair 2011; Mbow et al. 2014). However, while a substantial amount of data are available on C stocks of agroforests at the plot and farm level (Montagnini and Nair 2004; Nair et al. 2010; Wade et al. 2010; Somarriba et al. 2013; Jacobi et al. 2013), few studies have attempted to quantify the contribution of agroforests to C storage for entire landscapes.

Southern Bahia, Brazil's main cocoa production area in the Atlantic forest hotspot of biodiversity, is exceptional for its biodiversity, comprising one of the areas with the highest plant diversity so far inventoried in the world (Martini et al. 2007) and harbouring numerous endemic species of fauna and flora (Tabarelli et al. 2010). Although native forest cover has been reduced to less than 10 % of the area and is highly fragmented and almost always affected by uncontrolled logging and hunting (Landau et al. 2008; Cassano et al. 2012), the biota of the region remains remarkably well conserved (Faria et al. 2007). This is most likely due to the predominant land use of the region, the traditional shaded cocoa agroforests (locally known as cabrucas) that provide a favourable matrix to the fragmented primary habitat and offer habitat in their own right to many of the region's plant and animal species (Faria et al. 2007; Cassano et al. 2009; Pardini et al. 2009; Oliveira et al. 2011; Sambuichi et al. 2012).

These agroforests, which have expanded in the region mostly since the late 19th century, making Brazil temporarily the leading cocoa producer in the world, have been formed by removing the understorey of primary or secondary forests and then planting cocoa seedlings and often other fruit trees underneath the canopy trees. Cabrucas therefore consist of an understorey of cocoa trees shaded by an often highly diverse canopy of predominantly native forest trees. Cabrucas evolved as a labour-saving way of establishing and expanding cocoa farms into the then still largely forest-covered hinterland of the coastal areas (Ruf and Schroth 2004). Although insufficient regeneration of primary forest trees in cabrucas has been observed (Rolim and Chiarello 2004), extensive surveys in the region have shown that cabrucas remain an important reservoir for many of the region's tree species (Sambuichi et al. 2012). Forest conservation laws ensure that no new cabrucas are established through forest conversion in Bahia today, therefore biodiversity conservation in the region depends to a significant extent on the fate of the existing cabrucas and the forest fragments with which they are associated in the landscape (Faria et al. 2007; Cassano et al. 2009; Schroth et al. 2011).

However, since the middle of the 20th century, these agroforests have increasingly come under pressure. In the 1960s and 1970s, the government extension service tried to introduce green revolution techniques which included for established farms the reduction of shade and for new farms the clear-felling of the forest followed by planting of exotic legume trees (*Erythrina* spp.) to shade the cocoa, with partial success (Johns 1999). Then in the late 1980s, low cocoa prices coincided with the introduction of a cocoa disease, the witches' broom fungus (*Moniliophtora perniciosa* (Stahel) Singer), from the Amazon into Southern Bahia and plunged the region into a crisis from which it has not yet recovered. Farmers initially responded to falling cocoa yields with the illegal sale of timber trees from their shade canopies, and some farms were converted into pasture, coffee or rubber (Alger and Caldas 1994). Initial recommendations to control the disease were poorly conceived, but recent attempts have been more successful. They generally involve grafting of susceptible cocoa trees with resistant clones, planting of additional cocoa trees and often other commercial species such as rubber, correction of soil fertility, and the thinning of the shade canopies (Valle 2012).

While the need to increase the profitability of the traditional cabrucas with their generally low yields and high disease vulnerability is unquestionable, the challenge is to do this in such a way that as much as possible of the C stocks, biodiversity and other ecosystem services of the cocoa landscape, including its aesthetic and cultural services to local people, are conserved. While the biodiversity of the cocoa landscape of Southern Bahia and the contribution of the cabrucas to its conservation have been relatively well documented (Faria et al. 2007; Pardini et al. 2009; Cassano et al. 2009), other ecosystem services of this traditional agroforestry landscape and the threats to which they are exposed through land use intensification and land use change have received less attention. Here we focus on climate change mitigation as one of these ecosystem services.

The objective of the present research was to quantify the contribution of cabrucas to total aboveground C stocks in tree dominated vegetation in Southern Bahia, thereby highlighting their significant role in climate change mitigation in this landscape. We also document the threat to landscape C stocks arising from the intensification of these traditional agroforestry practices and provide some evidence that this intensification could be carried out in such a way that most of the C stocks are conserved. We suggest that our findings could underpin policies to simultaneously intensify traditional land use systems while conserving their environmental services, in Bahia as in other high-biodiversity and high-C agroforestry landscapes.

