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Soil organic matter and vegetation indices in a semi-arid preserved area of Brazil

Matéria orgânica do solo e índices de vegetação em uma área preservada do semiárido brasileiro

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Abstract: Preserved areas play an important role in sustaining ecological processes, particularly in semi-arid environments where resource availability is constrained. In this exploratory study, soil organic matter (SOM) was quantified at two depths (0–10 and 10–20 cm), and its relationship with soil pH and vegetation indices derived from remote sensing (NDVI and CO_2Flux) was investigated in a preserved area in Princesa Isabel, Paraíba, Brazil. Laboratory analyses showed higher SOM content in the surface layer, consistent with litter accumulation and enhanced biological activity. A positive association between SOM and pH was observed in the upper layer ($r = 0.87$), although the statistical robustness of this relationship is limited by the small sample size. Vegetation indices derived from Sentinel-2 imagery indicated heterogeneous vegetation cover, with NDVI values ranging from 0.01 to 0.78. The CO_2Flux index suggested spatial variability in photosynthetic activity; however, its interpretation as a direct proxy for carbon sequestration should be treated with caution due to its indirect nature. These results highlight the potential of integrating laboratory soil analyses with remote sensing data for preliminary characterization of soil–vegetation interactions. Nevertheless, the exploratory design and limited sampling restrict broader ecological inferences.

Keywords: Caatinga biome; Soil–plant interactions; Spectral indices.

Resumo: Áreas preservadas desempenham papel relevante na manutenção de processos ecológicos, especialmente em ambientes semiáridos, onde a disponibilidade de recursos é limitada. Neste estudo exploratório, avaliou-se o teor de matéria orgânica do solo (MOS) em duas profundidades (0–10 e 10–20 cm), sua relação com o pH e padrões de cobertura vegetal derivados de sensoriamento remoto (NDVI e CO_2Flux) em uma área preservada no município de Princesa Isabel, Paraíba, Brasil. As análises laboratoriais indicaram maior teor de MOS na camada superficial, consistente com o acúmulo de serrapilheira e maior atividade biológica. Foi observada associação positiva entre MOS e pH na camada superficial ($r = 0{,}87$), embora a robustez estatística dessa relação seja limitada pelo tamanho amostral reduzido. Os índices de vegetação derivados de imagens Sentinel-2 indicaram predominância de cobertura vegetal com valores de NDVI variando entre 0,01 e 0,78. O índice CO_2Flux sugeriu variação espacial na atividade fotossintética, porém sua interpretação como indicador direto de sequestro de carbono deve ser considerada com cautela, dado seu caráter indireto. Os resultados evidenciam o potencial da integração entre análises laboratoriais e dados de sensoriamento remoto para caracterização preliminar de sistemas solo–vegetação. No entanto, a natureza exploratória do estudo e as limitações amostrais impedem generalizações sobre dinâmica de carbono ou funcionamento ecossistêmico em escala mais ampla.

Palavras-chave: Caatinga; Interação solo-planta; Índices espectrais.

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1. Introduction

Soils are inherently heterogeneous systems, characterized by complex physical, chemical, and biological processes, particularly in environments with high environmental variability such as the Brazilian semi-arid region (Silva, 2020). In these systems, conventional soil analysis techniques are often applied to assess individual properties; however, they may fail to adequately capture the interactions among multiple soil components.

Soil organic matter (SOM) is a fundamental component of soil sustainability, especially in semi-arid regions, where it plays a critical role in improving soil fertility, increasing water retention capacity, and promoting soil biodiversity (Okolo et al., 2020). However, under semi-arid conditions, characterized by high temperatures, low precipitation, and reduced biomass production, SOM accumulation is typically limited, even in natural systems (Santos et al., 2019). This highlights the importance of understanding the balance between organic matter inputs and decomposition processes in such environments.

The quantification of SOM is particularly relevant due to its direct influence on soil quality. It contributes to soil structure stabilization, enhances nutrient availability, and supports biological activity, which together influence ecosystem productivity (Vezzani; Mielniczuk, 2009).

In parallel, remote sensing techniques have enabled the development of vegetation indices to monitor and quantify vegetation conditions and spatial distribution. These indices are derived from mathematical combinations of spectral reflectance data obtained from different regions of the electromagnetic spectrum (Liu, 2006). Among these, the Normalized Difference Vegetation Index (NDVI) is widely used to detect vegetation cover, estimate biomass, and assess vegetation vigor (Paruelo et al., 2000; Abreu; Coutinho, 2014).

Preserved areas play a crucial role in maintaining ecosystem services, including biodiversity conservation, water resource protection, and the regulation of environmental degradation. These areas also function as refuges for native vegetation, potentially enhancing carbon-related processes and stabilizing ecological dynamics.

The integration of soil chemical attributes, particularly SOM and pH, with remotely sensed vegetation indices (such as NDVI and CO_2Flux) is supported by biogeochemical processes linking soil conditions to vegetation performance. SOM acts as a primary reservoir of nutrients and carbon for soil biota, influencing the availability of essential elements such as nitrogen and phosphorus. Soil pH, in turn, regulates the solubility and bioavailability of nutrients and potentially toxic elements, shaping the chemical environment for plant growth (Araujo Filho et al., 2022).

