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# Soil Classification and Carbon Storage in Cacao Agroforestry Farming Systems of Bahia, Brazil

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*Information concerning the classification of soils and their properties under cacao agroforestry systems of the Atlantic rain forest biome region in the Southeast of Bahia, Brazil is largely unknown. Soil and climatic conditions in this region are favorable for high soil carbon storage. This study is aimed to classify soils under cacao agroforestry and further, to quantify carbon stocks in these soil profiles. Soil classification was performed, and the amount of C stored was estimated, based on the thickness of the soil horizons, their bulk density, and total organic carbon stored. In the sites studied under cacao, four general classes of soils were identified: Ultisols, Oxisols, Alfisols, and Inceptisols. Carbon stocks in these soil profiles showed wide variation, ranging from 719.24 to 2089.93 Mg ha$^{-1}$. Carbon stocks in soil surface and subsurface layers in different agroforestry systems with cacao (cacao cabruca, cacao × rubber tree, and cacao × erythrina) were comparable; however, total storage of organic C in these soils was higher than expected, compared to values reported for the International Soil Reference and Information Center (ISRIC), based on the FAO-UNESCO database, and were also higher than estimated regional soil data.*

*KEYWORDS* *soil management, soil organic carbon,* Theobroma cacao *L., cacao cabruca, shade cropping, pedology*

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## INTRODUCTION

In the last 260 yr, the South of Bahia has been characterized as the main cacao (*Theobroma cacao* L.) producing region of Brazil (Lobão, Setenta, Lobão, Curvelo, & Valle, 2007), and a unique place for rich natural resources, including the diversity of soils (Santana et al., 2002; Santana, Faria Filho, & Lisboa, 2010). The special hydrogeological conditions in a humid tropical climate located between 41° 30' W and 13° to 18° 15' S of the Atlantic Ocean, make this region favorable for sustainable cacao production and a link with the conservation of the central corridor of the Atlantic Forest (Lobão, 2007).

Atlantic Forest biome climatic conditions and soil fertility are very favorable for cacao farming, and this led to development and establishment of economic standards in rural and urban areas and further helped to establish the particular style of farming in rural areas (Santana et al., 2002; Chepote et al., 2012; Campos, 1981). Cacao farmers have faced many challenges due to the crisis created by the occurrence of witches-broom disease caused by the fungus *Moniliophthora perniciosa.* This disease has spread in the region causing serious losses to cacao production since 1989 (Oliveira & Luz, 2005). Socioeconomic issues of cocoa production should be discussed under the context of anticipated global climatic changes and the responsibility that agriculture has to develop more sustainable patterns of farming systems including rational use of soil and water for food and human health (Baiardi & Rocha, 1998; Aboim et al., 2010; Food and Agriculture Organization of the United Nations [FAO], 2009; Melo Filho, Souza, & Souza, 2007).

In the last decade, publications have characterized agricultural landscapes in different situations of conservation management to indicate specific regions and to propose the implementation of crop-based agricultural systems (Godoy & Lopes-Assad, 2002; Carvalho Júnior, Chagas, Pereira, & Strauch, 2003). Potential impacts of annual crops such as soybeans, corn, and rice on soil C sequestrations have been reported (Bordin et al., 2008; Rosa, Castilhos, Dick, Pauletto, & Gomes, 2008; Carvalho, Avanzi, Silva, Mello & Cerri, 2010). The study of soil C storage, combined with pedological characteristics of agricultural ecosystems, is an important tool to lead discussions on sustainability of crops in different soil conditions (Bortolon, 2008). Research on this subject with cacao began with recent studies (Ofori-Frimpong, Afrifa, & Acquaye, 2010; Gama-Rodrigues, Gama-Rodrigues, & Nair, 2011), highlighting the importance of agroforestry systems (AFS) for the socioeconomic development of the Southeast of Bahia (Müller, Sena-Gomes, & Almeida, 2002; Lobão 2007).

Quality and use of arable lands and conservation management are issues that have been discussed internationally, in predicting the emergence of new global climate scenarios (Intergovernmental Panel on Climate Change [IPCC], 2007), and many research findings have shown that agriculture can also mitigate the adverse impacts of greenhouse gases (Urquiaga, Jantalia, Alves, & Boddey, 2010). Such mitigation is mainly in the sequestration of carbon dioxide ($CO_2$) which is fixed by plants and incorporated into their biomass (Reicosky & Forcella, 1998; Larcher, 2004), and finally by storing it in the soil. Therefore, cacao agroforestry systems play an important role in the conservation and maintenance of biodiversity of native tree species and stabilization of soil by incorporation of plant residues (Araujo, Santana, & Mendonça, 2004; Comerford, Cropper, Grierson, & Araujo, 2006; Sambuichi, 2009; Schroth, D'Angelo, Teixeira, Haag, & Lieberei, 2002; Zanatta, 2006; Paiva & Araujo, 2012).

It has been suggested that substitution of forest by agroforestry-based cacao cultivation leads to a reduction of soil organic C (Andreux & Cerri, 1989; Rosa, Olszevski, Mendonça, Costa, & Correia, 2003). Resende, Curi, Rezende, and Corrêa (2007a) pointed out that the transformation of soil organic matter (SOM) in forest is more intense (higher yield and greater decomposition per unit time), compared to other systems of land use. The C stock in soil comes from incorporation of C in the soil profile in excess of C-$CO_2$ released from soil by respiration of plants and soil microorganisms (Carvalho, 2006). Such balance of C in soil (input/output) depends largely on climatic conditions prevailing in the soil system that control biological activities (Lal, 2008; Bayer & Mielniczuk, 2008).

