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Mapping of soil carbon balances changes in the dry tropical forest ecosystem in Pernambuco Brazil

Rafael Rodrigues da Silva[1], Rômulo Simões Cezar Menezes[2], Ana Lúcia Bezerra Candeias[3], Aldo Torres Sales[4], Alexandre Hugo Cezar Barros[5], Everardo Valadares de Sá Barreto Sampaio[6], Ivson Lucas de Santana[7], Tarcila Rosa da Silva Lins[8]

[1] Nuclear Energy Department, Prof. Luiz Freire Av., 1000, Federal University of Pernambuco, Recife - PE, 50740-540, Brazil. rodriguesrs19@gmail.com/ https://orcid.org/0000-0002-6673-6972 (author correspondent). [2] Nuclear Energy Department, Prof. Luiz Freire Av., 1000, Federal University of Pernambuco, Recife - PE, 50740-540, Brazil - romulo.menezes@ufpe.br/ https://orcid.org/0000-0001-8740-366X. [3] Cartographic Engineering Department, Acad. Hélio Ramos Av., s/n - 2º floor - room 201, Federal University of Pernambuco, Recife - PE, 50740-530, Brazil - analucia@ufpe.br /https://orcid.org/0000-0002-9021-7603. [4] Nuclear Energy Department, Prof. Luiz Freire Av., 1000, Federal University of Pernambuco, Recife - PE, 50740-540, Brazil. - aldotsales@gmail.com / https://orcid.org/0000-0003-2585-3221. [5] Embrapa-Uep Recife - PE, 51020-240, Brazil - alexhugo2006@gmail.com / https://orcid.org/0000-0002-7974-4402. [6] Nuclear Energy Department, Prof. Luiz Freire Av., 1000, Federal University of Pernambuco, Recife - PE, 50740-540, Brazil. - sampaio.everardo@gmail.com / https://orcid.org/0000-0002-4745-016X. [7] Nuclear Energy Department, Prof. Luiz Freire Av., 1000, Federal University of Pernambuco, Recife - PE, 50740-540, Brazil - ivson.lucas09@gmail.com/ https://orcid.org/0000-0001-9009-8950. [8] Nuclear Energy Department, Prof. Luiz Freire Av., 1000, Federal University of Pernambuco, Recife - PE, 50740-540, Brazil - tarcila.lins@hotmail.com/ https://orcid.org/0000-0002-5809-6741.

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A B S T R A C T

Land use changes represent an important part of anthropic greenhouse gas emissions. Studies on the dynamics of carbon stock in soil and vegetation resulting from changes in land use in dry tropical areas are still scarce and practically absent in the Northeast region of Brazil. Combining field and remote sensing information with spatial analysis can contribute to understanding the spatial dynamics of carbon in the soil. Given this, we aimed to estimate and map carbon balances in the semiarid region of Pernambuco state, Brazil (86,135 km^2). Maps of carbon stocks for soil and vegetation for 2000 and 2016 were created on a scale of 1: 100,000, stratified by land use and soil types. During the time-lapse of 16 years, 28% of the area carbon stocks (C) decreased in soil and vegetation, 57% had no significant changes and only 13% had increases. Most of the change was associated with converting the open native forest vegetation (Caatinga) into pastures. The net C loss was 291 million Mg, representing an average of 2 Mg ha^{-1} year^{-1} of C loss. Water bodies, urban areas, and other unclassified uses were not accounted for but amounted to only 2% of the area. Overall, the GIS method proved to be a fast and feasible approach to monitoring carbon balances derived from land use changes on a regional scale.