2 Material and methods

2.1 Study area

The cocoa region of Southern Bahia is located within the Atlantic forest biome in northeastern Brazil. It corresponds to the Litoral Sul economic subregion in local terminology, an area of 26,200 km^2 along the Atlantic coast between Valença (70 km southwest of the state capital Salvador) in the north and Canavieiras in the south, with the Jequitinhonha river as the southern delimitation (Landau 2003; Landau et al. 2008). The north-south extension is about 280 km, and the east-west extension is about 90 km on average with the Atlantic ocean as the eastern and the drier southwestern region as the western delimitation. The original vegetation is the Southern Bahian Wet Forest (Mori et al. 1983; Thomas and Barbosa 2008), with lowland rainforest in the lowlands and montane forest above 500 m altitude. A special type of tabuleiro forest occurs in the southern part of the area (Thomas and Barbosa 2008). The mean annual temperature is 24 °C and rainfall is around 2,000 mm per year. No clear seasonality exists in the area, although a warmer period usually occurs between December and March (Mori et al. 1983). Soil conditions are highly variable in the region but are dominated by Oxisols and Ultisols, while soils of higher fertility such as Alfisols and Inceptisols are of more limited extent (Santana et al. 2010).

We used information from 76 tree inventories (55 cocoa agroforests, 6 mature forests, 8 disturbed forests and 7 fallows or young secondary forests) that were carried out in the region between 1993 and 2009. We included published data as well as unpublished information from the same studies that was provided by their respective authors (Table 1). Three types of forest sites were included: (1) mature forest that showed no signs of anthropogenic disturbance and was generally located in the interior of protected areas; (2) disturbed forest that had not been clear-cut but showed signs of anthropogenic disturbance, especially from logging; (3) fallow or young secondary forest that had developed on sites previously used for slash-and-burn agriculture of food crops and was about 10–15 years old. Cocoa farms (cabrucas) were of two types: (1) In traditional cabrucas cocoa trees were shaded by a relatively dense and structurally complex canopy of native and sometimes exotic tree species. Some of these trees had been retained when under planting thinned primary or old secondary forest with cocoa seedlings many decades earlier (the so-called cabrucagem) and some had been planted at the time of establishment or regenerated later (Schroth et al. 2011). Management of cabrucas is usually extensive and often carried out by share-croppers, and cocoa yields tend to be low, often around 250 kg ha^{-1} per year. Midlej and Santos (2012) give average cocoa yields for

Table 1 Overview of sites of vegetation inventories in southern Bahia, Brazil

Vegetation type	Location	Area	Plot number and size	Reference
Traditional cabruca	31 farms in Arataca and Una	3.1 ha	4 plots of 10×25 m per site	Cassano et al. (2013)
Traditional cabruca	8 farms near Ilhéus	1.6 ha	10 plots of 10×20 m per site	D. Faria, unpublished
Traditional cabruca	11 farms across cocoa region	5.5 ha	5 plots of 20×50 m per site	R.H.R. Sambuichi, unpublished
Traditional cabruca	1 farm near Ilhéus	3 ha	1 plot of 150×200 m	Sambuichi and Haridasan (2007)
Intensified cabruca	4 farms near Ilhéus	0.8 ha	10 plots of 10×20 m per site	D. Faria, unpublished
Mature forest	2 sites near Uruçuca and Jussari	2 ha	50 plots of 10×20 m per site	Thomas et al. (2008), Thomas et al. (2009)
Mature forest	1 site near Uruçuca	0.1 ha	10 plots of 2×50 m	Martini et al. (2007)
Mature forest	3 sites near Ilhéus, Porto Seguro and Prado[a]	0.3 ha	10 plots of 2×50 m per site	A.M. Amorim, unpublished[b]
Disturbed forest	4 sites near Ilhéus	0.8 ha	10 plots of 10×20 m	D. Faria, unpublished
Disturbed forest	1 site near Ilhéus	1 ha	50 plots of 10×20 m	A.M. Amorim, unpublished[b]
Disturbed forest	2 sites near Uruçuca	0.2 ha	10 plots of 2×50 m per site	Martini et al. (2007)
Disturbed forest	1 site near Valença	0.1 ha	10 plots of 2×50 m	A.M. Amorim, unpublished[b]
Fallow	6 sites near Una	0.48 ha	1 plot of 4×200 m per site	Faria et al. (2009)
Fallow	1 site near Uruçuca	0.1 ha	10 plots of 2×50 m	A.M.Z. Martini, unpublished[b]

