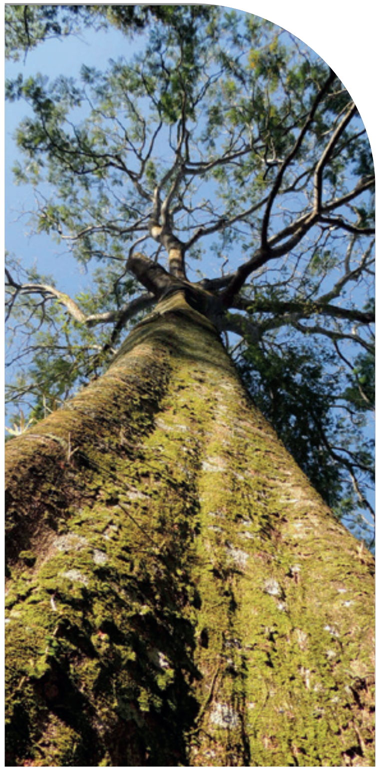
OVERVIEW OF SOIL CARBON STOCKS IN RIO DE JANEIRO STATE



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DO LADO DO POVO BRASILEIRO

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Brazilian Agricultural Research Corporation (Embrapa)
Embrapa Soils

GOVERNMENT OF THE STATE OF RIO DE JANEIRO

State Secretariat for Environment and Sustainability
Undersecretariat for Climate Change and Biodiversity Conservation
Superintendence of Climate Change and Forests
State Environmental Institute

OVERVIEW OF SOIL CARBON STOCKS IN RIO DE JANEIRO STATE

AN ESTRATEGIC ENVIRONMENTAL ASSET

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PRESENTATION

The publication *"Overview Of Soil Carbon Stocks In Rio de Janeiro State - An Estrategic Environmental Asset",* which the State Secretariat for Environment and Sustainability, in partnership with Embrapa Soils, now makes available to the public, represents a contribution and an effort to disseminate information about what lies beneath our feet – the soils!

Soils are responsible for housing a great diversity of fauna, serve as the primary substrate for flora, and ensure our food security. They also act as a natural filter for water impurities, functioning as a true "sieve" to purify water that infiltrates into the groundwater.

In this way, the information presented in this publication highlights the contribution of soils to mitigating greenhouse gas emissions, as well as the need to take local action to ensure a more sustainable future. This unprecedented study represents a contribution from science that encourages "out-of-the-box" thinking for public policies supporting the conservation and restoration of the Atlantic Forest, while also promoting sustainable economic activity in rural areas.

The State of Rio de Janeiro, through the State Secretariat for Environment and local and international partners, has been contributing to the national and global targets set forth in the Conventions on Climate Change and Biological Diversity Conservation.

With resources made available by the Future Fund, Climate Group, and the Under2 Coalition, facilitated by the State Atlantic Forest Fund (FMA), it became possible to conduct and deepen the analysis of soil data from the National Forest Inventory in the State of Rio de Janeiro, assessing the contribution of soil carbon stocks and mapping future scenarios within the state territory. The information obtained serves as the basis for this unprecedented study, which contributes to the improvement of public policies aimed at the conservation and restoration of the Atlantic Forest and the appreciation of the ecosystem services provided in the rural regions of the state of Rio de Janeiro.

We wish our readers an enjoyable experience with this information, and we hope that together we can chart a more sustainable path forward.

#SOMOS TODOS MATA ATLÂNTICA!

BERNARDO ROSSI
State Secretary for Environment and Sustainability

PREFACE

Soil is a vital resource, although often invisible to society. In addition to supporting the production of food and fibers, it functions as one of the planet's largest carbon reservoirs, playing a strategic role in addressing climate change.

This book comprises five chapters that together provide an applied overview of soil carbon stocks in the state of Rio de Janeiro and their sustainable management potential. Developed by the State Secretariat for Environment and Sustainability (SEAS) and Embrapa Soils, the chapters present innovative results from analyses, mapping, and scenario generation regarding soil carbon stocks in relation to land use across the state's various administrative regions.

The first chapter offers a brief socio-environmental diagnosis of the state of Rio de Janeiro, contextualizing its historical occupation and current land use. It explores forest remnants, silvopastoral uses, current vegetation cover, and carbon stocks in plant biomass.

The second chapter presents maps of soil carbon stocks developed using modern digital soil mapping techniques. The results identify regions of the state with the greatest carbon storage capacity, such as mountain ranges and mangroves, while highlighting critical areas, including coastal plains and zones under intensive agricultural use. These data are essential for guiding public policies, conservation projects, and more sustainable agricultural practices.

In the third chapter, the authors introduce the soil spectral library of Rio de Janeiro, built from visible and near-infrared reflectance spectroscopy analyses. This innovative technology enables rapid, accurate, and cost-effective estimation of soil carbon content, paving the way for rapid diagnostics, environmental inventories, and potentially enhancing compensation mechanisms based on best management practices that incorporate organic matter into the soils of Rio de Janeiro.

The fourth chapter is dedicated to carbon sequestration scenarios derived from adopting best agricultural practices and ecological restoration initiatives. The results indicate that degraded areas, particularly under pasture, can become significant carbon sinks if supported by adequate incentives and effective public policies. Simultaneously, the authors emphasize the importance of public policies and economic incentive instruments that facilitate the transition to more sustainable production systems.

Finally, Chapter 5 provides a theoretical framework for a future business plan aimed at valuing soil carbon in Rio de Janeiro, defining premises and guidelines that establish soil carbon as an economic asset. Despite the challenges of commercializing this asset, the authors highlight the role of farmers who care for their soil, resulting not only in higher productivity but also in healthier products and the delivery of numerous ecosystem services that extend beyond farm boundaries and benefit society as a whole. It is therefore clear that soil carbon is another product in the agricultural portfolio, and society should recognize and/or reward farmers for the vital role they play.

The data presented in this book aim to provide the necessary support for the development of public policies focused on analyzing soil and ecosystem health at the landscape scale, monitoring the impacts of forest restoration, and accounting for soil organic carbon. More than a technical compendium, this book is a call to action. It demonstrates how science, public management, agriculture, and forests can integrate and work together to build more multifunctional and resilient rural landscapes in the face of climate change.

