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Carbon stock in the development of different designs of biodiverse agroforestry systems

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biodiverse system

ABSTRACT
The objective of this study was to estimate the carbon stock in the different designs of biodiverse agroforestry systems (AFSs) in the region of the Environmental Protection Area (EPA) of Pratigi, Bahia, Brazil. Phytosociology aspects related to the potentiality of carbon stock of 10 farms were evaluated using plots of 10 x 50 m allocated in each AFS, inventorying 928 individuals of 17 families and 37 species, established in 2013. The biomass above and below the soil of the arboreal individuals were estimated by indirect method, using specific allometric equations for each species or group of species, with diameter above 1 cm. Carbon stock (CS) was estimated from the biomass. Cacao (*Theobroma cacao*) and rubber tree (*Hevea brasiliensis*) were the dominant species in all of the designs, which also contained fruit trees, and native and exotic shade trees. There was variation of the estimate of carbon stock (8.01-1.42 Mg ha^{-1}) between the types of AFSs. The designs with a larger relative density of fruit and shade trees led to larger carbon storage, influenced by the wealth and diversity of species in the initial phase of establishment of biodiverse AFSs.

Palavras-chave:
agrofloresta
Theobroma cacao
Hevea brasiliensis
sistema biodiverso

Estoque de carbono no desenvolvimento de diferentes desenhos de sistemas agroflorestais biodiversos

RESUMO
Objetivou-se, neste estudo, estimar o estoque de carbono nos diferentes desenhos de sistemas agroflorestais (SAFs) biodiversos na região da Área de Proteção Ambiental (APA) do Pratigi, Bahia. Foram avaliados aspectos da fitossociologia relacionados a potencialidade de estoque de carbono de 10 propriedades, utilizando parcelas de 10 x 50 m alocadas em cada um dos SAFs, sendo inventariados 928 indivíduos de 17 famílias e 37 espécies, implantados em 2013. A biomassa acima e abaixo do solo, dos indivíduos arbóreos foi estimada pelo método indireto, utilizando equações alométricas específicas para cada espécie ou grupo de espécies, com diâmetro acima de 1 cm. Estimou-se a partir da biomassa o estoque de carbono (EC). O cacau (*Theobroma cacao*) e a seringueira (*Hevea brasiliensis*) foram as espécies dominantes em todos os desenhos, sendo constituídos também por frutíferas, árvores de sombra nativas e exóticas. Houve variação da estimativa de estoque de carbono (8,01-1,42 Mg ha^{-1}) dentre os tipos de SAFs. Os desenhos com uma maior densidade relativa de frutíferas e árvores de sombra proporcionaram um maior armazenamento de carbono, influenciados pela riqueza e diversidade de espécies na fase inicial de implantação de SAFs biodiversos.

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Introduction

Changes in climate regimes affect food security and food production, with direct and indirect effects on agricultural activity, and agroforestry systems are recognized as an alternative to mitigate such impacts (Kirsch & Schneider, 2016). The possibility of food cultivation in agroforestry refers to several types of environmental services, with great current relevance to those related to carbon sequestration and fixation, aligning the needs of adaptation and mitigation of climate change (Somarriba et al., 2013).

The management of agroforestry systems has high potential for carbon sequestration due to multi-layered architecture, with shrub and tree species that occupy different niches in vertical and horizontal directions (Canuto et al., 2014). However, there is a variation in the amount of carbon stock, related to the design and tree species that make up the system (Brianezi et al., 2013).

In spite of the verification of the real socio-economic and environmental benefits resulting from the adoption of biodiverse AFSs by farmers, the knowledge base on this subject in the region of the Environmental Protection Area (EPA) of Pratigi needs to consolidate this form of cultivation. The conservation value of AFSs can be influenced by the intensification of management practices, such as species design and selection, and agroecological management (Armengot et al., 2016).

From the composition and density of the species, an AFS design can be established with a balance between environmental conditions favorable to cacao yield and maintenance of environmental services (Deheuvels et al., 2014).

In this context, this study was conducted with the purpose of establishing the relationship between the species in different designs of biodiverse AFSs and carbon stock, in their initial phase of development.

Material and Methods

The study was carried out in a microregion in the environmental protection area of Pratigi (EPAof Pratigi, 39º 07’ W, 39º 13’ W and 13º 30’ S, 13º 52’ S), inserted in the ombrophilous forest (perennial-rainforest) biome called Mata Atlântica (Atlantic forest), municipalities of Piraí do Norte and Ibirapitanga, Bahia, Brazil (Figure 1).