[a] The latter two sites are south of the study region but correspond to forest types that also occur in the study region

[b] Inventories carried out for the preparation of management plans for various public and private protected areas

Bahia in 2010 as 285 kg ha^{-1}, but this also includes more intensively managed areas. Besides the cocoa trees that are usually old and are widely and irregularly spaced as a result of mortality and lack of replanting, bananas (*Musa* spp.) are relatively common and the shade canopies often contain planted or self-regenerated fruit trees such as jackfruit (*Artocarpus heterophyllus* Lam.) and caja (*Spondias mombin* L.). (2) Intensified cabrucas are derived from traditional cabrucas through the intensification of management with the intent of increasing yields. Intensification measures include the grafting of the old cocoa trees with clones of more disease-resistant and productive material, increasing the density of cocoa and sometimes other crops (such as banana) through planting, more systematic weed control (often using chemical herbicides), correction of soil fertility, and thinning of the shade canopy as well as sometimes the replacement of non-commercial shade trees with commercial trees such as rubber. While the dataset was assembled from separate studies and did not follow a universal sampling design, the sites were spread over numerous municipalities within the cocoa region and each study attempted to representatively characterize the land use types in its respective study area. The cabruca and fallow sites were selected randomly, sometimes using stratification criteria such as the distance from forest fragments. Forest sites were mostly located within or around protected areas and were chosen through a stratified random sampling process to representatively characterize the vegetation of the respective reserve. The dataset as a whole can therefore be considered representative of the forest and agroforest types encountered in the cocoa region of Southern Bahia.

Sampling protocols varied among sites in terms of plot number and shape, total sampled area (Table 1) and minimum diameter for inclusion of trees. However, in all plots the diameter at breast height (dbh, at 130 cm) of the tree vegetation was measured. To standardize the data, we only included trees with a dbh of 10 cm or higher, with the exception of cocoa trees that were included irrespective of size. In 11 of the 51 traditional cabruca plots, cocoa trees had not been inventoried. In these plots, we added the mean C stocks of the cocoa layer of the remaining 40 traditional cabrucas (4.6 Mg ha^{-1}) to the C stocks of the tree vegetation to obtain the total aboveground C stocks.

2.2 Estimation of aboveground C stocks

We estimated the aboveground C stocks of trees, palms and bananas with published allometric equations based on dbh. Where a specific allometric equation was found for the species or genus in question, this was used. In other cases (the majority of native tree species), a general equation was used that was chosen from a survey of 26 published equations for its high coefficient of determination (R^2) and for having been created with data from the study region (Table 2). Aboveground C stocks were obtained from aboveground biomass through multiplication by 0.5.

For calculating C storage in the aboveground biomass of the tree vegetation of the landscape, area estimates of different types of tree based vegetation (forest, fallow, cocoa agroforest) were derived from Landau et al. (2008), which is based on the analysis of satellite images of 1996–7 and is the most recent analysis available. Based on our field experience, we believe that changes in the relative areas occupied by forest, fallow and cocoa agroforests that have occurred since these images were taken are relatively minor. Especially, little conversion of mature forest to other land uses has occurred since then as an effect of increasing enforcement of environmental legislation and the remoteness and unsuitability for agricultural use of the remaining forest. However, as a consequence of several centuries of often predatory land use, most forests of the region are disturbed by logging and extraction of other forest products, even within protected areas. We estimated that 25 % of the natural forest area of the region is relatively undisturbed, mature forest and the remaining 75 % is disturbed forest

Table 2 Allometric equations used for the estimation of aboveground biomass in natural forest and cocoa (*Theobroma cacao*) agroforests in southern Bahia, Brazil

