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Ecosystem Services, Carbon Sequestration in an Area Susceptible to Desertification: A Study in the North-Central Region of Ceará, Brazil.

Serviços Ecossistêmicos, Sequestro de Carbono de uma Área Susceptível à Desertificação: Um estudo no Centro-Norte do Ceará, Brasil.

Igor Bulhões Barros[1]; Níveo Moreira da Rocha[2]; Maria Lucia Brito da Cruz[3]

[1] State University of Ceará, Graduate Program in Geography (PropGeo), Fortaleza/CE, Brazil. Email: professorigorbulhoes@gmail.com
ORCID: https://orcid.org/

[2] State University of Ceará, Graduate Program in Geography (PropGeo), Fortaleza/CE, Brazil. Email: níveo.rocha@aluno.uece.br
ORCID: https://orcid.org/

[3] State University of Ceará, Department of Geography, Fortaleza/CE, Brazil. Email: lucia.cruz@uece.br
ORCID: https://orcid.org/

Abstract: This study analyzed the carbon sequestration potential in different land cover classes in a Desertification-Susceptible Area (ASD 1) in the North-Central region of Ceará, using remote sensing and spectral indices. Landsat 8 images were used to calculate NDVI, PRI, sPRI, and CO_2 Flux, aiming to estimate carbon sequestration efficiency. Land use and land cover classification was performed using the Random Forest algorithm, resulting in six classes: Water Body, Urban Area, Exposed Soil, Agriculture/Herbaceous Vegetation, Shrub Caatinga, and Arboreal Caatinga. The results indicated that Arboreal Caatinga (53% of the area) and Shrub Caatinga (33%) showed the highest CO_2 Flux values, especially during the rainy season. In contrast, Exposed Soil (10% of the area) and Agriculture/Herbaceous Vegetation (1%) exhibited significantly reduced capacities. Non-parametric statistical tests (Kruskal-Wallis and Dunn) confirmed significant differences between class medians. It was concluded that climatic seasonality and vegetation cover type are determinants for carbon sequestration dynamics, reinforcing the need for conservation policies and sustainable management to mitigate degradation and enhance ecosystem services.

Keywords: Carbon sequestration; Caatinga; Remote sensing; Desertification; Ecosystem services.

Resumo: Este estudo analisou o potencial de sequestro de carbono em diferentes classes de cobertura do solo em uma Área Suscetível à Desertificação (ASD 1) no Centro-Norte cearense, utilizando sensoriamento remoto e índices espectrais. Foram utilizadas imagens do Landsat 8 para calcular o NDVI, PRI, sPRI e CO_2 Flux, visando estimar a eficiência do sequestro de carbono. A classificação do uso e cobertura do solo foi realizada com o algoritmo Random Forest, resultando em seis classes: Corpo Hídrico, Zona Urbana, Solo Exposto, Agricultura/Vegetação Herbácea, Caatinga Arbustiva e Caatinga Arbórea. Os resultados indicaram que a Caatinga Arbórea (53% da área) e a Caatinga Arbustiva (33%) apresentaram os maiores valores de CO_2 Flux, especialmente durante o período chuvoso. Em contraste, o Solo Exposto (10% da área) e a Agricultura/Vegetação Herbácea (1%) exibiram capacidades significativamente reduzidas. Testes estatísticos não paramétricos (Kruskal-Wallis e Dunn) confirmaram diferenças significativas entre as medianas das classes. Concluiu-se que a sazonalidade climática e o tipo de cobertura vegetal são determinantes para a dinâmica do sequestro de carbono, reforçando a necessidade de políticas de conservação e manejo sustentável para mitigar a degradação e ampliar os serviços ecossistêmicos.

Palavras-chave: Sequestro de carbono; Caatinga; Sensoriamento remoto; Desertificação; Serviços ecossistêmicos.

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1. Introdução

The continuous expansion of various forms of land use and occupation, often disorderly and inconsequential, has been causing increasing degradation of the natural resources of the Caatinga (SOUZA, 2000; OLIVEIRA, 2022). Degradation can be understood as the loss of productivity, assuming negative changes, as it is related to the loss of environmental quality, which can be perceived to different degrees, with humans being the main cause of this deterioration (SÁNCHEZ, 2020).

Among the activities practiced that most degrade the Caatinga, the following stand out: logging, plant extraction, extensive cattle ranching, and rudimentary agriculture (SANTOS, 2021). Such practices are aggravating factors of climate change. In recent years, several studies and policy initiatives have begun to be carried out seeking to understand these practices, their impacts, as well as to apply possible actions to combat and mitigate these actions with a view to the climate change scenario (SILVA, 2018; NIEMEYER; VALE, 2022).

Ecological processes are responsible for the functioning and production of services that regulate and maintain quality of life, called *Ecosystem Services* (ES) (DAILY, 1997; MEA, 2005; COSTANZA et al., 2014; SANTOS, 2022). The intensive and inconsequential use of the environment without taking into account their natural limits has caused these services to be affected. Currently, one of the most alarming problems is the emission of gases that intensify climate change. In Brazil, these gases are generated mainly due to deforestation and poor agricultural practices. Data from the Greenhouse Gas Emissions and Removals Estimation System (SEEG) (2023) reveal that in Brazil, land use change is the main source of carbon emissions.