Keywords: Caatinga, pasture, crops, semiarid, carbon stocks

Mapeamento das mudanças no balanço de carbono do solo no ecossistema da floresta tropical seca em Pernambuco Brasil

R E S U M O

As mudanças de uso do solo representam parte importante das emissões de gases de efeito estufa, estudos acerca da dinâmica do estoque de carbono no solo e na vegetação resultantes de mudanças no uso da terra em áreas tropicais secas ainda são escassos e praticamente ausentes na região Nordeste brasileira. A combinação de informações de campo e de sensoriamento remoto com a análise espacial pode contribuir no entendimento da dinâmica espacial do carbono no solo. Diante disso, objetivou-se estimar e mapear os balanços de carbono na grande região semiárida (86.135 km^2) do estado de Pernambuco, Brasil. Foram elaborados mapas de estoques de carbono do solo e da vegetação para os anos de 2000 e 2016 na escala de 1:100.000, estratificados por uso da terra e tipos de solo. Neste período, 28% da área apresentou reduções nos estoques de C no solo e na vegetação, 57% não teve alterações significativas e apenas 13% tiveram aumentos. A maior parte da mudança esteve associada à conversão da vegetação de floresta nativa aberta (Caatinga) em pastagens. A perda líquida de C foi de 291 milhões de Mg, representando uma perda média de 2 Mg C ha^{-1} ano^{-1}. Corpos de água, áreas urbanas e outros usos não classificados não foram contabilizados, mas representaram apenas 2% da área. No geral, o método provou ser uma abordagem rápida e viável para monitorizar os balanços de carbono derivados de mudanças no uso da terra à escala regional.

Palavras-chave: Caatinga, pastagem, plantações, semiárido, estoques de carbono

Introduction

Soil and vegetation are important carbon reservoirs. However, without correct landscape management practices, they can act as emitters of greenhouse gasses (GHG) (Zanini et al., 2021; Ondiek et al., 2021). Changes in land use and land cover associated with deforestation and soil degradation are among the main factors contributing to greenhouse gas emissions (IPCC, 2018; BRASIL, 2022; Nazir, 2024). On the other hand, forest restoration can contribute to soil carbon sequestration (Zanini et al., 2021).

For centuries, the landscape of the Brazilian semiarid has been changing due to the deforestation of native vegetation, which has established agricultural fields and pastures (Silva, Leal e Tabarelli, 2017). However, it is essential to mention that in the Brazilian semiarid, livestock breeding, rainfed agriculture, and firewood extraction are the main economic activities of the rural population, although they result in negative impacts on stability, soil, and vegetation regeneration capacity in dry tropical forests (Menezes et al., 2021; Refati et al., 2023).

The semiarid area of the state of Pernambuco covers more than 80,000 km^2, including a diversity of climates, soil types and land uses (Menezes et al., 2021; Silva, 2023). Despite the great extension and socioeconomic relevance of the Brazilian semiarid region, spatially explicit data on carbon balances are scarce due to changes in land use in this region (Medeiros, 2023). The limited availability of financial and human resources to carry out scientific research to obtain data are factors that hinder the dissemination of this information.

Given this scenario, developing studies on the dynamics of land use and coverage is a necessity, as well as understanding the negative impacts caused to the soil by anthropogenic disturbances in the semiarid region of Pernambuco are essential to understand the biogeochemical carbon cycle and the interactions between the biosphere and the atmosphere in this region (Menezes, 2021; Medeiros, 2023). For this, gathering existing data in databases and obtaining new data through other studies is necessary.

Among the possibilities for obtaining data, combining field and remote sensing information with spatial analysis demonstrated its potential to expand the data collected in the field (Sales et al., 2021). This new way of processing information can be a supportive approach to modeling efforts to evaluate climate and land use change scenarios, give subsidies to formulating public policies for adaptation, and better guide the development of more sustainable long-term land use systems Nascimento et al., 2021).

Thus, the present study aimed to estimate variations in soil carbon stocks due to changes in land use and cover in the dry tropical forest ecosystem part (Caatinga biome) of Pernambuco State - Brazil. Furthermore, it calculates carbon balances based on soil and land use data and specializes in carbon balances from 2000 to 2016.

Material and methods

Study area

The study area was the semiarid portion of Pernambuco state, located in the Brazilian Northeast region (Figure 1). The region comprises 122 municipalities and 85,900 km² (Nascimento et al., 2022).

