

Estimation of the spatiotemporal distribution of soil carbon fluxes in the Conceição do Coité region (Bahia, Brazil) using remote sensing data

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Abstract: As climate change worsens, it is essential to seek efficient climate monitoring strategies and develop low-cost, broad-coverage models to assess carbon dioxide (CO₂) fluxes in semiarid ecosystems. This study proposed to estimate the spatiotemporal dynamics of carbon flux (CO₂flux) in soils of the semiarid region, in the municipality of Conceição do Coité (Bahia, Brazil), between 2020 and 2024. Data from Sentinel-2 satellite images were used, processed in Google Earth Engine, integrating the NDVI and PRI indices. The data were evaluated in two climatic periods: rainy period (RP) and dry period (DP). Overall, the average soil carbon flux indices between each climatic period, across the years studied, were 0.172 for RP and 0.112 for DP. The results revealed that CO₂flux is directly related to the rainfall regime, with higher values in wetter years, such as 2021, and a significant drop in 2023 and 2024. The Caatinga vegetation responded positively to the rainfall, resulting in higher rates of carbon sequestration in areas with vegetation cover. Adapted to the conditions of the semi-arid climate, the cultivation of *Agave sisalana*, widespread in the studied region, has the potential to contribute to the reduction of greenhouse gas emissions and the recovery of degraded areas. The study also showed that remote sensing data can be considered a low-cost strategic tool for environmental monitoring associated with CO₂ fluxes in soils and for the implementation of actions aligned with the Sustainable Development Goals (SDGs). In the context of the current climate crisis, reduced carbon flux in water deficit scenarios may contribute to a decrease in the carbon sink potential of soils, weakening their role as climate regulator.

Keywords: *Agave sisalana*. Caatinga. Carbon flux. Remote sensing. Semi-arid.

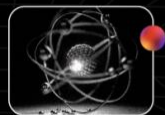
Abbreviations: NDVI, Normalized Difference Vegetation Index. PRI, Photochemical Reflectance Index. CO₂Flux, Carbon Sequestration Index. GEE, Google Earth Engine. RP, Rainy Period. DP, Dry Period.

1. Introduction

The growing interest in carbon (C) dynamics in arid and semiarid zones stems from recent evidence pointing to significant changes in the stock of this chemical element in the soil, associated with climate change and intensive land use in these regions [1-3]. In Brazil, the semiarid region represents almost 11% of the national territory and 76% of the Northeast region. It is a region traditionally prone to droughts, which has faced an intensification of desertification and soil erosion, driven by anthropic actions, combined with edaphoclimatic conditions [4-5]. The caatinga, the predominant vegetation of the semiarid

region, has a unique biodiversity among seasonally dry tropical forests (SDTF), being an ecosystem that has characteristics of both tropical forests and seasonally dry areas [6]. With a total area of 912,529 km², it is considered the largest STDF in the world, which reinforces its ecological importance [7].

The historical process of occupation of the territory belonging to the Caatinga has drastically altered its original coverage, where only 11.04% of the Caatinga area currently retains natural vegetation, and only 4.34% remains as forest cover, where 1.3% has full protection (Full Protection Conservation Units)



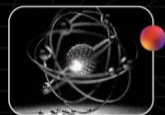
and 6.2% are Sustainable Use Conservation Units [7-8]. There are numerous consequences generated by high population density and anthropic activities of predatory models in the Caatinga [9-10]. Anthropic actions such as deforestation, intensive land use, and biomass burning directly interfere with the carbon cycle, an essential chemical element for terrestrial ecosystems [11].

In this cycle, carbon dioxide (CO_2) and water vapor are absorbed by plants through the process of photosynthesis. Solar energy is converted into organic compounds rich in carbon, which is stored in the different parts of the plant, transferring C from the atmosphere to the biosphere and, consequently, this chemical element is transferred to the soil, contributing to carbon stocks below the surface [12-13]. It is worth noting that in 2023, the terrestrial carbon sink absorbed only 0.44 Gt C, compared to the average of 2.6 Gt C/year in the previous decade. This decline was associated with extreme drought and heat events that led to weakened CO_2 absorption, reduced net photosynthesis, and increased emissions from burning and decomposition of organic matter [14].