The global soil organic carbon (SOC) pool, stored primarily in SOM, is estimated at 1,500 Pg (petagram = $1 \times 10^{15}$ g = 1 billion metric tons) to 1-m depth and 2,400 Pg to 2-m depth (Lal, 2001). This represents approximately 60% of the pedologic pool (Batjes, 1996), equivalent to approximately 3.2 times the atmospheric pool and 4.4 times the biotic pool (Sparks, 2003).

Agricultural systems vary in capacity to store C according to their tendency for increasing or decreasing the process of residue decomposition and synthesis and decomposition of SOM (Bayer & Mielniczuk, 2008). It has been estimated that the C sequestration potential of the world's cropland soils is approximately 0.73–0.87 Pg $yr^{-1}$ (Lal & Bruce, 1999). This potential for C storage in soil horizons is influenced by pedogenesis and its related factors (climate, organisms, parent material, relief, and time; Resende et al., 2007a). The intensity of one or more of these factors during pedogenesis determines soil or horizonal richness in the input of organic residues (Oliveira, 2008a).

Because dominant vegetation is the principal factor responsible for pedogenesis in addition of organic materials in the soil (Resende et al., 2007b), it is important to establish and manage crops that contribute to the natural storage of C, and further to increase its addition. Depending on the plant species grown, roots (a component of the living part of the SOM) can add a large amount of soil carbon (Silva & Mendonça, 2007). It is argued that soils with high organic matter would be able to sustain higher productivity (Marin, 2002). Cultivated soil undergoes several changes in temperature, moisture, aeration, uptake, and leaching (Sanchez, 1976). For that reason, sudden changes in composition of natural vegetation can have large impacts on soil C. It is expected, for example, that the soil bulk density of a natural ecosystem is altered with an imposed agricultural activity.

As a possible environmental service, carbon storage in soils (Havstad et al., 2007) can be used to address the carbon credit market in Brazil and worldwide, and further, this could be linked to sustainable development (Pinho, 2008) because organic C is an indicator of soil and air quality (Larson & Pirce, 1994; Lal, 2008). Thus, the conservation management of AFS can potentially store between 12 and 228 t C $ha^{-1}$ (Dixon 1995), increase storage of organic C in the soil, and sequester atmospheric $CO_2$, the main greenhouse gas (Salton, 2005).

Our investigation provides a basis for the definition and establishment of geographical areas for the agroforestry-based cacao planting system, including edaphic aspects of soil C stocks, which will define future agronomic recommendations. This report also looks beyond the pedoclimatic scenario and seeks to explain the maintenance of organic C in soils under cacao in different agroforestry-based cacao cropping systems (cacao cabruca, cacao × rubber tree, and cacao × erythrina). Such evaluations will increase understanding of cacao and its interactions with the soil studied, in order to promote the region for new scientific and market perspectives about products and by-products of cacao.

## MATERIALS AND METHODS

The study areas (Table 1) are located in Southeast Bahia, a region between 41° 30' W and 13° to 18° 15' S along the Atlantic Ocean (Lobão, 2007). Fourteen study sites selected are distributed in the municipalities of Arataca, Gandu, Ilhéus, Itabuna, Ituberá, Piraí do Norte, Porto Seguro, Santa Luzia, and Uruçuca. The general description of these sites (geographical coordinates, altitude, cacao farming system, and predominant and number of shade trees) are given in Table 1.

At each site, soil samples were collected from different soil horizons and described in accordance with the methodology by the *Manual of Description and Sampling of Soil in the Field* (Santos, Lemos, Santos, Ker, & Anjos, 2005), and also characterized by the Munsell Color Company (2000) and the Brazilian System of Soil Classification (Empresa Brasileira de Pesquisa Agropecuária [Embrapa], 2006). Physical and chemical analyses were performed according to the methods of Serôdio, Leão, and Maia Sobrinho (1979) and Santana, Pereira, and Morais (1977). Total organic carbon (TOC) was obtained by the Walkley-Black method (1934), and soil bulk density (BD) was determined based on undisturbed soil samples according to the method of Embrapa (1997). For quantification of organic C (C stock) stored in each horizon in the sampled profiles, the following equation (Amado, Bayer, Eltz, & Brum, 2001) was used:

**TABLE 1** Study Areas—Site and Location, Geographical Coordinates, Altitude, Nature of Cacao Farming Systems, and Predominant and Number of Shade Trees