These soil properties can be reflected in plant physiological responses, including variations in photosynthetic activity, leaf biomass, and chlorophyll content, which are indirectly captured by spectral indices such as NDVI. In semi-arid ecosystems like the Caatinga, where water availability is a limiting factor, the interaction between SOM and pH becomes particularly relevant for sustaining vegetation activity and productivity (Mendes et al., 2020; Mendes et al., 2021).

Despite their widespread use, it is important to recognize that vegetation indices and derived metrics, such as CO_2Flux, represent indirect proxies of ecosystem processes and are subject to uncertainties, especially when not validated with field-based measurements (Xu et al., 2025).

In this context, the present study aimed to evaluate, within an exploratory framework, the distribution of soil organic matter at different depths and its relationship with soil pH, as well as to characterize vegetation patterns using spectral indices (NDVI and CO_2Flux) in a preserved area of the semi-arid region of northeastern Brazil. Specifically, the objectives were: (i) to quantify SOM content in two soil layers; (ii) to examine the association between SOM and pH; and (iii) to describe vegetation patterns using remote sensing data.

Given the limited sampling design and the use of indirect proxies, the results should be interpreted as preliminary, without extrapolation to broader spatial or temporal scales.

2. Material and methods

2.1 Study area

The study was conducted at the Centro de Capacitação Agrocomunitário (Figure 1), located along highway BR-426 in the municipality of Princesa Isabel, Paraíba, Brazil, at the geographic coordinates 7°41′48″ S and 37°55′04″ W, near the Açude dos Jerônimos reservoir.

The institution, managed by the Missionary Carmelite Sisters, offers a variety of activities aimed at social, environmental, and educational development for both the local community and visitors. Among its initiatives are ecological trails that promote contact with nature and learning about local biodiversity, as well as exchange programs with elementary, secondary, and higher education institutions. The center also functions as a social space, providing facilities for recreation and hosting training events with either religious or social purposes.

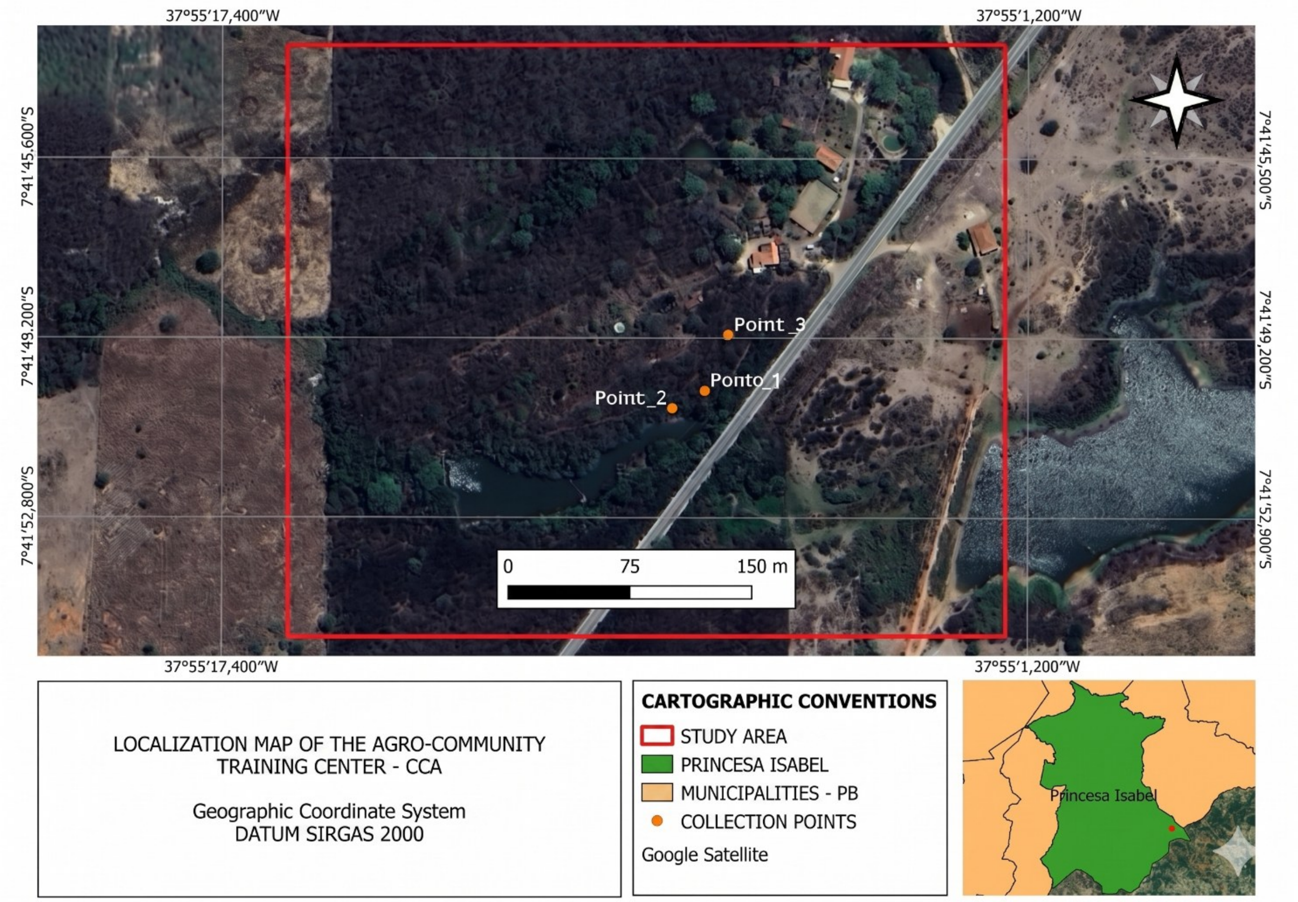

Figure 1 – Location map of the Centro de Capacitação Agrocomunitário (CCA).
Source: Authors (2025).