Species group for which equation was developed	Allometric equation	Reference
Native trees of Atlantic Forest in southern Brazil	$AGB=21.297-6.953*(dbh)+0.74(dbh)^2$	Tiepolo et al. (2002)
Cecropia spp. in tropical forest in Bolivia	$AGB=2.764+0.2588*(dbh)^{2.0515}$	Pearson et al. (2005)
Native palms in tropical forest	$AGB=6.6666+(12.826*(dbh^{0.5})*\ln(dbh))$	Pearson et al. (2005)
Cocoa (*Theobroma cacao*) in Costa Rica	$AGB=10^{(-1.625+2.63*LOG(D30))}$	Andrade et al. (2008)
Bananas (*Musa* spp.) in tropical forest in Java, Indonesia	$AGB=0.030*(dbh^{2.13})$	Pearson et al. (2005)
Citrus spp. in agroforestry in the Brazilian Amazon	$AGB=-6.64+0.279*BA+0.000514*BA^2$	Schroth et al. (2002)
Rubber trees (*Hevea brasiliensis*) in agroforestry in the Brazilian Amazon	$AGB=-3.84+0.528*BA+0.001*BA^2$	Schroth et al. (2002)
Cupuaçu trees (*Theobroma grandiflorum*) in agroforestry in the Brazilian Amazon	$AGB=-3.9+0.23*BA-0.0015*BA^2$	Schroth et al. (2002)
Peach palm (*Bactris gasipaes*) in agroforestry in the Brazilian Amazon	$AGB=0.97+(0.078*BA)-0.00094*(BA^2)+0.0000064*(BA^3)$	Schroth et al. (2002)

AGB aboveground biomass; *dbh* diameter at breast height (130 cm); *D30* diameter at 30 cm height; *BA* basal area affected by the extraction of large trees and presence of a larger number of pioneer species than would be expected in mature forest.

The total area of cocoa agroforests (cabrucas) was taken from Landau et al. (2008). Although some cocoa farms were converted into cattle pasture, coffee or other land uses after the introduction of the witches' broom fungus in 1989 that intensified an existing crisis of the cocoa sector, such conversions were not as common as initially feared (Alger and Caldas 1994). More commonly, farm owners sold timber trees from their farms to compensate for lost cocoa income and reduced the management intensity without converting their farms into other uses. This was also because many farms were indebted and did not have the financial means for such major investments. We estimated the area of cabruca farms that had been intensified from unpublished survey data of the government cocoa research and extension service, CEPLAC. These data indicated that by 2010, 22.6 % of the cocoa area had been grafted with improved cocoa clones. Since grafting with improved clones is usually only one component of an intensification package, as mentioned earlier, we used the percentage of grafted cocoa as a proxy for the area of intensified cabruca and assumed that the remainder (77.4 %) was traditional cabruca.

What Landau et al. (2008) call secondary forest is equivalent to what was called forest in an initial stage of regeneration in an earlier publication (Landau 2003) and refers mostly to areas in regeneration after slash-and-burn agriculture (fallows). The fallow plots in our inventories were all relatively old (about 10 to 15 years), close to the upper limit of fallow periods typical for the region. In fact, there has recently been a trend for the shortening of fallow periods (sometimes to as little as 2 years) to avoid fines for the re-conversion of more advanced fallows or secondary forests for cropping. We estimated the time-average C stocks of the fallow vegetation by dividing the C stocks of our sample plots by 2 (that is, assuming that these plots had reached their maximum aboveground C stocks within the fallow cycle, and after conversion and a short period of agriculture, would show linear accumulation of biomass and C stocks until they reached the same biomass again). Since fallows have become shorter over recent years, this method may result in a certain overestimation of average fallow biomass, but on the other hand some fallow areas may have been abandoned and grown into secondary forests.

2.3 Statistical analysis

For the five vegetation types, mean values of estimated aboveground C stocks were compared by one-way analysis of variance. Data were log-transformed to meet the assumptions of homogeneity of variance as tested by Bartlett's test and absence of correlation between means and variances. Where the effect of the vegetation type was significant at $P<0.05$ or higher, means were compared by Least Significant Difference test. For the structural variables (mean tree density, median tree diameter, mean contribution of native species), the assumptions of ANOVA were not met, therefore vegetation types were compared by Kruskall-Wallis tests.

