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Papers

# Changes in Soil Organic Carbon Stocks Due to Land Use Changes in the Extended São Francisco River Basin

***Saniel Carlos dos Santos*[1]**
***Higor Costa de Brito*[2]**
***Iana Alexandra Alves Rufino*[3]**
***Stoécio Malta Ferreira Maia*[4]**

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**Abstract**
As the largest carbon reservoir in terrestrial ecosystems, soils play a critical role in food production, mitigation and adaption to climate change, and sustainability of agroecosystems. In this context, the aim of this study is to estimate variations in soil carbon stocks resulting from land use and management changes in different biomes that compose the Bacia Estendida do Rio São Francisco (BESF - Extended São Francisco River Basin), between 1985 and 2017. For this, remote sensing data and information from the IBGE agriculture and livestock census were used, in addition to emission factors to estimate soil organic carbon (SOC) changes. The results indicate that BESF had about 5.70 million ha degraded in the analyzed period, in addition to an increase of 0.72 Tg C year-1 in SOC stocks. The sub-medium São Francisco River basin recorded the highest SOC gain, with an increase of 0.54 Tg C ha-1; on the other hand, the sub-medium São Francisco River sub-basin had the greatest SOC losses, with an estimated reduction of 0.07 Tg C year-1. In short, this study provides important evidence on changes in SOC stocks in the region, emphasizing the importance of native vegetation conversion to agriculture and livestock systems under sustainable soil management for mitigating greenhouse gas emissions and maintaining soil quality.



[1] Universidade Federal de Alagoas - UFAL, Rio Largo, AL, Brazil. sanielcarlosst@gmail.com
[2] Universidade Federal de Campina Grande – UFCG, Campina Grande, PB, Brazil. h_igor@hotmail.com
[3] Universidade Federal de Campina Grande – UFCG, Campina Grande, PB, Brazil. iana.alexandra@ufcg.edu.br
[4] Instituto Federal de Alagoas – IFAL, Marechal Deodoro, AL, Brazil. stoecio.maia@ifal.edu.br

## INTRODUCTION

Global climate changes caused by the increase in the concentration of greenhouse gases (GHG) in the atmosphere, resulting from human activities, culminated in the interest and need for methods capable of mitigating the emissions of these gases. In this context, soils can act as carbon (C) sources or sinks, depending on management, biomass input levels and climate conditions and changes (Baker, 2007; Zomer *et al.*, 2017). Soils have the largest C reservoir in terrestrial ecosystems, estimated at around 2500 Gt of C, with storage capacity considered 3.3 times greater when compared to the stock in the atmosphere and 4.5 times greater than the amount present in plant biomass (Lal, 2010; FAO, 2015). Soil organic carbon (SOC) is a primary indicator of soil quality as it plays a critical role in food production, GHG balance, and mitigation and adaptation to climate change, which is fundamental for the sustainability of agroecosystems, acting on soil structure, nutrient cycling, water dynamics, microbial activity and biodiversity (Lorenz; Lal, 2016; Tautges *et al.*, 2019).

SOC contents reflect the dynamics that occur between input rates due to the input of organic residues, and carbon outputs due to changes in decomposition rates, soil organic matter (SOM) mineralization or by erosion in agricultural systems in a given edaphoclimatic regime (Lal, 2018; Santos *et al.*, 2019). Changes in SOC storage can occur through the action of microorganisms, environment-modifying organisms, abiotic processes related to the soil's physical structure, porosity and mineral fraction, as well as climatic conditions and land use and management practices (Dignac *et al.*, 2017).

Despite the high deforestation of Brazilian biomes during the period from 1985 to 2021, the areas covered by native vegetation represent in 2021, 66.3% of the country's entire area. The fact that the removal of native vegetation in the Pampa (29.5%), Cerrado (20.9%), Amazon (11.5%), Caatinga (10.1%) and Mata Atlântica (5.9%) biomes was replaced by anthropic activities, mainly agriculture and livestock, is among the main findings. Areas destined for agriculture registered expansion of 43.3 million ha, mainly converted into temporary crops on already anthropized lands, especially with pasture (Mapbiomas, 2021).

The BESF is an ecosystem of great worldwide relevance in terms of biodiversity, considered a hotspot due to its biological richness. It is composed of three distinct biomes, the Caatinga, the Cerrado and the Atlantic Forest, in addition to the São Francisco River, one of the main rivers of Brazil. The combination of these different environments results in unique conditions, which are influenced by different land use and management changes. Therefore, BESF becomes an excellent option to assess the dynamics of land and soil management changes. BESF is largely located in the semiarid region of Brazil, playing a key role in water supply and C stock, in addition to its social and economic importance. In the semiarid region of Brazil, Medeiros *et al.* (2021) demonstrated that changing land use from native vegetation to pasture reduces SOC stocks by 12%-27%, with influence of use time and soil layer.

