ASSESSMENT OF SOIL CARBON STOCK CHANGES AGAINST LAND USE AND LAND COVER CHANGES IN RIO DE JANEIRO STATE, BRAZIL

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ABSTRACT

Carbon is a key element in the contemporary context of climate change, and its cycle in nature is interconnected with various ecosystem functions. This study uses soil organic carbon (SOC) stock and land use/land cover (LULC) maps from the MapBiomas project to evaluate SOC stock changes against LULC changes in the state of Rio de Janeiro, Brazil, between the years 1985 and 2021. The results suggest a relative stability in SOC stocks, despite local stock changes ranging from -196 to 226 Mg ha^{-1}. Major SOC increases can be observed in pastures and moderate increases in forests, while high decreases are associated with urban areas and close to fragile environments with high biodiversity, such as *restinga* and mangrove ecosystems. Attention should be given, however, to the limitations posed by the uncertainties of the SOC stock and LULC input maps.

Key words **—** *below-ground carbon, geoprocessing, MapBiomas, LULC.*

RESUMO

O carbono é um elemento-chave no contexto atual de mudanças climáticas, e seu ciclo na natureza está interligado a diversas funções ecossistêmicas. Este estudo utiliza mapas de estoque de carbono orgânico do solo (SOC) e de uso e cobertura da terra (LULC) do projeto MapBiomas para avaliar as mudanças no estoque de SOC em relação às alterações de LULC no estado do Rio de Janeiro, Brasil, entre os anos de 1985 e 2021. Os resultados sugerem uma relativa estabilidade nos estoques de SOC, apesar de mudanças locais variando de -196 a 226 Mg ha^{-1}. Os maiores aumentos no SOC podem ser observados em pastagens, e aumentos moderados em florestas, enquanto as maiores reduções estão associadas a áreas urbanas e a ambientes frágeis com alta biodiversidade, como ecossistemas de restinga e manguezais. Deve-se, no entanto, dar atenção às limitações impostas pelas incertezas nos mapas de entrada de estoque de SOC e LULC.

Palavras-chave **—** *carbono abaixo do solo, geoprocessamento, MapBiomas, LULC.*

1. INTRODUCTION

Soils can function as large carbon reservoirs acting as sinks or sources of greenhouse gas emissions. Globally, in the current context of global warming and climate change, the burning of fossil fuels by industry, wildfires, and land use and land cover change are the main contributors to increases in CO_2, CH_4, and N_2O in the atmosphere [7].

In Brazil, according to the National Inventory of Anthropogenic Emissions and Removals of Greenhouse Gases [4], the average increase in CO_2 was mainly due to the agricultural sector (33.2%), the energy sector (28.9%), and land use and land cover change (27.1%), while the industrial and waste sectors contributed only 6.4 and 4.5%, respectively.

Soil carbon sequestration is a natural process closely tied to land use and cover, as it involves the removal of CO2 from the atmosphere and its storage in a portion of the land through plant growth and organic materials over long periods [15]. While dense planting and maintaining land cover enhance the SOC reservoir, management practices that promote increased erosion and degradation—such as excessive tillage and intensive use of pesticides—lead to significant loss of soil mass, and consequently, SOC [11, 14, 15].

As part of an international collaboration, the MapBiomas project compiled a soil data repository for all of Brazil, collecting over 20,000 records on soil, vegetation, topography, and climate from 1985 to 2021 [12]. The initiative made it possible to produce annual carbon stock maps by organizing, harmonizing, and standardizing soil data along with environmental covariates for a range of applications.

This study aims to assess SOC stock changes in the state of Rio de Janeiro, Brazil, under the influence of land use/land cover (LULC) changes.

2. MATERIAL AND METHODS

First, SOC stock maps (0 – 30 cm deep) from the MapBiomas Beta Collection [12] and LULC Maps from Collection 9.0 [13], with 30 m resolution, were downloaded using the toolkit available on the Google Earth Engine platform [8] for the state of Rio de Janeiro, Brazil, for the years of 1985 and 2021. Then, the maps were processed using tools from the Spatial Analyst package of ArcGIS Pro 3.0.1

software (ESRI, Redlands, USA), as described in the next paragraphs.

The LULC maps from 1985 and 2021 contain 20 and 21 classes, respectively. Three major LULC classes were selected for the analysis, including: 1 – Forest (native and planted), 2 – Pasture, and 3 – Crops (annual and perennial). To assess LULC changes among these classes from 1985 to 2021, map algebra was performed in the Raster Calculator, combining the 1985 and 2021 layers using a weighted sum equation (Equation 1).