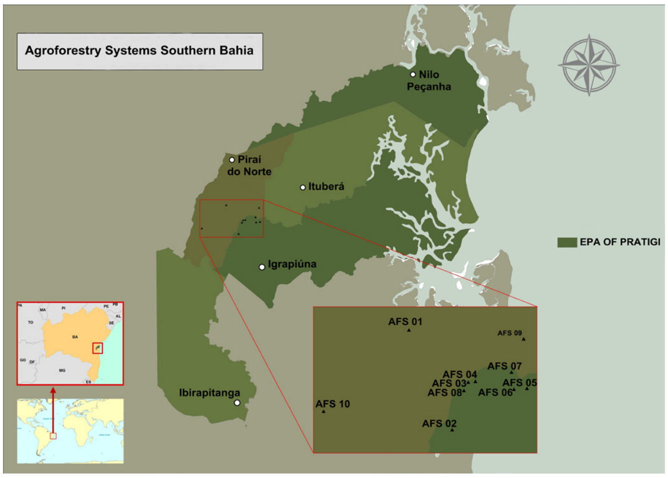

Figure 1. Location of the environmental protection area of Pratigi, Bahia, Brazil

This region is characterized by considerable rainfall, with vegetation in areas of primary and secondary forests. The predominant climate in the region is Tropical rainforest (Af) and Tropical monsoon (Am), according to the classification of Köppen. The precipitation is higher than 60 mm for the driest month and the total annual mean is above 1600 mm, with mean temperature of 24 ºC and relative air humidity around 80% (CRA, 2000). Soil classification indicates a predominance of abrupt (or not) yellowish Argisol, sandy/clayey texture, undulating or strongly undulating phase + Haplic Cambisol Typical Tb, clayey medium texture, strong undulating relief phase, both Moderate Dystrophic A (CRA, 2000).

The plots were established in ten small farms of family farmers, where each one has one hectare of biodiverse AFS, aged four years, established in an abandoned pasture area, with the purpose of recovering unproductive areas, and the designs of these systems were defined in a participatory manner between Technical Assistance and Rural Extension professionals and farmers. Therefore, 10 rectangular plots of 10 x 50 m (500 m^2) were leased, one in each farm.

AFS designs were characterized by dominant species (cacao and rubber trees) and groups of arboreal species according to their function in the system. The functions were differentiated in species of commercial use (fruit trees), characterized by the commercialization of the fruits, and native and exotic species (shade trees). All trees present in the plot were identified by popular names, with the help of farmers. These data were used to determine the absolute density, relative density of cacao trees, rubber trees, shade trees, wealth, Shannon-Weaver diversity index (H'). This index expresses wealth and uniformity and in its calculation considers as equal rare and abundant species, and generally this index is usually between 1.5 and 3.5 (Magurran, 1989).

The evaluation of the amount of biomass was carried out using the indirect method. In this method, biomass can be inferred through plot-level measurement of structural variables, using allometric equations specific to each species or group of species, considering the local situation (climate, ecosystem, and species) from measurements of diameter and height of the trees (Table 1) (Pearson et al., 2005).

For native trees and rubber trees, individuals with diameter equal to or greater than 1.27 cm, measured with bark, at a height of 1.3 m (DBH, diameter at breast height) were used. For cacao and fruit trees the diameter determination was performed at 30 cm from the soil, maintaining the bark, in individuals with diameter equal to or greater than 1 cm. For palm trees occurring in clumps, such as açaí and cacao, each stipe represented an individual (Pearson et al., 2005).

After determination of the biomass above the soil, the biomass under the soil was calculated, through the root-shoot ratio. For this, the above-ground biomass was multiplied by the factor 0.22 according to the Protocol of measurement and estimation of biomass and forest carbon of EMBRAPA (Higa et al., 2014) based on studies conducted by Mokany et al. (2006).

Table 1. Allometric equations used to estimate the total aerial biomass of the tree components of different species in the studied models

Species or group of species	Equation	Interval of DBH (cm)	Author (s)
Native species	$Y = 21.297 - 6.953 * DBH + 0.74 * (DBH^2)$	> 4	Tiepolo et al. (2002)
Native species	$Y = -2.292 + 0.369 * (DBH) + 0.087 * H$	1.27-4	Saldarriaga et al. (1988)
Cacao	$Y = 10^{(-1.625 + 2.63 * LOG (D30))}$	1.3-26.8	Andrade et al. (2008)
Palm trees	$Y = \exp(-6.3789 + 0.877 \ln(1/(DBH)2) + 2.151 \ln(H))$		Saldarriaga et al. (1988)
Fruit trees	$Y = 10^{(-1.11 + 2.64 * LOG(D30))}$	1.9-46.5	Andrade et al. (2008)
Peach palm	$Y = 0.97 + 0.07 * BA - 0.949 \times 10^{-3} * BA^2 + 0.65 \times 10^{-5} * BA^3$	2-12	Schroth et al. (2002)
Shade Rubber trees	$Y = \exp(-0.834 + 2.223 (\log10D30))$	Up to 44	Segura et al. (2006)

