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D E C L A R A Ç Ã O

Declaramos, para os devidos fins, que o artigo intitulado “"Economic valuation of soil organic carbon stock in the Amazon Forest-Cerrado transition, Brazil” dos autores: Thiago Cândido dos Santos, Facundo Alvarez, Andreza Maciel de Sousa, Marcos Vinícius da Silva, Maria Beatriz Ferreira, Edvander Prudente de Almeida, Bruno de Souza Barreto, Guilherme Domingos Ferreira, Glécio Machado Siqueira e Aldair de Souza Medeiros, foi aceito para publicação na Revista Brasileira de Engenharia Agrícola e Ambiental.

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Original Article

Economic valuation of soil organic carbon stock in the Amazon Forest-Cerrado transition, Brazil

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HIGHLIGHTS:

Social cost of carbon values for soil organic carbon stocks depends on biome and soil type.

The Cerrado biome has higher total soil organic carbon values than the Amazon Forest

Amazon Forest has higher soil organic carbon valuation per area than Cerrado.

ABSTRACT: The average annual deforestation rate in the Amazon Forest-Cerrado transition zone is approximately 2,098.08 km², restricting numerous ecosystem services. There is a pressing need to develop policies to reduce greenhouse gas emissions in the region. The objective of this study was to evaluate the economic potential of total soil organic carbon (SOC) stocks in different soil types and depths in the Amazon Forest and Cerrado biomes, considering the social cost of carbon (SC-CO_2) derived by the United States Environmental Protection Agency (EPA). Soil samples were collected at 2,869 points, distributed across 178 municipalities in the Amazon Forest and Cerrado biomes in Maranhão state, Brazil, in the 0-5, 5-15, and 15-30 cm layers. To carry out the soil organic carbon valuation, two main approaches were combined: accounting framework and economic valuation. The results show that in the Amazon Forest, the total SOC stored in the 0-30 cm layer has an estimated value of 76.52 billion dollars, while in the Cerrado the amount corresponds to 143.73 billion dollars. SOC stock valuation represents an important strategy for sustainable agricultural production, which seeks global food security and at the same time the mitigation of greenhouse gas emissions.

Key words: biodiversity, ecosystem services, economic valuation, climate change, sustainability

Avaliação econômica do estoque de carbono orgânico do solo na transição Floresta Amazônica-Cerrado, Brasil

RESUMO: A taxa média anual de desmatamento na zona de transição entre a Floresta Amazônica e o Cerrado é de aproximadamente 2.098,08 km², restringindo inúmeros serviços ecossistêmicos. Há uma necessidade urgente de desenvolver políticas para reduzir as emissões de gases de efeito estufa na região. O objetivo do presente estudo foi avaliar o potencial econômico dos estoques totais de carbono orgânico do solo em diferentes tipos de solo e profundidades na transição entre a Floresta Amazônica e o Cerrado, considerando o custo social do carbono determinado pela Agência de Proteção Ambiental dos Estados Unidos (EPA). Foram coletadas amostras de solo em 2.869 pontos, distribuídos por 178 municípios nos biomas Amazônia e Cerrado no Estado do Maranhão, nas camadas de 0-5, 5-15 e 15-30 cm. Para realizar a valoração do carbono orgânico do solo, foram combinadas duas abordagens principais: a estrutura contábil e a valoração econômica. Os resultados mostram que, na Floresta Amazônica, o total de carbono orgânico do solo armazenado na camada de 0-30 cm tem um valor estimado de 76,52 bilhões de dólares, enquanto no Cerrado esse valor corresponde a 143,72 bilhões de dólares. A valoração dos estoques de carbono orgânico do solo representa uma estratégia importante para a produção agrícola sustentável, que busca a segurança alimentar global e, ao mesmo tempo, a mitigação das emissões de gases de efeito estufa.

Palavras-chave: biodiversidade, serviços ecossistêmicos, valoração econômica, mudanças climáticas, sustentabilidade

INTRODUCTION

In the Amazon Forest-Cerrado transition zone in Maranhão state, Brazil, between 2008 and 2023, the average annual deforestation rate was approximately 2,098.08 km² (INPE, 2024). The Eastern Amazon Forest of Maranhão state has been reduced to 24% of its original formation (Silva Júnior et al., 2020). Native Cerrado has already been reduced by 48,523.41 km² (INPE, 2024) due to the advance of grain production (soybeans and corn). Agricultural expansion in areas of native vegetation in the Amazon Forest and Cerrado has resulted in losses of soil organic carbon (SOC) stocks in Maranhão state, on the order of 1.57 and 1.36 Mt C in areas converted to intensive agriculture and pasture (Mendes et al., 2021).

Progressive anthropization in the Amazon Forest and Cerrado biomes restricts numerous ecosystem services, as the transition zones are hyperdynamic and host complex biodiversity patterns (Aragão et al., 2023). Despite growing evidence of SOC losses with agricultural expansion, there is still a lack of state-level, biome-targeted economic valuations of SOC across soil types and depths in Maranhão's Amazon–Cerrado transition. This gap limits the design of place-based incentives and policies (Rodrigues et al., 2022; Naorem et al., 2023). SC-CO_2 emerges as key indicator for developing climate change mitigation strategies and reducing greenhouse gas (GHG) emissions (Nordhaus, 2017). The result is a monetary value expressed in US dollars per ton of CO_2, which aims to maximize the net benefits to society as compensation for the use of ecosystem services and excess CO_2 emissions (Trivedi et al., 2018; Kikstra et al., 2021).

In the soil ecosystem services context, SOC valuation can be incorporated into the policy for the regularization and pricing of ecosystem services (Groshans et al., 2019; Mikhailova et al., 2019). Furthermore, it is an important method to contribute to the 13th Sustainable Development Goal (SDG), which seeks action against global climate change and environmental impacts (UN, 2022). However, estimating the economic value of SOC requires a broad social and ecological analysis of the processes involved in CO_2 sequestration or emission.