3 Results and discussion

3.1 Structure and C storage in different vegetation types

Mature forest had the highest average density of trees of >10 cm diameter at breast height (dbh), although it was not statistically different from disturbed forest and fallow, while traditional cabruca and especially intensified cabruca had markedly lower tree densities (Table 3). In the three forest categories, almost all trees were native, while the percentage of

Table 3 Means and range of density, diameter and aboveground carbon (C) stocks in trees over 10 cm diameter at breast height (dbh, 130 cm) of cocoa (*Theobroma cacao*) agroforest (cabruca), forest and fallow vegetation in southern Bahia, Brazil

	Traditional cabruca (n=51)	Intensified cabruca (n=4)	Mature forest (n=6)	Disturbed forest (n=8)	Fallow or young secondary forest (n=7)
Mean tree density (trees ha^{-1})	197 a (70–480)	65 a (25–105)	898 b (622–1120)	840 b (570–1120)	596 b (438–862)
Percent of native trees	63 a (18–100)	54 ab (20–90)	100 bc (99–100)	99 c (93–100)	100 bc (98–100)
Median tree diameter (cm)	23 a (14–53)	38 ab (11–61)	16 ac (15–20)	16 bc (15–17)	14 c (12–15)
Carbon in trees (Mg ha^{-1})	82 a (14–182)	42 b (11–53)	183 c (98–258)	102 a (58–152)	33 b (16–69)
Percent of carbon in native trees	77 a (9–100)	37 a (2–68)	100 b (98–100)	98 b (84–100)	100 b (99–100)

Values followed by the same letters are not significantly different at P=0.05. All main effects were significant at P<0.001

native trees varied between about 20 % to 90–100 % in the cabrucas. Many of the non-native trees were legume trees (*Erythrina* spp., *Gliricidia sepium*), of which the former has been promoted as cocoa shade in the 1960s and 1970s by the government extension service, but it is fragile and has no commercial value and has therefore lost its popularity among cocoa farmers. Jackfruit (*Artocarpus heterophyllus*) and cajá (*Spondias mombin*) are introduced fruit trees that are popular with farm workers and regenerate easily and can therefore reach considerable densities in cocoa farms (Sambuichi et al. 2012).

Although the cabrucas had fewer trees than forest, these tended to be of larger average size since many smaller trees had been eliminated (Table 3, Fig. 1). Therefore, the differences in aboveground C stocks in the trees between cabrucas and forests were not as large as could have been expected from the tree densities alone. While average C stocks in the aboveground biomass of mature forest were 183 Mg ha^{-1} and those of disturbed forest were 102 Mg ha^{-1}, the corresponding values were 87 Mg ha^{-1} for traditional cabrucas and 46 Mg ha^{-1} for intensified cabrucas (Table 4, Fig. 1). Aboveground C stocks in mature forest, traditional cabruca and intensified cabruca differed significantly among each other. The latter values included 4.6 and 4.1 Mg ha^{-1} of C, respectively, in the cocoa trees. These relatively low values compared to reported aboveground C stocks in cocoa trees in Bahia of 7.6 to 15.3 Mg ha^{-1} (Gama-Rodrigues et al. 2011) reflected a low density of cocoa trees in the traditional cabrucas and the presence of many young cocoa trees in the intensified cabrucas. While the traditional cabrucas conserved on average 47 % of the aboveground C stocks of the mature forests from which they were derived, this value fell to 25 % for intensified cabrucas. Even lower average C stocks were found for the fallow vegetation (Table 4).

In all vegetation types, aboveground C stocks were highly concentrated in the largest trees. Dividing the trees of each vegetation type into 10 classes according to their diameter, in mature forest the C stocks increased almost linearly from each class to the next larger one (Fig. 1). The largest 10 % of the trees alone, with a dbh between 35 cm and 200 cm, were responsible for 61 % of the C stocks, the largest 30 % of the trees were responsible for 76 % of the C stocks,