Eq. 1 LULCchange = (100 * LULC1985) + LULC2021

Each raster contains a 'Value' column, which represents the classes, and a 'Count' column, which holds the number of pixels corresponding to each class. The 'Value' column of the LULC 1985 raster was multiplied by 100 to prevent class overlap. For example, forests in 1985 are assigned a Value = 1 and in 2021 a Value = 1. Thus, areas remaining as forests will have a Value = (100 * 1) + 1 = 101, areas that transitioned from forest to pasture a Value = 102, and areas converted to agriculture a Value = 103.

To calculate the SOC stock change from 1985 to 2021 (36 years), simple subtraction was done in Raster Calculator (Equation 2).

Eq. 2 SOCchange = SOC2021 – SOC1985

To support interpreting the output SOC change map, SOC stock changes were factorized based on the standard deviation (sd) of the SOC change raster. Variations (positive or negative) smaller than one sd were classified as weak changes, variations greater between one and two times the sd as moderate changes, and variations greater than two times the sd as strong changes. This created six classes: 1 – strong decrease (change < -2*sd), 2 – moderate decrease (-2*sd < change < -1*sd), 3 – weak decrease (-1*sd < change < 0), 4 – weak increase (0 < change < 1*sd), 5 – moderate increase (1*sd < change < 2*sd), and 6 – strong increase (change > 2*sd).

Finally, using Zonal Statistics as Table tool was used to calculate the descriptive statistics (minimum, maximum, mean, and sd) of SOC change (input raster) by LULC change (zone raster). This approach allows for assessing which LULC changes most favored SOC gains or losses, and which had minimal or no influence on SOC stock changes.

3. RESULTS

There were no remarkable changes between 1985 and 2021 in areas of forests, pastures, and crops (Figure 1). About 52% of the data corresponds to areas that remained as pastures. It is evident that pastures cover a large portion of the territory, with high concentration in the northeastern part of the state.

Meanwhile, 39% of the areas remained as forest, mainly concentrated in protected areas and their buffer zones in the *Serra do Mar* (mountain range) region. Only 2% of areas changed from pasture to forest or from forest to pasture. Less than 1% of the data corresponds to crop classes.

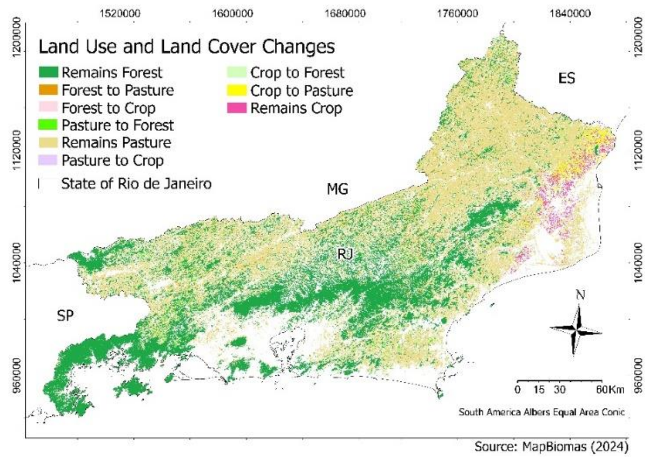

Figure 1. Map of land use/land cover changes from 1985 to 2021.

In Figure 2, the most representative SOC stock change classes are weak decrease and weak increase, highlighting the small variation in SOC stocks over the 36 years. The moderate increase class is concentrated around areas that remained as forests but also appears in lowland regions. Areas with moderate to strong SOC decrease are concentrated near urbanized areas around Guanabara and Sepetiba bays in the metropolitan region, and in localized areas in Rio das Ostras, Macaé and Campos dos Goytacazes in the northeastern part of the state

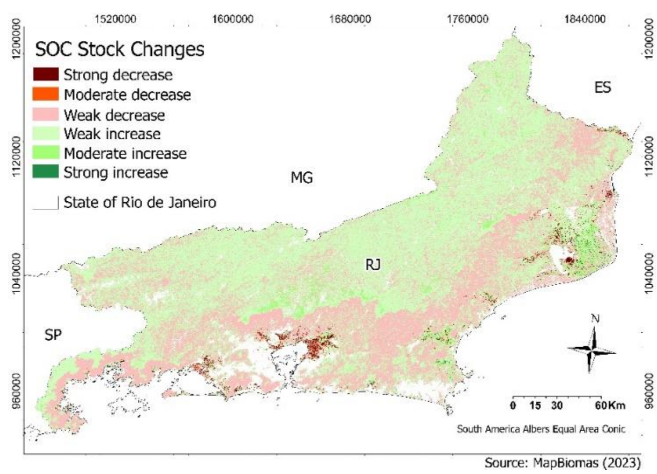

Figure 2. Map of soil organic carbon stock changes from 1985 to 2021.