Following established frameworks (Groshans et al., 2019; Mikhailova et al., 2019), this study aimed to: (i) quantify SOC stocks by biome, soil class, and depth; (ii) convert stocks to monetary values using SC-CO_2; and (iii) contextualize damage avoided to inform regional policy. This approach is important in the face of the current scenario and future projections on climate change impacts (IPCC, 2022), as it allows the analysis of which parts of the C cycle and its ecosystem services are affected by anthropogenic actions (Medeiros et al., 2022).

SC-CO_2 can collaborate with the “4 per 100” initiative, which seeks to increase SOC content by 0.4% per year in agricultural soils globally (Minasny et al., 2017). It can also be an important tool to help Brazil achieve its Nationally Determined Contributions presented in the Paris Agreement (UNFCCC COP21) (BRASIL, 2023) and strengthen the

Brazilian government's sectoral plan for adaptation and low carbon emissions in agriculture: ABC+ Plan (BRASIL, 2021).

It is hypothesized that state-targeted SOC valuation in the Amazon–Cerrado transition of Maranhão state can inform targeted public policies and payments for ecosystem services. The objective of this study is to evaluate the economic potential of total SOC stocks in different soil types and depths in the Amazon Forest and Cerrado biomes, considering the SC-CO_2 derived by the U.S. Environmental Protection Agency (EPA).

MATERIAL AND METHODS

The Amazon Forest and Cerrado biomes occupy 49.5% (4,196,943 km²) and 23.3% (2,045,000 km²) of the national territory (BRASIL, 2020). In Maranhão, the Amazon Forest occupies 34.8% (112,397.32 km²) and the Cerrado 64.1% (217,061.05 km²) of the state's total area (Figure 1) (IMESC, 2021). According to Köppen's classification, the region's climate is tropical hot humid (As) in the Amazon Forest area of the state, and tropical hot and semi-humid (Aw) in the Cerrado area (Oliveira et al., 2021).

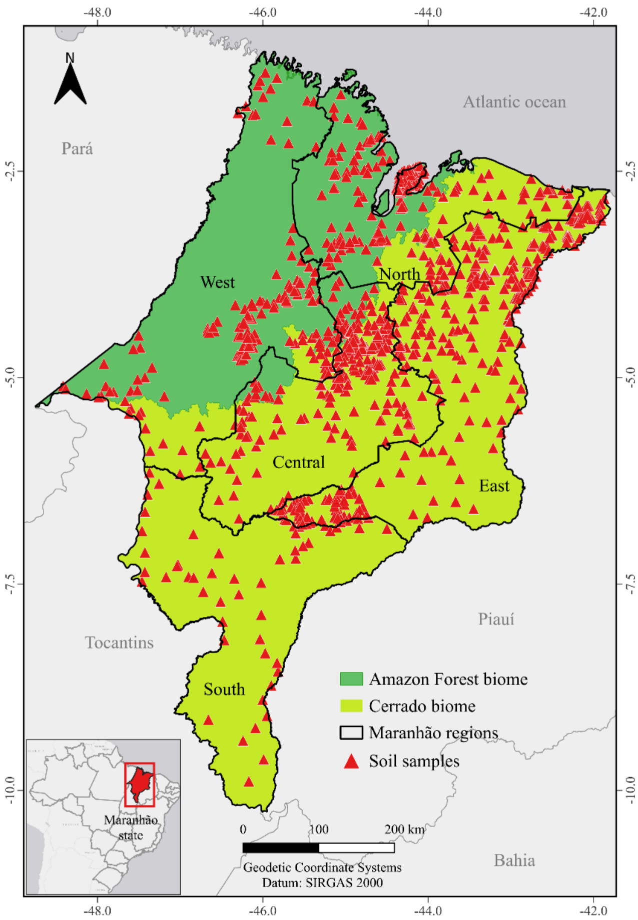

Figure 1. Spatial location of soil sampling points in the Amazon Forest and Cerrado biomes in the administrative regions of Maranhão state, Brazil

Maranhão state contains a wide range of soil classes (Figure 2), predominantly Oxisols, Entisols and Ultisols according to the United States Department of Agriculture classification (USDA, 2022), or Latossolos, Neossolos, Plintossolos and Argissolos according to the Brazilian Soil Classification System (Santos et al., 2018).

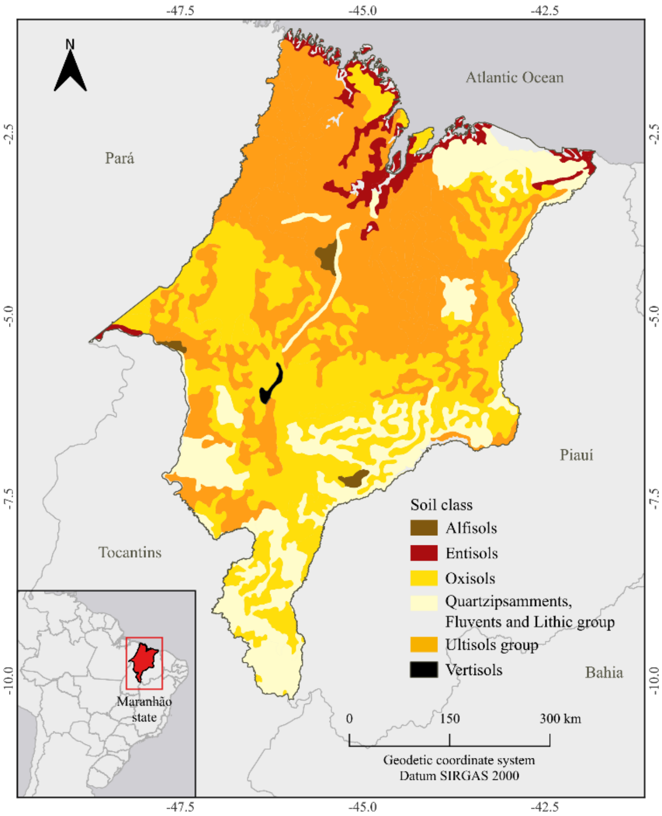

Figure 2. Main soil classes of the state of Maranhão, Brazil

Maranhão is part of the MATOPIBA, a geographic region that encompasses the territories of Maranhão, Tocantins, Piauí, and Bahia states. Currently, MATOPIBA is the main Brazilian agricultural frontier, with 73 million hectares, in which it is estimated that 33 million tons of soybeans will be produced by 2030 (Bachi et al., 2023). Therefore, the tendency is for the native vegetation area to continue decreasing due to the advancement of agribusiness in Maranhão state.