C sequestration is one of the main solutions and cost-effective options to mitigate climate change. Leaders from several countries have been discussing the topic since the early 1970s, holding conferences on climate change and signing international agreements between member countries to reverse GHG accumulation (Rumpel *et al.*, 2018). With the aim of bringing together voluntary entities from the public and private sectors to improve soil C stock management, the Brazilian government announced a commitment to reduce GHG emissions through the adoption of sustainable production technologies. As part of this commitment, the ABC Plan (Low Carbon Emission Agriculture) was established for the agricultural sector nationwide (Brasil, 2012). In addition, other countries are also implementing important initiatives in this area, such as France, which, before the COP21 in Paris, defined the ambitious international research program "4 per 1000 – soils for food and climate security", through the Ministry of Agriculture (Minasny *et al.*, 2017).

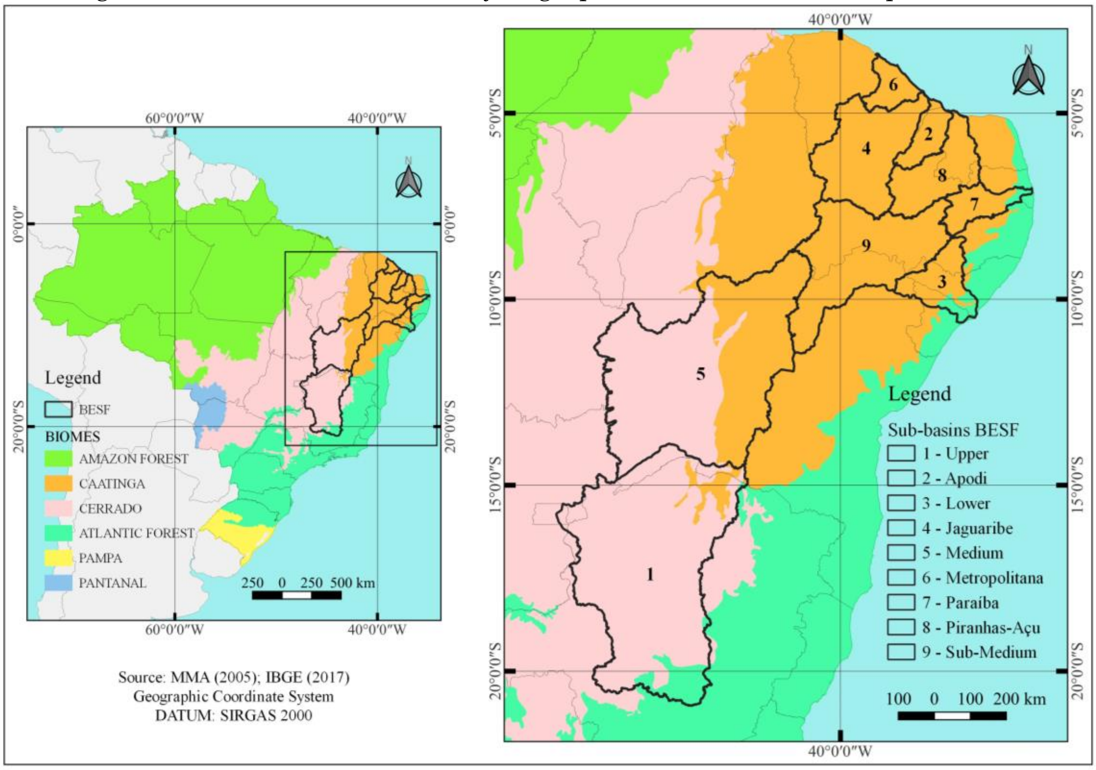
In this context, the present study aims to integrate geoprocessing resources and information from the agricultural sector to estimate variations in soil C stocks resulting from land use and management changes in different biomes and sub-basins that compose BESF from 1985 to 2017. Thus, this study seeks to contribute to the understanding of soil C dynamics in the region, providing relevant information for decision-making and the adoption of strategies for sustainable soil management, complying with international commitments to mitigate climate change.

## MATERIALS AND METHODS

### *Characterization of the study area*

The area selected for the study is within BESF, a basin that was delimited through the Integration Project of the São Francisco River with Hydrographic Basins of Northeastern Brazil (Figure 1). BESF covers a drainage area of approximately 841,600 km², located between latitudes 3°23' and 20°55' S and longitudes 34°49' and 47°38' W, distributed throughout the states of Minas Gerais, Bahia, Pernambuco, Alagoas, Sergipe, Goiás, Tocantins, Paraíba, Rio Grande do Norte, Ceará and the Federal District, circumscribed by 984 municipalities included in the region. The BESF is composed of nine sub-basins (Upper, Medium, Sub-Medium, Lower, Paraíba, Jaguaribe, Piranhas-Açu, Apodi and Metropolitan), which flow into the São Francisco River and it is supplied by the transposition project. In turn, the waters of the São Francisco River flow into the Atlantic Ocean on the border between the states of Alagoas and Sergipe.

Figure 1 - Brazilian biomes and hydrographic sub-basins that compose BESF.




Source: The authors (2023).