Changes in environmental characteristics can trigger an imbalance in the flow of matter and energy. This is particularly the case when interfering with the deposition of soil organic matter (PRIMIER; MUNIZ; LISBOA, 2014; ASSUNÇÃO et al., 2019) and the processes of gross primary production and plant respiration (OLIVEIRA et al., 2021). According to the Common International Classification of Ecosystem Services (CICES), carbon sequestration is included among the main ecosystem services, being part of regulation services (HAINES-YOUNG; POTSCHIN 2018; DANTAS, 2024).

As an environmental management instrument, carbon sequestration is part of national and international market policies for maintaining the reduction of Carbon in the atmosphere (SILVA, 2018). Initiatives aimed at reducing and storing this gas are part of the Clean Development Mechanism (CDM), proposed at the Climate Convention (FUJIHARA, 2023), and are also included in UN SDG 13 (2015). In this sense, understanding the spatial distribution of areas of greatest relevance for the provision of ecosystem services, especially the carbon sequestration capacity, provides important structures for new methodological approaches to territorial management (BURKHARD et al., 2009; OLIVEIRA, 2022).

Forests are at the center of discussions due to their ability to sequester and store carbon; despite this, the Caatinga is still a vegetation type that lacks studies regarding its carbon sequestration potential, especially when considering the phenological cycle as well as the appropriation that this natural framework undergoes. In the case of Ceará, productive forces have been acting on this domain since the 17th century (SOUZA, 2000; 2006a); since that time, changes in vegetation cover, as well as in other landscape components, have altered natural environmental conditions.

In recent years, remote sensing has been a widely used tool in estimating forest biomass and carbon sequestration (SILVA, 2018; SILVA, 2021). Even though Brazilian tropical forests have a known role in CO_2 sequestration, studies on ES, especially carbon sequestration in the ASD (Areas Susceptible to Desertification), still seem to be insufficient given the current climate change scenario. In this sense, this research aims to analyze the potential for carbon sequestration and the provision of ES by vegetation in different periods in ASD 1 in the North-Central region of Ceará, linked to the impacts and modifications caused by land use and occupation.

2. Metodology

2.1 Characterization of the Study Area

The study area is located in one of the three main desertification nuclei of the state of Ceará. Based on state mappings, it was identified that the worst vegetation conservation states coincide with regions of low rainfall, degraded soils, a long history of use, high poverty rates, and high illiteracy rates (BRASIL, 2004; CEARÁ, 2010). These regions, considered the most critical, were classified as Areas Susceptible to Desertification (ASDs). This work focuses specifically on ASD 1, called the North-Central Sertões, which covers the municipalities of Irauçuba, Canindé, Sobral, Miraíma, Itapajé, and Santa Quitéria (Figure 1) (IPECE, 2010; FUNCEME, 2015).

The climate of the ASD region is classified as semi-arid, with annual precipitation below 800 mm, average temperature above 26°C, and extremely high rates of evaporation and evapotranspiration (FERREIRA, 2021). Regarding water resources, the water bodies are predominantly intermittent, with seasonal flow regime and high salt concentrations.

The geology of ASD 1 is mostly composed of the Ceará Central Domain, inserted in the Borborema Province (CORRÊA et al., 2010), and covers the Canindé and Independência Units (FUNCEME, 2015; CPRM, 2021). The geomorphology of the area is marked by ductile and brittle deformational structures imprinted on the Precambrian crystalline basement (MAIA; BEZERRA, 2014). The relief features that most characterize the study area are the sertaneja depression FUNCEME (2015), hills and residual ridges (SOUZA, 2000; CLAUDINO-SALES, 2016).