In this study, a series of methodological steps was used to estimate the economic valuation of SOC stocks, applying the methods and analysis already established in the literature. The steps follow the sequence shown in Figure 3.

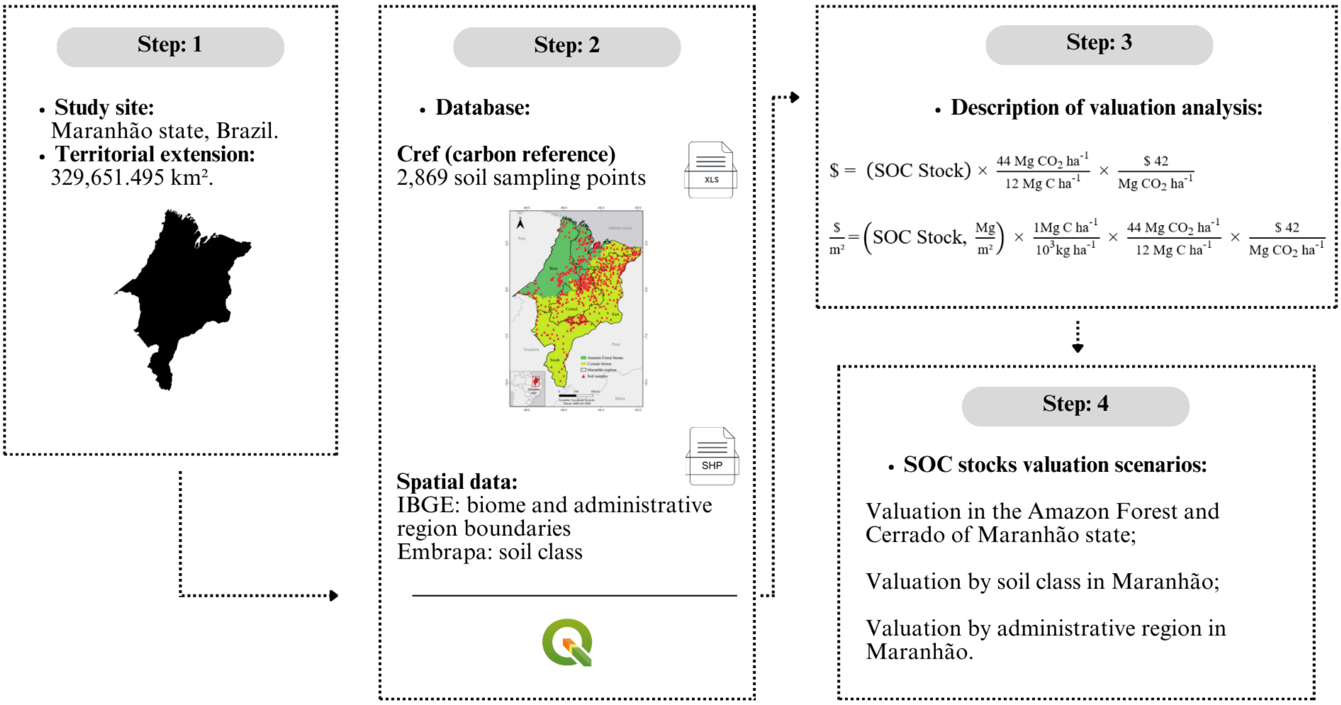

Figure 3. Methodological flowchart of steps and construction of results

Soil samples were collected between January and December of 2021 at 2,869 sampling points distributed in native vegetation areas across 178 municipalities in Maranhão state at a depth of up to 30 cm, in the 0-5, 5-15, and 15-30 cm soil layers (Figure 1). Sampling followed a stratified random design across Amazon forest and Cerrado biomes. All locations were georeferenced (WGS84) using a Garmin GPS device with an accuracy of approximately 3 m. At each point, 10 single samples per layer were collected within a 10-m radius. The points were spatialized, and their distribution and number within each stratum were determined after intersecting the coordinate points with 1:250,000-scale vector layers containing biome boundaries and administrative regions (IBGE, 2023), and soil classes (EMBRAPA, 2011) using QGIS software. This approach was necessary to determine the area and SOC stock values based on the averages of the polygons.

The soil samples were dried in an oven at 60 ºC for 24 hours and sieved through a 2 mm mesh to remove stones and fragments of branches and roots before analysis. SOC content was determined following the methodology proposed by Raij et al. (2001). Soil density (SD) was obtained using the volumetric ring method with volume of 100 cm^3 (Teixeira et al., 2017). For each soil layer, SOC stock was calculated by multiplying SOC content (g dm^{-3}) by SD (g cm^{-3}) and soil layer thickness (cm).

The SOC valuation methodology combines two main approaches: accounting framework and economic valuation. The accounting framework uses biophysical analyses, based on scientific data and administrative analyses based on geographic limits. This information is used to assist in the economic valuation or pricing stage of SOC stocks (Table 1).