### *Estimates of changes in soil carbon stocks for BESF*

Changes in C stocks were estimated according to the methodology described by IPCC (2006), which assumes that in mineral soils, changes in C stocks are estimated using Equation 1:

$$\Delta C = \frac{\sum_{h=1}^{H}(SOC_f(h) - SOC_i(h))}{10^6 \times T} \quad (1)$$

Where, H: number of associations between BESF region and soil types by soil use and management system; $SOC_f(h)$: soil organic carbon stock (Mg C) in system *h* in the last year of the inventory period; SOCi(h): soil organic carbon stock (Mg C) in system *h* in the first year of the inventory period; $10^6$: convert from Mg C to Tg C; T: number of years of the inventory period to obtain the annual rate of C accumulation or loss.

C stocks in the 0-30 cm surface layer were estimated using Equation 2:

$$SOC(h) = \sum_{e,m} \left(C_{REF_{e,m}} \times F_{LU_{e,m}} \times F_{MG_{e,m}} \times F_{I_{e,m}} \times A_{e,m}\right) \quad (2)$$

Where, e: represents the associations between BESF region and soil types; m: management systems present in the study region; $C_{REF}$: soil C stock under native vegetation (Mg C ha$^{-1}$); $F_{LU}$: stock change factor for land use systems; $F_{MG}$: stock change factor for management practices; $F_I$: stock change factor for organic matter input; A: area (ha) of a given land use category and management practice.

### Land use data

The primary land cover and land use data for BESF originate from the Mapbiomas 3.1 collection, from the time series from 1985 to 2017. The collection is based on Landsat mosaics in matrix format (30 x 30 m pixel). For the C stock estimate, the time interval of 20 years was chosen based on the emission factors of pastures and agricultural systems used in the estimate, considering the years from 1985 to 2005, from 1997 to 2017 and from 1985 to 2017.

Initially, land cover and use maps available in Mapbiomas were composed of 27 classes divided into six categories represented by: forest, natural non-forest formation, agriculture and livestock, non-vegetated area, water bodies and unobserved. However, for a better adaptation to the use of emission factors in estimating SOC changes, reclassification was adopted. For this, information from LAPIG (2020) and IBGE (2020a) was used to verify the area and classify pasture conditions in the region, while data on permanent and temporary crop areas were acquired from the IBGE agricultural census (2020b; 2020c), which allows the identification of no-tillage and conventional cultivation categories. To estimate the proportions of the different types of sugarcane harvesting, information from CONAB (2018) was considered, which indicates the percentage of mechanized (without burning) and manual (with burning) harvesting, by regions and states.

Thus, reclassification resulted in the following land cover and use classes: native vegetation; natural pastures; well-managed planted pastures; degraded planted pastures; agriculture (no-tillage); agriculture (conventional cultivation); perennial crop; sugarcane (with burning); sugarcane (without burning); exposed soil; built-up area and water bodies.

### Reference carbon (CREF)

The reference organic carbon stocks in the soils ($C_{REF}$) are the same used in the Third and Fourth National Inventories of GHG Emissions (MCTI, 2015; 2020). The estimate followed the methodology proposed by Bernoux *et al.* (2002), which was based on the association of soil classes and vegetation type.

With maps of reclassified Mapbiomas and soil $C_{REF}$, data pre-processing took place based on cross-tabulation. To simplify and make the processing feasible, due to the territorial extension of BESF, a shapefile containing the carbon information was dissolved to unify areas that contained the same carbon values using the QGIS software. After treatment, the shapefile was rasterized by sub-basins, in which nine rasters were obtained (one for each sub-basin). Subsequently, cross-tabulation between rasters, soil $C_{REF}$ and Mapbiomes classes was performed using a script developed with the aid of the R programming language (R Core Team, 2021), which allows quantifying the soil carbon ratio in each land use and cover class. In the end, SOC stock changes were estimated.

### Soil carbon change factors

Soil carbon change factors for the different land use classes were obtained through technical and scientific information sources in the period under study (Table 1).

**Table 1** - Soil organic carbon change factors as a function of land use and cropping system change.

| Land use | Biomes | | | Source |
|---|---|---|---|---|
| | Cerrado | Caatinga | Atlantic Forest | |
| Native pasture | 1.00 | 1.00 | 1.00 | MCTI (2020); MEDEIROS *et al.* (2021) |
| Well-managed pasture | 1.11 | 1.00 | 1.11 | |
| Degraded pasture | 0.94 | 0.75 | 0.94 | |
| Conventional tillage | 0.90 | 0.83 | 0.86 | MEDEIROS *et al.* (2020); MCTI (2020) |
| No-tillage | 1.22 | 1.09 | 1.13 | |
| Perennial crop | 0.98 | 0.71 | 0.98 | MCTI (2020) |
| Burnt sugarcane | 0.74 | 0.74 | 0.74 | MELLO *et al.* (2014) |
| Unburnt sugarcane | 1.24 | 1.24 | 1.24 | CERRI *et al.* (2011) |

Source: The authors (2023).