| Site | Geo. coord. | Altitude (m) | Cacao farming system | Shade (trees ha$^{-1}$) |
|---|---|---|---|---|
| 1 Ituberá | 13° 51’ 08” S<br>39° 17’ 54” W | 261 | Intercrop (AFS) cacao × rubber tree (*Hevea brasiliensis* L.)—spacing 7 m × 3 m. | 400 |
| 2 Ituberá | 13° 46’ 07” S<br>39° 17’ 52” W | 346 | Intercrop (AFS) cacao × rubber tree (*H. brasiliensis* L.)—spacing 7 m × 4 m. | 350 |
| 3 Ituberá | 13° 40’ 30” S<br>39° 14’ 27” W | 195 | Intercrop (AFS) cacao × rubber tree (*H. brasiliensis* L.)—irregular spacing. | 150 |
| 4 P. Norte | 13° 45’ 21” S<br>39° 20’ 25” W | 173 | Cabruca strictu sensu(1) including: gameleira (*Ficus doliaria* Mart.), vinhático (*Persea indica* [L.] Spreng.), cedro (*Cedrella fissilis* Vell.), cobi (*Anadenathera colubrina* [Vell.] Brenan), louro (*Cordia trichotoma* [Vell.] Arrab. ex Steud.), eritrina (*Erythrina glauca* Willd), gliricidia (*Gliricidia sepium* [Jacq.] Kunth ex Walp.), bananeira (*Musa* spp.), jaqueira (*Artocarpus integrifólia* L.), *Citrus* spp. | 60 |
| 5 Gandu | 13° 44’ 38” S<br>39° 30’ 10” W | 176 | Intercrop cacao × erithrina (*Erythrina glauca* Willd) including: bananeira (*Musa* spp.), jaqueira (*Artocarpus integrifólia* L.), gliricídia (*Gliricidia sepium* [Jacq.] Kunth ex Walp.), (scattered). | 60 |
| 6 P. Seguro | 16° 29’ 02” S<br>39° 23’ 56” W | 142 | Intercrop (AFS) cacao × rubber tree (*H. brasiliensis* L.)—spacing 7 m × 3 m. | 400 |
| 7 Sta. Luzia | 15° 23’ 15.1” S<br>39° 25’ 48.6” W | 159 | Cabruca intermediate(1) including: cobi (*Anadenathera colubrina*_[Vell.] Brenan), eritrina (*Erythrina glauca* Willd), bananeira (*Musa* spp.), gliricídia (*Gliricidia sepium* [Jacq.] Kunth ex Walp.), cajazeira (*Spondias mombin*_ L.). With fertirrigation. | 35 |
| 8 Sta. Luzia | 15° 23’ 08” S<br>39° 26’ 04” W | 148 | Cabruca intermediate(1) including: cobi (*Anadenathera colubrina* Vell.), eritrina (*Erythrina glauca* Willd), bananeira (*Musa* spp.), jaqueira (*Artocarpus integrifólia* L.), cajazeira (*Spondias mombin* L.). | 35 |
| 9 Arataca | 15° 17’ 04” S<br>39° 28’ 43” W | 256 | Cabruca intermediate(1) including: bananeira (*Musa* spp.), gliricídia (*Gliricidia sepium* [Jacq.] Kunth ex Walp.), jaqueira (*Artocarpus integrifolia* L.), cajazeira (*Spondias mombin* L.), Sapucaia (*Lecythis pisonis* Cambess.), araçá (*Psidium cattleianum*_Sabine). | 35 |

(*Continued*)

**TABLE 1** (Continued)

| Site | Geo. coord. | Altitude (m) | Cacao farming system | Shade (trees ha$^{-1}$) |
|---|---|---|---|---|
| 10 Uruçuca | 14° 31’ 14” S<br>39° 15’ 45” W | 195 | Cabruca strictu sensu(1) including: cedro (*Cedrella fissilis* Vell.), pinho (*Pinus radiata* D.Don), putumuju (*Centrolobium robustum* [Vell.] Mart.), gameleira (*Ficus adhatodifolia* Schott), caroba (*Jacaranda brasiliana* Pers.). | 50 |
| 11 Ilhéus | 14° 51’ 36” S<br>39° 14’ 42” W | 243 | Cabruca intermediate(1) including: cajazeira (*Spondias mombin_* L.), louro (*Cordia trichotoma_* [Vell.] Arrab. ex Steud.), bananeira (*Musa* spp), gliricídia (*Gliricidia sepium* [Jacq.] Kunth ex Walp.), jaqueira (*Artocarpus integrifólia* L.). Organic farming. | 35 |
| 12 Itabuna | 14° 42’ 40.9” S<br>39° 20’ 13.2” W | 88 | Cabruca spread(1) including: cajazeira (*Spondias mombin* L.), jenipapo (*Genipa americana* L.), jequitibá (*Cariniana estrellensis* [Raddi] Kuntze) e cedro (*Cedrella fissilis* Vell.). Temporaly irrigated. | 20 |
| 13 Ilhéus | 14° 51’ 47” S<br>39° 06’ 47” W | 40 | Cabruca strictu sensu(1) including: cajazeira (*Spondias mombin* L.), cedro (*Cedrella fissilis* Vell.), bananeira (*Musa* spp.), gliricídia (*Gliricidia sepium* ([acq.] Kunth ex Walp.), jaqueira (*Artocarpus integrifólia* L.). | 70 |
| 14 Ilhéus | 14° 46’ 08” S<br>39° 13’ 26” W | 60 | Cabruca strictu sensu(1) including: eritrina (*Erythrina glauca* Willd), bananeira (*Musa* spp.), jaqueira (*Artocarpus integrifólia* L.), gameleira (*Ficus adhatodifolia* Schott), sapucaia (*Lecythis pisonis* Cambess.), ingazeiro (*Inga eduli* Mart.). No inorganic chemicals used last 20 yr. | 50 |

*Note*. (1)Cabruca (trees of shade by hectare) strictu sensu: ≥50; Intermediate: 21–49; and Sparse: ≤20.

$$\text{C stock} = (\text{TOC} \times \text{BD} \times \text{t})/10,$$

where C stock is the total of organic carbon in a given depth (Mg $\text{ha}^{-1}$); TOC is the total organic carbon content (g $\text{kg}^{-1}$); BD is soil bulk density at each depth (kg $\text{dm}^{-3}$); t is the thickness of the horizon (cm).

## RESULTS AND DISCUSSION

### Classes of Soil

The morphological characterization and physical-chemical properties of soils were used as a basis for the description of the main soil properties (Table 2). These soil properties provided the basis for soil classification by the Brazilian System of Soil Classification (Embrapa, 2006) and for grouping soils from each site into various Soil Taxonomic classes (Soil Survey Staff, 2006). Table 3 presents the classification of soils in the Brazilian system, with their respective abbreviations, regional name (popular), and correspondence to Soil Taxonomy.