Table 1. Conceptual view of the soil organic carbon valuation process for the different Maranhão regions in Brazil

Biophysical Accounts (Science-Based)	Administrative Accounts (Boundary-Based)	Monetary Account(s)	Benefit(s)	Total Value
Soil extent:	Administrative extent:	Ecosystem good(s) and service(s):	Sector:	Types of value:
Separate constituent stock: SOC				
			Environment:	$SC\text{-}CO_2$:
- Soil type - Soil depth	- State - Regions - Biomes	- Regulation (e.g., carbon sequestration)	- Carbon sequestration in soil organic matter (SOM)	- $ 42 per metric ton of CO_2 (2007 US dollars with an average discount rate of 3%)

SOC - Soil organic carbon; SOM - Soil organic matter; $SC\text{-}CO_2$ - Social cost of carbon and avoided emissions; US - United States

The valuation calculations of SOC stocks based on $SC\text{-}CO_2$ were carried out for the contiguous Maranhão state. First, the valuation was calculated for the Amazon Forest and

Cerrado biomes, using the spatial data provided by IBGE (2023). Then, soil spatial data from the Brazilian Agricultural Research Corporation (EMBRAPA, 2011) were used to calculate SOC stock valuations in the following soil classes: Alfisols, Entisols, Oxisols, the Quartzipsamments–Fluvents–Lithic group, the Ultisols group, and Vertisols according to the Soil Taxonomy classification (2022). The Ultisols group corresponds to a grouping of three soil classes that were analyzed together because they have an equivalent classification in Soil Taxonomy (2022); these classes correspond to Argissolos, Nitossolos, and Plintossolos in the Brazilian Soil Classification System (Santos et al., 2018). The Quartzipsamments–Fluvents–Lithic group followed a similar approach and was also a merger of three soil classes, corresponding to Neossolos Quartzarênico, Flúvico, and Litólico. The remaining soil classes are single classes, with Alfisols being equivalent to Luvissolos, Entisols to Gleissolos, Oxisols to Latossolos, and Vertisols to Vertissolos according to same Brazilian classification. Finally, the valuation was calculated for administrative regions of Maranhão state defined by IBGE (2023): North, South, East, West, and Central Maranhão.

An economic valuation for SOC stocks was calculated using the social cost of carbon (SC-CO_2) and avoid emissions estimated by the U.S. Environmental Protection Agency (EPA), which corresponds to the amount of \$ 42 Mg CO_2. This value, which increases over time due to future emissions and their potential damage, is applicable for the year 2020 based on 2007 US dollars, with a discount rate of 3% (EPA, 2016). The SC-CO_2 used in this study was estimated by an interagency working group led by EPA.

The estimates took into account various sources of uncertainty through a combination of a multi-model ensemble, probabilistic analysis, and scenario analysis, using Monte Carlo techniques to run the integrated assessment models. The 3% discount rate is the central value, representing the average across the models (EPA, 2016). However, many of the important climate change impacts reported in the literature were not included in the values estimated by EPA, which attributes this deficiency to current limitations in modeling and data availability (Groshans et al., 2019).

The SOC stock values (Mg ha^{-1}) were obtained from 2,869 sampling points; 400 in the Amazon Forest and 2,469 in the Cerrado of Maranhão state, considering soil depths of 0-5, 5-15, 15-30 and 0-30 cm (Figure 1). These values were converted into US dollars ($) and dollars per square meter ($ m^{-2}), using the methodology proposed by Mikhailova et al. (2019), according to Eqs. 1 and 2.

$$\$ = \text{(SOC Stock)} \times \frac{44\ \text{Mg CO}_2\ \text{ha}^{-1}}{12\ \text{Mg C ha}^{-1}} \times \frac{\$\ 42}{\text{Mg CO}_2\ \text{ha}^{-1}} \quad (1)$$

$$\frac{\$}{\text{m}^2} = \left(\text{SOC Stock, } \frac{\text{Mg}}{\text{m}^2}\right) \times \frac{1\text{Mg C ha}^{-1}}{10^3\text{kg ha}^{-1}} \times \frac{44\ \text{Mg CO}_2\ \text{ha}^{-1}}{12\ \text{Mg C ha}^{-1}} \times \frac{\$\ 42}{\text{Mg CO}_2\ \text{ha}^{-1}} \quad (2)$$

Where:

$ - represents estimated value for total of SOC stocks per hectare; and,

$\frac{\$}{\text{m}^2}$ - represents estimated value for SOC stocks per square meter.

To better visualize the distribution of financial resources across different regions and soil depths in the state of Maranhão, a Sankey diagram was created using Microsoft Excel software with the help of SankeyArt Diagram Creator plugin. The methodology employed uses data in nodes and flows. The nodes represent the geographic regions of the state (North, South, East, West, and Central) and the soil depths sampled in each region (0-5 cm, 5-15 cm, and 15-30 cm). The flows, represented by bands with widths proportional to the values, connect these nodes, demonstrating the distribution of the resource between the different combinations of region and depth.

RESULTS AND DISCUSSION

SOC storage is highly variable in the contiguous Maranhão state, whether it is on biome extent, soil class extent, soil depth or administrative regions. The monetary value estimates based on SOC-CO_2 in this study properly capture this variability. Analysis of the fractional SOC between soil layers in the Amazon Forest found that the 0-5 cm soil layer has a stock of 0.11 Pg C, estimated at $ 16.57 B, and an average per unit area of $ 0.15 m^{-2} (Table 2). The 5-15 cm soil layer has a stock of 0.17 Pg C, an estimated value of $ 25.75 B, and an average value of $ 0.23 m^{-2}. For the 15-30 cm soil layer, a stock of 0.22 Pg C was estimated, corresponding to the value of $ 34.19 B, while its average value per unit area is $ 0.30 m^{-2}. The total SOC stored in the 0-30 cm soil layer is equivalent to 0.50 Pg C, with an estimated value of 76.52 billion dollars and an average value per unit area of $ 0.68 m^{-2}.