The municipality of Princesa Isabel is located at latitude 7°44′17″ S and longitude 37°59′42″ W, at an altitude of 683 meters, approximately 420 km from the state capital, João Pessoa. According to the most recent demographic census, the municipality has a population of 21,114 inhabitants (IBGE, 2022).

According to Beltrão et al. (2005), the vegetation is of small size, typical of xerophytic Caatinga, characterized by the presence of cacti, shrubs, and small to medium-sized trees. The soil is classified as a Red-Yellow Ultisol (Argissolo Vermelho-Amarelo), characterized by the presence of a textural B horizon with reddish-yellow colors and a clayey texture beneath an A or E horizon of lighter color and sandy to medium texture, commonly found in the states of Ceará, Bahia, Rio Grande do Norte, and Paraíba (EMBRAPA, 2018).

2.2 Data collection procedure

Soil samples were collected using a manual auger at three random points (Figure 2), during the months of August and November 2024, in the dry season, as this was an exploratory sampling. This type of sampling is widely used in reconnaissance studies aimed at identifying trends and supporting future research with more robust sampling designs (Marconi; Lakatos, 2009).

A total of six samples were collected, with three samples at a depth of 0–10 cm and three at a depth of 10–20 cm. The sampling points were georeferenced using the CR Campeiro 7 application.

The samples were collected at these depths to evaluate soil fertility in a preserved area that has remained undisturbed for more than thirty years. This preservation contributes to biodiversity conservation, soil protection against erosion, and climate regulation.

Figure 2 – Sample collection process.
Source: Authors (2025).

After field collection, the samples were stored in labeled plastic bags and transported to the chemistry laboratory for processing and analysis. The samples, with disturbed structure, were air-dried, manually disaggregated, and sieved through a 2 mm mesh to obtain the air-dried fine earth fraction (TFSA), following EMBRAPA (1997).

To determine soil organic matter (SOM), the Loss on Ignition method was used, based on heating the samples in a muffle furnace at 500 °C (Ramírez; Matos, 2022). As illustrated in Figure 3, approximately 100 g of each sample were initially dried at 105 °C in an oven. Subsequently, about 4 g of each sample were placed in a muffle furnace at 500 °C for 4 hours. The SOM content was calculated based on the ratio between mass loss after ignition and the initial dry mass, according to Davies (1974).

Figure 3 – SOM determination process.
Source: Authors (2025).

The samples were weighed using a digital balance with a precision of 0.001 g. Soil pH was measured once per sample, following the procedures described in the soil analysis manual (EMBRAPA, 1997). Figure 4 illustrates the sample processing steps.


[redacted]

Figure 4 – Sieving, pH measurement, and weighing procedures.
Source: Authors (2025).

2.3 Statistical analysis

Microsoft Excel was used to perform descriptive statistical analyses. According to Marconi and Lakatos (2009), descriptive statistics aim to summarize data in a clear and concise manner through tables, graphs, and numerical indicators.

Data normality was tested, and Pearson's linear correlation coefficient was applied to evaluate the relationship between variables. This coefficient measures the strength of the linear relationship between two numerical variables, ranging from −1 (perfect negative correlation) to +1 (perfect positive correlation) (Levine et al., 2016).

2.4 Image acquisition and processing

The first step consisted of acquiring the satellite images from the Sentinel-2 data collection available on the Google the first step consisted of acquiring satellite images from the Sentinel-2 data collection available on the Google Earth Engine (GEE) platform. Sentinel-2 provides high-resolution optical imagery for terrestrial applications, including vegetation monitoring, land cover mapping, water bodies, inland waterways, and coastal zones.

The indices computed using a script in GEE were the Normalized Difference Vegetation Index (NDVI) and CO_2Flux. The selected images were acquired on August 27, 2024, corresponding to the same month as the first soil sampling campaign. This temporal alignment ensured consistency between laboratory and satellite data.

Additionally, August corresponds to the dry season in the semi-arid region of Paraíba, which is characterized by reduced cloud cover and greater atmospheric stability, favoring the acquisition of images with minimal atmospheric interference (Barbosa; Huete; Baethgen, 2006). The use of a single image is justified by the exploratory nature of the study and by the expected stability of vegetation cover in an area preserved for more than 30 years, where abrupt NDVI variations on a daily scale are unlikely. Nevertheless, the absence of a temporal series is acknowledged as a limitation and should be addressed in future studies.