MARIE IKEMOTO
Undersecretary of Climate Change and Biodiversity Conservation

CLAUDIA POZZI JANTALIA
Deputy Head of Research and Development, Embrapa Soils

CONTENTS

CHAPTER 1

CLIMATE CHANGE, FOREST ECOSYSTEMS, AND GHG MITIGATION IN THE STATE OF RIO DE JANEIRO

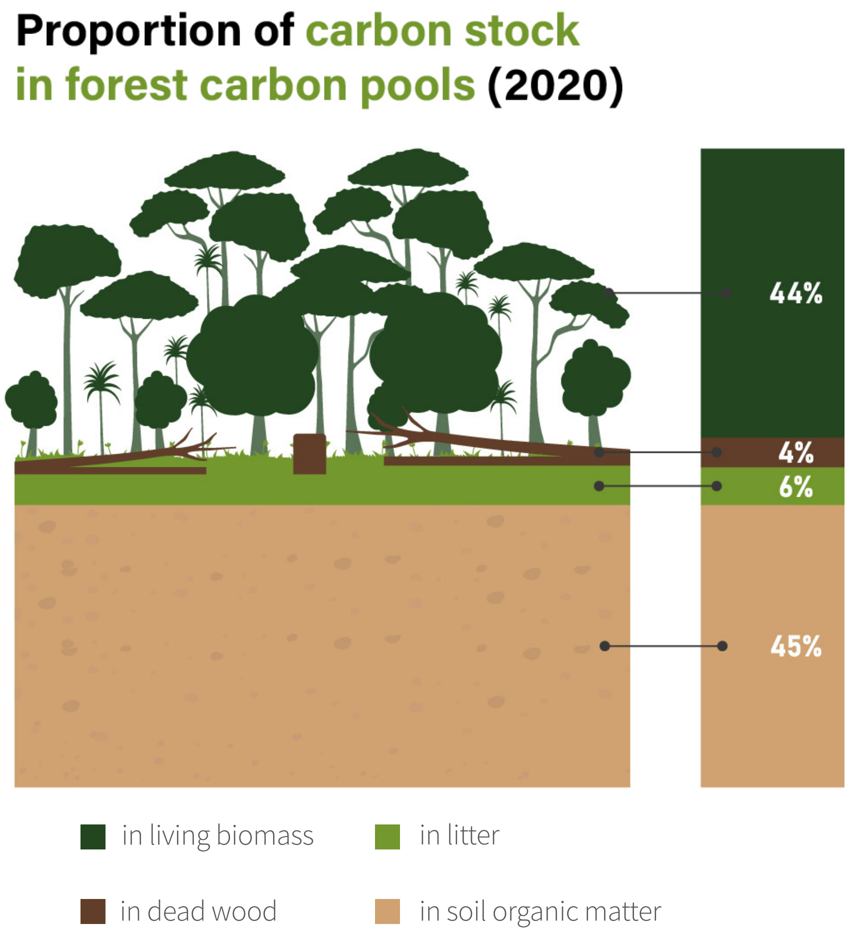
Telmo B. Silveira Filho, Fabiano C. Balieiro, Monise A. F. Magalhães

The challenges posed by climate change, which are already a reality in many aspects of daily life, require a multi-sectoral dialogue and strategies distinct from those already addressed by various societal actors, particularly scientists, policymakers, companies, and investors. Mitigation actions for greenhouse gas (GHG) emissions depend substantially on the contribution of forest ecosystems, especially tropical forests. Additionally, adaptation actions are crucial to minimize population risks in the face of current challenges, where Nature-based Solutions (NbS) once again emerge as key allies.

Thus, forest ecosystems, which have often been and still are perceived as obstacles to "development", as a reflection of delayed modernization, are in fact the main strategy for climate change mitigation and adaptation. However, these same ecosystems, along with their biodiversity and functionality, are affected by climate change. Therefore, it is necessary to reinforce the global alliance for the monitoring, conservation, and restoration of forest ecosystems, which have soil as their primary substrate.

Terrestrial ecosystems store large amounts of carbon (C) in plants and soil, playing an important role in global climate regulation, which is undergoing rapid changes due to anthropogenic actions, especially land-use dynamics (Heimann & Reichstein, 2008; Harris *et al.*, 2021). According to Food and Agriculture Organization of the United Nations (FAO, 2020), most forest carbon is found in living biomass (44%) and soil organic matter (45%), with the remainder in deadwood and litter (Figure 1).

FIGURE 1. Proportion of carbon stocks in forest compartments



Source: Adapted by authors from FAO (2020).

Due to the importance of ecosystems in climate regulation, public policies and sustainable practices based on scientific evidence should be pursued by societies, governments, and officially constituted institutions. Thus, decision-making regarding forest management at regional, national, and international levels, aimed at biodiversity conservation and maintenance of forest services, requires consistent and up-to-date forest information (Nesha *et al.*, 2022).

Therefore, we believe that in tropical regions it is essential to create or strengthen local and regional capacities to compile, recompile, and analyze data to generate and disseminate information, especially regarding forest assets and their biodiversity, in order to meet the needs and specificities of diverse audiences.