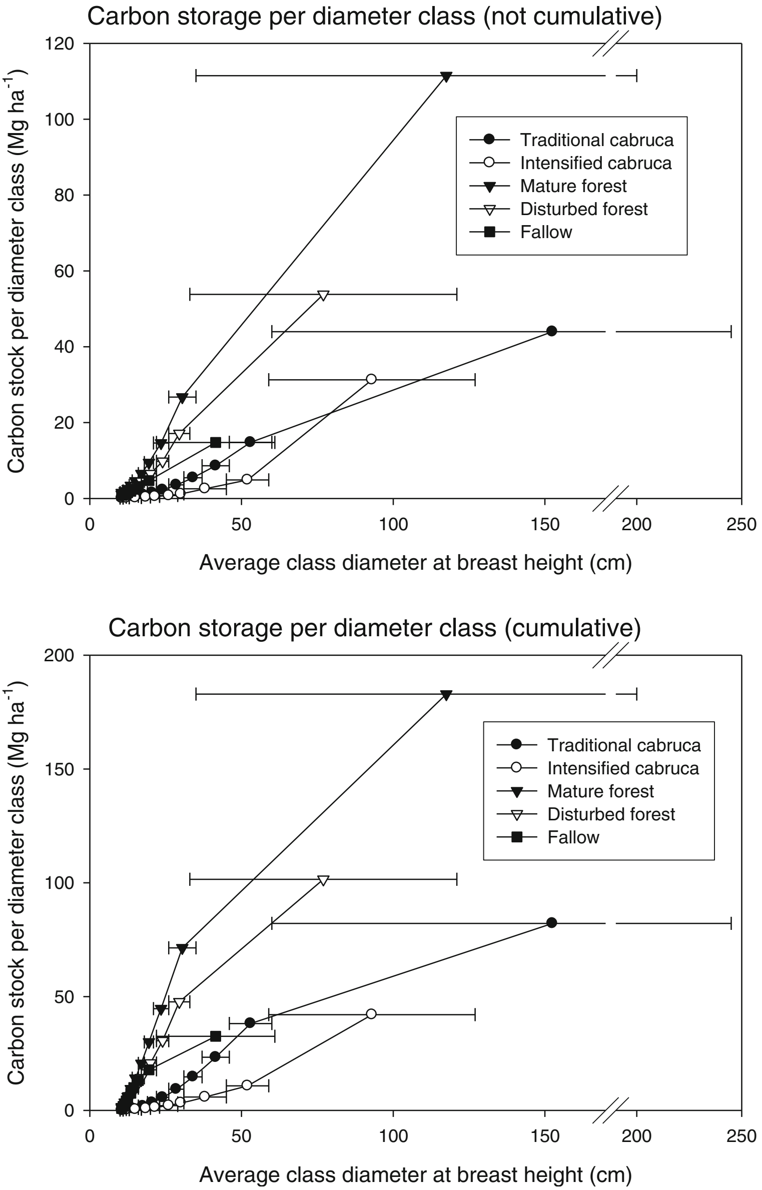

Fig. 1 Aboveground carbon (C) stocks per 10-percentile of the trees according to their diameter at breast height (dbh, 130 cm) in cocoa (*Theobroma cacao*) agroforest (cabruca), forest and fallow vegetation in southern Bahia, Brazil. *Values* are plotted on the mean of their respective diameter class, and *horizontal error bars* indicate the width of the respective diameter class. The *upper half* of the figure shows the C storage per diameter class, and the *low half* shows the cumulative C storage of the respective diameter class and all smaller diameter classes

and the smallest 50 % of the trees were responsible for a mere 8 % of the C stocks. The distribution of C stocks across diameter classes in disturbed forests was similar, except that as a consequence of selective logging the largest trees were missing (Fig. 1). In fact, these disturbed forests were generally very similar to mature forests in their appearance, except that they had

Table 4 Means and range of aboveground carbon (C) stocks in trees over 10 cm diameter at breast height (dbh) and cocoa (*Theobroma cacao*) trees in agroforest (cabruca), forest and fallow vegetation in southern Bahia, Brazil

	Traditional cabruca (n=51)	Intensified cabruca (n=4)	Mature forest (n=6)	Disturbed forest (n=8)	Fallow or young secondary forest (n=7)
Plot-level C storage[1] (Mg ha^{-1})	87[1] a (17–182)	46[2] b (15–56)	183 c (98–258)	102 a (58–152)	33 b (16–69)
Area (ha)[3]	522,787 (37 %)	152,649 (11 %)	58,164 (4 %)	174,492 (12 %)	498,324 (35 %)
Landscape C storage (Tg)	45.3 (51 %)	7.0 (8 %)	10.6 (12 %)	17.7 (20 %)	8.1[4] (9 %)

Values followed by the same letters are not significantly different at P=0.05. The main effect was significant at P <0.001

[1] Including 4.6 Mg ha^{-1} of C in cocoa trees

[2] Including 4.0 Mg ha^{-1} of C in cocoa trees

[3] Data recalculated after Landau et al. (2008)

[4] Assuming that the time-average of the C stock is half the maximum C stock

more open canopies as a result of logging. Since in mature forest the largest trees contained such a major share of the total C stocks, the aboveground C stocks of disturbed forests were only 55 % of those of mature forests (Table 3).