NDVI was originally proposed by Rouse et al. (1973, cited by Yan et al., 2025) and remains widely applied for purposes such as vegetation detection, biomass estimation, crop vigor assessment, and vegetation cover analysis (Paruelo et al., 2000; Abreu; Coutinho, 2014).

The NDVI is calculated using the red (R) band, which is absorbed during photosynthesis, and the near-infrared (NIR) band, which is reflected by vegetation. The index is defined as the ratio between the difference and the sum of these reflectances (ρ), ranging from −1 to 1. Higher values indicate greater photosynthetic activity (Eq. 1).

$$NDVI = \frac{\rho IV - \rho V}{\rho IV + \rho V} \quad \text{Eq. 1}$$

Vegetation mapping based on NDVI allows the estimation of biomass and, consequently, its relationship with carbon stocks (Silva and Baptista, 2025). To estimate CO_2Flux, NDVI, the Photochemical Reflectance Index (PRI), and its rescaled version (sPRI) were calculated. PRI (Eq. 2) was developed to assess photosynthetic efficiency using reflectance in the blue (B) and green (G) spectral bands (Moreira, 2005).

$$PRI = (\rho B - \rho G)/(\rho B + \rho G) \quad \text{Eq. 2}$$

PRI represents the relationship between the green and blue bands and, according to Xu et al. (2025), is associated with light-use efficiency in photosynthesis. However, PRI values must be rescaled to a positive range, resulting in the sPRI index (Eq. 3), which varies from 0 to 1 and is therefore comparable to NDVI.

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

The CO_2Flux index is obtained by integrating sPRI, which represents photosynthetic efficiency, with NDVI, which reflects vegetation vigor (Xu et al., 2025). This combination allows the indirect representation of spectral features associated with carbon uptake. This integrated index was defined as CO_2Flux by Baptista (2003) (Eq. 4).

$$CO_2\ Flux = sPRI\ x\ NDVI \quad \text{Eq. 4}$$

3. Results and discussion

The soil organic matter (SOM) content determined by the loss-on-ignition method varied among the analyzed samples, ranging from 1.71% to 2.08% in the 0–10 cm layer and from 1.65% to 1.73% in the 10–20 cm layer, based on a total of six samples (Table 11).

Table 1 – Calculation of soil organic matter at the two evaluated soil depths.

Sample	Soil dried at 105 °C	Soil after combustion at 500 °C	Soil organic matter (g)	Soil organic matter (%)
Sample 1 Depth 0-10cm	19,00	18,85	0,14	1,85
Sample 2 Depth 0-10cm	20,02	19,77	0,25	1,71
Sample 3 Depth 0-10cm	17,00	16,65	0,35	2,08
Sample 1 Depth 10-20cm	20,00	19,81	0,18	1,75
Sample 2 Depth 10-20cm	20,02	19,77	0,25	1,65
Sample 3 Depth 10-20cm	18,11	17,79	0,31	1,73

Source: Authors (2025).

The results of the descriptive analysis of soil attributes in the 0–10 cm and 10–20 cm layers are presented as mean values of SOM (g) and SOM (%), respectively, in Table 2.

Table 2 – Mean values of SOM (g) and SOM (%).

Depth	SOM (g)	SOM (%)
0-10cm	0,25	1,88
10-20cm	0,25	1,71

Source: Authors (2025).

The amount of soil organic matter (SOM) in Brazilian soils is influenced by several factors, including tropical climate conditions (which accelerate organic matter decomposition), vegetation type, land use (such as agriculture or pasture), and management practices.

Soils containing between 1% and 2% SOM are more common, as tropical climates tend to favor the mineralization of organic matter rather than its accumulation. In contrast, soils with SOM contents above 4% to 5% are considered relatively rare in Brazil. Due to the generally low SOM content in Brazilian soils, there has been an increasing use of organic residues as amendments in agricultural systems (Fonseca et al., 2024).

3.1 Soil organic matter in the forest fragment

Based on the obtained results, it was observed that the soil organic matter (SOM) content was higher in the surface layer (0–10 cm). This pattern can be explained by factors related to SOM accumulation dynamics, such as plant–soil interactions, increased biological activity (e.g., decomposer organisms such as earthworms and insects), and the accumulation of plant residues (litter). Although biological activity occurs throughout the soil profile, it is typically more intense in surface layers, where organisms are more abundant and active (Philippot et al., 2013).

Due to the continuous input of organic material from forest cover, the upper soil layers receive a greater contribution of organic residues. This explains the observed decrease in total organic carbon content with increasing depth (Ozório et al., 2019; Lima; Souza; Lima, 2024). This pattern is further supported by Figure 5, which shows a reduction in SOM content in the 10–20 cm layer.