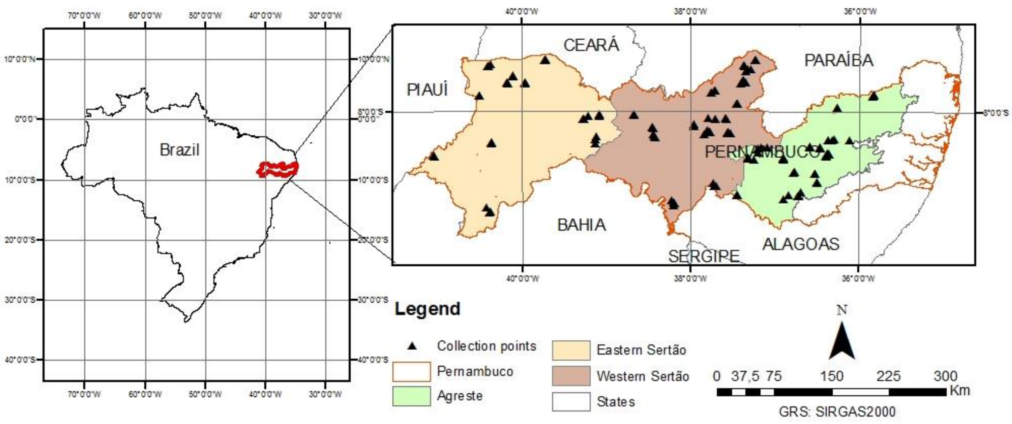


Figure 1. Graphical representation of the state of Pernambuco (Brazil), where the three different types of vegetation relevant to this study can be seen (Agreste, Eastern Sertão and Western Sertão) and the distribution of collection points throughout the state.

The spatial and temporal irregularity of rainfall is undoubtedly the most remarkable characteristic climatic feature of the region. However, other climatic variables, such as low relative air humidity, high air temperatures, and annual potential evapotranspiration rates much above rainfall, converge towards limited water availability to the plants for most of the year.

This climate condition allows the growth of water shortage-adapted vegetation, classified as dry tropical forests. However, the intensity and magnitude of these climatic events have been the environmental variables used to divide the semiarid portion of Pernambuco state into three major zones (Agreste, and Eastern and Western Sertão). The Agreste zone has an average annual rainfall of around 680 mm, most distributed between April and August. In the Eastern Sertão, the average rainfall is 582 mm, but more than 80% occurs between March and June. In the Western Sertão, the average rainfall is 473 mm, most occurring between January and April (Pinheiro et al., 2018).

The high seasonal water deficit in all three zone conditions sets the conditions for the growth of a seasonally deciduous forest with a high diversity of trees, shrubs, and forbs known as "Caatinga" (Sampaio, 1996). This diversity is also marked in the various soil classes in the region, which vary from shallow and clayey to deep and sandy soils (Marcelino et al., 2022; Sampaio et al., 1996).

Soil C stocks

Data on soil C stocks were obtained from a large regional project, which had been published for the Agreste and Eastern Sertão (Jesus et al., 2019) and Western Sertão (Santana et al., 2019) zones. In summary, the soil sampling was spatially distributed in both studies following a two-level procedure. The first level selected the ten most representative soil classes for the study. The soil classes were obtained from the Agroecological Zoning of Pernambuco (Silva, 2001) on a scale of 1:100.000 (Figure 2), updated for the new Brazilian soil classification system (Jacomine, 2013).

In the second level, four land use and cover types were sampled in each of the ten soil classes: 1) dense native Caatinga; 2) open Caatinga; 3) pasture; and 4) agricultural fields (Figure 3). These land uses had been established based on the methodology described by Aciolly (2017) to represent the predominant land uses in the semiarid area of Pernambuco. The combination of these land uses and soil classes covers more than 90% of the area of the semiarid region of Pernambuco state (Menezes et al., 2021).

In both studies (Jesus et al., 2019; Santana et al., 2019), three sampling areas were selected for each soil class, so they were spatially distributed as evenly as possible among the different patches of the soil classes in the zones. In each of these three areas, one sampling point was located for each land use, so they were as closely positioned as possible. A total of 156 points were sampled in both studies across the three zones. In each sampling point, soil and root samples were collected opening a 0.7 m x 0.7 trench, down to 1.0 m deep (or until a rock layer was reached), separately for seven soil depth layers: 0-10, >10-20, >20-30, >30-40, >40-60, >60-80 and >80-100 cm. The average soil C stock for each combination of soil class and land use was calculated from the values of the three replicates.