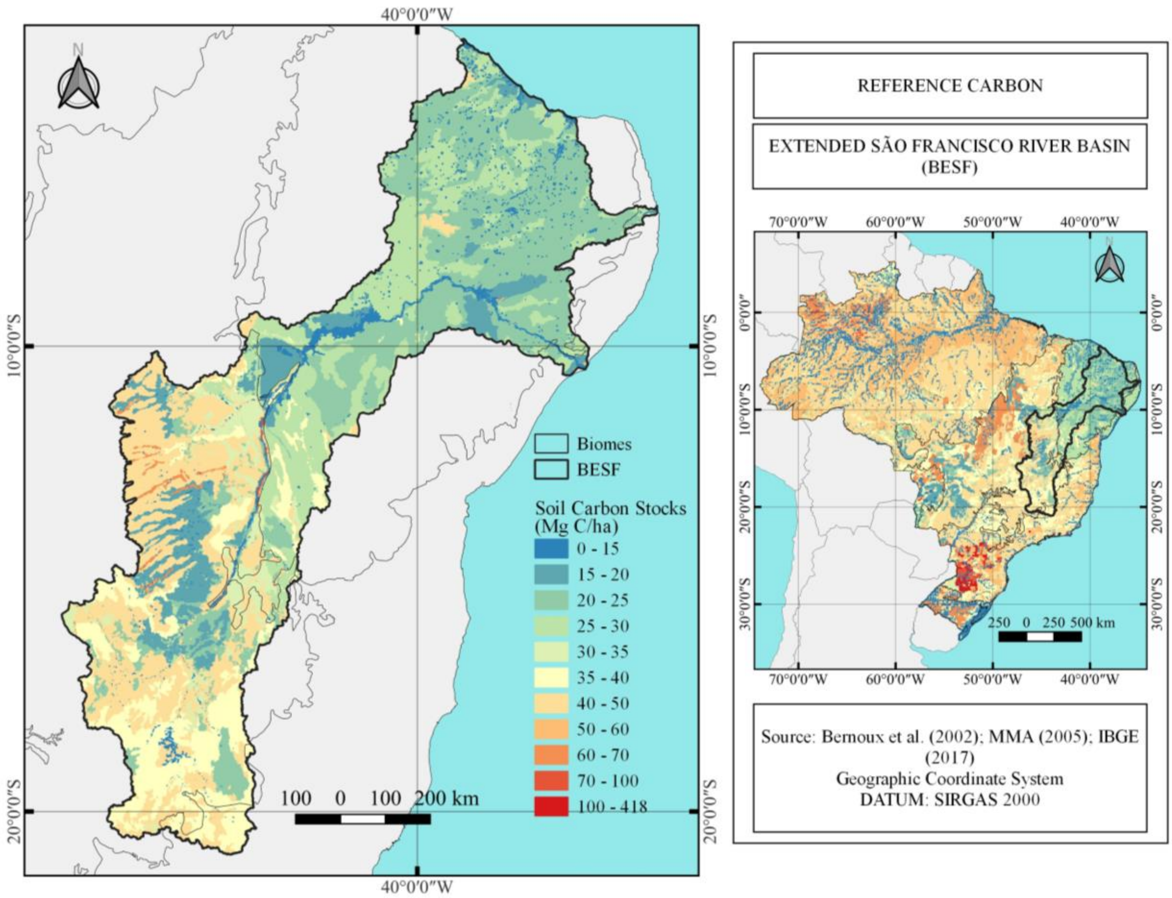
## RESULTS AND DISCUSSION

### *Reference carbon (CREF)*

$C_{REF}$ stocks in the BESF territory showed high variability in the distribution of values, which range from 15 Mg C ha$^{-1}$ to 73 Mg C ha$^{-1}$ in the 0-30 cm layer (Figure 2). The largest stocks in this layer occurred in the Upper and Middle São Francisco sub-basins, predominantly covered by the Cerrado biome, while the lowest stocks occurred in the northern region of BESF, where the climate is dry and mainly covered by xerophytic plants. In the 0-30 cm layer, approximately 2.6 Pg C are stored in a total area of 814,600 km$^2$. The Caatinga biome present in BESF registers the highest amount of stored C in the soil (1.7 Pg C) among biomes that cover BESF, followed by Cerrado (0.8 Pg C) and Atlantic Forest (0.1 Pg C). Spatial variation shows that the highest soil carbon stocks are predominantly distributed in the Cerrado biome, with records ranging between 30 and 73 Mg C ha$^{-1}$, while the spatial distribution of the lowest levels is found in the Caatinga biome, varying between 15 and 30 Mg C ha$^{-1}$.

The smaller $C_{REF}$ stocks in the Caatinga are probably related to the climatic condition of this biome, which is characterized by an average precipitation that is rarely greater than 1000 mm year$^{-1}$, and high temperature, with peaks that can reach 37.5°C between months of August and October (Nascimento; Novais, 2020). In the Cerrado, temperatures are also high, however, precipitation varies between 1200 and 1800 mm year$^{-1}$ (Alvares *et al.*, 2013). The lower and irregular precipitation in the Caatinga biome, besides resulting in a lower plant biomass input, when combined with high temperatures, will also result in higher rates of soil organic matter decomposition. Furthermore, there is also the soil component, where in the Cerrado there is a predominance of Oxisols and Ultisols, soils with high potential for the formation of organo-mineral complexes, while in the Caatinga, there is a high occurrence of Entisol Lithic and Quartzpsaments, Aridisol, which they are more susceptible to loss of soil (and organic matter) via erosion (Gomes *et al.* 2019).