Table 2. Average soil organic carbon stocks (SOC) estimated in the Amazon Forest and Cerrado of Maranhão state, Brazil

Biome	Area	SOC stock (Pg)			
		0-5	5-15	15-30	0-30
	km²	cm			
Amazon Forest	112,397.32	0.11	0.17	0.22	0.50
Cerrado	217,061.05	0.18	0.32	0.44	0.93

In the Cerrado biome, the estimated total values were higher than in the Amazon (Table 3). However, the average values per area did not show major changes; the only exceptions were the soil depths of 15-30 cm, where the results for the Cerrado showed relatively higher value compared to those for the Amazon Forest. For the Cerrado biome, the SOC stock in the 0-5 cm soil layer was estimated at 0.18 Pg C ($ 27.28 B), with an average value per area of $ 0.13 m^{-2}. In the 5-15 cm soil layer, a total stock of 0.32 Pg C was found, with an estimated price of $ 49.02 B, with an average per unit area of $ 0.23 m^{-2}.

Estimates for the 15-30 cm soil layer indicate a stock of 0.44 Pg C, with a total value of \$ 67.42 B, and a contiguous average of \$ 0.31 m^{-2}. The total SOC stock estimated for the 0-30 cm soil layer was 0.93 Pg C (\$ 143.72 B), with an average per unit area of \$ 0.66 m^{-2}.

Table 3. Economic valuation of total soil organic carbon (SOC) stocks in the Amazon Forest and Cerrado biomes in Maranhão state, Brazil

Biome	Area	Total value in billions of US dollar (\$)				Value per unit area (\$ m^{-2})			
		0-5	5-15	15-30	0-30	0-5	5-15	15-30	0-30
	km²	cm							
Amazon Forest	112,397.32	16.57	25.75	34.19	76.52	0.15	0.23	0.30	0.68
Cerrado	217,061.05	27.28	49.02	67.42	143.72	0.13	0.23	0.31	0.66

US – United States

The soil classes that had the highest SOC stocks in Maranhão state, considering the 0-30 cm soil layer, were Ultisols group (0.598 Pg C; \$ 92.16 B), Oxisols (0.42 Pg C; \$ 65.3 B), and the Quartzipsamments-Fluvents-Lithic group (0.20 Pg C; \$ 30.2 B) (Table 4). Soil classes with smaller spatial coverage such as Entisols (0.087 Pg C; \$ 13.47 B), Alfisols (0.009 Pg C; \$ 1.53 B) and Vertisols (0.005 Pg C; \$ 0.81 B) showed results for stocks and values that were less pronounced in the 0-30 cm soil layer.

Table 4. Average soil organic carbon (SOC) stocks estimated by soil class in Maranhão state, Brazil

Soil class	Total area	SOC stock (Pg)			
		0-5	5-15	15-30	0-30
	km²	cm			
Ultisols group	137,119.81	0.112	0.204	0.282	0.598
Entisols	13,288.81	0.020	0.030	0.037	0.087
Oxisols	110,571.93	0.089	0.144	0.192	0.424
Alfisols	2,124.38	0.002	0.003	0.005	0.010

Quartzipsamments-Fluvents-Lithic group	59,882.96	0.042	0.065	0.090	0.196
Vertisols	644.50	0.001	0.002	0.002	0.005

The estimated average values per unit area (0-30 cm soil layer), for the soil classes Vertisols ($ 1.25 m^{-2}), Entisols ($ 1.01 m^{-2}) and Alfisols ($ 0.72 m^{-2}), were those that provided the highest average values of SOC stocks. The lowest values were observed in the soil classes Ultisols group ($ 0.67 m^{-2}), Oxisols ($ 0.59 m^{-2}), and the Quartzipsamments-Fluvents-Lithic group ($ 0.50 m^{-2}), considering the 0-30 cm soil layer. However, these values tend to vary in smaller soil depths (Table 5).

Table 5. Valuation of total soil organic carbon (SOC) stocks by soil class in Maranhão state, Brazil

Soil class	Area — km² —	Total value in billions of US dollar ($)				Value per unit area ($ m⁻²)			
		0-5	5-15	15-30	0-30	0-5	5-15	15-30	0-30
		cm							
Ultisols group	137,119.81	17.26	31.42	43.49	92.16	0.13	0.23	0.32	0.67
Entisols	13,288.81	3.05	4.66	5.77	13.47	0.23	0.35	0.43	1.01
Oxisols	110,571.93	13.64	22.11	29.58	65.33	0.12	0.20	0.27	0.59
Alfisols	2,124.38	0.26	0.53	0.74	1.53	0.12	0.25	0.35	0.72
Quartzipsamments-Fluvents-Lithic group	59,882.96	6.40	10.01	13.79	30.20	0.11	0.17	0.23	0.50
Vertisols	644.50	0.19	0.26	0.36	0.81	0.29	0.40	0.56	1.25

Regarding SOC stocks in these regions, it was identified that in the 0-30 cm soil layer, the largest estimated stocks were in the East (0.303 Pg C), South (0.298 Pg C), and North Maranhão regions (0.251 Pg C). The lowest stocks in the 0-30 cm soil layer were estimated for the West (0.228 Pg C) and Central Maranhão (0.249 Pg C) regions (Table 6).