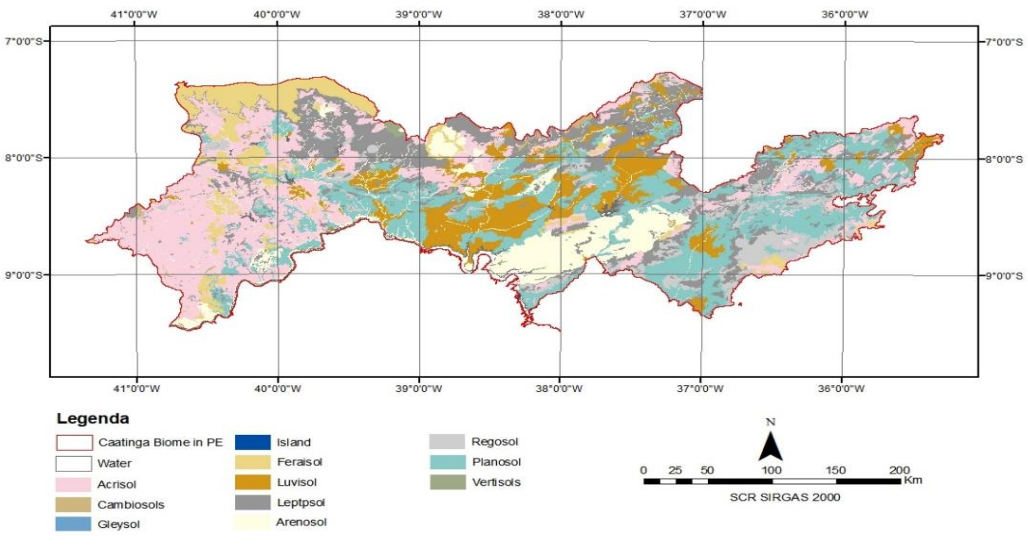
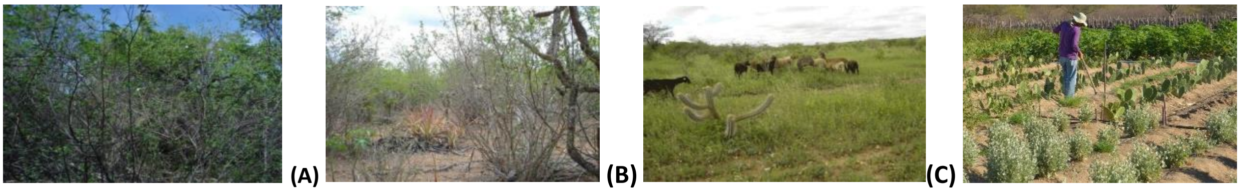


Figure 2. Soil classes in the semiarid area of Pernambuco state, Brazil.



(A) (B) (C) (D)

Figure 3. Diversity of vegetation types found in the study area, located in the semi-arid region of the state of Pernambuco (Brazil). A) Dense native Caatinga; B) Open Caatinga; C) pasture; and D) agricultural fields

Carbon stocks were mapped for the whole dry tropical forest portion of Pernambuco state, estimates had to be made for the soil classes and land uses not represented in both studies (Jesus et al., 2019; Santana et al., 2019). They comprise less than 10% of the area (Menezes et al., 2021) and some soil uses have meager carbon stocks, but they must be considered to fulfill the whole map.

Stocks in Cambisols and Vertisols, which cover 1.8 and 3.1% of the area, were obtained from published studies (Jacomine 1971 and 1972, Jacomine et al. 1973, 1975 and 1976, and Funceme 2012). Stocks in areas classified as "urban", "water bodies" and "non-observed", which cover still lower proportions of the semiarid area of Pernambuco (0.1, 1.3 and 0.2%, respectively), were considered null (Brasil, 2015).