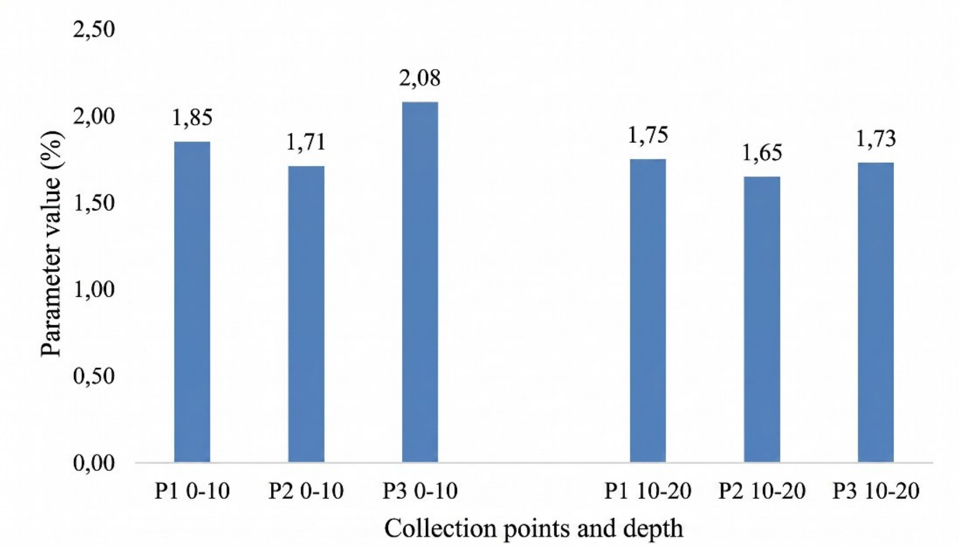

Figure 5 – Soil organic matter content (%).
Source: Authors (2025).

According to Silva et al. (2019), in a review addressing soil organic matter and its interrelationships with soil physical properties, organic matter is strongly associated with cation exchange capacity (CEC), with direct implications for soil density. In this context, increased organic matter content contributes to a reduction in soil bulk density.

In recent years, studies focusing on soil organic matter as an indicator of soil quality have intensified in the Brazilian semi-arid region (Iwata et al., 2020).

3.2 Soil pH

The analysis of mean pH values indicated acidic conditions in both soil layers. The vertical distribution showed that pH was higher in the surface layer (0–10 cm) and decreased in the subsurface layer (10–20 cm), suggesting a general trend of decreasing pH with increasing depth.

In semi-arid regions, soils are generally classified as moderately acidic to moderately alkaline, with pH values (in water) ranging from 5.3 to 8.3. However, under specific conditions related to parent material and local drainage, soils may exhibit strongly acidic (pH < 5.3) or strongly alkaline (pH > 8.3) reactions (Araújo Filho et al., 2022).

Soil pH is an important indicator of nutrient availability for plants. Therefore, understanding soil acidity or alkalinity is essential for proper soil management, as nutrient availability is typically optimized within a pH range of 5.5 to 6.5 (Malavolta, 1979). Within this range, nutrients are generally more accessible to plants.

Based on these considerations, the pH values observed in the preserved area fall within an adequate range, suggesting that natural nutrient cycling processes—supported by native vegetation and litter input—are sufficient to maintain soil chemical balance without the need for external intervention.

According to Freitas et al. (2017), soils with pH values ranging from 3.7 to 6.2 may indicate the availability of macro- and micronutrients for plants under different management systems. Similarly, Oliveira et al. (2023) reported that the optimal pH range for crop performance is between 5.5 and 6.5. Freire Filho et al. (2011) classify soils with pH around 5.5 as having good agronomic conditions, and values above 7 as very high. Based on these classifications, the analyzed samples can be considered to present favorable conditions, as illustrated in Figure 6.

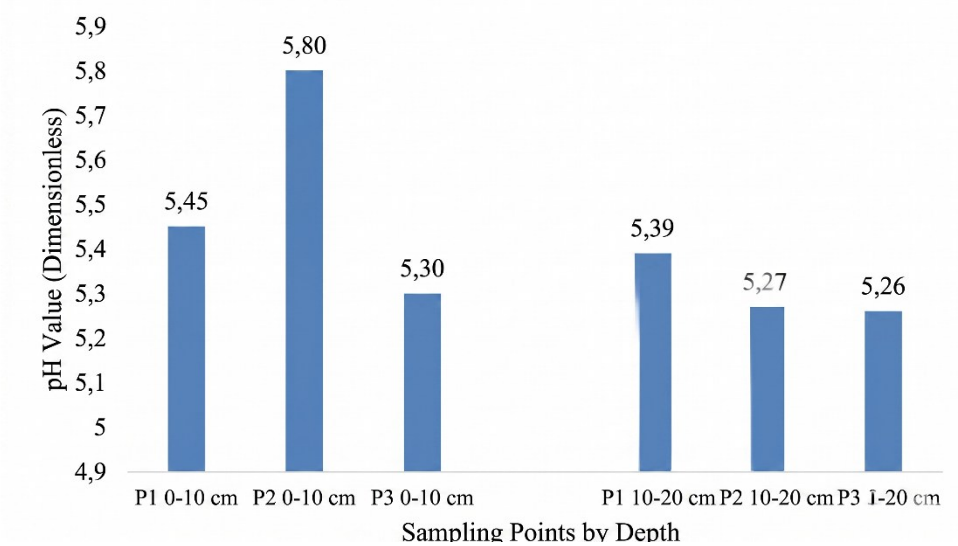

Figure 6 – Soil pH values across soil layers.
Source: Authors (2025).