Table 6. Average soil organic carbon (SOC) stocks estimated by region in Maranhão state, Brazil

Region	Area	SOC stock (Pg)			
		0-5	5-15	15-30	0-30
	km²	cm			
North Maranhão	49,919.43	0.055	0.084	0.112	0.251
South Maranhão	67,693.42	0.071	0.099	0.128	0.298
East Maranhão	70,721.22	0.057	0.104	0.142	0.303
West Maranhão	86,947.16	0.047	0.078	0.104	0.228
Central Maranhão	54,370.26	0.045	0.083	0.120	0.249
Total	329,651.50	0.276	0.448	0.606	1.329

The results also showed that in the 0-30 cm soil layer, the Maranhão regions with the highest SOC stock values were the East with $ 46.64 B for a stock of 0.30 Pg C, and the South with $ 45.95 B for a stock of 0.30 Pg C. The regions with the lowest values were the North ($ 38.68 B; 0.25 Pg C), Central ($ 38.68 B; 0.25 Pg C) and West ($ 35.17 B; 0.23 Pg C). However, the highest total stocks were observed in the East and South regions, while the North and Central regions showed the highest average values per area. Therefore, the pattern differs depending on whether total stock or stock normalized by area is considered (Table 6 and Figure 4).

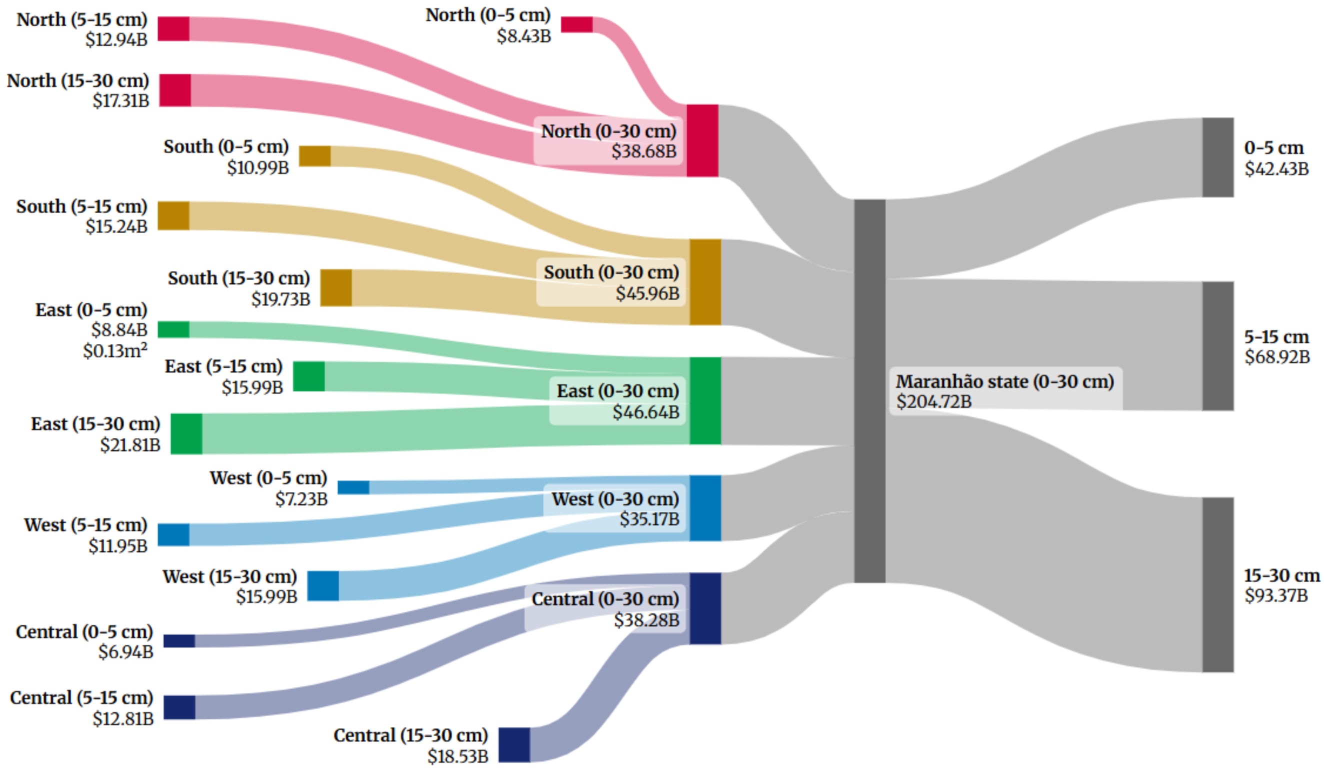

Figure 4. Estimated valuation using social cost of carbon ($SC\text{-}CO_2$) for soil organic carbon (SOC) stocks in Maranhão state, demonstrating: 1) total valuation in the regions, 2) total valuation in the state, and 3) valuation by soil depth

Concerning the average values per unit area, the estimates showed that the North ($ 0.77 m^{-2}), Central ($ 0.70 m^{-2}), South ($ 0.68 m^{-2}), and East ($ 0.66 m^{-2}) regions have the highest SOC stock values when considering the 0-30 cm soil layer. The lowest valuation per unit area was observed in the West region with an average value of $ 0.40 m^{-2} (Table 7). This order changes between soil layers, except the highest value obtained in the North region and the lowest value obtained in the West, at all depths analyzed.

Table 7. Average soil organic carbon (SOC) value per unit area estimated by region in Maranhão state, Brazil

Region	Area	Value per unit area ($ m^{-2})			
		0-5	5-15	15-30	0-30
	km²	cm			
North Maranhão	49,919.43	0.17	0.26	0.35	0.77
South Maranhão	67,693.42	0.16	0.23	0.29	0.68
East Maranhão	70,721.22	0.13	0.23	0.31	0.66
West Maranhão	86,947.16	0.08	0.14	0.18	0.40
Central Maranhão	54,370.26	0.13	0.24	0.34	0.70
Maranhão state	329,651.50	0.13	0.22	0.29	0.64

For the Amazon Forest ($ 76.52 B) and Cerrado ($ 143.72 B) biomes, the total costs based on SC-CO_2 and avoided emissions/damage were quite significant considering the 0-30 cm soil layer (Table 3). Maintaining or increasing SOC stocks in these regions, in addition to environmental improvements (Maia et al., 2022; Medeiros et al., 2022), can also bring significant financial benefits (Mikhailova et al., 2019), as it provides parameters of pricing for carbon stored in the soil. Furthermore, it contributes relevant information to guide climate policies and adequate pricing of ecological-environmental services (Feitosa et al., 2023).