### Classes of Soil, Agroforestry Systems, and C Stock

The cabrucas (shade-cropping systems in which cacao is planted in the understory of residual forest trees) were characterized in terms of the number of residual shade trees per hectare: Cabruca *stricto sensu* with 50 or more trees $\text{ha}^{-1}$; Cabruca *intermediate* between 21–49 trees $\text{ha}^{-1}$; and Cabruca *sparse* with 20 or fewer trees $\text{ha}^{-1}$ (Tables 1, 4, and 5 Carbon stocks in soil profiles and their possible interactions with changes in the cropping system (cacao cabruca, cacao × rubber tree, and cacao × erythrina), density of shade trees, and depth of the profile were verified.

The C stocks in soil profiles showed wide variation with values ranging from 719.24 to 2,089.927 Mg $\text{ha}^{-1}$ (Table 4). The highest C stocks were observed in the profiles of Ultisols and Oxisols. The Oxisols in general have advanced weathering and structure and are well drained, allowing good root development of the cacao, shade, and intercropped trees (Toxopeus, 1986). The input of organic residues by deep roots and a slight increase in clay in deep horizons increased the C stock in all four profiles of LVAd, LAd, LVAd arg, and Lad cam (Table 4). Especially for the Oxisols, the SOM represents great importance for maintenance of physical stability and cation exchange capacity (Table 2). In the AFS-based cacao cultivated soils of Bahia Brazil, Gama-Rodrigues et al. (2011) reported accumulation of about 302 Mg $\text{ha}^{-1}$ of total C in the top 1-m depth of an Oxisol soil.

The Ultisols studied varied in profile thickness from 60 to 200 cm (Table 4). With the exception of Site 8, all soil profiles had a thickness greater

**TABLE 2** Soil Identification—Classification, Basic Description, and Physical-Chemical Attributes of Soils Under Various Cacao Cultivation Systems

| Rocks/Lithology | Profile | pH | SOM g $kg^{-1}$ (1) | CEC $cmol_c$ $dm^{-3}$ (1) | BS % (1) | Clay % (1) | BD g $dm^{-3}$ | C/N ratio |
|---|---|---|---|---|---|---|---|---|
| Site 1. Latosol Red-Yellow Dystrophic tipic A moderate kaolinitic clayey phase tropical perennial rainforest wavy relief. | | | | | | | | |
| Intermediates: Proterozoic/Archean | Deep, permeable, and porous | 4.7–4.9 | <44.5 | 10.75 | 7–10 | 35.7–58.6 | 0.91–1 | 11–17 |
| Site 2. Latosol Yellow Dystrophic tipic A moderate kaolinitic epieutrophic clayey phase tropical perennial rainforest strong wavy/mountainous relief. | | | | | | | | |
| Intermediates: Proterozoic/Archean | Deep, very porous | 4.5–6.3 | <44.3 | 11.8 | 5–66 | 42.3–58.2 | 1.02–1.2 | 10–13 |
| Site 3. Latosol Yellow Dystrophic cambisolic A moderate kaolinitic epieutrophic clayey phase tropical perennial rainforest strong wavy/mountainous. | | | | | | | | |
| Intermediates: Proterozoic/Archean | Deep and porous | 5.0–6.3 | <29.1 | 8.28 | 15–10 | 31.8–54.9 | 1.06–1.17 | 11–15 |
| Site 4. Argisol Red-Yellow Dystrophic abrupt A moderate epieutrophic clayey-loam phase tropical perennial rainforest strong wavy relief. | | | | | | | | |
| Gneiss of intermediate character. Proterozoic. | Deep, well drained | 4.7–5.7 | <43.6 | 12.61 | 7–63 | 33.5–55.9 | 1.07–1.19 | 8–30 |
| Site 5. Argisol Red-Yellow Dystrophic tipic A moderate epieutrophic clayey-loam phase tropical perennial rainforest wavy relief. | | | | | | | | |
| Gneiss of intermediate character. Middle Proterozoic. | Deep, well drained | 4.7–5.7 | <25.2 | 8.31 and 8.59 ($B_{t1}$) | 6–63 | 13.0–65.0 | 1.27–1.5 | 8–14 |
| Site 6. Argisol Red-Yellow Dystrophic Cohesive abrupt A moderate loam phase tropical perennial rainforest smooth / slightly wavy relief. | | | | | | | | |
| Clay-sandy sediments. Terciary. Barreiras Group. | Deep, well drained. | 5.0–6.1 | 13.3–16.2 | 4.98 | 15–26 | 8.4–32.5 | 0.92–1.49 | 4–23 |
| Site 7. Argisol Red-Yellow Alitic tipic A moderate epieutrophic silty phase tropical perennial rainforest slightly wavy relief. | | | | | | | | |
| Metassedimentary rocks. | Deep, well drained | 4.4–6.0 | <49.3 | 21.34 | 2–79 | 39.1–64.4 | 1.09–1.39 | 3–10 |