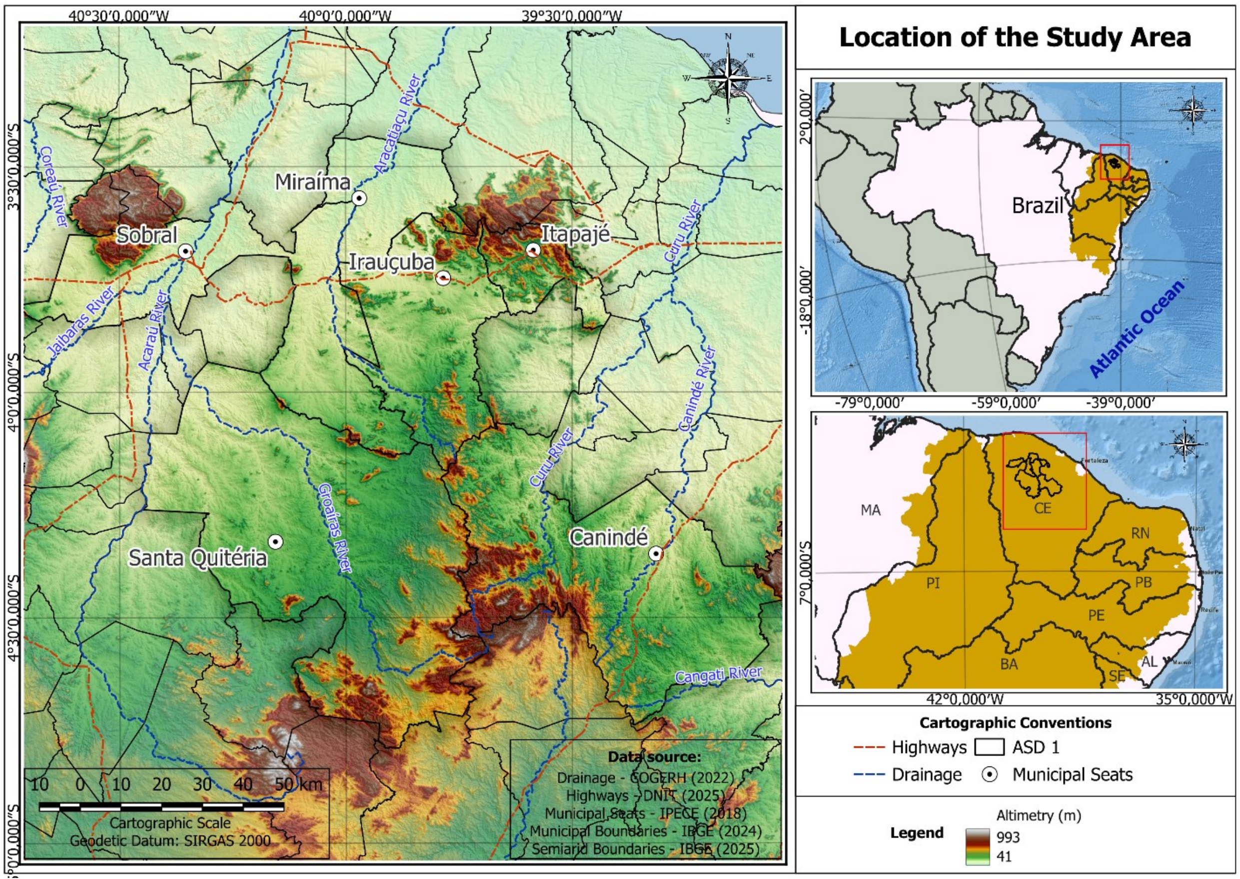

Figure 1 – Location of the Study Area.
Source: Authors (2025).

The vegetation cover of the ASD is predominantly characterized by Crystalline Caatinga and Crystalline Dry Forest (MORO et al., 2015). This vegetation is composed of shrubby species, with the presence of arboreal individuals. Furthermore, in small areas of higher altitude, fragments of humid or semi-deciduous tropical forests stand out (FERNANDES, 2006; REIS et al., 2024).

2.2 Processing of Spectral Scenes, Generation of the Carbon Flux Potential Index, and Statistical Tests

For the analysis of the carbon sequestration potential in the study area, images from the Landsat 8 satellite were acquired at various wavelengths of the electromagnetic spectrum. Bands 5 (infrared), 4 (red), 3 (green), and 2 (blue) were chosen to generate the Normalized Difference Vegetation Index (NDVI), the Photochemical Reflectance Index (PRI), and the Carbon Flux Potential Index (CO_2 Flux), according to contributions from the works of Silva et al., (2021) and Oliveira; Guedes; Costa (2023). All procedures were performed on Google Earth Engine (GEE).

Firstly, the NDVI was calculated to estimate photosynthetically active biomass and subsequently relate it to carbon stock. The spectral bands used were band 4, which expresses chlorophyll absorption in the red (R), and band 5, which has high internal leaf reflectance in the near-infrared (NIR). This index is calculated by the relationship between red and near-infrared (HUETE; JACKSON, 1987). NDVI is expressed in the following Equation:

$$NDVI = \frac{\mathrm{NIR} - \mathrm{RED}}{\mathrm{NIR} + \mathrm{RED}}$$

The PRI calculation was also performed; this calculation aims to verify changes in carotenoid pigments (mainly xanthophyll) of the foliage (SILVA, 2025). These are indicative of the efficiency of photosynthetic light use or the rate of carbon dioxide stored by the foliage (CANAVESI; PONZONI; VALERIANO, 2010). PRI is expressed in the following Equation:

$$PRI = \frac{\mathrm{blue} - \mathrm{green}}{\mathrm{blue} + \mathrm{green}}$$

After generating the PRI index, it is necessary to rescale its values to positive ones, generating the sPRI index (SILVA et al., 2017). This rescaling is necessary to normalize the vegetation "greenness" data. This index has its values ranging between 0 and 1 (SILVA; BAPTISTA, 2015). The sPRI is expressed in the following Equation:

$$sPRI = \frac{(\mathrm{PRI} + 1)}{2}$$

Finally, the equation proposed by Rahman et al. (2000) was used to obtain the CO_2 Flux index from NDVI and sPRI. Thus determining the potential for carbon dioxide sequestration by photosynthetically active vegetation. In this sense, the higher its value, the greater the efficiency of the carbon sequestration process by vegetation in the light phase of photosynthesis (OLIVEIRA; GUEDES; COSTA, 2023). CO_2 Flux is expressed in the following Equation:

$$\mathrm{C\ Flux} = NDVI * sPRI$$

Regarding the mapping of carbon sequestration ES, the proposal by Costanza et al. (2014) was used. For their quantification, the classification scale according to Burkhard et al. (2014) was used. Based on the classes identified in the field, a reference image generated through an average of the year 2024 was used, seeking to understand the natural cycle of Caatinga vegetation (FERNANDES, 2006) and agriculture, considering that they are strongly influenced by rainfall. Initially, the RGB composition of the Landsat 8 satellite was used; the generated product was also calculated using slope and altimetry data. The entire procedure was carried out using *GEE*; the class collection was performed in the QGIS 3.44 software.

Upon completion of this stage, classification was performed based on the data found in the field, which were grouped into six classes (Water Body; Urban Area; Exposed Soil; Agriculture and Herbaceous Vegetation; Shrubby Caatinga and Shrubby-Arboreal Caatinga), a total of 200 samples of each class were collected. The identification of classes in the field took place between the years 2024 and 2025. The classification was performed using *Random Forest* (BREIMAN, 2001; BIAU; SCORNET, 2016), a function was established to determine which number of trees offered the best model; for this research, the total of 90 trees demonstrated greater accuracy, overall accuracy, and the highest *Kappa* index value.

All images referring to the year 2024 (23) were used, without taking cloud incidence as a criterion in order to obtain the largest possible number of clean pixels. It was necessary to apply a cloud shadow, cloud, and cirrus cloud mask to eliminate any and all pixels that had the influence of these targets. Immediately after, CO_2 Flux was calculated with all images (RAHMAN et al., 2000), extracting the pixel values according to the land use and land cover image classes that were used in the *Land Use/Land Cover* (LULC) mapping. In order to understand the behavior of the vegetation, as well as the other environmental characteristics and the degradation of the area, the urban area and water body classes were not used, and their relationship with carbon (SILVA et al., 2017). The data were tabulated and statistical tests were performed with the preparation of the Boxplot.

Subsequently, the *Kruskal-Wallis* test was performed, which is a non-parametric method used to compare three or more independent groups. It is used to test the null hypothesis (H_0), that the medians of the groups are equal distributions in relation to the alternative hypothesis (H_1). Seeking to understand whether there are differences between at least two data groups. If the *P-value* ≤ 0.05, the null hypothesis is rejected. This indicates that there is a statistically significant difference between at least two groups. Complementing the *Kruskal-Wallis* test, the *Dunn's Post Hoc* test was used, also non-parametric, used for multiple groups.

3. Results and discussion

In the ASD, the higher altitude areas harbor denser formations such as shrubby-arboreal and arboreal caatinga, and sometimes stretches of ombrophilous vegetation; these areas remain relatively more preserved due to the rugged topography, which imposes natural barriers to agricultural and livestock expansion. However, it is recorded that even these remnants have been undergoing progressive transformations.