The SC-CO_2 values associated with SOC varied depending on the biome type, soil type, and administrative Maranhão regions. This could derive from spatial variations in SOC stocks (Lin et al., 2023), adjusted to the orogenic, edaphic, and climatic-environmental factors of the biomes and associated vegetation and biodiversity (Medeiros et al., 2022). The spatial SOC stock variations have implications for defining the ideal value to be paid for carbon sequestration in the soil, aiming to mitigate climate change (Groshans et al., 2019).

It is important to highlight that Maranhão state is in a strategic region of Brazil, a transition zone between biomes (Caatinga-Cerrado and Cerrado-Amazon Forest), and is part of MATOPIBA. The state has suffered in recent decades from the pressure caused by the expansion in the production of commodities for export, mainly soybeans (Bachi et al., 2023). Although some studies indicate that the advance of the agricultural frontier causes significant SOC stock losses in this Brazilian region (Mendes et al., 2021; Rodrigues et al., 2022), studies that analyze their impacts on biodiversity and, consequently, on ecosystem services are still incipient.

The SC-CO_2 values and emissions/damage avoided per area are slightly higher in the Amazon Forest biome (\$ 0.68 m^{-2}) than in the Cerrado (\$ 0.66 m^{-2}) (Table 3).This difference interferes with the costs related to climate control, that is, the relationship between the cost of generating a good or service and the subsequent benefit after its consumption (Groshans et al., 2019; Kikstra et al., 2021; Feitosa et al., 2023). The climate control cost in the Cerrado biome is higher than in the Amazon Forest biome, as the additional benefit of SOC, which positively impacts carbon sequestration, is influenced by the SC-CO_2 value per area.

The higher the SC-CO_2 value per area, the lower the climate control costs for a given region, as in the case of the Amazon Forest in Maranhão state (Groshans et al., 2019; Feitosa et al., 2023), which reinforces once again the importance of this study to value the local increase in SOC stocks, and consequently, the reduction of GHG emissions, helping Brazil to fulfill its Nationally Determined Contribution (BRASIL, 2023).

Soil classes influenced the variation in total SC-CO_2 values and by area throughout the biomes and Maranhão regions. The soil classes Ultisols group (\$ 92.16 B) and Oxisols (\$ 65.33 B), common in both the Cerrado and Amazon Forest areas, had the highest total SC-CO_2 values, but with low SOC values normalized by area. Oxisols have high potential for agriculture, as they are deep, porous, well-drained soils with a flat topography, which facilitates the use of agricultural machinery (Santos et al., 2018). This soil type has high

Fe and Al oxide levels (Bayer et al., 2006), which generate greater physical and chemical protection for SOC (Medeiros et al., 2022).

The Quartzipsamments-Fluvents-Lithic group had the lowest SC-CO_2 values per square meter (\$ 0.50 m^{-2}), possibly related to the sandy texture and fragile structure, which hinder SOC accumulation and stabilization (Bayer et al., 2006; Santos et al., 2018), especially in Quartzipsamments, which occupy a large territorial area within this group of soils. Due to high sand content and low levels of silt and clay, Quartzipsamments have a weakly developed structure, which results in low water and nutrient retention capacity, directly affecting SOC concentrations (Ramos et al., 2023).

The lower SOC value per area observed in the Cerrado biome in Maranhão state may be related to the wide distribution of Quartzipsamments in this region. Entisols, which have an extensive distribution in coastal areas and flooded regions such as the North of Maranhão state, had the second highest SOC value per area (\$ 1.01 m^{-2}) and the fifth in total values (\$ 13.47 B). Vertisols had the highest SOC value per area, with \$ 1.25 m^{-2}; however, the restricted spatial distribution (644 km^2) reduced the influence on the total SC-CO_2 values in the biomes and Maranhão regions (Table 5).

The conspicuous presence of Entisols in the Amazon Forest biome and in the northern Maranhão region probably contributed to the higher SC-CO_2 values per area identified in these regions. It is important to mention that Entisols have a high SOC stock, especially in forest areas and swampy areas (Black et al., 2021).

The SC-CO_2 values of SOC stocks did not vary greatly between the administrative Maranhão regions, except for the West region, which had the lowest values both for the total valuation (\$ 35.17 B) and per area (\$ 0.40 m^{-2}). It is important to highlight that the area was not a preponderant factor in the total stocks by region. For example, the North

Maranhão region has a smaller territorial area than the West region; however, its total SOC stock was higher than those estimated for the West.

The Western region has large territorial extensions designated as indigenous reserves (Silva Júnior et al., 2020), which makes large-scale soil sampling difficult. The smaller number of sampling points (Figure 1) probably influenced the SOC valuation estimate in the Western Maranhão region. The East and South Maranhão regions had the highest total SOC values (Figure 4). However, the rapid advance of the agricultural frontier over the native Cerrado areas in these regions represents a major threat to SOC stock maintenance (Bachi et al., 2023; MapBiomas, 2024). In the last 23 years, 48,523.41 km² of native Cerrado have been deforested in Maranhão state, with an annual average of 2,109.71 km² (INPE, 2024).

According to data from the Greenhouse Gas Emissions and Removals Estimating System (SEEG, 2023), in 2022, activities related to changes in land use and cover in Maranhão emitted around 86.0 million Mg CO_2 equivalent (CO_2eq), of which 21.5 million Mg CO_2eq are related to activities in the pasture and agriculture areas. Historically, depending on the management adopted, these activities can cause significant losses in SOC stocks (Maia et al., 2022; Bachi et al., 2023; Medeiros et al., 2022; 2023a,b).