Traditional cabrucas also showed an almost linear increase of C stocks across diameter classes of trees, with the largest 10 % of trees responsible for 54 % of the aboveground C stocks, the largest 30 % responsible for 72 % of aboveground C stocks, and the smallest 50 % of trees responsible for 7 % of the aboveground C stocks (Fig. 1). This was very similar to the C distribution across classes in mature forest. Also, the largest trees were of approximately the same average size as in mature forest. However, each diameter class contained on average only 45 % of the C of the corresponding diameter class in mature forest, as a result of the thinning of the forest that was involved in the establishment of the cabrucas and their subsequent management. This management may in many cases have involved some (illegal) selective logging of large trees, occasional removal of medium-sized trees where these had grown too dense, as well as weeding of the understorey reducing natural tree regeneration (Rolim and Chiarello 2004; Sambuichi et al. 2012). However, contrary to expectation, the cabrucas were not stands of large remnant trees with the smaller trees removed and replaced with cocoa trees, but rather a type of shrunk forest where all diameter classes had fairly uniformly been reduced to a little less than half their original biomass.

Comparing the intensified cabrucas with the traditional cabrucas, two changes are apparent. The first is that the aboveground C stocks in the smaller nine diameter classes in the intensified cabrucas were on average only 26 % of those in the traditional cabrucas. The second is that the largest diameter class in the intensified cabrucas consisted of much smaller trees than in the traditional cabrucas (Fig. 1). Clearly, the intensification of these cabrucas had involved not just the clearing of smaller trees to increase space for replanting and the light environment for the cocoa trees, but also the removal of large trees, resulting in a reduction by almost half of the aboveground C stocks compared to the traditional cabrucas.

Finally, the fallows consisted of only small trees owing to their relatively young age (10–15 years) and therefore had the lowest aboveground C stocks of all tree-based vegetation types in this landscape (Fig. 1).

3.2 Contribution of vegetation types to landscape C stocks

According to Landau et al. (2008), of the 26,200 km^2 of the Litoral Sul economic region that broadly corresponds to the cocoa region of Southern Bahia, 14,064 km^2 (53.7 %) were covered by various types of tree vegetation (including cabrucas and fallows). The remainder were mostly pasture and agricultural fields (10,333 km^2 or 39.4 %) as well as smaller areas of water, coastal vegetation and urban areas (together 1,803 km^2 or 6.9 %) with little or no aboveground biomass. Of the total area covered by tree vegetation, 16.5 % were mature and disturbed forest, 48.1 % were cocoa and 35.4 % were fallow (Table 4). Considering their respective per-hectare C stocks, we estimate that the total aboveground C stocks in the tree vegetation of the region was 89 Tg, or 63 Mg ha^{-1}. Of this, 28 Tg of C (32 %) were contained in mature and disturbed forest vegetation, 8 Tg of C (9 %) in fallow vegetation, and 52 Tg of C (59 %) in cocoa agroforests (Table 4). Although traditional cabrucas covered only 37 % of the area with tree vegetation, they contributed 51 % to total aboveground C stocks. Intensified cabrucas, on the other hand, covered 11 % of the area and contributed 8 % of the aboveground C stocks (Table 4).

3.3 Effect of intensification on C storage in agroforests

The intensified cabrucas had on average only one-third the tree density of traditional cabrucas (Table 3), and their aboveground C stocks were little more than one-half of those of the traditional cabrucas (46 vs. 87 Mg ha^{-1}, Table 4). The higher density of cocoa trees in the intensified cabrucas (1,164 cocoa trees ha^{-1}) compared to the traditional cabrucas (771 cocoa trees ha^{-1}) did little to compensate for the lower C stocks in the shade canopy of the intensified systems (42 vs. 82 Mg ha^{-1}, Table 3). If all traditional cocoa farms in the region were intensified in the same way as our sample plots, total aboveground C stocks in the tree vegetation of the region would fall from 89 Tg to 68 Tg, that is by 24 %. This would release 21 Tg of C from aboveground biomass, equivalent to the 75 % of the C contained in all (mature and disturbed) natural forests of the region.