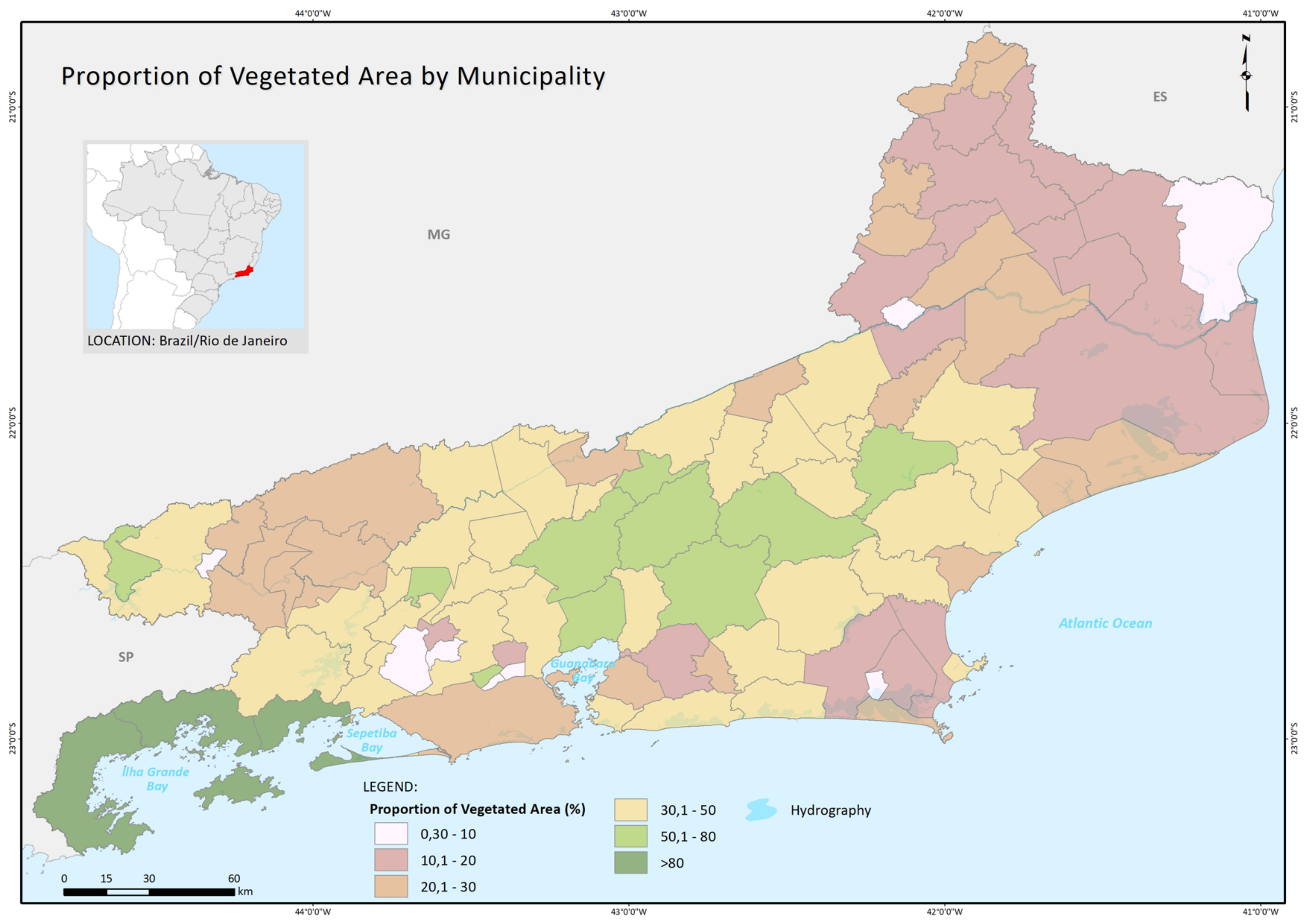
Considering the effects of climate change, large-scale forest inventories become essential to assess, develop scenarios, and contribute to adaptation and mitigation policies for impacts already in place. In this context, while total aboveground living biomass is a forest characteristic of particular interest, the contribution of soil remains underemphasized. Forest soils and woody biomass hold most of the terrestrial biomass carbon on Earth (Houghton, 1999).

Land use changes caused by human activities in terrestrial ecosystems, particularly in forest ecosystems such as burning or deforestation for agriculture and mining can account for 15 to 40% of annual GHG emissions.

Such land use changes have exerted and continue to exert strong pressure on the Atlantic Forest, Brazil's oldest forest formation. According to Paduá (2004), this biome was subjected to several land exploitation cycles, with nineteenth-century reports documenting over 300 years of human activity that denied the identity and benefits of native Brazilian ecosystems. The marks of this past persist and hinder the recovery processes of the Atlantic Forest degraded areas.

The territory of the state of Rio de Janeiro is entirely covered by the Atlantic Forest, which was established around 50 to 70 million years ago, when three factors occurred simultaneously: i) formation of the Atlantic Ocean; ii) formation of mountain systems along the Atlantic edge of South America; and iii) increase in Earth's temperature (Marques *et al.*, 2016; Leitão-Filho, 1987). This evolution ensured the formation of distinct geomorphological regions and diverse soil-forming environments within the state's small territory. With an area of 4,378,158 ha, the state's surface corresponds to 0.5% of Brazil's total area, and its natural heritage has been almost entirely depleted. As a consequence of occupation and land use, forest cover in the state has been gradually reduced, currently representing just over 15% of the original forest, although about 33% of forest cover remains in various successional stages, with the largest remnants covering the mountain massifs (Figure 2).

FIGURE 2. Proportion of forest areas in the Atlantic Forest biome in municipalities of the state of Rio de Janeiro
Base year 2013, mapping scale 1:25,000.
Source: Silveira-Filho (2024).



Proportion of Vegetated Area by Municipality
LOCATION: Brazil/Rio de Janeiro
MG
ES
SP
Atlantic Ocean
Guanabara Bay
Sepetiba Bay
Ilha Grande Bay
LEGEND:
Proportion of Vegetated Area (%)
0,30 - 10
10,1 - 20
20,1 - 30
30,1 - 50
50,1 - 80
>80
Hydrography
0 15 30 60 km
44°0'0"W
43°0'0"W
42°0'0"W
41°0'0"W
21°0'0"S
22°0'0"S
23°0'0"S
N