Estimation of soil C balances

To calculate the loss or gain of soil C due to land-use changes between 2000 and 2016, we used the methodology proposed by the IPCC (2006), taking as reference data the Third Brazilian Inventory of Anthropogenic Greenhouse Gas Emissions and Removals (MCTIC, 2015). Gains or losses of soil C stock resulting from changes in land use over 20 years (Table 1) were calculated based on equation 1

Equation 1: $ESi = Ai \times Csoil\ (fc(t°) - fc(tf)) \times (T/2)/20$ (IPCC, 2003)

Where: ESi: net emission associated with polygon i in period T due to variation in soil carbon (tC); Ai: Area of the polygon i (ha); Csoil: soil C stock under the soil-vegetation association of the polygon (reference C); fc(t): soil carbon change factor at time t (dimensionless).

Table 1: Soil carbon change factors with land-use change, adapted from Brasil (2015).

Land use and land cover	Fc	Cod. MapBiomas 2.3	Class MapBiomas 2.3
FNM – Unmanaged Forest	1	3 + 4	Forest Formation and Savana Formation
FM – Managed Forest	1	3 + 4	Forest Formation and Savana Formation
GNM – Unmanaged Grasslands	1	12	Grassland
GM – Managed Grasslands	1	12	Grassland
Gsec – Secondary Grasslands	1	12	Grassland
AP – Planted Pasture	0,97	15 -16 - 17	Pasture
AC – Agricultural Area	0,612	18-19-20-21-28	Agriculture
S – Urban Area	0	24	Urban Infrastructure
A – Rivers and Lakes	0	26	Water
Res – Reservoirs	0	26	Water
O - Non-observed	0	27	Non-observed

Soil carbon change factors (Table 1) were based on the Third National Communication of Brazil to the United Nations Framework Convention on Climate Change (Brasil, 2015), which is also an adaptation of the Good Practice Guidance Tables 3.3.4 and 3.4.5 (IPCC, 2014).

The third and fourth columns of Table 1 were taken from collection 2.3 of the MapBiomas project, where "Cod. MapBiomas 2.3 " corresponds to the associated code for each pixel-rated use and coverage (MapBiomas, 2018).

Geodatabase and mapping methodology

The values for each combination of soil class and land use and cover were inserted in the generated maps for 2000 and 2016, which made it possible to perform the spatial analysis and the calculations of the carbon balances in the study area during this period. The spatial (geodata) data were unified for the Geocentric Reference System for the Americas 2000 (IBGE, 2005). A geographic database (Geodatabase) containing geo-referenced spatial information, including geographic coordinates and quantitative attributes with soil and vegetation C stocks was organized. The intersection of these information plans for the two years evaluated made it possible to identify whether or not changes in C stocks occurred in this period.

Results and discussion

The conversion of forests into cropland and pastures were the most important soil use change during the period evaluated (Table 2). Overall, land-use changes promoted more negative than positive changes in the of C stocks dynamics in the dry tropical forests of Pernambuco, given the higher C stocks of dense and open caatinga forests compared to pastures and cropland (Althoff et al., 2016; Moura et al., 2016).

The conversion of large areas of forests into pastures during the first decade of the century was driven by a combination of environmental and economic factors. More specifically, there was a sequence of years with near or above-average rainfall between 2004 and 2011, which was associated with regional economic growth and, therefore, there was a boost in the cattle herd in the region that led to the increase in the area of pastures. After this period, the severe drought between 2012 and 2017 allowed for relatively little recovery of the forest cover in the region.

Table 2: Comparison of covered area with the main land uses of the semiarid region of Pernambuco state, Brazil, for two years (2000 and 2016).

Land use	Area 2000		Area 2016		Change
	(km²)	(%)	(km²)	(%)	(km²)
Open Caatinga (Savana Formation)	39148,2	46,9	32257,2	38,6	-6891
Pasture	24093,7	28,9	26791,8	32,1	2698,1
Agriculture or Pasture	11475,3	13,7	12517,8	15,0	1042,5
Grassland	6024,9	7,2	8806,3	10,5	2781,4
Dense Caatinga (Forest Formation)	1273,4	1,5	1200,8	1,4	-72,7
Water	1076,1	1,3	1053,0	1,3	-23,1
Agriculture	165,3	0,2	272,5	0,3	107,2
Non-observed	158,0	0,2	119,4	0,1	-38,6
Urban Infrastructure	93,0	0,1	482,6	0,6	389,6
Total	83507,9	100,0	83501,3	100,0	-