Figure 2 - Map of soil carbon stocks (0-30 cm) in Brazilian and BESF soils under native vegetation.




Source: The authors (2023).

In the semiarid region of Northeastern Brazil, Sampaio e Costa (2011) estimated C stock in the 0-100 cm layer at 8.8 Pg C; and when stratified in the 0-20 and 20-100 cm layers, C stocks were estimated at 2.8 Pg C and 6.0 Pg C, respectively. Gomes *et al.* (2019) recorded values of total soil C stock values of 4.88, 17.07 and 11.49 Pg C, in the 0-100 cm layer, for the Caatinga, Cerrado and Atlantic Forest biomes, respectively. According to Bernoux *et al.* (2002) and Gomes *et al.* (2019), the distribution of soil carbon stocks in Brazil is mainly influenced by soil classes, average monthly temperature, precipitation and vegetation, soil depth, in addition to climatic influences that act directly on the production of biomass by native vegetation, which play a fundamental role in the input of carbon into the soil.

### *Land use and cover dynamics*

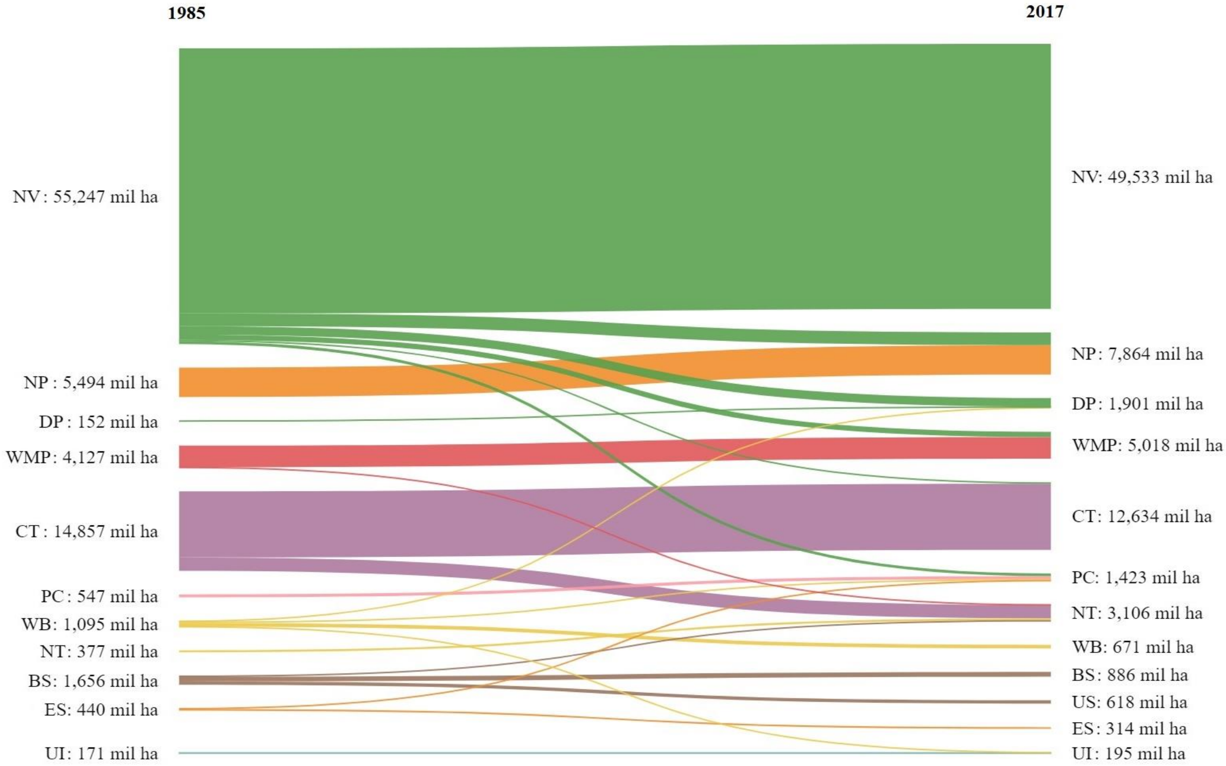
BESF has varied natural attributes, consisting of three major biomes (Caatinga, Cerrado and Atlantic Forest), which results in an environment of high biodiversity with ecological, cultural and socioeconomic importance. Spatial data with information on land use and cover are fundamental for carbon stock estimates, with a critical influence on the balance between SOC input and output.

Based on the area quantification of land use and cover classes at BESF, it was found that native vegetation occupied approximately 49.5 million ha in 2017 (58.9% of the territory), despite the substantial reduction that occurred over the period from 1985 to 2017 due to deforestation (Figure 3). The intensive environmental degradation, due to human actions, resulted in the reduction of the native vegetation area by about 6.6%, which corresponds to 5.70 million ha, which was replaced mainly by agricultural activity, over the 32 years under analysis. Anthropogenic activities and water bodies occupied 41.1% of the total area, mainly for agriculture, which covered about 18.6 million ha in 2017 (Figure 3). It is noteworthy that areas of agriculture with no-tillage system (3.1 million ha), perennial crops (1.4 million ha) and conversion from manual sugarcane harvesting (with burning) to mechanized harvesting (without burning) (618 thousand ha) grew during the evaluated period.