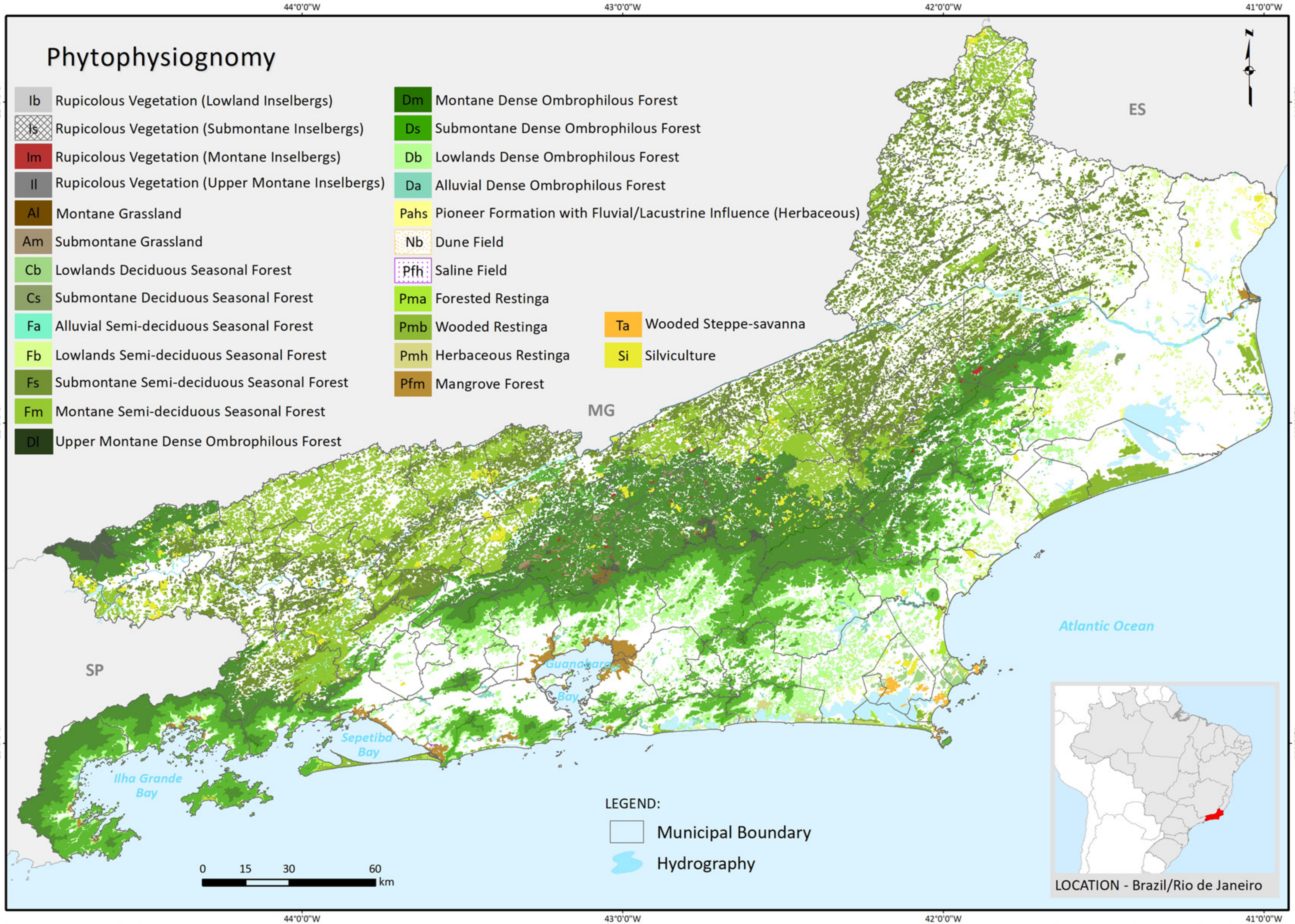
This rich natural heritage has a diversity of habitats, ranging from restingas and mangroves in coastal and river plains, lowland forests, mountain massifs, to high-altitude grasslands reaching around 2,790 meters at Pico das Agulhas Negras (Figure 3). This wide altitudinal variation in a relatively small territory, associated with diverse geomorphology, climate, and other factors, is responsible for the high diversity of fauna and flora, recognized as among the richest in the country. The state is also considered an important region of biodiversity endemism (Silveira-Filho & Rambaldi, 2018).

Housing 8% of Brazil's population across its 92 municipalities over 16 million inhabitants Rio de Janeiro is one of the most densely populated states in the country, with the second-highest population density (365.23 inhabitants/km^2), and around 90% of the population living in urban environments (IBGE, 2024). As one of the first regions in the country settled by colonizers, Rio de Janeiro's secular human activity has profoundly modified its landscape, currently consisting of a mosaic of natural and semi-natural areas surrounded by urban zones.

In its rural environment, Rio de Janeiro has approximately 65,000 establishments, of which 43,599 (about 66.8%) are family farms (EMATER-RIO, 2024). Additionally, around 88% of rural holdings are classified as small properties, indicating an urgent need for strategies focused on soil conservation management.

Soils show great variability in characteristics and properties due to their formation environments and anthropogenic modifications (Figure 4). Soil can be defined as the surface layer of the Earth's crust, composed of mineral and organic material, capable of storing water and air, and providing support for plant growth and other soil organisms. As a growth medium for plants, soil has four main functions: i) supporting root growth; ii) storing water and supplying it to plants; iii) storing air for plant roots; and iv) providing nutrients to plants (Anjos & Pereira, 2013). In other words, soils sustain life, forests, and food security, providing multiple ecosystem services.

FIGURE 3. Vegetation cover classes in the state of Rio de Janeiro Base year 2013, mapping scale 1:25,000 .
Source: Silveira-Filho (2024).