|  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|
| Site 8. Argisol Red-Yellow Dystrophic A moderate silty phase tropical perennial rainforest plan relief. |  |  |  |  |  |  |  |  |
| Metassedimentary rocks. | Low lands, imperfectly drained. | 5.3–5.7 | <36.9 | 13.64 | 28–73 | 39.1–64.4 | 1.4–1.5 | 3–71 |
| Site 9. Argisol Yellow Dystrophic latosolic A moderate clayey-loam phase tropical perennial rainforest strong wavy relief. |  |  |  |  |  |  |  |  |
| Intermediates. Proterozoic/Archean | Deep, markedly drained | 4.3–4.8 | <24.1 | 8.33 | 8–18 | 31.5–52.1 | 1.08–1.54 | 7–18 |
| Site 10. Argisol Red-Yellow Eutrophic cambisolic A moderate hypereutrophic clayey-loam phase tropical perennial rainforest wavy relief. |  |  |  |  |  |  |  |  |
| Gneiss of intermediate character. Proterozoic | Moderately deep, well drained | 5.7–6.5 | 22.8–30 | 11.44 and 35.35 ($B_{t3}$) | 63–90 | 12.0–42.7 | 1.14–1.43 | 3–51 |
| Site 11. Cambisol Haplic Dystrophic tipic A moderate clayey phase tropical perennial rainforest slightly wavy relief. |  |  |  |  |  |  |  |  |
| Intermediates. Proterozoic | Deep, moderate drainage | 4.8–5.7 | <28.3 | 8.51 | 10–76 | 20.2–54.6 | 0.92–1.18 | 5–18 |
| Site 12. Argisol Red-Yellow Dystrophic abrupt A moderate epieutrophic clayey-loam phase tropical perennial rainforest slightly wavy relief. |  |  |  |  |  |  |  |  |
| Gneiss of intermediate character | Deep, well drained | 5.2–5.8 | <30.5 | 10.81–28.78 | 26–76 | 13.4–58.1 | 1.24–1.6 | 5–18 |
| Site 13. Latosol Red-Yellow Dystrophic argisolic A moderate kaolinitic clayey phase tropical perennial rainforest wavy relief. |  |  |  |  |  |  |  |  |
| Intermediates. Proterozoic/Archean | Deep, markedly drained | 5.1–5.7 | <36.2 | 6.62 | 10–29 | 26.6–54.9 | 1.12–1.29 | 6–68 |
| Site 14. Nitosol Haplic Eutrophic tipic A moderate clayey/very clayey phase tropical perennial rainforest slightly wavy relief. |  |  |  |  |  |  |  |  |
| Regolith of alkaline rocks referred to Proterozoic | Moderately deep, well drained | 5.3–6.2 | <21 | 15.34 | 30–79 | 43.3–65.7 | 1.05–1.25 | 6–14 |

*Note*. SOM: soil organic matter, superficial average; CEC: cation exchange capacity, superficial; BS: base saturation; BD: bulk density. (1) Diagnostic horizon.

**TABLE 3** Soil Classification by the Brazilian System (SBCS–Brazilian Society of Soil Science), Regional Denomination (Unit), and by the Soil Taxonomy

| Site | Soil | SBCS* | Unit | Soil taxonomy |
|---|---|---|---|---|
| 1 | Latosol Red-Yellow Dystrophic tipic | LVAd | Una Úmido | Typic Hapludox |
| 2 | Latosol Yellow Dystrophic tipic | LAd | Una Úmido (Cristalino) | Typic Hapludox |
| 3 | Latosol Yellow Dystrophic cambisolic | LAd cam | Una Úmido (Cristalino) | Hapludox |
| 4 | Argisol Red-Yellow Dystrophic abrupt | PVAd | Cepec Rochoso | Hapludult |
| 5 | Argisol Red-Yellow Dystrophic tipic | PVAd | Itabuna | Hapludult |
| 6 | Argisol Red-Yellow Dystrophic Cohesive abrupt | PVAd coe | Tabuleiro (Colônia) | Hapludult |
| 7 | Argisol Red-Yellow Alitic tipic | PVA ali | Vargito | Hapludult |
| 8 | Argisol Red-Yellow Dystrophic | PAd | Vargito | Hapludult |
| 9 | Argisol Yellow Dystrophic latosolic | PAd lat | Água Sumida | Hapludult |
| 10 | Argisol Red-Yellow Eutrophic cambisolic | PVAe cam | Cepec Rochoso | Hapludalf |
| 11 | Cambisol Haplic Dystrophic tipic | Cxd | Rio Branco | Dystropept |
| 12 | Argisol Red-Yellow Dystrophic abrupt | PVAd | Cepec Rochoso | Hapludult |
| 13 | Latosol Red-Yellow Dystrophic argisolic | LVAd arg | Una (Cristalino) | Hapludox |
| 14 | Nitosol Haplic Eutrophic tipic | Nxe | Série Germoplasma | Hapludalf |

*Note*. *Abbreviation by the Brazilian System of Soil Classification.

than 150 cm, allowing good root development of cacao and other perennial tree species that make up the AFS (Table 1). This means that the supply of organic residues in deeper soil depths has helped to maintain good physical and chemical qualities of these soils (Dick et al., 2009). The clay fraction in the soil profile plays a key role for the characterization of this class of soil (Embrapa, 2006), and in protection and prevention of SOM decomposition (Dick, Novotny, Dieckow, & Bayer, 2009).

Clayey soils, regardless of the management system, tend to provide high physical stability to SOM as compared to sandy soils (Roscoe & Buurman, 2003). Clay hinders the decomposition of organic compounds associated with it (Resende et al., 2007a). It has been reported that in a wide range of soils, 53 to 98% of the soil organic C was associated with the clay fraction (Greenland, 1965) . Conceptual concerns must assist the interpretation of the quantification of SOM and clay (Table 2), to diagnose the loss of organic carbon related to management practices. The assessment of the relationship between clay and SOM could assist in clarification of C storage capacity of the soil profiles under consideration. In soil rich in clay and oxides of Fe and Al, most of the SOM is protected inside the microaggregates and, therefore, is less affected by management and climatic variables (Pillon, 2000). In Oxisols there is a pronounced difference between carbon stocks in the surface and subsurface soil layers. In other soil classes higher amount of total C may