Based on the obtained results, it can be inferred that the preserved area presents favorable conditions in terms of nutrient availability. According to Moreira, Cares, and Stürmer (2013), the evaluation of soil acidity requires knowledge of both soil pH and aluminum content.

The term pH defines the relative acidity or alkalinity of a solution, ranging from 0 to 14. A pH value of 7 is considered neutral, values below 7 indicate acidic conditions, and values above 7 indicate alkaline conditions. According to these authors, most productive soils typically exhibit pH values between 4 and 9.

3.3 Correlation between SOM and pH

The results of the Pearson linear correlation analysis (r) between soil organic matter (SOM) and pH indicated a strong correlation in the 0–10 cm layer (r = 0.87), suggesting a high degree of linear association between the variables (Figure 7). In contrast, a moderate correlation was observed in the 10–20 cm layer (r = 0.36) (Figure 8).

This pattern represents a key finding of the study, indicating that SOM accumulation in the surface layer—driven by litter input and increased biological activity—may influence soil acid–base balance. In the context of the Caatinga biome, where water availability often limits both biomass production and nutrient cycling, this relationship may be particularly relevant.

The strength of the correlation in the surface layer suggests that SOM may contribute to buffering soil pH, potentially moderating acidification processes typical of soils under native vegetation (Ebeling et al., 2008). Such interactions may favor the maintenance of soil fertility and biological activity over time.

According to Cohen (1988), correlation coefficients between 0.10 and 0.29 are considered small, values between 0.30 and 0.49 moderate, and values between 0.50 and 1.00 large. Dancey and Reidy (2006) propose a similar classification, where r values between 0.10 and 0.30 are considered weak, 0.40 to 0.60 moderate, and 0.70 to 1.00 strong. In general, the closer the coefficient is to 1 (regardless of sign), the stronger the linear dependence between the variables. The correlation results for SOM and soil pH in both layers are presented below.

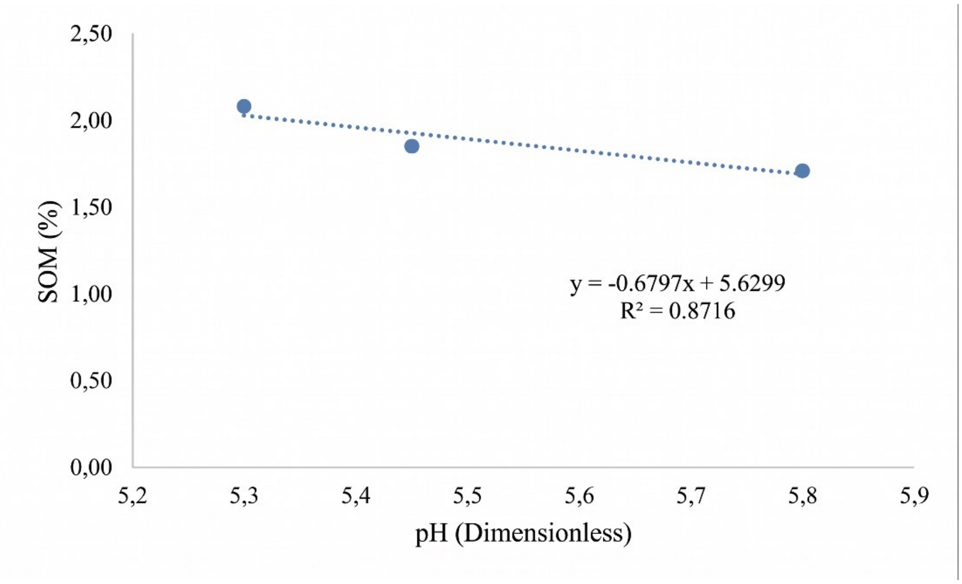

Figure 7 – Correlation between SOM and pH in the 0–10 cm layer.
Source: Authors (2025).

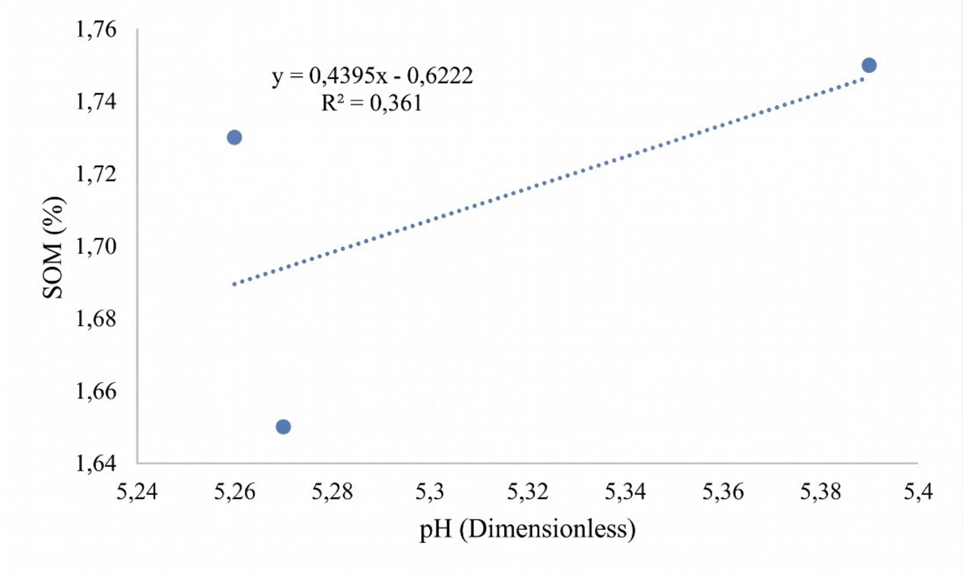

Figure 8 – Correlation between SOM and pH in the 10–20 cm layer.
Source: Authors (2025).