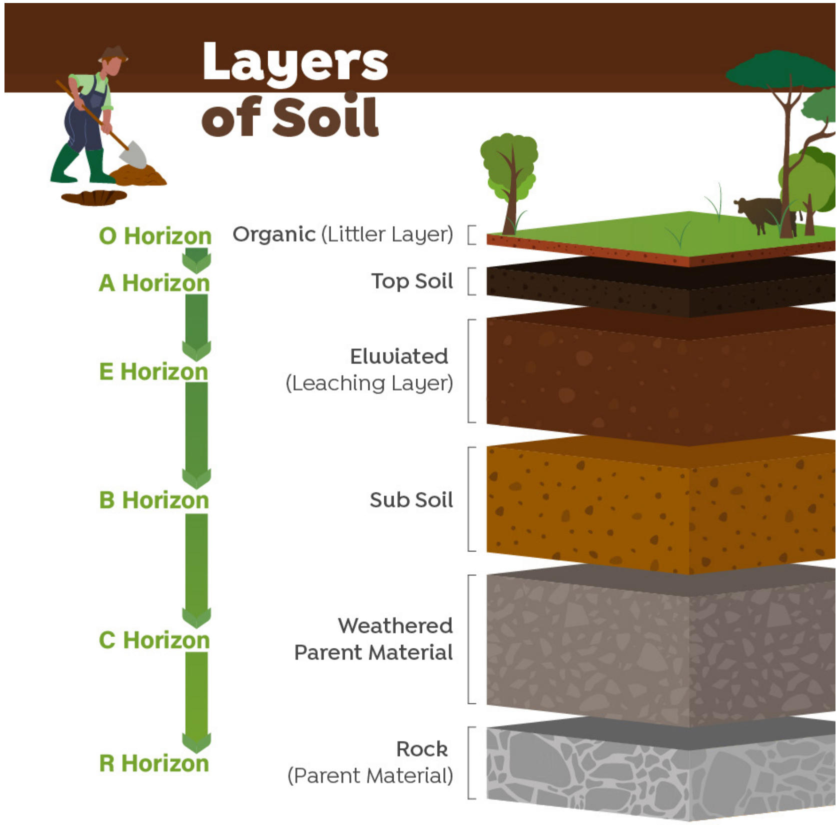


Phytophysiognomy
Ib Rupicolous Vegetation (Lowland Inselbergs)
Is Rupicolous Vegetation (Submontane Inselbergs)
Im Rupicolous Vegetation (Montane Inselbergs)
Il Rupicolous Vegetation (Upper Montane Inselbergs)
Al Montane Grassland
Am Submontane Grassland
Cb Lowlands Deciduous Seasonal Forest
Cs Submontane Deciduous Seasonal Forest
Fa Alluvial Semi-deciduous Seasonal Forest
Fb Lowlands Semi-deciduous Seasonal Forest
Fs Submontane Semi-deciduous Seasonal Forest
Fm Montane Semi-deciduous Seasonal Forest
Dl Upper Montane Dense Ombrophilous Forest
Dm Montane Dense Ombrophilous Forest
Ds Submontane Dense Ombrophilous Forest
Db Lowlands Dense Ombrophilous Forest
Da Alluvial Dense Ombrophilous Forest
Pahs Pioneer Formation with Fluvial/Lacustrine Influence (Herbaceous)
Nb Dune Field
Pfh Saline Field
Pma Forested Restinga
Pmb Wooded Restinga
Pmh Herbaceous Restinga
Pfm Mangrove Forest
Ta Wooded Steppe-savanna
Si Silviculture
44°0'0"W
43°0'0"W
42°0'0"W
41°0'0"W
21°0'0"S
22°0'0"S
23°0'0"S
ES
MG
SP
Atlantic Ocean
Guanabara Bay
Sepetiba Bay
Ilha Grande Bay
LEGEND:
Municipal Boundary
Hydrography
0 15 30 60 km
LOCATION - Brazil/Rio de Janeiro

Among the main activities and alternative land uses in the rural environment of Rio de Janeiro, the most economically significant are: i) cattle ranching, present in 89 municipalities, with pasture areas in all 92 municipalities, occupying 52% of the state territory; ii) vegetable farming, present in 85 municipalities; iii) small and medium animal husbandry, mainly broiler poultry, beekeeping (found in 77 municipalities), and egg production (found in 76 municipalities); iv) fruit farming, the most economically important agricultural activity in the state, especially pineapple, citrus, and banana crops; and v) other traditional crops such as sugarcane, cassava, corn, and coffee. Additionally, crops such as bay laurel (*Laurus nobilis* – Lauraceae), native to the South Mediterranean, and annatto (*Bixa orellana* – Bixaceae), widely distributed in Brazil, are cultivated. Less economically significant, but still important, are floriculture, artisanal fishing, forestry, and cereals (EMATER-RIO, 2024).

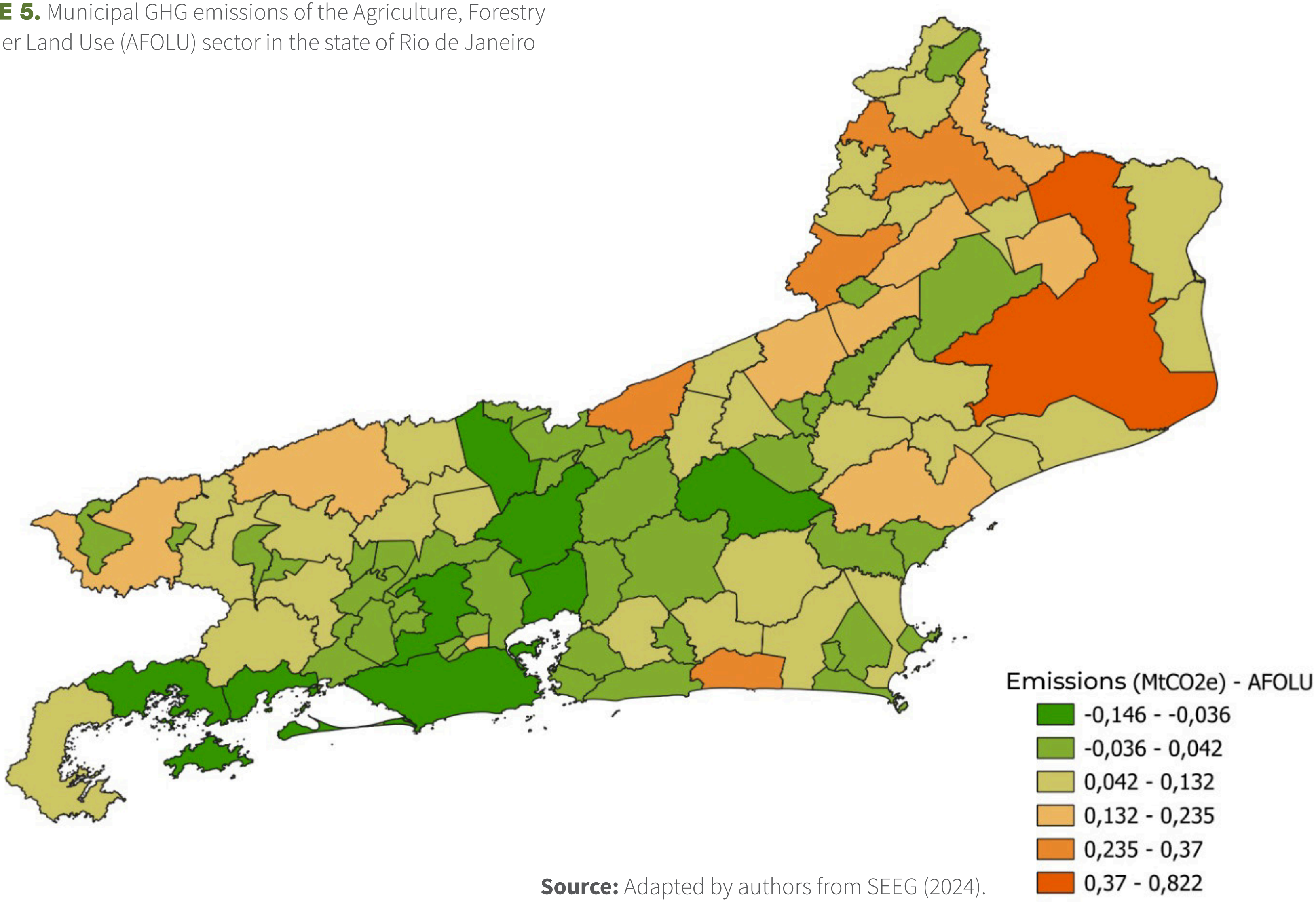
In this context, the state of Rio de Janeiro has great potential to contribute to GHG emission mitigation and to promote conservation practices that ensure water security, food security, and other ecosystem services.