Areas covered by pastures expanded during the period from 1985 to 2017, with a total area, at the end of this period, of 14.8 million ha. Land with well-managed planted pastures occupied an area equivalent to 5.0 million ha in 2017, which represents an increase of 891.76 thousand ha when compared to 1985. On the other hand, even greater increase in areas covered with degraded pastures, associated with inadequate management and low adoption of technologies was observed, which covered, in 2017, about 1.9 million ha, an increase of 12.5 times the area initially found in 1985 (Figure 3).

The use of pastures at BESF becomes worrying due to the expansion of degraded pasture areas, resulting from inadequate management and low use of technology in these areas, which is a negative factor for impacting, in several ways, the conservation and biodiversity of the environment, resulting in losses such as deforestation of native vegetation, erosion and soil compaction. Among factors related to pasture degradation, inadequate animal management and lack of replacement of soil nutrients stand out. The excessive stocking rate, without the necessary adjustments for adequate support capacity of pastures, and the absence of maintenance fertilization, accelerate the degradation process (Macedo; Araújo, 2012). Table 2 shows the changes in land use classes between 1985 and 2017 in each sub-basin, which is essential for understanding changes in soil C stocks.

Figure 3 - Area evolution ($10^4$ ha) of land use and cover classes in BESF (1985-2017).




NV: native vegetation; NP: native pasture; DP: degraded pasture; WMP: well-managed pasture; CT: conventional tillage of annual crops; PC: perennial crop; WB: water; NT: no-tillage of annual crops; BS: burnt sugarcane; US: unburnt sugarcane; ES: exposed soil; UI: urban infrastructure.
Source: The authors (2023).

**Table 2 -** Land-use changes ($10^3$ ha) between 1985 and 2017 by Sub-basin of BESF

| Sub-basins | Land-use classes | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | NV | NP | WMP | DP | NT | CT | PC | BS | US |
| | $10^3$ ha | | | | | | | | |
| Upper SF | -359.3 | -21.3 | 82.4 | 95.3 | 229.5 | -59.9 | 69.2 | -96.3 | 65.4 |
| Medium SF | -2,212.0 | -135.9 | 566.9 | 489.8 | 2,241.4 | -946.4 | 290.9 | -293.4 | 214.6 |
| Sub-medium | -1,134.9 | 657.4 | 52.9 | 408.6 | 322.0 | -413.8 | 107.9 | -28.3 | 42.7 |
| Lower SF | -351.3 | 611.0 | -179.7 | 276.5 | 44.2 | -453.3 | 8.6 | 16.4 | 12.9 |
| Metropolitan | -144.7 | 21.2 | 3.5 | 9.4 | -10.5 | 85.9 | 43.4 | -15.7 | 18.2 |
| Jaguaribe | -859.6 | 694.3 | 94.3 | 190.9 | -101.1 | 8.4 | 111.9 | -82.4 | 85.2 |
| Piranhas-Açu | -241.8 | 276.9 | 151.7 | 147.2 | 17.2 | -312.1 | 105.0 | -146.9 | 95.3 |
| Apodi | -386.5 | 265.9 | 40.6 | 58.7 | -19.6 | -43.3 | 148.2 | -75.4 | 55.5 |
| Paraíba | -17.2 | 0.2 | 79.1 | 73.0 | 6.2 | -97.4 | -9.0 | -47.5 | 28.2 |
| BESF ($10^3$ ha) | -5,707.3 | 2,369.7 | 891.8 | 1,749.3 | 2,729.3 | -2,231.8 | 876.1 | -769.4 | 618.0 |

NV: native vegetation; NP: native pasture; DP: degraded pasture; WMP: well-managed pasture; CT: conventional tillage of annual crops; PC: perennial crop; WB: water; NT: no-tillage of annual crops; BS: burnt sugarcane; US: unburnt sugarcane.
Source: The authors (2023).

### *Changes in soil organic carbon stocks (SOC)*

In BESF territory, it is estimated that there was an increase of 0.72 Tg C year$^{-1}$ in SOC stocks, with an average rate of 0.12 Mg C ha$^{-1}$ year$^{-1}$, during the period from 1985 to 2017 (Table 3). This increase (~1%) is associated with the expansion of no-tillage areas, well-managed pastures and mechanized sugarcane harvesting, without burning. The significant increase in SOC stocks is only possible with a management system that reduces soil organic matter degradation (Lal, 2018). Other studies corroborate the results found due to the expansion of areas under conservative management in BESF and point out that carbon accumulation may be associated with the adoption of no-tillage systems (Ogle *et al.*, 2019; Wang *et al.*, 2020), harvesting sugarcane without burning (Cerri *et al.*, 2011; Signor *et al.*, 2014) and well-managed pastures (Maia *et al.*, 2009; Braz *et al.*, 2013). Thus, the adoption of conservationist managements reduces $CO_2$ emissions, which are considered tools for mitigating and adapting to climate change (Lorenz; Lal, 2016), with potential to increase the amount of SOC due to the high production of plant biomass above and below ground (Lal, 2018; Bai *et al.*, 2019).