In this sense, remote sensing has consolidated itself as a fundamental tool for investigating the terrestrial carbon cycle, allowing both the quantification of carbon fluxes and stocks in ecosystems [15], and the assessment of the impacts of global changes on

carbon dynamics [16-17]. In this context, spectral indices such as NDVI (Normalized Difference Vegetation Index) [18] and PRI (Photochemical Reflectance Index) [19] have stood out as fundamental tools for monitoring vegetation dynamics. The integration between these two indices allows the derivation of a new parameter, known as CO_2 flux, which is related to carbon sequestration, by quantifying photosynthetically active vegetation in a study area.

Thus, this study aimed to estimate the spatiotemporal distribution of CO_2 flux based on multispectral remote sensing data in the region of the municipality of Conceição do Coité (Bahia, Brazil), which encompasses a considerable area of semiarid climate and Caatinga vegetation, in the Northeast region. The work was carried out in a semiarid municipality characterized by a high rate of cultivation of *Agave sisalana*, a plant widely used in fiber production. *Agave* species have great potential for biomass expansion as a source of bioenergy in future climate scenarios, especially in semiarid agricultural lands that present some degree of degradation or are categorized as unsuitable [20]. Therefore, this work reinforces the relevance of studies aimed at monitoring carbon fluxes and environmental conditions in these regions, since such crops can play a strategic role in the recovery of degraded areas and in mitigating CO_2 emissions [21-22].



2. Methodology

2.1. Area of study

This study evaluated the spatiotemporal distribution of CO₂ flux in soils in the municipality of Conceição do Coité, located approximately 210 km from the capital of Bahia state, Salvador. The municipality is part of the Sisal Territory, which is composed of 20 municipalities and covers an area of 20,454.29 km². Agriculture is the predominant activity in this region, with *Agave sisalana* being the main agricultural crop, aimed at the export of its fiber [23].

The municipality is located in the Northeast Semi-arid region, which has a Bsh climate classification (hot semi-arid), with high average temperatures (25°C to 30°C) and precipitation between 400 and 1200 mm per year, with two distinct seasons during the year: a rainy season and a dry season, with an irregular rainfall regime during the years [24]. The main characteristic of the semiarid rainfall regime is the irregularity in the temporal and spatial distribution of precipitations [25-26].

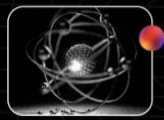
The predominant vegetation in the region corresponds to the Caatinga biome [7], which is adapted to reduced precipitation and high temperature and evapotranspiration [27-28], adjusting their physiological mechanisms to improve the efficiency of water use and carbon fixation, so that changes in plant phenology are reflected in the dynamics of

carbon exchange between the biosphere and the atmosphere [29,10].

2.2. Obtaining remote sensing data

The scenes chosen for the spatiotemporal estimation of carbon fluxes in soils in the studied region refer to the rainy period (RP) (months from November to May) and the dry period (DP) (months from June to October), from 2020 to 2024. These scenes were acquired and processed free of charge through Google Earth Engine (GEE), using Sentinel-2 satellite images, MSI sensor. For the spatialization of the spectral indices, a regular vector grid with a spatial resolution of 25 km² (5 km × 5 km) was generated, covering the entire extent of the study area. This grid was used as a basis for the extraction and statistical aggregation (average) of the spectral values of the dry and rainy periods, allowing a comparative evaluation between the years and the mapping of intra-annual variability.

We chose to use images from the Sentinel-2 satellite due to their high spatial resolution. The images were acquired at processing level 2A, meaning they were already atmospherically corrected using the Sen2Cor processor, which eliminates interference caused by aerosols and water vapor [30]. On the Google Earth Engine (GEE) platform, these images are made available as “Surface Reflectance”, eliminating the need for additional atmospheric correction. This ensures



greater precision in the extraction of spectral indices, such as NDVI, in areas of vegetation with seasonal variation, such as the Caatinga.

2.3. Spectral indices of carbon flux

To estimate CO₂ fluxes in the studied area, after obtaining remote sensing data, the Forest Carbon Sequestration Index (CO₂flux), initially proposed by Rahman (2001) [31], was used, which integrates the NDVI and PRI indices into a single carbon sequestration metric. The NDVI was calculated using the reflectance of the red and near-infrared bands with a central wavelength of 490 nm (RED) and 842 nm (NIR) (Equation 1).

$$NDVI = \left(\frac{R_{NIR} - R_{RED}}{R_{NIR} + R_{RED}} \right) \quad (Eq. 1)$$

where R is the reflectance of the wavelengths of the near infrared (NIR) and red (RED) bands.