Y - Dry biomass above ground (kg); DBH - Diameter at breast height (1.3 m) in cm; H - Height; D30 - Diameter at 30 from soil surface; BA - Basal area; BA - $\pi \times (DBH/2)^2$

For the calculation of the total dry biomass (DB) of the plot, the sum of the biomass above and below the soil was used. After determination of the DB of each individual, the biomass per plot was calculated, the result being expressed in Mg ha^{-1}. Carbon stock (CS) estimation was performed by multiplying by the DB factor of 0.485, because DB contains approximately 48.5% of carbon (Montagnini & Nair, 2004).

Data were tabulated and analyzed using ASSISTAT software, version 7.7, SAEG, version 9.1 and Microsoft Excel 2010. To verify the association between the variables, the Pearson linear correlation analysis was carried out. The methodology of dissimilarity grouping, Tocher's method, presented in Cruz & Carneiro (2006) was used. For this grouping, the carbon stock and the diversity index of Shannon-Weaver were considered, since they were the most important characteristics for this study.

Results and Discussion

In the 10 AFSs, 928 arboreal individuals belonging to 17 families and 37 species were analyzed (Table 2). The floristic classification indicates that the five most representative families were: Fabaceae (eight species), Anacardiaceae (four species),

Table 2. Tree composition of the ten plots of the biodiverse AFSs in Pratigi EPA, Bahia, Brazil

Family	Scientific name	Popular name	Total	Plot (AFS)	Species group
Anacardiaceae	*Schinus terebinthifolius*	Aroeira	4	8-9	NST
Anacardiaceae	*Mangifera indica*	Manga	2	2-3	F
Anacardiaceae	*Tapiriramar chandii*	Pau Pombo	1	9	NST
Anacardiaceae	*Rapanea guyanensis*	Pororoca	1	8	NST
Annonaceae	*Rollinia deliciosa*	Biriba	1	5	NST
Annonaceae	*Annona muricata*	Graviola	4	1-2	F
Bignoniaceae	*Tabebuia ochracea*	Ipê	2	8	NST
Bixaceae	*Bixa orellana*	Urucum	11	2-6	F
Caricaceae	*Carica papaya*	Mamão	19	5-6-7-8	F
Euphorbiaceae	*Hevea brasiliensis*	Seringueira	96	All	D
Fabaceae	*Anadenanthera colubrina*	Angico	1	2	NST
Fabaceae	*Gliricidia sepium*	Gliricídia	42	2-3-4-5-6-7-8-10	EST
Fabaceae	*Inga edulis*	Ingá	14	6-7-8	NST
Fabaceae	*Inga marginata*	Ingá Periquito	7	6-10	NST
Fabaceae	*Albizzia angolensis*	Muanza	6	8	NST
Fabaceae	*Paubrasilia echinata*	Pau Brasil	3	8	NST
Fabaceae	*Centrolobium robustum*	Putumujú	4	8	NST
Fabaceae	*Caesalpinia pluviosa*	Sibipiruna	1	10	NST
Lamiaceae	*Aegiphila sellowiana*	Fidalgo	1	8	NST
Lauraceae	*Persea americana*	Abacate	3	5-6	F
Lauraceae	*Laurus nobilis*	Louro	2	8	NST
Lecythidaceae	*Cariniana legalis*	Jequitibá	7	6-7-10	NST
Malvaceae	*Theobroma cacao*	Cacau	581	All	D
Malvaceae	*Spondias mombin*	Cajá	4	4-5-10	F
Malvaceae	*Theobroma grandiflorum*	Cupuaçu	50	2-3-4-5-6-7-8-9	F
Malvaceae	*Heliocarpus popayanensis*	Pau jangada	1	6	NST
Meliaceae	*Swietenia macrophylla*	Mogno	3	8	EST
Myrtaceae	*Psidium guineense*	Araçá	1	8	NST
Myrtaceae	*Syzygium aromaticum*	Cravo	1	2	F
Myrtaceae	*Psidium guajava*	Goiaba	3	1-7	F
Myrtaceae	*Syzygiumaqueum*	Jambo Branco	1	2	NST
Palm trees	*Euterpe oleracea*	Açaí	12	7-8-9	F
Palm trees	*Cocos nucifera*	Côco	1	2	F
Palm trees	*Bactris gasipaes*	Pupunha	25	5	F
Rubiaceae	*Genipa americana*	Jenipapo	3	2-10	F
Rutaceae	*Citrus limon*	Limão	1	10	F
Sapotaceae	*Manilkara huberi*	Maçaranduba	7	7-9-10	NST
Verbenaceae	*Cytharexylum myrianthum*	Pau viola	2	2-5	NST
17 Families	37 Species		928 Individuals		