When analyzing SOC stocks by sub-basin from 1985 to 2017, the highest C increase was recorded in the Medium São Francisco basin, comprising the Caatinga and Cerrado biomes, which resulted in increase of 0.54 Tg C ha$^{-1}$ and average rate of 0.22 Mg C ha$^{-1}$ year$^{-1}$. This increase in carbon stocks is associated with the expansion of the no-tillage system and the conversion of sugarcane cultivation systems from manual to mechanized. The Sub-Medium São Francisco sub-basin had the highest losses in SOC stocks, with an estimated reduction of 0.07 Tg C year$^{-1}$ and an average loss rate of 0.06 Mg C ha$^{-1}$ year$^{-1}$ (Table 3). In the Sub-Medium sub-basin, the area of degraded pasture increased by 408.5 thousand hectares between 1985 and 2017, which represented 23.3% of the increase observed for this category of land use throughout BESF (Table 2). Likewise, the area with permanent crops increased by 107.9 thousand hectares in the evaluated period. These are two types of land use that result in losses of soil C, especially in the Caatinga biome (Table 1). In the Metropolitan sub-basin, there were significant increases in the areas of degraded pastures and perennial crops, but there was also a decrease in the area of no-tillage system (Table 2). Therefore, these land use dynamics explain the average carbon loss in these two sub-basins.

**Table 3** - Estimates of changes in carbon stocks and changes in area by sub-basin and biomes that comprise the Extended São Francisco River Basin, during the period from 1985 to 2017.

| Land use | Area (10$^3$ ha)* | C stock change (Tg C) | C stock change / yr (Tg C year$^{-1}$) | C stock change / ha / yr (Mg C ha$^{-1}$ year$^{-1}$) |
|---|---|---|---|---|
| **Sub-basin** | | | | |
| Upper SF | 364.45 | 1.22 | 0.04 | 0.10 |
| Medium SF | 2,427.99 | 17.35 | 0.54 | 0.22 |
| Sub-medium SF | 1,149.49 | -2.18 | -0.07 | -0.06 |
| Lower SF | 336.64 | 0.09 | 0.00 | 0.01 |
| Metropolitan | 155.43 | -0.20 | -0.01 | -0.04 |
| Jaguaribe | 1001.50 | 2.40 | 0.08 | 0.08 |
| Piranhas-Açu | 334.29 | 2.98 | 0.09 | 0.28 |
| Apodi | 430.42 | 0.46 | 0.01 | 0.03 |
| Paraíba | 32.73 | 0.82 | 0.03 | 0.78 |
| **Biome** | | | | |
| Cerrado | 2,125.08 | 18.29 | 0.57 | 0.27 |
| Caatinga | 3,654.20 | -1.38 | -0.04 | -0.01 |
| Atlantic Forest | 453.64 | 6.03 | 0.19 | 0.42 |
| BESF | 6,232.93 | 22.94 | 0.72 | 0.12 |

* Refers to the anthropized area.

Source: The authors (2023).

The increase in the adoption of the no-tillage system, the use of mechanization in sugarcane cultivation and the use of soil with natural and well-managed pastures promoted significant increase in SOC stocks, as recorded in Piranhas-Açu, Jaguaribe, Alto São Francisco, Paraíba and Apodi sub-basins (Table 2). BESF has significant area with sugarcane cultivation and the burning harvesting has been gradually replaced by mechanized harvesting, without the use of fire, which is a practice that can reduce

GHG emissions, guaranteeing increase in soil carbon content and stocks (Signor *et al.*, 2014).

Changes in the land use in the Cerrado biome led to the highest soil carbon gains among biomes that comprise BESF, with an estimated gain equivalent to 0.57 Tg C year$^{-1}$, with average changes of 0.27 Mg C ha$^{-1}$ year$^{-1}$. Likewise, the Atlantic Forest biome recorded soil carbon gain estimated at 0.19 Tg C year$^{-1}$, with average gain rate equivalent to 0.42 Mg C ha$^{-1}$ year$^{-1}$ (Table 2). This increase in soil carbon corroborates changes in management that have occurred over the years, with the conversion from conventional agricultural systems to conservationist systems and better management of pastures in these biomes, associated with greater biomass input and adequate soil management in areas cultivated with these agricultural systems, with high capacity to accumulate carbon combined with minimal soil disturbances, which favor carbon protection, despite the growth of areas with degraded pastures.

The Caatinga biome had losses in soil carbon stocks estimated at 0.04 Tg C year$^{-1}$ and an average loss rate equivalent to 0.01Mg C ha$^{-1}$ year$^{-1}$, from 1985 to 2017 (Table 3). The change in land use through non-conservationist agricultural practices contributes to the loss of carbon in this biome. Despite the growth in the adoption of conservationist managements, such as the no-tillage system and well-managed pastures, which increased by 1.04 and 0.586 million hectares between 1985 and 2017 in the Caatinga biome, was enough to compensate for losses due to inadequate soil management.