The PRI was also calculated, which reflects the photosynthetic efficiency of vegetation from the blue and green bands. To calculate the PRI, the ratio of bands corresponding to the central wavelength 490 nm (blue) and 560 nm (green) was considered, with the absorption of the blue band in relation to the peak occurring in the green reflection band [32], ranging from -1 to +1 (Equation 2).

$$PRI = \left(\frac{R_{blue} - R_{green}}{R_{blue} + R_{green}} \right) \quad (Eq. 2)$$

where R is the reflectance of the wavelengths of the respective bands.

To adapt the PRI to the model, a scaling was applied to make it positive (sPRI; Equation 3), as proposed by Rahman et al. (2001) [31], improving the correlation with net primary output.

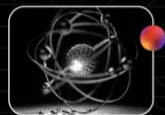
$$sPRI = \frac{(PRI + 1)}{2} \quad (Eq. 3)$$

The CO₂flux estimate (Equation 4) results from the relationship between the NDVI and sPRI values, measuring the efficiency of carbon sequestration by vegetation, with its result expressed in the range between -1 and +1.

$$CO_2flux = NDVI \times sPRI \quad (Eq. 4)$$

The CO₂flux index was used as a dimensionless and proportional measure of carbon flux, as it is derived from the NDVI and PRI indices [33]. To obtain quantitative values of the CO₂flux index expressed in μmol m⁻² s⁻¹, it would be necessary to use data from micrometeorological towers, performing a regression between the real CO₂ fluxes and the values estimated by the index, as proposed by Silva & Baptista (2015) [32].

Finally, the values were subjected to descriptive statistical analysis (including mean, standard deviation and percentage of valid data), according to approaches used in studies



based on orbital data and without in situ validation [34].

3. Results and discussion

The estimated values for soil carbon flux indices between RPand DP are presented on Table 1.

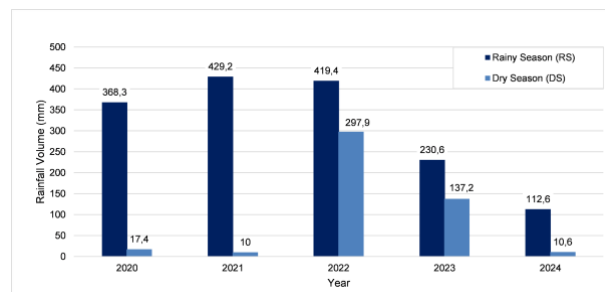
Table 1. Estimates of soil carbon flux over different climatic periods (2020–2024).

Year	Rainy period		Dry period	
	Minimum	Maximum	Minimum	Maximum
2020	0,074	0,265	0,031	0,249
2021	0,027	0,236	0,094	0,308
2022	0,039	0,257	0,068	0,220
2023	0,068	0,232	0,042	0,144
2024	0,068	0,255	0,052	0,195
Range	0,027 - 0,265		0,031 - 0,308	
Mean $\pm$ SD*	0,172 $\pm$ 0,051		0,112 $\pm$ 0,071	

*SD = standard deviation.

High levels of soil carbon flux during dry periods may be associated with the presence of organic matter in the soil and occasional significant rainfall (as observed in 2021, where soil carbon flux remained high during both periods, DP and RP). Soil carbon flux is directly associated with soil respiration, organic matter decomposition, and microbial activity, and is influenced by factors such as humidity, temperature, and rainfall dynamics [10, 26]. Therefore, Figure 1 shows the annual precipitation rates for the municipality of Conceição do Coité, for the years 2020 to 2024, during the dry (DP) and rainy (RP) periods.

Figure 1. Average rainfall volume (mm), between 2020 and 2024, divided by rainy (RS) and dry (DS) periods for the Conceição do Coité region, Bahia, Brazil.