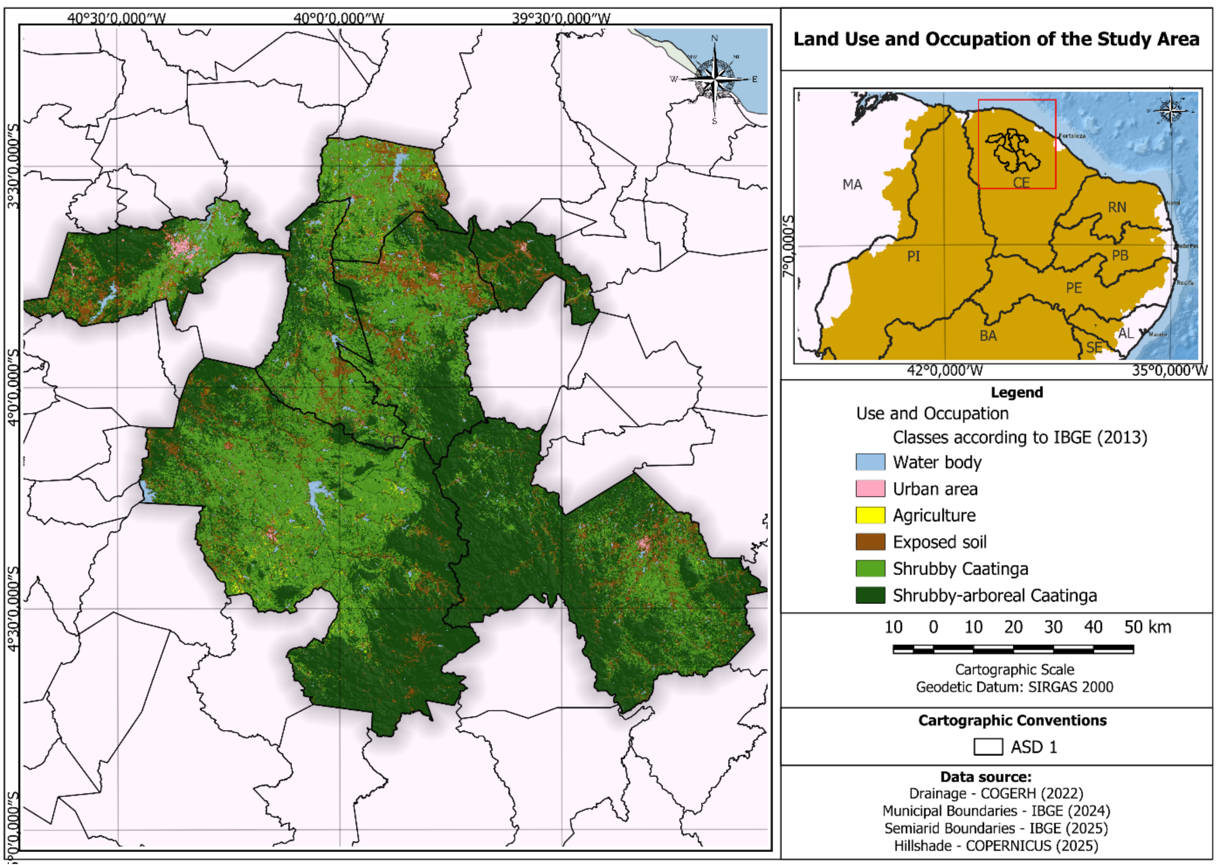

Figure 2 – Land Use and Occupation of the Study Area.
Source: Authors (2025).

Studies such as those by Sampaio et al. (2021) and Mendes et al. (2025) show how land use can influence carbon sequestration and the provision of ecosystem services; furthermore, deforestation of areas for conversion to agriculture (MAIA et al., 2010), selective wood removal, and overgrazing directly affect the CO_2 flux in the caatinga (FALCÃO et al., 2021). The study area reflects intensive land use that has manifested more intensely since the 17th century.

The pattern of land use and occupation in the ASD highlights the historical dynamics of predatory appropriation to which the area was subjected. As a consequence, the landscape is mostly composed of large expanses of shrubby caatinga, a clear manifestation of secondary vegetation, as seems to be the pattern found throughout the semi-arid vegetation (SOUZA; ARTIGAS; LIMA, 2015; OLIVEIRA; SAMPAIO, 2020; SILVA; SANTOS; SILVA, 2020; DANTAS, 2024).

Table 1 – Land cover values in ASD 1.

Land Cover Class	**Area in km²**	**Percentage**
Water Body	232.113	2%
Urban Area	56.297	0,48%
Agriculture/Herbaceous Vegetation	65.697	1%
Exposed Soil	1193752	10%
Shrubby Caatinga	3.990.998	33%
Arboreal Caatinga	6.449.706	53%
Total:	232.113	**100%**

Source: Authors (2025).

As it is an area susceptible to desertification, exposed soil manifests itself in a considerable part of the study area. Compared to the other classes used in this study, it proved to be the one with the least effective role in carbon sequestration. Considering, above all, the close relationship between degradation and consumption patterns, this data must be considered with regard to greenhouse gas emissions, given the change in coverage. These values are shown in (Table 1), where the exposed soil class represents 10% of the total area.

In agreement with the rainfall throughout the quarters of the classes found by the CO_2 Flux index, it is clear that the vegetation of the ASD was greatly influenced by precipitation throughout the year and by the occupational characteristics of the area. This directly affected the phenology and the potential for atmospheric exchanges throughout the period analyzed by the caatinga vegetation. Understanding this influence is essential for comprehending carbon sequestration in the caatinga (NISHIWAKI, 2023).

In this sense, the highest carbon sequestration values in the study area were recorded in the second quarter, with values ranging from very high relevant capacity to medium relevant capacity. The first quarter showed lower potential compared to the second, ranging between the following values: medium relevant capacity and relevant capacity. Nevertheless, this period is the moment of greatest carbon assimilation by the caatinga due to the beginning of the rainy season, where the highest gross primary production is recorded.

The third quarter, characterized by a transition process between the rainy and dry periods, presented values ranging from medium to low relevant capacity, thus showing a significant decrease in relation to the period with frequent rains and greater photosynthetic activity. Regarding the monthly variation of carbon sequestration, it is clear that the seasonal variability of precipitation exerts a strong influence on the amount of carbon sequestered by the vegetation (BRITO MORAIS et al., 2017).