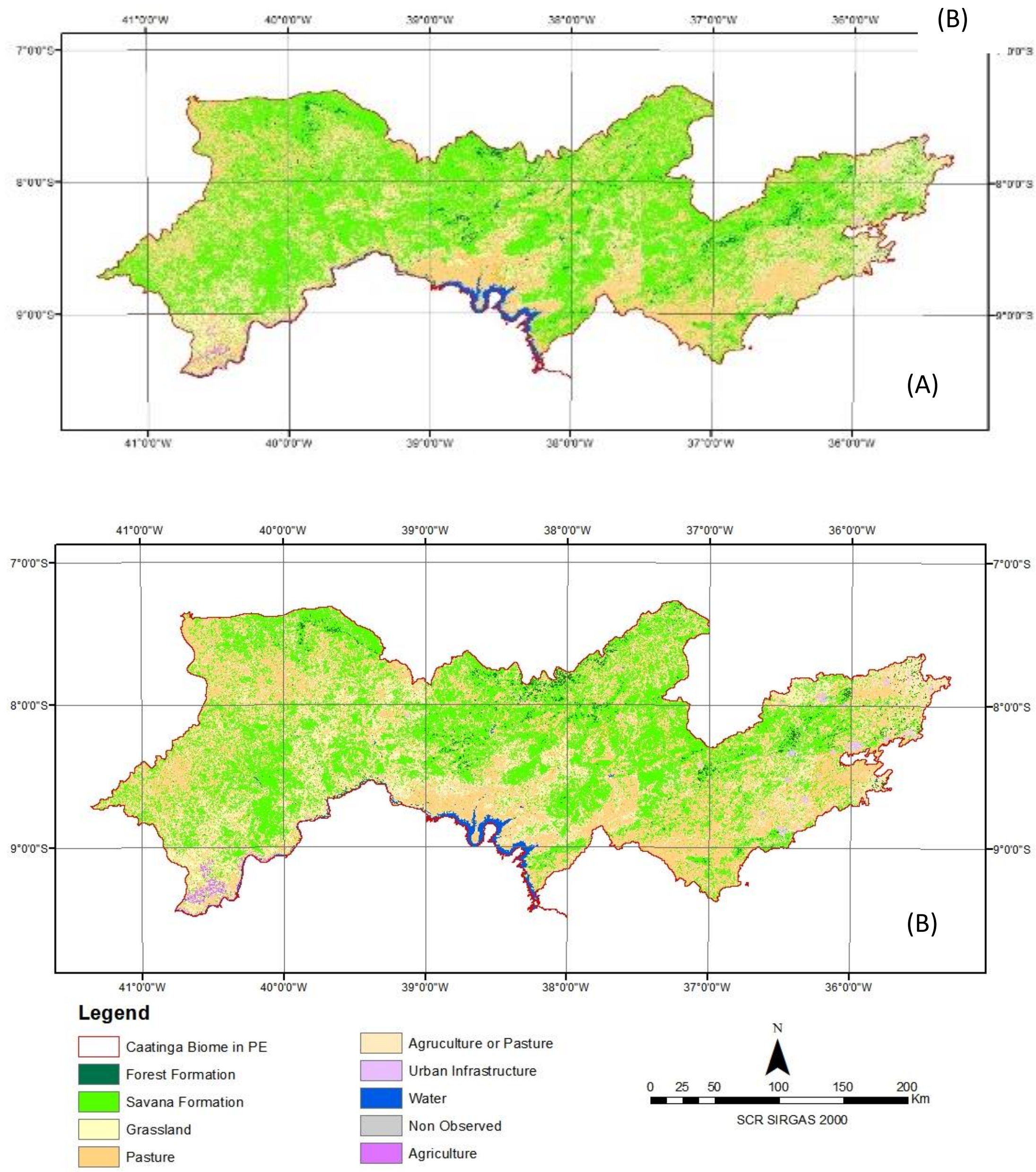


Figure 4 Maps representing changes in land use and cover in the state of Pernambuco (Brazil), in the years 2000 (A) and 2016 (B)

In the evaluated period, the Agreste region had the most considerable conversion of Caatinga into anthropic uses (Agriculture, pastures, urban infrastructure), followed by the Eastern Sertão and Western Sertão regions. This reduction was marked by an increase in Grassland (2.781,4 km²), Pastures (2.698,1 km²), and Agriculture and Pasture (1.042,5 km²) areas (Figure 4 A e 4 B).