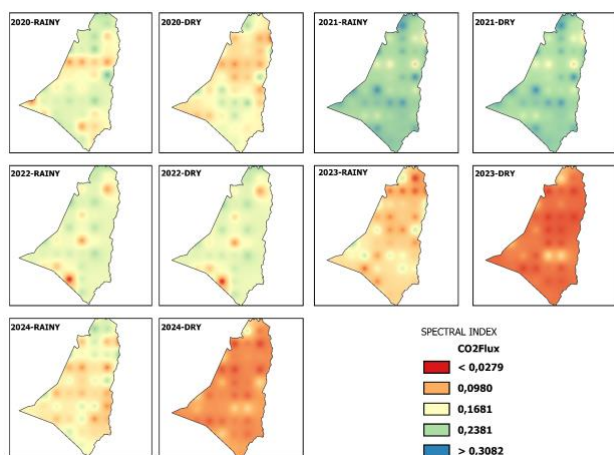
Source: National Institute of Meteorology (2025) [37].

It can be observed that, during this period, there was great seasonal variability in the rainfall regime, with averages varying between 94 mm (DP) and 312 mm (RP). Studies on the homogeneous rainfall zones in Bahia indicate that precipitation in the semi-arid region of this state is strongly conditioned by different meteorological systems such as Frontal Systems, the South Atlantic Convergence Zone and Cyclonic Vortices, which promote rainfall between November and April, peaking in December, with averages of 127 mm (DP) and 544 mm (RP) [36].

The complex interaction between rainfall seasonality and carbon exchange in the Caatinga suggests that seasonal climate change plays a crucial role in modulating carbon fixation rates in this ecosystem [26].

Carbon flux spectral index (CO₂Flux) maps demonstrated a clear correlation between rainfall patterns and soil-atmosphere carbon exchange dynamics (Figure 2).

Figure 2. Carbon Flux Maps between 2020 and 2024, in the respective rainy and dry periods.



The values for the indexes presented range from <0.0279 (dark red tones, indicating very low flow) to values >0.3082 (bluish tones, corresponding to the highest estimated flow level). Baptista (2004) [35] mentions that the greater the photosynthetic activity, the greater the effectiveness of the carbon sequestration process, and thus, the greater the spectral index.

It was observed that, in the years 2023 and 2024, especially during dry periods, there was a significant reduction in soil carbon flux, with minimum spectral index values concentrating below 0.0980. This trend followed the significant drop in precipitation recorded in these years, with emphasis on the rainy season of 2024, which recorded only 112 mm, compared to 230 mm in 2023, which may highlight the impact of water restriction on plant activity and soil respiration. Another factor that can affect carbon sequestration, and may have influenced local indices, is deforestation.

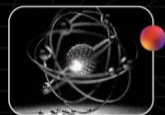
The Caatinga biome faces increasing anthropic pressures, being among the three most deforested in the country in 2023, which highlights the serious threat to its environmental balance. That year, the state of Bahia was responsible for 93,437 hectares of native vegetation lost, representing a 34% increase compared to 2022 [7].

Junior Silva (2020) [38] verified that, in regions where there is an increase in deforestation, changes in the configuration of vegetation cover are observed, resulting in direct carbon losses. Additionally, the reduction in relative humidity compromises processes such as the decomposition of organic matter and microbial activity, which are fundamental for the flow of carbon in the soil.

Understanding the dynamics of carbon flow in the environment can contribute to the assessment and management of environmental resources in relation to land use. Furthermore, it can provide support for assessing the consequences of the current climate crisis, contributing to the adoption of practices aimed at combating desertification and restoring degraded lands, in accordance with the UN Sustainable Development Goals (SDGs) (especially SDGs 13 and 15).

4. Conclusions

Soil carbon flux was shown to be sensitive to hydric regime variability, with marked responses to climatic seasonality.



In the context of the current climate crisis, in which rainfall variations have become more intense, irregular, and unpredictable (especially in semiarid regions), the results demonstrated that the reduction in carbon flux in water deficit scenarios can contribute to the reduction of the carbon sink potential of soils, weakening their function as climate regulators.

The use of strategic tools such as remote sensing has proven to be efficient in environmental monitoring and in planning actions aimed at sustainability, especially in regions that suffer the severe effects of variations in climatic conditions. Implementing these tools reduces the costs of continuous soil monitoring, making it more accessible, and enabling an understanding of seasonal variations and the effects of different management practices.

To achieve this, it is essential to define clear metrics or local indicators, such as carbon stocks, seasonal fluxes, moisture indices, and vegetation cover. Integrating these data with national inventories, following internationally recognized methodologies (IPCC), ensures that the results support climate mitigation policies and sustainable soil management strategies.

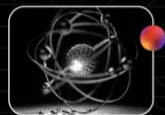
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