In the fourth quarter, which presents the harshest dry season, the carbon sequestration potential showed a significant reduction in values, even when compared to the second quarter, presenting values ranging from medium relevant capacity in the higher areas to low and no relevant capacity in most of the study area. Despite this, it is noted that the higher areas tend to present values that remain with little change compared to the flatter areas.

It is noted that, even during the rainy season, the areas of anthropized caatinga in the ASD assimilated less carbon compared to other areas. It is also noteworthy that the areas that show no relevant capacity for Carbon fluxes are precisely the water bodies, as they are features in the landscape where there is no vegetation cover, when riparian vegetation is not considered (SILVA et al., 2017). Throughout the year, the phenological behavior of the vegetation combined with land use and occupation reflects the relationship between ecosystem services and land use and cover.

The changes that occur in the vegetation cover of the study area between the dry and rainy periods modify the radiation balance, which is the main factor of interaction between the surface and the atmosphere, and can initiate or cease the deciduous stage of plant species. Furthermore, the extensive portions of degraded land and the use of the biomass produced to sustain goat, sheep, and cattle farming characteristic of this region must be highlighted. The work of Da Costa et al. (2025) evidences the role of the caatinga as a carbon sink, especially due to the rapid response of vegetation to rainfall conditions. Despite this, it is noteworthy that approximately 10% of the ASD has exposed soil, a reflection of poor land use and conservation practices.

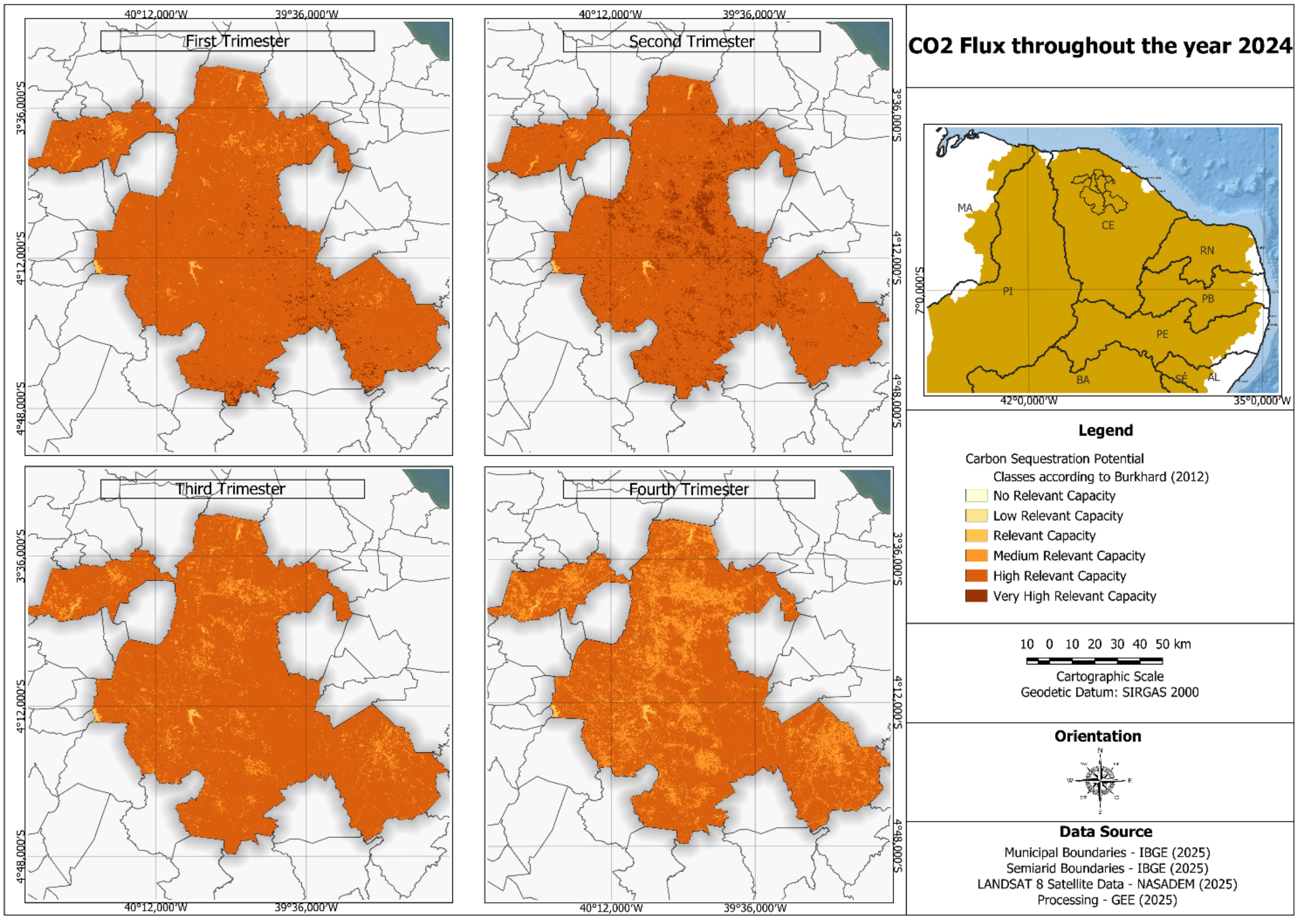

Figure 3 – Carbon Sequestration throughout the year 2024 in the Study Area.
Source: Authors (2025).