**TABLE 4** Carbon Stocks in Soils of 14 Studied Sites Under Different Cacao Cultivation Systems in Southeast Bahia, Brazil

| Site | SBCS* | Total C stock (Mg ha$^{-1}$) | C stock A-horizon (Mg ha$^{-1}$) | C stock B-horizon (Mg ha$^{-1}$) | C stock C-horizon (Mg ha$^{-1}$) | Profile depth (cm) | Farming system | Shade (tree ha$^{-1}$) |
|---|---|---|---|---|---|---|---|---|
| 1 | LVAd | 1,858.7 | 363.8 | 1,494.9 | – | 200 | Cacao × rubber tree | 400 |
| 2 | LAd | 1,736.7 | 340.8 | 1,395.9 | – | 220 | Cacao × rubber tree | 350 |
| 3 | LAd cam | 1,483.4 | 393.9 | 1,089.5 | – | 200 | Cacao × rubber tree | 150 |
| 4 | PVAd | 1,749.4 | 490.8 | 1,258.5 | – | 200 | Cabruca *strictu sensu* | 60 |
| 5 | PVAd | 1,241.1 | 326.5 | 914.6 | – | 180 | Cacao × erythrina | 60 |
| 6 | PVAd coe | 1,324.6 | 218.0 | 1,106.7 | – | 200 | Cacao × rubber tree | 400 |
| 7 | PVA ali | 1,405.2 | 331.8 | 896.5 | 177.0 | 180 | Cabruca intermediate | 35 |
| 8 | PAd | 719.2 | 561.7 | 157.5 | – | 60 | Cabruca intermediate | 35 |
| 9 | PAd lat | 2,089.9 | 431.2 | 1,658.7 | – | 200 | Cabruca intermediate | 35 |
| 10 | PVAe cam | 1,319.9 | 369.8 | 895.8 | 54.3 | 140 | Cabruca *strictu sensu* | 50 |
| 11 | Cxd | 1,182.4 | 401.6 | 780.8 | – | 180 | Cabruca intermediate | 35 |
| 12 | PVAd | 1,221.6 | 350.2 | 698.0 | 173.4 | 179 | Cabruca spread | 20 |
| 13 | LVAd arg | 1,484.1 | 249.9 | 1,234.2 | – | 200 | Cabruca *strictu sensu* | 70 |
| 14 | Nxe | 912.2 | 263.0 | 649.3 | – | 165 | Cabruca *strictu sensu* | 50 |

*Note*. *Brazilian System of Soil Classification.

**TABLE 5** Soil Carbon Sequestration in the 14 Studied Sites in Southeast Bahia, Brazil, by Group of Soil Classes

| Site | SBCS* | Total C stock (Mg ha$^{-1}$) | C stock A-horizon (Mg ha$^{-1}$) | C stock B-horizon (Mg ha$^{-1}$) | C stock C-horizon (Mg ha$^{-1}$) | Farming system | Shade (tree ha$^{-1}$) |
|---|---|---|---|---|---|---|---|
| 1 | LVAd | 1,858.7 | 363.8 | 1,494.9 | – | Cacao × rubber tree | 400 |
| 2 | LAd | 1,736.7 | 340.8 | 1,395.9 | – | Cacao × rubber tree | 350 |
| 13 | LVAd arg | 1,484.1 | 249.9 | 1,234.2 | – | Cabruca *strictu sensu* | 70 |
| 3 | LAd cam | 1,483.4 | 393.9 | 1,089.5 | – | Cacao × rubber tree | 150 |
| 11 | Cxd | 1,182.4 | 401.6 | 780.8 | – | Cabruca intermediate | 35 |
| 9 | PAd lat | 2,089.9 | 431.2 | 1,658.7 | – | Cabruca intermediate | 35 |
| 4 | PVAd | 1,749.4 | 490.8 | 1,258.5 | – | Cabruca *strictu sensu* | 60 |
| 7 | PVA ali | 1,405.2 | 331.8 | 896.5 | 177.0 | Cabruca intermediate | 35 |
| 6 | PVAd coe | 1,324.6 | 218.0 | 1,106.7 | – | Cacao × rubber tree | 400 |
| 10 | PVAe cam | 1,319.9 | 369.8 | 895.8 | 54.3 | Cabruca *strictu sensu* | 50 |
| 5 | PVAd | 1,241.1 | 326.5 | 914.6 | – | Cacao × erythrina | 60 |
| 12 | PVAd | 1,221.6 | 350.2 | 698.0 | 173.4 | Cabruca spread | 20 |
| 14 | Nxe | 912.2 | 263.0 | 649.3 | – | Cabruca *strictu sensu* | 50 |
| 8 | PAd | 719.2 | 561.7 | 157.5 | – | Cabruca intermediate | 35 |

*Note*. *Brazilian System of Soil Classification.

occur at different depth; however, in Red Yellow Oxisols, the subsurface soil layer contained twice the level of total C as that for the surface soil layer (Guedes, Schaefer, & Costa, 2010).

The Ultisols and Oxisols in pedogenic processes have remarkable capacities to store SOM in soil profiles from the organic residues deposited on the soil surface (Diógenes et al., 2010) and this phenomenon clearly demonstrates that these soils have a natural potential to store C. Because of this intrinsic relationship between soil and vegetation in C storage in soil profiles, it is understood that organic residue supply should be managed in order to increase the sequestration of $CO_2$, and store C in the soil profiles by means of crops. Fontes (2006) describes the deposition of organic residues through litter, estimated at about 7.0 Mg ha$^{-1}$ yr$^{-1}$, which highlights the cacao tree as a unique species to sequester atmospheric $CO_2$ and contribute to the increase of C in the soil.