In no-tillage areas, Araújo *et al.* (2017) recorded a 25.2% increase in SOC stocks in the 0-20 cm layer compared to native Cerrado areas. Campos *et al.* (2013) and Rossetti and Centurion (2015), in the Cerrado biome, reported an increase of 14.3% and 29.7% in soil carbon stocks, respectively, upon conversion from conventional cultivation to no-tillage system. Similarly, when well managed in the Cerrado biome, pastures can promote the maintenance or even the increase of SOC stocks when compared to native vegetation. Ogle *et al.* (2004) and Maia *et al.* (2009) also demonstrate that improved pastures in tropical regions increase SOC stock on average by 17% to 19%, respectively. Urquiaga *et al.* (2010) reported that the significant increase in SOC stocks is only possible under a management system that reduces soil organic matter degradation and contributes to an increase in N in the soil-plant system.

Despite the growth in the adoption of conservationist managements (~93%), in areas delimited by the Caatinga, as in the sub-medium São Francisco sub-basin, no SOC gain was observed, which suggests that deforestation and non-conservationist practices, such as the use of degraded pastures, contributes to carbon losses in the system. In addition to agricultural management practices, high temperatures and evapotranspiration, and low and irregular rainfall frequencies in the region limit plant biomass production, which, among other factors, harms SOC stocks in the semiarid region (Oliveira *et al.*, 2015). Smaller-proportion SOC reductions, estimated between 3 and 9% in degraded pastures in tropical regions, for the 0-30 cm soil layer, were recorded after a few years of pasture use (Ogle *et al.*, 2004; Maia *et al.*, 2009). Conventional annual cropping systems, in the Brazilian semiarid region, reduce SOC stocks by 13-26%, depending on land use, time and soil depth (Medeiros *et al.*, 2020). This region is characterized by small and medium-sized rural properties, with low purchasing power and without adequate access to conservative techniques, which results, in many cases, in soil degradation and consequent SOC losses.

The adoption of the no-tillage system, well-managed pasture and the conversion from manual sugarcane harvesting (with burning) to the mechanized system (without burning), in general, resulted in SOC gains at BESF, offsetting SOC losses generated by the remaining extensive areas of conventional cultivation and the increase in areas of poorly-managed pasture. Thus, these results show the need to encourage the adoption of these practices or conservationist systems, especially in the semiarid region of BESF, which is known to be more susceptible to soil carbon losses. Conventional cultivation in the semiarid region leads to a 17% SOC loss, while in the Cerrado and Atlantic Forest, losses are 10 and 14%, respectively (Medeiros *et al.*, 2020, MCTI, 2020). In this context, the challenge is to spread soil management systems and practices in the Caatinga biome, such as agroforestry systems, crop consortium and no-tillage, which allow raising or at least maintaining carbon and SOM (Maia *et al.*, 2007; Maia *et al.*, 2019). Such a challenge; however, will face great vulnerability related to the climate and soil conditions of the region, but also, to land structure and limitations regarding the educational level of the rural population and the difficulty of accessing technologies and appropriate technical assistance.

Finally, the need to promote sustainable land use and soil management at BESF is highlighted in order to preserve and recover SOC stocks and contribute to the mitigation of

GHG emissions. In this sense, public policies and government actions must be directed towards the promotion of sustainable agricultural practices and environmental conservation, in addition to raising awareness and training of rural producers and other actors involved in the management of the São Francisco river basin.

## CONCLUSIONS

Throughout this study, changes in SOC stocks as a result of changes in land use in BESF were observed. It was possible to observe that soils play a crucial role in mitigating GHG emissions and adapting to climate change, thus being an important indicator of soil quality and sustainability of agroecosystems.

Based on the results obtained, it was found that BESF soils store 2.6 Pg C in the 0–30 cm layer, with the Caatinga biome having the highest amount of stored carbon (1.7 Pg C). The main land use system at BESF in territorial extension is native vegetation, covering 66.3% of the total area. However, this system has suffered significant reductions over the years, with areas deforested and converted mainly into pasture and agriculture.

Overall, it was observed an increase in soil carbon stock in seven of the nine BESF sub-basins during the period from 1985 to 2017, resulting in an increase of 0.72 Tg C year$^{-1}$, with an average annual rate of 0.12 Mg C ha$^{-1}$ year$^{-1}$. Positive highlights for the Medium SF, Piranhas-Açu and Paraíba sub-basins, which presented soil C accumulation rates of 0.22, 0.28 and 0.78 Mg C ha$^{-1}$ year$^{-1}$, while the Sub-medium SF and Metropolitan sub-basins had losses of 0.06 and 0.04 Mg C ha$^{-1}$ year$^{-1}$. Among the biomes, the Caatinga, even with the considerable increase in the adoption of more conservationist systems, such as no-tillage and well-managed pastures, was the biome that showed loss of soil C, which is mainly due to its greater susceptibility to losing C from the soil, but also greater difficulty in accumulating it even in conservationist land use systems.

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## AUTHOR CONTRIBUTION

Saniel Carlos dos Santos collected all the data, analyzed and wrote the text. Higor Costa de Brito extracted and processed the land use data (MapBiomas) and wrote the text. Iana Alexandra Alves Rufino extracted and processed the land use data (MapBiomas) and wrote the text. Stoécio Malta Ferreira Maia conceived the study, supervised and wrote the text.