Highlight the low conversion of Dense Caatinga (Forest Formation) into anthropic uses over the seventeen years of study in the dry tropical forest portion of Pernambuco (Table 2). We attributed this result to the fact that Dense Caatinga remnants in Pernambuco are located in hilly areas of difficult access and, therefore, were not significantly affected by the expansion of pastures observed during this period (Santos et al., 2022).

The urban area grew significantly during the seventeen years, going from 93 km² to 483 km², although still covering a small proportion of the total semiarid area in Pernambuco (0.6%). Although the urban growth may have occupied a small area, on a regional scale, it demonstrates the strength of the urbanization process in the region over a relatively short period (16 years). The increase in the urban population may also help explain the smaller increase in croplands, which demand more labor than pastures (Livestock systems). Maybe for this reason, deforested open caatinga areas were mainly converted into pastures, not cropland.

Mapping of C balances

Differences in C stocks resulting from the land use changes were observed throughout the whole semiarid region of Pernambuco. The dispersion of areas that had increases or decreases in soil C within the analyzed period is plotted in Figure 5. In the Agreste, soil C stocks increased due to the conversion of agriculture into pasture areas. Meanwhile, in some parts of the Agreste, where Pasture and Agriculture have replaced the Forest Formation, soil C stocks have been reduced (C emissions)

The highest C stocks were found in western Sertão, and this could be attributed to a large portion of the region still being covered in forest. In other areas, the changes in C stocks were caused mainly by converting Forest Formation into Pasture or Agriculture. Generally, soil and vegetation C stocks can be explained mainly through converting native forest areas to other uses (Kabiri et al., 2015). Menezes et al. (2021) reported that converting forested areas into pastures and agriculture in the semiarid NE region of Brazil may lead to fast ecosystem C losses, usually greater than 50%. Alternatively, the recovery of C stocks occurs in a much slower process, as suggested by Althoff et al. (2016), which reported periods of more than 60 years for the recovery of soil and vegetation C stocks when agricultural/pasture areas are allowed to recover the native caatinga vegetation.

Eastern Sertão had the most significant decrease in C stocks, which we addressed to as an intense loss of the native vegetation. In the last 16 years, the Gypsum Industrial Hub has been the main economic activity in the eastern region. Although this activity is mainly located in the western sertão, it also causes substantial economic and social progress in the region once it demands a high amount of fuelwood to calcinate the gypsum, transcending the offer of wood available in the region. Most of the fuelwood used comes from illegal logging in the Caatinga, reducing C stocks in the ecosystem.

Overall, the study region lost about 45.1 x 106 Mg of C, distributed in 2,33 x 106 ha, corresponding to 28% of the whole dry tropical forest area in Pernambuco. The average C loss in the areas with negative C balance was 19.4 Mg ha-1 (Table 3). In the same period, the soil C stock increased 9.0 x 106 Mg of C in 1.12 x 106 ha, corresponding to 13% of the area. In these areas, there was an average gain of 8.11 Mg ha^{-1} of C.

In most areas (57%), the land cover remained about the same between 2000 and 2016, i.e., there were no significant changes in the soil and vegetation C stocks. In 2000, 96.7% of the soils in the Pernambuco semiarid portion were covered by Savana Formation, Pasture, Agriculture or Pasture, and Grassland. In 2016 the land cover was quite similar to 2000 when the same classes covered 96.2%. However, the land cover changed between classes: the Open Caatinga Formation area had an increase of 17.7%, and the other classes had increases of 11.07% (Pasture), 9.49 % (Agriculture/Pasture), and 45.83% (Grassland).

These results demonstrate the need for the detailed monitoring of the C cycle dynamics in the semiarid region since C balances may vary strongly according to the land use and cover changes through time. C balances may also differ depending on the geographical scale and period of the study.