Because of the existence of pedogenesis differences, profiles (Table 3) that represent Cambisol-Cxd (Inceptisol, Site 11) and Nitosol-Nxe (Alfisol, site 14) were not initially included among the other classes of soils. The existence of a morphogenetic similarity between the Horizons Bi and Bw (Embrapa, 2006) allowed the inclusion of the Cambisol-Bi into the group of Oxisols-Bw (Table 5), and similarly the Nitosol-Bt was included in the comparison with the group of Ultisols-Bt (Table 5). Both soil horizons need to be carefully examined with more accurate parameters to define their function in storing of C. It is understood that the surface soil horizons protect and increase the reserves of soil carbon in the subsurface layers. Data in Table 5 show that it is possible to observe changes in C stock among the profiles and their horizons in textural and morphogenetic aspects, which include surface and subsurface layers. Changes in carbon storage in surface horizons do not correspond to variations in the total storage in the profiles, but in Horizon B diagnostic of all the profiles there is evidence of a relationship between the inputs of organic residues in the subsurface layers and total storage in the profile of C soil. Therefore, it is vital to follow the sustainable management of soil conservation strategy to keep the carbon in these horizons, otherwise C is vulnerable to losses resulting from cultivation (Polidoro, Winowiecki, Johnson-Maynard, McDaniel, & Morra, 2008; Suddick et al., 2010).

The diversity of tree species in the cacao cabruca cropping system (Table 1) in addition to their ecological significance are responsible for the sequestration of atmospheric $CO_2$, where edaphic conditions are closer to a natural ecosystem that did not suffer severe anthropogenic changes such as adopted in conventional farming.

In the current study, the Cxd soil with cacao cabruca cropping system in Site 11 (Table 4) had a C stock of 1,182.4 Mg ha$^{-1}$, whereas a similar soil with cacao × erythrina (*Erythrina glauca* Willd) had a C stock of 800 Mg ha$^{-1}$ (Souza, Araujo, & Faria Filho, 2009).

The LAd (Site 2) with 1,736.7 Mg C ha$^{-1}$ and LAd cam (Site 3) with 1,483.4 Mg C ha$^{-1}$ both under an intercropping cacao and rubber tree consortium presented C reservoirs similar to those estimated by Souza et al. (2009) for a LAd under forest (1,100 to 2,000 Mg ha$^{-1}$).

The LVAd (Site 1) with 1,858.7 Mg C ha$^{-1}$ (Table 4) under intercropping cacao and rubber trees and the LVAd arg (Site 13) with 1,484.1 Mg C ha$^{-1}$ (Table 4) under cabruca had C stocks higher than those estimated by Souza et al. (2009) for Latosol Red-Yellow dystrophic (LVAdf ) under pasture and forest with 1,200 to 1,700 Mg ha$^{-1}$ respectively.

The Nitosols, by definition, are soils with little textural difference, less eroded, and usually are deep in profile and, in spite of their clayey texture, these soils possess good permeability (Oliveira, 2008b). In the current study Nitosol, Nxe in Site 14 (Table 4) recorded satisfactory total C stock of 912.2 Mg ha$^{-1}$ in the cacao cabruca system with a profile depth of 165 cm.

Souza et al. (2009) reported that the PAd soil under pasture, piaçava (*Attalea funifera* Mart) and cassava (*Manihot esculenta* Crantz) recorded C stocks between 820 to 1,300 Mg ha$^{-1}$, while in our work, the cabruca intermediate characterized with 35 shade trees, presented two different situations consistent with the profile depth—the PAd in Site 8 (Table 4) with total C storage of 719.2 Mg ha$^{-1}$ at 60 cm, and the PAd lat in Site 9 (Table 4) with total stock of 2,089.9 Mg ha$^{-1}$ at 200 cm.

Similar C stocks were observed in experimental sites of soil with order Argisol and suborder Red-Yellow (Table 4). The C Stocks (Table 4) in the PVAd (site 4) with 1,749.4 Mg ha$^{-1}$ under cabruca, PVAd (Site 5) with 1,241.1 Mg ha$^{-1}$ under cabruca spread and PVAd (Site 12) with 1,221.6 Mg ha$^{-1}$ under system cacao × erythrina are larger than the estimate by Souza et al. (2009) for PVAd under cultivation of banana, citrus, coconut, palm oil, and pasture (700 Mg C ha$^{-1}$). The C stock values found in the same regional survey (Souza et al., 2009) are also lower than the reservoir estimated in PVAd coe (Site 6) with 1,324.6 Mg ha$^{-1}$ under intercropping cacao and rubber tree (Table 4). Souza et al. (2009) estimated a C stock of 1,500 Mg ha$^{-1}$ in PVAe under forest similar to the C stocks of PVA ali (Site 7) with 1,405.2 Mg C ha$^{-1}$ under cabruca intermediate and of PVAe cam (Site 10) with 1,319.9 Mg ha$^{-1}$ under cabruca (Table 4).

The cabruca system proves to be a good potential for maintenance of organic carbon in the soil. For example, the cabruca studied in this work (Site 12), with 20 shade trees ha$^{-1}$, and a profile of 179-cm depth, reached the total C storage of 1,221.6 Mg ha$^{-1}$.

The consortium of cacao trees with rubber trees (Table 4) provide a good reservoir of C coinciding with the storage potential of soils (Batjes, 1996), besides providing a more rapid economic response to farmers to improve the environment for carbon markets (Marques, Monteiro, & Lopes, 2002; Cotta et al., 2008). The high C stocks observed in this cropping system are a reflection of high shade tree density of 150 to 400 trees ha$^{-1}$ compared to with that of cacao cabruca system where tree density was from 35 to 70 trees ha$^{-1}$ (Table 4).

In Costa Rica, the legume erythrina—eg., *E. verna* Vell. and *E. poeppigiana* (Walp.) O.F. Cook—is used as an intercrop to provide shade to cacao and coffee. Frequently erythrina is pruned and plant residues are used as green manure. Erythrina also fixes N, thereby improving soil fertility (Beer et al., 1990, Estívariz-Coca, 1997). The shading with erythrina may favor the deposition of organic waste in the soil.