In general, environmental degradation is independent of the mode of production, but its intensity occurs according to the mode of material appropriation. In a study carried out in ASD 1 by Lima et al. (2024), the authors found that soil degradation reduces its functionality by more than 50%, reducing the capacity to support plant growth as well as decreasing carbon sequestration and the provision of other ecosystem services. In this sense, the continuous expansion of areas with exposed soil directly interferes with the lower carbon sequestration capacity, as can be seen in (Figure 4).

Exposed soil, which corresponds to 10% of the total area, was the least efficient class in carbon sequestration. The class represented by agriculture and herbaceous vegetation, which corresponds to 1% of the ASD, had a greater interaction regarding carbon flux, but lower than the other classes. The vegetative cycle of herbaceous plants in the caatinga is conditioned mainly by seasonal characteristics (ANDRADE-LIMA, 1981), it denotes an initial stage of secondary ecological succession. Like herbaceous vegetation, agriculture in the semi-arid region of Ceará is directly conditioned by the water regime.

When analyzed throughout the year, herbaceous vegetation and agriculture play a significantly smaller role compared to shrubby and arboreal vegetation, due to their shorter cycle in relation to the other vegetation strata. Such classes in the caatinga have their vegetative peak in line with the peak of the rainy season and a subsequent decline. Despite this, large portions of vegetation are cleared for conversion into planting areas and, after the harvest period, abandoned. From then on, without proper management, the erosive process begins, forming crusts on the surface, hindering water infiltration and the establishment of vegetation.

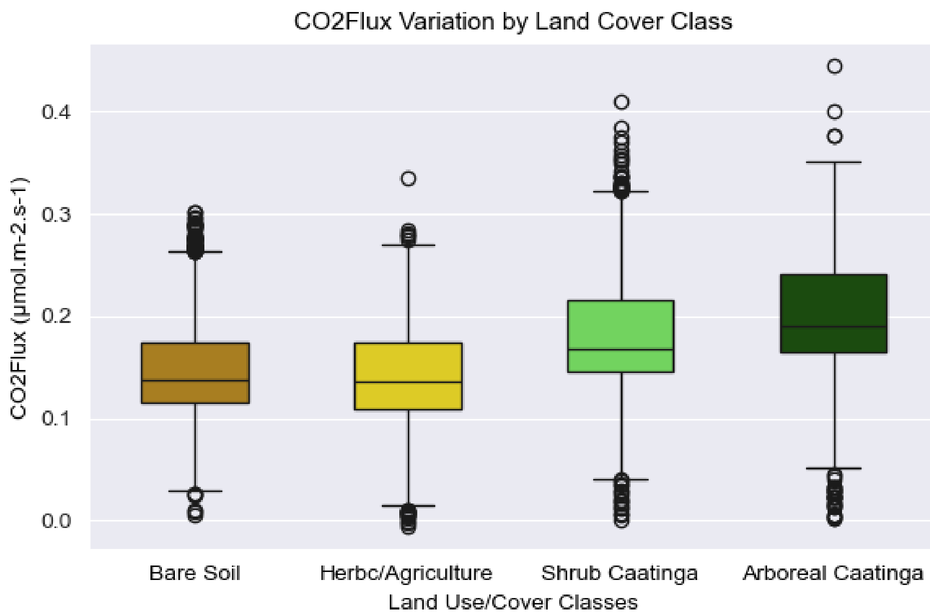

Figure 4 – Boxplot of the interaction of the CO2 Flux index with land cover classes.
Source: Authors (2025).

The shrubby and arboreal caatinga classes, approximately 33% and 53% of the total ASD area, showed the highest CO_2 Flux values, indicating greater efficiency in carbon sequestration. These vegetation classes have more stable biomass and a longer photosynthetic cycle, especially during the rainy season. Even though the vegetation with the greatest provision of ecosystem services is evidenced in the shrubby and arboreal caatinga classes, mainly arboreal vegetation, they are the most affected by intensive land use, especially for supplying the primary economic sector and for cooking food. Thus, it is evident that the maintenance of vegetation is essential for the maintenance of carbon regulation ecosystem services.