FIGURE 4. Diagram of soil layers



Source: Adapted by authors from FAO (2020).

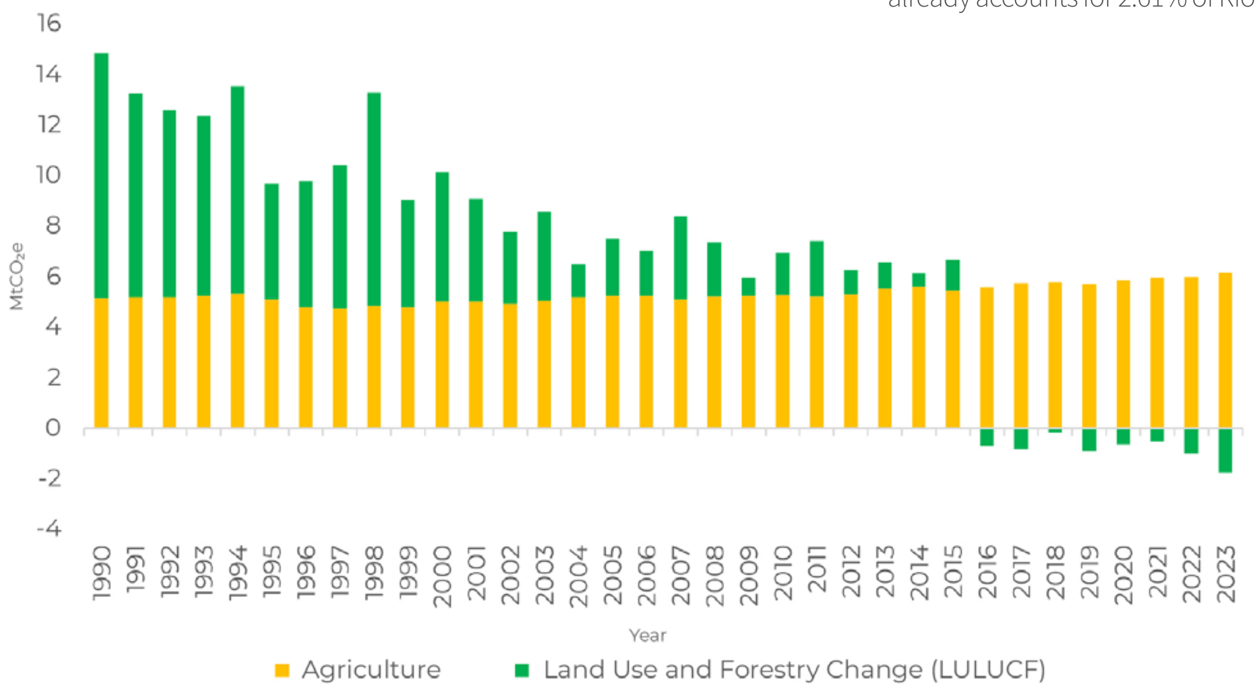
FIGURE 5. Municipal GHG emissions of the Agriculture, Forestry and Other Land Use (AFOLU) sector in the state of Rio de Janeiro



Source: Adapted by authors from SEEG (2024).

The municipalities and governmental regions that stood out as the main AFOLU emitters in 2023 are located in the North and Northwest of Rio de Janeiro. Their municipalities have the lowest Atlantic Forest cover rates, resulting from the historical land use changes and soil degradation, mostly linked to agricultural activities (Figure 5).

FIGURE 6. Historical series of GHG emissions from agriculture and land use change in the state of Rio de Janeiro



Source: Adapted by authors from SEEG (2024).

Unlike the national GHG emissions profile, in which the Agriculture, Forestry and Other Land Use (AFOLU) sector accounted for 27.4% in 2023 (SEEG, 2024), in the state of Rio de Janeiro, Agriculture and Land Use and Forestry Change (LULUCF) represented the smallest contributions to the state's emissions, with total emissions estimated at 6.17 and -1.75 Mt of CO_2 equivalent, respectively (Figure 6). In the net emissions scenario, the Agriculture sector represents 9.2% of total emissions, and negative emissions from LULUCF represent 2.61% of the state's positive emissions. In other words, in the current scenario, carbon removal from this sector already accounts for 2.61% of Rio de Janeiro's total emissions (SEEG, 2024).

As shown in Figure 6, emissions from the Land Use Change (LULUCF) subsector are expected to decrease in the coming years. This results from reductions in emissions from deforestation, other land-use changes, and forest restoration categories. More detailed analyses show an increase in emission removals promoted by the conservation of native vegetation.

Given the land-use scenario and its relation to GHG emissions presented so far, some initiatives within the scope of state public policy aimed at combating deforestation and fires, as well as creating and managing Conservation Units (CUs) and promoting forest restoration to reduce GHG emissions, stand out: Olho no Verde Program, Program to Support the Creation and Management of Municipal Conservation Units (PROUC), State Program Supporting Private Natural Heritage Reserves (RPPNs), CEDAE's Replanting Lives Program, and the Forests of Tomorrow Program.

These contributions can be even more significant if soil carbon monitoring, assessment, and accounting at the landscape scale are applied to sustainable practices, such as the Integration of Crop-Livestock-Forestry (ILPF), in addition to expanding Atlantic Forest restoration based on the suitability of rural properties.

15 PROTEGER A VIDA TERRESTRE

The maintenance of healthy and functional soils contributes to Goal 15 of the United Nations (UN) 2030 Agenda for Sustainable Development, which is to "Protect, restore and promote the sustainable use of terrestrial ecosystems," aiming to combat desertification, soil degradation, and biodiversity loss, while ensuring the sustainable management of forests and freshwater ecosystems and the conservation of mountains and arid areas.