High temperatures and rainfall are very much prevalent in cacao growing regions of Southeast Bahia, and such climatic conditions lead to enhanced microbial activities and decomposition of SOM which, in theory should reduce the total C stocks in soil profiles. In tropical regions, reduced annual additions of organic material, coupled with high rates of organic matter decomposition, have led to declines in soil organic carbon before it reaches the equilibrium state with the native vegetation (Fernandes, Cerri, & Fernandes, 1999). The decrease in value of annual additions of organic carbon in agriculture, as well as high rates of decomposition, characteristics of the tropical regions, cause a decline in organic C content previously in equilibrium with the native vegetation (Fernandes et al., 1999).

The exchange of $CO_2$ between the atmosphere and the soil is fast (Lorenz, Lal, Preston, & Nierop, 2007), and the rate of exchange is intensified by high humidity and temperatures that increase soil microbial activity (Juarez, Nunan, Otten, & Chenu, 2011). But according to Murray (1975), shade trees and cacao systems reduce fluctuations in soil and air temperatures during the day, reduce wind velocity, and enhance nutrient cycling. Such changes that occur in cacao agroforestry cropping systems have positive effects on increasing stored organic carbon in soil. The rates of biomass accumulation and carbon fixation in cacao agroforestry systems, correlating with climatic factors such as temperature and rainfall (Órtiz, Riascos, & Somarriba, 2008), have been investigated. The amount of C stored in soil is directly related to the rate of addition of plant residues and inverse to the rate of decomposition of organic matter, which is influenced by the degree of aeration and nature of crop residue and its C/N ratio (Moreira & Siqueira, 2006). Gama-Rodrigues et al. (2011) have shown that in the cacao agroforestry systems of Bahia, Brazil, soil C storage was dependent on soil aggregation, thickness of soil profile, and depth of root penetration.

The economic utilization of tree species that make up the AFS of cacao cabruca could provide goods and services for personal consumption by farmers (Albrecht & Kandji, 2003; Mello, Ahnert, Viana, & Ornellas, 2009, Carvalho et al., 2005; Carvalho, Nacif, Araujo, & Oliveira, 2008). Such systems of cropping could be profitable and can lead to a long-term solution to environmental services such as sequestration of $CO_2$.

Tree compositions of cacao cabruca are similar to the natural forest of the region, which means these systems of cacao cultivation represent a less negative impact on the ecosystems of the Atlantic Forest (Epps, Araujo, & Comerford, 2006). In the cacao-cabruca systems, the vegetation structure and stratification of tree species are similar to those of natural forests (Gama-Rodrigues et al., 2011).

The descriptions of chemical and physical properties of soils have been used as a basis for classification of soils, and detailed soil macro- and micromorphological characteristics can be used as a starting point for investigation of soil quality and its relation to quality of cocoa.

Assessment of soil properties will help to evaluate the impact of cacao management systems on total C stocks in the soil profiles and how cacao management systems affect the SOM fractions that are most sensitive to agricultural practices and to evaluate management strategies (Rangel, Silva, Guimarães, & Guilherme, 2008; Campanha, Nogueira, Oliveira, Teixeira, & Romero, 2009).

As observed for agroforestry ecosystems, total C stocks in subsurface soil horizons of cacao forestry systems are directly linked to total C storage of the soil profile (Beer et al., 2003). Total C stocks in cacao forestry systems are comparable to regional estimates of C stocks (Souza et al., 2009) and international estimates to the classes of soils studied with values presented in the database of the International Soil Reference and Information Center (ISRIC; Batjes, 1996). However, cacao cabruca systems showed good storage C with lower densities of shade trees varying between 20−70 shade trees ha$^{-1}$, compared to cacao × rubber tree systems (Table 4).

However cacao cabruca systems with low density of shade trees (20–70 trees ha$^{-1}$) stored C stocks comparable to those of cacao × rubber systems with high density of shade trees (150–400 trees ha$^{-1}$). Considering the aspect of soil quality (associated with the management of SOM) and its correlation to productivity, the diversification of cacao cabruca systems (FS) allows sustained production of cacao by farmers of the region. Shade tree density of 16–18 trees ha$^{-1}$ with a cacao planting density of 1,111 trees ha$^{-1}$ has been recommended by CRIG (Cocoa Research Institute of Ghana) to increase the accumulation of carbon in soils (Ofori-Frimpong et al., 2010). It has been proposed that for the Bahia region of Brazil, the composition of shade and number of native tree species per hectare should be considered in relation to tree diameter, canopy architecture, and potential uses (timber species, medicinal, fruit, condiments, leguminous; Sambuichi, 2006). Composition of trees in the AFS of cacao cabruca reflects the total C storage in soil and soil quality; therefore, its ability to sustain cocoa production over the years depend on strategic management and conservation.

## CONCLUSIONS

Soils under the various cacao production systems studied were identified as four general classes: Ultisols, Oxisols, Alfisols, and Inceptisols. Total C stocks observed in the soil profile under the sites studied ranged from 719.24 to 2,089.93 Mg $ha^{-1}$. The C stock values observed in different cacao agroforestry systems (cacao cabruca, cacao × rubber tree, and cacao × erythrina) indicated satisfactory levels of C stocks in the surface and subsurface soil horizons. Overall, total organic C stored in the soil profile of the cacao agroforestry systems studied were higher than average total C stocks reported for soils in the International Soil Reference and Information Center (ISRIC), based on the database of the FAO-UNESCO, and also higher than regional data estimates.

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