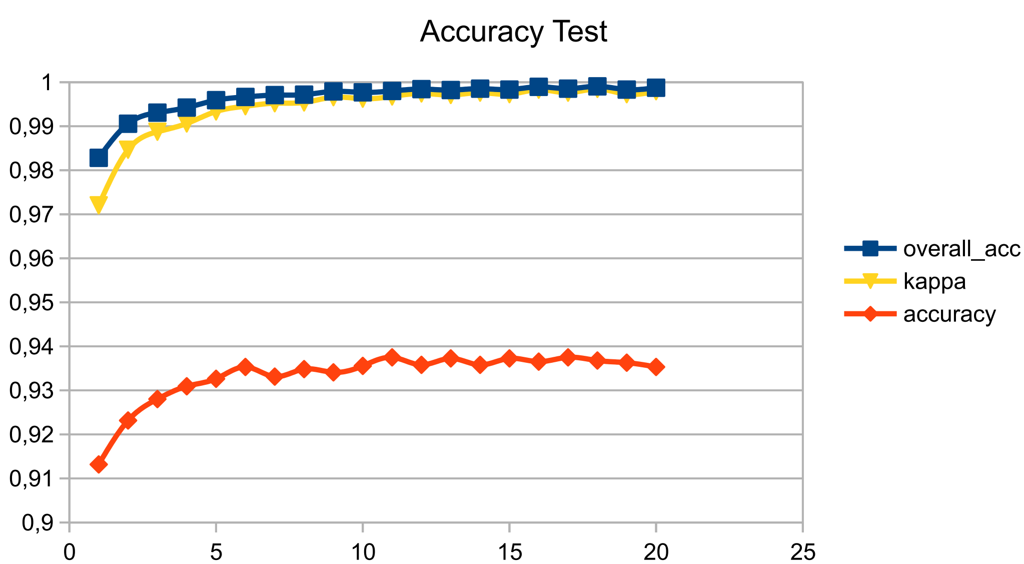

Figure 5 – Data accuracy test.
Source: Authors (2025).

Statistical tests between the classes revealed that the overall accuracy reached values close to 0.99, and the *Kappa* index also reached high values, close to 0.98, indicating that the classification of the mapped classes was extremely precise. The high accuracy reveals that the *Random Forest* model used with 90 trees was able to correctly classify 99% of the pixels into land use categories, thus showing a very strong correspondence between the samples collected in the field (200 per class) and the automatic classification performed. The high reliability of the land use and land cover mapping supported the carbon sequestration analyses by class. These results justified their use for the statistical tests performed*: Kruskal-Wallis* (Table 2) and *Dunn* (Table 3).

The *Shapiro-Wilk* test indicated that the samples did not have a normal distribution. Thus, the application of the *Kruskal-Wallis* test was used as a non-parametric alternative to compare the medians between groups. *Dunn's Post hoc* test identified that there are significant differences between the groups. Furthermore, *the Kruskal-Wallis* test determined the p-value = 0.0, demonstrating that there are significant differences between the medians of the classes; therefore, the null hypothesis (H0) was rejected.

Table 2 – Teste of Kruskal Wallis.

Teste Kruskal Wallis	
Test statistic:	4229.584310016773
p-value	0.0
Reject H0	The groups present significantly different distributions (p-value = 0.0)

Source: Authors (2025).

Table 3 – Teste Posthoc.

Posthoc Dunn				
Arboreal Caatinga	1.000000e+00	2.510464e-79	0.000000e+00	0.000000e+00
Shrubby Caatinga	2.510464e-79	1.000000e+00	1.267798e-282	2.502668e-237
Herba/Agriculture	0.000000e+00	1.267798e-282	1.000000e+00	1.497513e-02
Exposed Soil	0.000000e+00	2.502668e-237	1.497513e-02	1.000000e+00

Source: Authors (2025).

Given the scenario revealed by (Table 3), it is clear that the most similar classes are Herbaceous Layer/Agriculture and Exposed Soil, performing lower carbon sequestration compared to the others. The classes referring to Arboreal Caatinga and Shrubby Caatinga, on the other hand, present values that represent more distinct environmental conditions between themselves and in relation to other land uses.

4. Final Considerations

This study analyzed the carbon sequestration potential in different land cover classes in an Area Susceptible to Desertification (ASD 1) in the North-Central region of Ceará, using an integrated approach of remote sensing and spectral indices. The results demonstrated a direct relationship between the type of vegetation cover and the carbon sequestration capacity, with Arboreal Caatinga (53% of the area) and Shrubby Caatinga (33%) presenting the highest CO_2 Flux values, especially during the second quarter, corresponding to the peak of the rainy season. In contrast, areas of Exposed Soil (10% of the area) and Agriculture/Herbaceous Vegetation (1%) exhibited significantly reduced capacities, reflecting the history of degradation and intensive land use in the region.

Climatic seasonality proved to be a determining factor in the dynamics of carbon sequestration, with significant reductions during the dry season. However, even in the most favorable period, the anthropized areas showed lower efficiency in CO_2 assimilation, evidencing that the structure of the vegetation and the state of conservation are as important as water availability. Furthermore, the higher altitude areas maintained relative stability in carbon sequestration, suggesting the importance of conservation actions focused on these remnants.

The results reinforce the urgency of public policies and management practices that consider the heterogeneity of the landscape and ecosystem seasonality. Priority ecological restoration strategies in degraded areas, associated with encouraging sustainable management in preserved caatinga areas, can enhance the ecosystem services of carbon regulation, simultaneously contributing to the mitigation of climate change and the fight against desertification.

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