With average current cocoa yields in southern Bahia of 285 kg ha^{-1} (Midlej and Santos 2012), less than in major producing countries in Africa, there is clearly a need for intensification if cocoa agroforestry is to persist in the region. However, we suggest that ways need to be found for this intensification process to take place while maintaining a maximum of the C stocks, biodiversity and other ecosystem services of these traditional systems. These services include the cultural and aesthetic value of cocoa agroforests in a region with high tourism value.

Our data suggest that there are possible pathways for biodiversity- and carbon-friendly intensification. The main principle should be the conservation of large trees when thinning the shade canopies of overgrown cocoa farms to make space for more cocoa and other commercial trees and improve their light environment, as is often done when intensifying cabruca farms. Traditional cabrucas are similar to natural forest in the sense that a disproportional part of the total C stocks in the biomass is contained in the largest trees (Fig. 1). Even when considering only trees with a dbh above 10 cm, the smallest 50 % of the trees in an average cabruca contained less than 10 % of the total C storage in the vegetation and could therefore be thinned out with little loss of total C stocks. Trees of large diameter are usually also tall and compete less with the cocoa trees for light than do smaller trees, including because their high canopies are more permeable to lateral light. The decrease of aboveground C stocks by almost one-half in intensified cabrucas compared to traditional cabrucas was mostly due to the loss of the largest trees, while the thinning out of smaller trees to the number necessary to ensure the eventual replacement of the large trees could have been done with little detriment to C stocks (Fig. 1). Large trees do not only contain a disproportional percentage of total C stocks, but are also of particular importance for the conservation of biodiversity in these traditional agroforestry landscapes. For example, large trees provide structural heterogeneity to the system, which is an important predictor of their habitat value (Tews et al. 2004). They also often offer specific resources for other species, such as cavities, nesting sites, and support for epiphytes that provide food and habitat for fauna species (Cassano et al. 2009; Oliveira et al. 2011). Large individuals of climax and late secondary species are also particularly important as seed sources for surrounding cabruca and forest areas (Boshier 2004).

However, cocoa farmers intent on increasing the profitability of their farms will only have an interest in conserving large trees if they see a direct benefit from them. There is now a discussion about permitting the extraction of timber from cocoa farms under a sustainable management plan, which currently is not permitted in the Atlantic forest biome of Brazil. While the management of cabrucas for timber is not necessarily incompatible with the conservation of high C stocks, technical and economic studies of the feasibility and profitability of such operations are needed, and the details of such management plans would determine their impacts on system C stocks.

An alternative (or additional) pathway would be to include traditional cabruca farms in environmental service reward schemes to provide incentives to cocoa farmers for maintaining high C stocks in their farms. This could involve the definition of a baseline value for the C stocks of a cocoa farm under best management practices (perhaps equivalent to a reasonably intensified cabruca system) and a reward for long-term C storage above this baseline. Certifiers such as the Rainforest Alliance (www.ra.org) are also working on ways to certify the climate-friendliness of land use systems, in the expectation that this may facilitate access to special markets and premiums. Besides government, chocolate companies, cocoa grinders and other actors of the cocoa value chain with an interest in reducing their corporate environmental footprints and concerns about the economic and environmental sustainability of their suppliers and sourcing regions could be among potential investors in such incentive programs.

4 Conclusions

We show that in established agricultural landscapes such as the cocoa region of southern Bahia in the Atlantic forest biome, traditional agroforestry systems can make a fundamental contribution not only to the conservation of biodiversity, but also to the conservation of landscape C stocks. In the case discussed here, the aboveground C stocks in traditional agroforests exceeded those of natural forest in the landscape by a considerable margin. Under such conditions, focusing REDD+ incentives on natural forest alone will not be efficient either in terms of safeguarding landscape C stocks nor biodiversity. The intensification of traditional cabrucas through yield increases and product diversification is unavoidable if these land use systems are to persist over the long term. However, this intensification process should consider the environmental services provided by these traditional agroforests, including C storage and biodiversity. Opportunities for this exist since, contrary to common belief, cabruca agroforests are not merely composed of large remnant trees shading an understorey of cocoa trees, but are in fact shrunk forests with a C distribution across diameter classes similar to that of mature forest. As long as the largest trees are conserved, there is considerable flexibility to reduce the overall tree density in these agroforests to create space and improve the light environment for the tree crops, with little effect on total C stocks. This strategy would also benefit biodiversity conservation compared to current intensification methods. In order to create direct financial incentives for such a green intensification strategy, we suggest that traditional agroforests should be included in REDD+discussions and related incentives programs.

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