NST - Native Shade Trees; EST - Exotic Shade Trees; F - Fruit Trees; D - Dominant

Malvaceae (four species) and Myrtaceae (four species), constituting 40.12% of the total species listed.

For the designs of AFSs regarding their tree composition when related to the profile of the farmer (Table 2), it was observed that their design is linked to yield. Farmers who have retirement or other incomes outside the AFS make an option for lower concentration of cacao and larger concentration of native species, in contrast to those who have AFS as one of the main incomes.

In the Soubre region, located in the Republic of Côte d'Ivore, it was verified the preference of small farmers less financially benefited and those isolated from the larger centers for the introduction of tree species whose products had high demand in the local community (Gyau et al., 2015). The possibility of producing crops with high value in large markets was not an important factor in the choice of species composition of AFSs by these farmers.

This result was reported by other authors such as Tsuchiya & Hiraoka (1999) for whom the farmer's profile defined the dominant crop and the number of shade species as a function of common agricultural practices in the region. For Donato & Lima (2014) the designs were influenced by economic characteristics, popular knowledge, ecological knowledge about the species and regional climatic conditions of the Ribeira Valley, in the state of São Paulo.

In the AFSs of this study, the designs led to differences in the carbon stock, varying from 1.42 to 8.01 t ha^{-1} (Figure 2A), reflex of the different densities and species diversity that compose them. Similar data were found by Torres et al. (2014) in which the different designs studied in biodiverse AFSs varied the carbon content according to the established arrangement and the age of the system.

In all ten plots of AFSs, land use patterns were identified with individuals at different stages of vegetative development, however, there was difference between structural and floristic information, and carbon content estimates. The designs were classified by dissimilarity into three groups, from the potential of the quantified carbon stock and Shannon-Weaver diversity index (Table 3, Figure 2A). CS conditioned the largest contribution to the proposed grouping in relation to the Shannon-Weaver diversity index.

When the relative density of the main components of the AFSs is observed, it is verified that the increase of the relative density of shade trees and fruit trees and the reduction of the relative density of cacao trees are associated with the greater capacity of carbon stock (Figure 2B). The wealth and diversity of species evaluated from the Shannon-Weaver diversity index (H') also have a great relation with the carbon stock potential of the AFSs under study (Figures 2C and D). This fact was previously corroborated by Noiha et al. (2015).

Table 3. Grouping based on measures of similarity between attributes, according to their characteristics (variables), relating the items in groups, from the Tocher's method, considering the Euclidean distances