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CHAPTER 2

SOIL CARBON STOCK MAPS FOR THE STATE OF RIO DE JANEIRO: IN SUPPORT OF CARBON SEQUESTRATION AND OFFSET OPPORTUNITIES

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Mitigating climate change and its negative impacts requires multiple complementary strategies. One of these strategies consists of sequestering carbon in the soil and keeping the sequestered soil carbon stored in the long term. This can be done by improving soil organic matter by adopting better soil management strategies, restoring degraded soils and landscapes, or intensifying agricultural systems by planting trees, to name a few. This strategy can be combined with carbon offset programs and agreements to monetize the sequestered soil carbon by selling carbon credits or soil ecosystem services.

For the carbon offset programs to work, an initial soil carbon stock value is needed as baseline to calculate how much carbon is sequestered in the soil after an assessment period. By extension, regional soil carbon stock assessments require regional baseline soil carbon stock values. Soil carbon stock maps are presented for Rio de Janeiro state aiming to characterize the regional distribution of this natural asset across the state, and how environmental heterogeneity influences its distribution. The maps support carbon inventories and policy decisions at large scale, as well as a starting point to assess the potential for soil carbon sequestration fostering soil carbon offset programs.

The soil carbon stock maps for Rio de Janeiro state were derived at two layers, 0-20 and 30-50 cm, with 30 m spatial resolution (pixel size), which is roughly equivalent to a 1:100,000 scale. Soil carbon stock values were calculated from soil samples obtained by the National Forest Inventory of the state of Rio de Janeiro (SFB, 2018), carried out between 2013 and 2016. Soil samples were collected at 188 sampling points distributed throughout the state in a grid of approximately 20 x 20 km. Soil carbon contents were measured in these samples by dry combustion in a CHNS 2400 elemental analyzer (Perkin Elmer, Waltham, USA).

The maps were produced using digital soil mapping (McBratney *et al.*, 2003). The multivariate method used was quantile regression forests (Meinshausen, 2006) implemented in R software (The Comprehensive R Archive Network, 2024) using the quantregForest package (Meinshausen, 2017). Using this method, soil carbon stock prediction models were derived for the two layers (0-20 and 30-50 cm) using the field soil carbon stock values as the target variable, and a set of geospatial raster covariates as the predictor variables. Then, the soil carbon stock maps were produced by applying the derived prediction models to the whole state using the state-wide geospatial covariates.

The geospatial covariates represent soil forming factors that are expected to explain the spatial distribution of soil carbon stock across Rio de Janeiro state. They were obtained from public sources and included:

• Soil: soil taxonomic order, and suborder (Carvalho Filho *et al.*, 2003);

• Climate (from 1981-2010): mean annual temperature, mean monthly precipitation, mean monthly evaporation, mean monthly potential evapotranspiration, and mean monthly number of sunny hours (INMET, 2025);

• Land use/land cover: land use/land cover of 2016 (Projeto MapBiomas, 2023), and selected Landsat 8 Operational Land Imager (OLI) bands and derived indices (green, near infrared, shortwave infrared, normalized difference vegetation index and iron oxides index) (EROS, 2023);

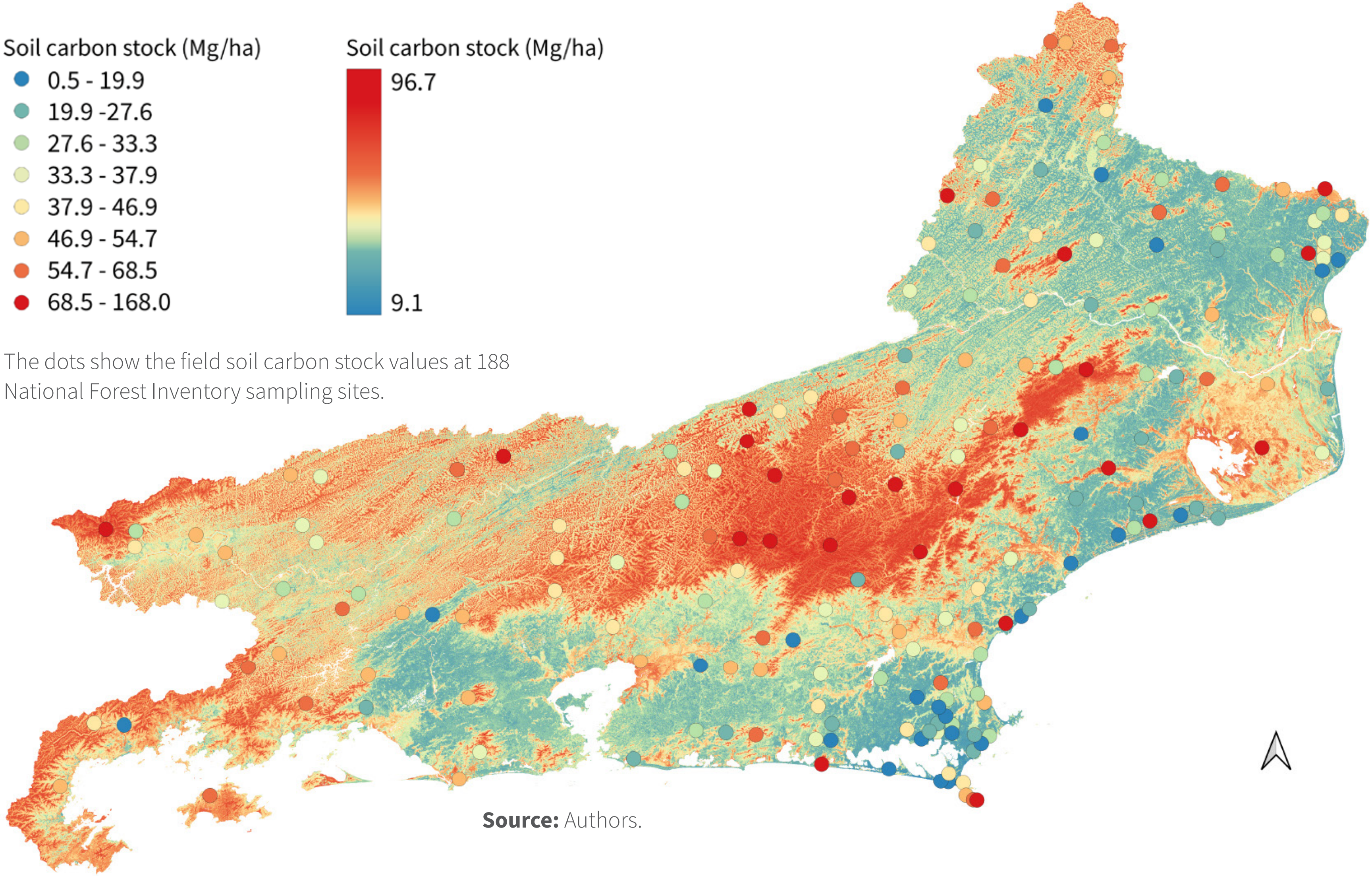
• Relief: elevation, midslope position, modified catchment area, multiresolution index of valley bottom flatness, normalized height, SAGA wetland index, slope height, standardized height, surface area, valley depth, and vector ruggedness measure (IBGE, 2023);

• Parent material: geological era, and lithology (Heilbron *et al.*, 2016).