Lambers et al. (2020) confirm that the combined effects of the changes in land use intensification and occupation with climate change, enhanced by anthropogenic GHG emissions, will probably limit agricultural productivity and the stability of ecosystem services in the Brazilian Amazon Forest and Cerrado biomes.

The SC-CO_2 values obtained in this study provide an opportunity for financial incentives for the efficient environmental management of agricultural soils both in the Amazon Forest and in the Cerrado, reallocating soil goods and services to different uses, including payment for the benefits provided. The adoption of sustainable agricultural production models (no-tillage, agroforestry systems, and integrated crop-livestock-forestry systems) has the potential to reduce SOC losses, and consequently, increase soil carbon sequestration in areas that are currently sources of GHG emissions (Minasny et al., 2017; Medeiros et al., 2022).

This process is essential to reduce GHG emissions by the land use sector, promoting changes in land use and forests (644,456 Gg CO_2eq), and agriculture (554,989 Gg CO_2eq), as they are the main sources of emissions in Brazil (BRASIL, 2024).

The SC-CO_2 costs and avoided emissions/damage were also analyzed considering the Maranhão state, where the valuation of SOC stocks was estimated at \$ 204.72 B for the 0-30 cm soil layer. This information positively influences the financial resources that can be preserved/generated by maintaining or increasing SOC stocks on large spatial scales (Trivedi et al., 2018; Feitosa et al., 2023). Climate policies aimed at SOC must be also developed at regional (biome) and local (administrative regions) levels, especially in the states that make up the Amazon Forest and the Cerrado.

It is possible to understand variations in SOC stocks and develop management strategies based on the different soil and climate characteristics of each region (Figure 4). It is worth noting that, in 2023, in the MATOPIBA region, located in the Cerrado biome, deforestation was recorded in a total area of 988,069 ha, representing an average increase of 13.5% compared to 2022. Maranhão state recorded a deforested area of 331,225 ha, that is, an increase of 18.1% compared to the previous year (MapBiomas, 2024).

The East, South, and Central Maranhão regions have large extensions of agricultural areas, where soils with low SOC values per area prevail: Quartzipsamments and Oxisols (Table 5). However, it is possible to expand agricultural production areas under conservation systems, such as no-tillage and integrated crop-livestock and crop-livestock-forestry systems (ICL and ICLF), which are systems with high potential to significantly increase SOC stocks, and consequently, the valuation of SOC stocks in these soils (Maia et al., 2022). Different studies have demonstrated that the adoption of conservation management systems is capable of sequestering carbon at levels close to or even greater than those recorded in the native vegetation area (Corbeels et al., 2016; Minasny et al., 2017; Maia et al., 2022; Medeiros et al., 2022).

The Amazon Forest areas in the degradation process, common in the North and West Maranhão regions, have great potential for restoration through secondary succession, which can reestablish SOC stock levels and reverse the biodiversity loss process (Silva Júnior et al., 2020). It is important to point out that these regions also have the largest amount of carbon stored in mangroves in Brazil, with a total of 91.3 Tg C (Rovai et al., 2022). This heritage needs to be maintained and protected by local communities through remuneration for the multiple ecological and social benefits they provide.

SOC is a key component for maintaining multiple ecosystem services, not exclusively in Maranhão state, but on a global scale. It is urgent that decision-makers set goals to maintain or increase SOC stocks at local, regional, and global scales. This information gains more prominence in the current climate change context, as investments in keeping carbon in the soil are part of the sustainable development goals established by the United Nations, which involve public policies to combat poverty, protect the planet, and guarantee prosperity for everyone (Trivedi et al., 2018).

In Brazil, there are some initiatives to reduce GHG emissions in the agricultural sector, and, consequently, contribute to climate change mitigation. For example, the ABC+ Plan aims to reduce carbon equivalent emissions by 1.1 billion tons by 2030, through the adoption of conservationist and sustainable food production systems, combining increased agricultural productivity with low GHG emissions (BRASIL, 2023).

This incentive demonstrates Brazil's efforts to expand its agricultural area under sustainable systems, thus recognizing the vital importance of agriculture for the country's economy and mitigating environmental impacts (Feitosa et al., 2023). The SC-CO_2 values estimated in this study for Maranhão (Figure 4, Tables 4, 5, and 7) can contribute to the improvement of public policies aimed at agricultural sustainability in Brazil, guiding decision-making and assisting in the recarbonization process of agricultural soils and preservation of biodiversity and ecosystem services.

CONCLUSIONS

1. The total and per unit area monetary values varied depending on the biome type and soil class and depth in Maranhão state, Brazil.

2. The Cerrado biome had the highest total value with 143.72 billion United States dollars, in the 0-30 cm soil layer, while the Amazon Forest biome had the highest valuation per unit area with 0.68 United States dollar per square meter.

3. Among the soil classes, Ultisols group, Oxisols and Quartzipsamments-Fluvents-Lithic group had the highest SOC storage and total values, while Vertisols and Entisols had higher valuation per unit area.

4. The West, East and South regions had the highest total SOC storage and total value, but low valuation per unit area. However, Central and North regions showed the highest value per normalized land area.

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interpretation of data, preparation of the manuscript. Maria Beatriz Ferreira: Participation in the design of the research, analysis and interpretation of data, preparation of the manuscript. Edvander Prudente de Almeida: collection, preparation of the manuscript. Bruno de Souza Barreto: Participation in the design of the research, analysis and interpretation of data, preparation of the manuscript. Guilherme Domingos Ferreira: Participation in the design of the research, analysis and interpretation of data, preparation of the manuscript. Glécio Machado Siqueira: participation in the design of the research, collection, supervision of the work, administration or acquisition of funding. Aldair de Souza Medeiros: participation in the design of the research, collection, analysis and interpretation of data, preparation of the manuscript, supervision of the work, administration or acquisition of funding.

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