The results indicate that SOM exhibited a stronger positive correlation with pH in the surface layer (0–10 cm). This relationship may be explained by the interconnected roles of these soil attributes in supporting microbial communities, as soil organic matter serves as an important source of nutrients for microorganisms (Andrade, 2020).

Regarding pH, Ebeling et al. (2008) reported that higher carbon content may be associated with increased soil acidity. However, organic matter can also contribute to buffering processes, potentially promoting more stable pH conditions depending on the balance between organic acid production and cation exchange mechanisms.

Based on the observed results, SOM and pH can be considered key components of soil health, as they are closely interrelated and influence soil structure, aggregation, and porosity. These properties, in turn, affect nutrient availability and microbial activity, indirectly influencing soil pH dynamics.

A positive correlation coefficient indicates that increases in SOM are associated with increases in pH, whereas a negative coefficient would indicate the opposite trend. In this study, the observed relationship suggests that SOM–pH interactions may contribute to soil fertility and productivity.

Understanding this association may provide insights into the natural processes regulating soil fertility in preserved ecosystems, highlighting the role of conservation in maintaining soil chemical balance without the need for anthropogenic intervention.

3.4 NDVI and CO_2Flux

The processing results generated a map showing the spatial distribution of NDVI and CO_2Flux values across the analyzed area in the municipality of Princesa Isabel (Figure 9).

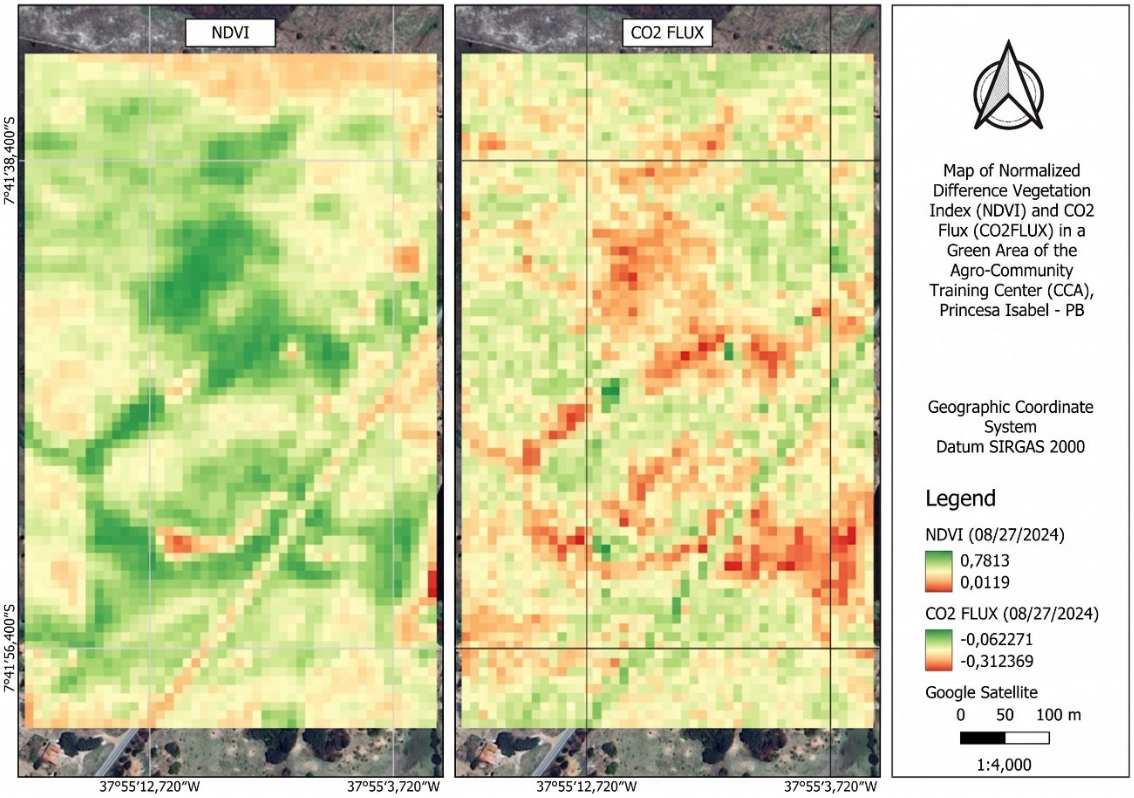

Figure 9 – Characterization of NDVI and CO$_2$Flux vegetation indices.
Source: Authors (2025).

The results presented in Figure 9 for the Normalized Difference Vegetation Index (NDVI) indicate that values closer to 1 are associated with denser vegetation, whereas values near zero correspond to non-vegetated or sparsely vegetated surfaces (Pinto and Pamboukian, 2024). In this study, NDVI values ranged from 0.01 to 0.78, suggesting spatial variability in vegetation density across the study area.