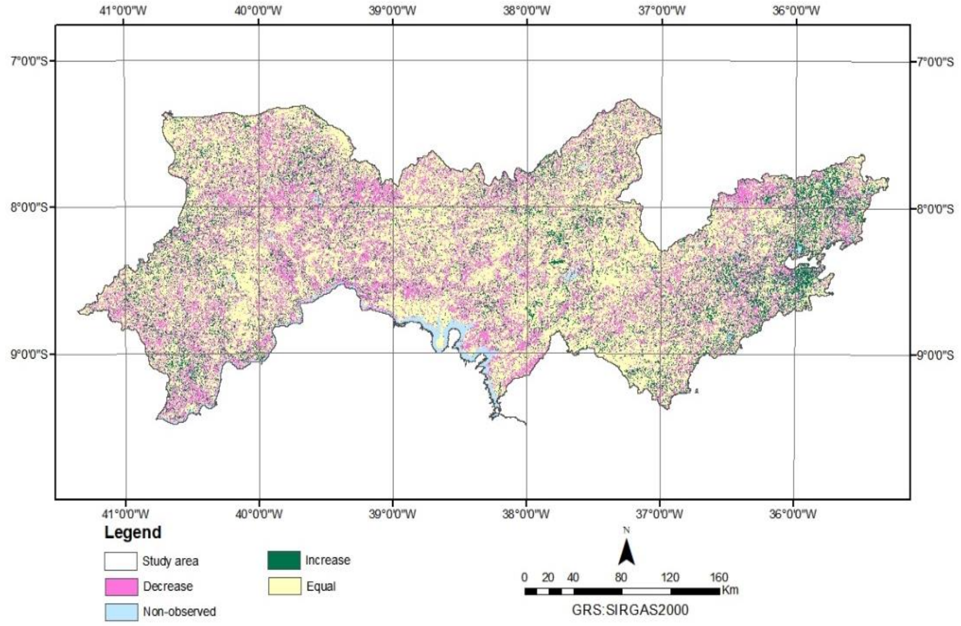


Figure 5 - Representation of soil carbon balances occurred in the state of Pernambuco (Brazil) during the period between 2000 and 2016.

For example, Mendes et al. (2020) concluded that a dry tropical forest in Rio Grande do Norte State in NE Brazil acted as an atmospheric carbon sink during the years 2014 and 2015, which contrasts with our findings on the same ecosystem in Pernambuco state, which acted as a source of atmospheric CO2 between 2000 and 2016.

Finally, it is important to mention that the areas classified as water bodies, urban and non-observed, were considered null due to a lack of methodology to determine carbon stocks in these land covers quickly. However, water bodies have some C stocked in their sediments, and urban areas also have some soil C in private and public gardens and other green areas (e.g. vacant lots). These green areas vary from city to city but usually constitute a small extent due to the soil sealing most of the area by floor pavements and buildings. The possible error on the mapping of the state stocks due to the assumption of zero stock in these three land covers is considered to be low because they represent less than 2% of the studied area and, more importantly, changes in their C stocks over the period may be an even smaller proportion.

Table 3: Carbon balance in the soil (layer 0-100 cm) due to the change of cover and land use in the semiarid region of Pernambuco from 2000 to 2016.

Changes in carbon stocks in the soil	Area (ha)	ES Total	Change (%)
Increase	1.115.170,92	-9.040.877,359	13%
Non-observed	172.910,88	-	2%
Decrease	2.326.448,34	45.063.310,46	28%
No significant changes	4.736.263,95	-	57%
	8.350.794,09	**Total**	100%

Conclusion

Significant losses in carbon stock in soil and vegetation in the study area occurred between 2000 and 2016. There were considerable losses of Open Caatinga, mainly due to the conversion of this native forest vegetation into pastures and, to a lesser extent, into agricultural fields. Overall, land use and cover changes during the period were responsible for the emission of 291 million Mg of C, representing an average loss of 2 Mg C ha-1 year^{-1}.

Combining field and remote sensing data has been demonstrated to be a feasible methodological approach to estimating carbon balances on a regional scale derived from land use changes. Thus, this methodological approach can be applied to the entire biome and contribute to supporting discussions about reducing greenhouse gasses (GHG) emissions and implementing public policies for the dry tropical forest ecosystems of the semiarid region of Northeast Brazil.

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