Considering LULC changes, the greatest average SOC increase occurred in areas that remained as pasture, with the highest mean (2.03 Mg ha^{-1} in 36 years) and maximum (119 Mg ha^{-1}) values in the set, followed by zones that shifted from crops to pasture (Table 1). Meanwhile, the latter has the highest standard deviation (6.11 Mg C ha^{-1}), indicating high variation in SOC stock change values for these areas.

LULC changes	Minimum	Maximum	Mean	Standard deviation
Remains Pasture	-149.00	119.00	2.03	2.95
Crop to Pasture	-115.00	75.00	1.93	6.11
Remains Crop	-127.00	74.00	1.63	4.66
Remains Forest	-136.00	99.00	1.16	2.61
Pasture to Crop	-133.00	104.00	0.94	5.56
Pasture to Forest	-131.00	72.00	0.37	1.59
Crop to Forest	-3.00	6.00	0.01	0.81
Forest to Crop	-86.00	10.00	-0.10	3.13
Forest to Pasture	-139.00	102.00	-0.18	2.56

Table 1. Statistics of soil organic carbon change within zones of land use/land cover (LULC) change.

On the other hand, the SOC stocks decreased, on average, in areas that transitioned from forests to pastures or to crops. It is noteworthy, though, that these values are much smaller than the standard deviation. In all other areas, an increase was observed. Although less pronounced, the SOC stock increases related to areas that remained as forests or converted to forests showed the smallest standard deviations, suggesting greater reliability of the direction of SOC stock change, in these cases, of the SOC stock increases.

4. DISCUSSION

Regarding SOC, it is known that its content is relatively stable in soil. Once carbon stocks are lost—e.g., due to plowing, deforestation, or burning—the soil can take decades to recover [7]. Therefore, annual increases in SOC are generally small, with the predominance of areas that had a weak increase or decrease in SOC stock. Moreover, several studies have correlated SOC with certain covariates, such as altitude, landscape position, climate (temperature and precipitation), and soil texture. These covariates are also generally stable over time [6, 18, 19].

Topographically higher areas, such as the *Serra do Mar* and interior regions toward the *Serra da Mantiqueira*, are expected to have higher SOC stocks [12]. Additionally, soil beneath forests is better protected from erosion, allowing carbon to accumulate within soil aggregates [14].

On the other hand, the SOC stock change map (Figure 2) shows more pronounced depletions in the coastal lowlands, which, besides being covered by pastures and crops, are among the most densely populated areas. According to [15], population growth is directly linked to LULC change, as well as to SOC depletion. Furthermore, these areas are adjacent to mangroves, ecosystems that act as carbon reservoirs and are recognized for their high biodiversity [10]. In the northeastern region of the state, along the coast, Spodosols are also found. These are sandy soils with organic matter accumulation at depth [9]. They are fragile soils under coastal vegetation (*restinga*) and should be protected.

Despite a decline in crop and pasture areas over the last 36 years, nearly 2 million hectares of the state were covered by pastures in 2021. Of these, about three-quarters were in an intermediate to severe state of degradation [13]. The SOC stock decreases observed, particularly in lowland regions, support these findings. In this context, these areas are well-suited for soil restoration projects and, consequently, for SOC stock recovery [15].

The maps from the MapBiomas project are created by harmonizing a vast open database, encompassing a wide range of methodologies, work scales, and associated errors. Since the maps are generated using data from a single year, periods with less data availability result in less accurate maps, especially in areas where no data was collected [12]. These issues affect the results of the present study.

Some studies in the Atlantic Forest report increases in SOC stock in pastures, from the conversion of forests to pastures or in integrated systems [2, 5]. In global studies, [15] noted SOC stock increment rates of up to 1 Mg ha^{-1} year^{-1} in well-managed ecosystems. Therefore, increases greater than 100 Mg ha^{-1}, such as those observed in the model, can be considered unlikely over a span of 36 years. Similarly, significant depletions were estimated in areas that remained as forests. In fact, many studies indicate that SOC stocks generally increase or remain stable in these areas [1, 3, 17].

5. CONCLUSIONS

The LULC and SOC stock change maps reveal a scenario of relative stability over the 36 years from 1985 to 2021. The most significant LULC conversions occurred prior to the available data. Consequently, since the start year of the study (1985), most of the land was originally pasture or had been previously converted to pasture, which had been degraded at various levels. Overall, the SOC stock remained relatively stable in the state, however, attention should be given to the observed SOC stock depletion in lowland regions and close to fragile areas, which should be protected. Moreover, degraded areas of the state should be recovered fostering SOC stock enhancement, especially in those areas with low SOC stock.

The maps derived from the MapBiomas collections provide an overview of the LULC and SOC dynamics in the Rio de Janeiro state, but the results should be interpreted with caution due to the uncertainty of the MapBiomas LULC and SOC stock maps.

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