Group	Number	Belonging individuals
1	4	2, 5, 4, 10, 7
2	3	1, 9, 3
3	2	2, 9

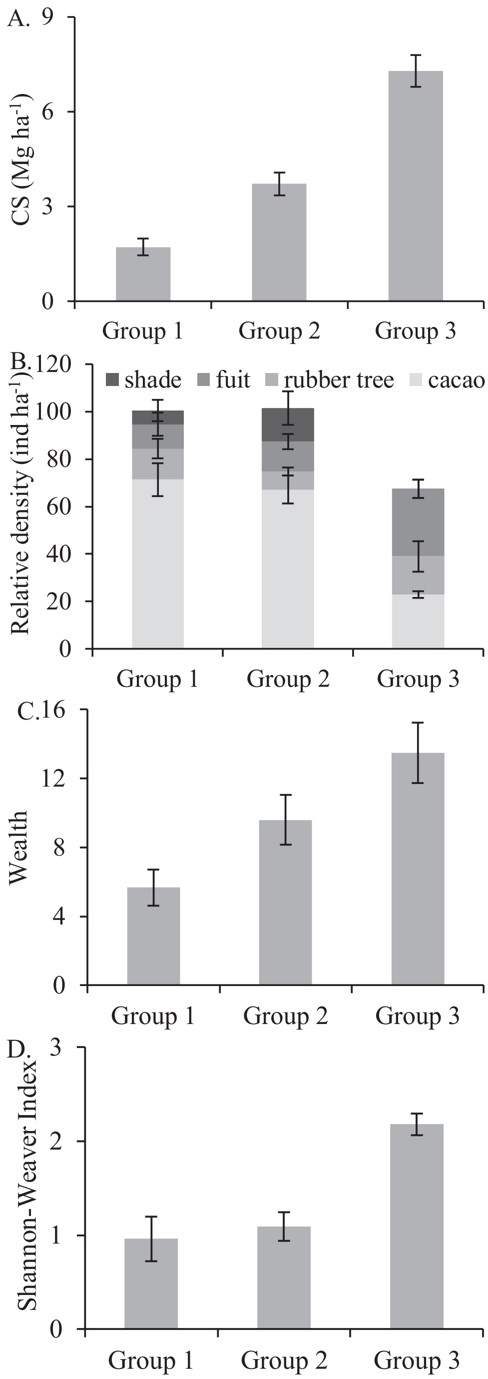

Figure 2. (A) Carbon stock - CS (Mg ha^{-1}); (B) relative density of cacao trees, rubber trees, shade trees, and fruit trees; (C) wealth; (D) Shannon-Weaver diversity index (H') (D) evaluated in agroforestry systems located in Pratigi EPA, Bahia, Brazil

The AFSs of Group 3 had higher estimates of carbon stock, in relation to the other groups (Figure 2A). This result was attributed to its composition, prioritizing the native tree component (Figure 2C). In a study conducted by Kurzatkowskiet al. (2007), similar results were obtained, in which the design of arboreal composition with the occurrence of large trees planted in suitable spacing for each species allows the rapid growth, reflecting the total biomass and carbon stock.

Wealth, diversity (H'), and relative density of fruit trees maintained positive correlation with the carbon stock potential of the systems (Table 4). Because these were AFSs

Table 4. Pearson's linear correlation matrix between the variables used in the quantification of AFS carbon in Pratigi EPA, Bahia Brazil

	Wealth	H'	AD	FTD	STD	CTD	RTD
CS	0.7836**	0.7319*	0.2526	0.6862*	0.5920	-0.7096*	0.0980
Wealth	-	0.7715*	0.2156	0.7290*	0.6877*	-0.7046*	-0.2641
H'	-	-	-0.2784	0.8324**	0.8920**	-0.9748**	0.0151
AD	-	-	-	0.0497	-0.4429	0.3607	-0.1452
FTD	-	-	-	-	-0.2348	-0.8383**	-0.0395
STD	-	-	-	-	-	-0.8637**	-0.2348
CTD	-	-	-	-	-	-	-0.1764

CS - Carbon Stock; Wealth - Wealth; H' - Shannon-Weaver index; FTD - Fruit tree relative density, STD - Shade trees relative density, CTD - Cacao trees relative density, RTD - Rubber trees relative density, AD - Absolute density. ** Significant at 0.01 probability level ($p < 0.01$); * Significant at 0.05 probability level ($0.01 \leq p < 0.05$); NS - Not significant ($p \geq 0.05$); t-test at levels of 0.05 and 0.01

with four years of establishment, the carbon sequestration potential of shade trees had less expression in relation to fruit trees. The initial vigorous growth of fruit trees was a factor associated with this response, similar to that verified by Silatsa et al. (2017).

The relative density of cacao trees maintained negative correlation with the carbon stock, wealth, H', relative density of fruit trees, and shade trees (Table 4). The increase in the relative density of cacao trees, considered as crop intensification, is observed in many areas of AFSs of cacao trees, being a restriction factor for the insertion of shade trees and fruit trees, reducing the carbon content of the system (Magne et al., 2014; Vaast & Somarriba, 2014).

Decision-making in the establishment of a biodiverse AFS, even taking into account the objectives of each farmer and the local potentialities, tends to form agroecosystems with good multiplicity of use, generating sustainable model of agriculture and at the same time a supplier of environmental services, making these strategic systems to mitigate greenhouse gas (GHG) emissions.

Conclusions

1. The intensification of cacao plantations results in restriction of carbon stock capacity in the initial phase of establishment of biodiverse AFSs.

2. The designs with higher relative density of fruit trees and shade trees led to greater carbon storage in the initial phase of establishment of biodiverse AFSs.

3. The wealth, diversity of species, are directly related to the greater carbon sequestration potential of cocoa AFSs.

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