The color scale, ranging from red (lower values) to green (higher values), further illustrates this variability, with higher NDVI values corresponding to greater vegetation vigor. NDVI values in the vicinity of the soil sampling points showed a consistent pattern, with higher values generally associated with areas of denser vegetation. However, attributing this directly to soil properties such as SOM content and pH requires caution, as NDVI is influenced by multiple factors, including canopy structure, leaf area, and moisture availability.

In analogy to cultivated systems, where vegetation density is often positively correlated with NDVI (Lopes et al., 2011), it can be inferred that, in preserved Caatinga vegetation, NDVI variability may be primarily related to differences in leaf area rather than changes in plant density over short time scales. Given that the study area has remained preserved for more than 30 years, the vegetation structure is expected to be relatively stable, with limited short-term fluctuations in plant density. Similar relationships between vegetation parameters and spectral responses have been reported for deciduous forests (Wang et al., 2005; Barbosa; Huete; Baethgen, 2006).

The application of spectral indices for estimating CO$_2$Flux allowed the identification of spatial patterns that may be associated with variations in photosynthetic activity (Figure 9), with values reaching up to –0.31. Such values are commonly reported in ecosystems with strong hydrological seasonality, such as the Caatinga, particularly during the dry season.

Variability in carbon flux-related indices has also been observed in other semi-arid regions, such as in Pernambuco, where Oliveira et al. (2023) reported that Caatinga ecosystems may alternately function as carbon sources or sinks depending on environmental conditions. Similarly, Pereira et al. (2020) suggested that areas with higher vegetation density tend to exhibit greater efficiency in carbon uptake.

However, it is important to emphasize that CO_2Flux derived from spectral indices represents an indirect proxy and should not be interpreted as a direct measurement of carbon sequestration without field validation. It is important to note that the observed dynamics are likely associated with the low rainfall recorded during the data collection period (August), which resulted in prolonged water deficit conditions. Water limitation, characteristic of years with below-average precipitation, can significantly reduce photosynthetic activity, leading to stomatal closure and, consequently, decreased carbon assimilation.

Under such conditions, reduced carbon uptake may result in lower net ecosystem productivity. However, interpreting these patterns solely based on spectral indices requires caution, particularly in the absence of direct measurements of carbon fluxes.

Despite the observed water stress, the preserved area may exhibit characteristics associated with carbon retention processes. This behavior can be partially attributed to the protective role of litter and vegetation cover. The relatively continuous canopy, as indicated by NDVI values (up to 0.78), may reduce direct solar radiation reaching the soil surface, thereby lowering soil temperature and potentially slowing down organic matter decomposition processes (Philippot et al., 2013).

In addition, litter accumulation contributes to carbon input and forms a protective layer that helps retain soil moisture during dry periods, supporting microbial activity involved in carbon stabilization. These mechanisms may enhance the resilience of preserved ecosystems under water-limited conditions, as also reported for Caatinga environments (Mendes et al., 2020; Mendes et al., 2021).

Overall, the combined presence of soil organic matter, moderate pH conditions, and vegetation cover suggests that the studied area provides favorable conditions for maintaining soil functionality and ecological stability. However, these interpretations should be considered indicative, given the absence of direct measurements of carbon fluxes and the exploratory nature of the study.

Seasonally dry tropical forests in Brazil are known to play an important role in carbon dynamics; however, detailed and region-specific assessments are still needed. Remote sensing techniques, particularly vegetation indices, represent valuable tools for characterizing vegetation patterns in such environments, especially in areas with limited accessibility (Mendes et al., 2020; Pereira et al., 2020; Mendes et al., 2021).

NDVI and CO_2Flux indices can provide useful insights into vegetation condition and spatial variability, supporting environmental monitoring and conservation strategies. Nevertheless, their interpretation should be complemented with field-based data to ensure robust assessments of ecosystem processes.

4. Conclusions

The results obtained in this study indicate that soil organic matter (SOM) is more concentrated in the surface layer, reflecting the influence of litter input and biological activity typical of preserved environments. This vertical distribution highlights the role of vegetation cover in sustaining nutrient cycling and maintaining soil structure under semi-arid conditions.

The observed association between SOM and soil pH suggests a potential interaction between these attributes in regulating soil chemical conditions. However, given the limited sample size, this relationship should be interpreted with caution and cannot be generalized without further investigation.

Vegetation indices derived from remote sensing, particularly NDVI and CO_2Flux, proved to be useful for identifying spatial patterns in vegetation cover and potential variations in photosynthetic activity. Nevertheless, these indices represent indirect proxies and should not be interpreted as direct measurements of carbon fluxes or sequestration.

The integration of laboratory soil analyses with remote sensing data demonstrates potential as a preliminary approach for assessing soil–vegetation interactions in preserved semi-arid environments. However, the exploratory nature of the study, the limited sampling design, and the absence of temporal analysis limit the robustness of the conclusions.

Future studies should incorporate larger sample sizes, temporal monitoring, and field-based validation of carbon dynamics to provide more reliable insights into ecosystem functioning.

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