The geospatial covariates were processed in R, ArcGIS (ESRI, Redlands, USA) and SAGA GIS (Conrad *et al.*, 2015). The climate variables were interpolated by ordinary kriging from 54 climate stations inside and within a 100 km buffer around Rio de Janeiro state border. The elevation raster was derived from a 1:25,000 elevation map (IBGE, 2023) using the Topo to Raster tool in ArcGIS that implements the ANUDEM algorithm (Hutchinson, 2011) to create hydrologically correct digital elevation models. From this raster, all other relief covariates were derived in SAGA GIS. The soil and parent material rasters were prepared by, first, reducing the number of categories by grouping similar ones, and then converting the shapefiles to raster. The projection used was Lambert Conformal Conic and the spatial resolution (pixel size) of the processed covariates and output soil carbon stock maps was 30 m.

Soil carbon stocks in Rio de Janeiro state add up to ~189 million tons (189 Tg; 1 Tg = 1012 g) at 0-20 cm, and ~119 million tons (119 Tg) at 30-50 cm, respectively. Minimum, mean and maximum soil carbon stock values are 9.1, 44.5 and 96.7 Mg ha^{-1} at 0-20 cm, and 7.0, 28.0 and 63.8 Mg ha^{-1} at 30-50 cm, respectively (Figures 1 and 2).

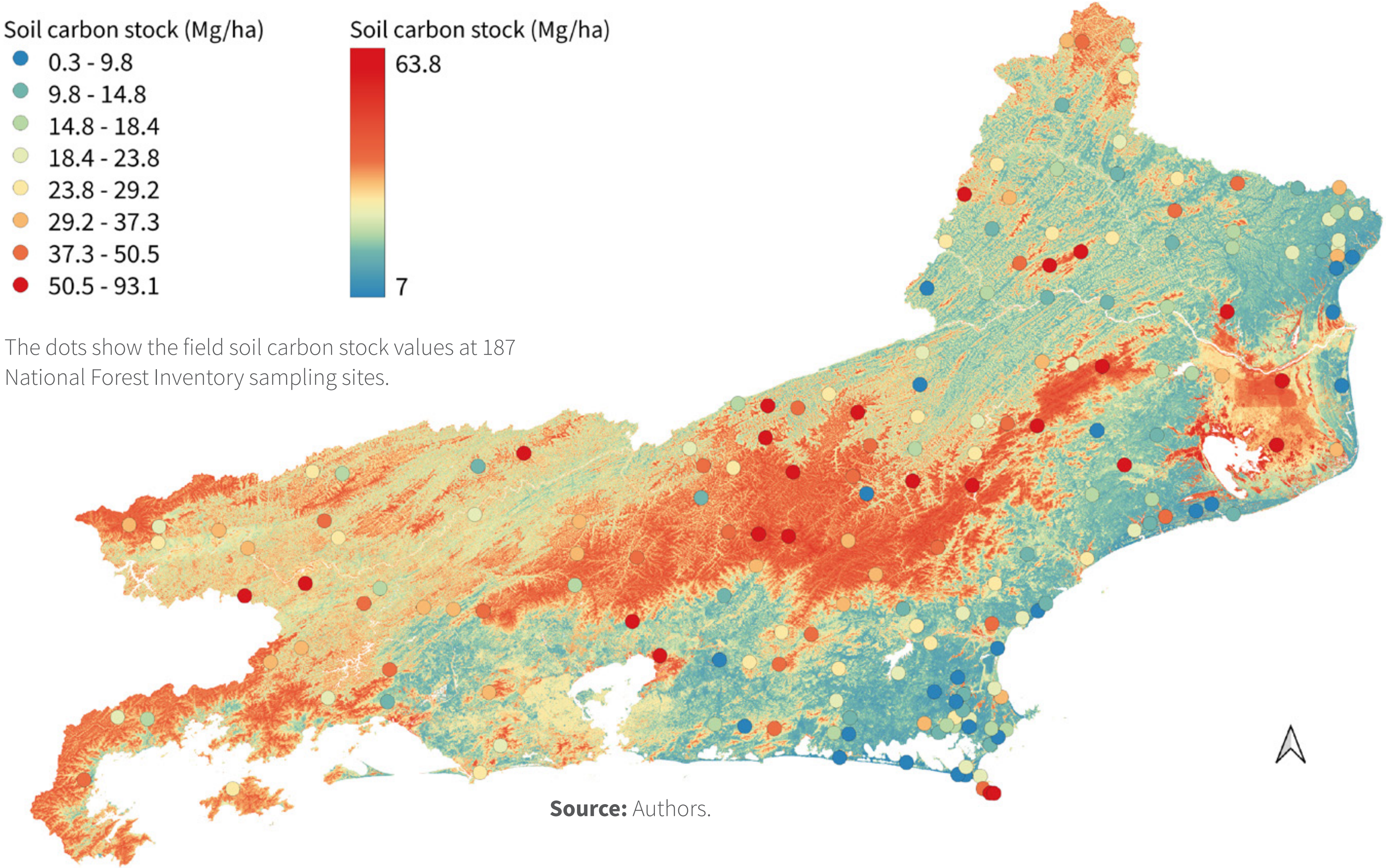
FIGURE 1. Soil carbon stock at 0-20 cm in Rio de Janeiro state, Brazil



The dots show the field soil carbon stock values at 188 National Forest Inventory sampling sites.

Source: Authors.

FIGURE 2. Soil carbon stock at 30-50 cm in Rio de Janeiro state, Brazil



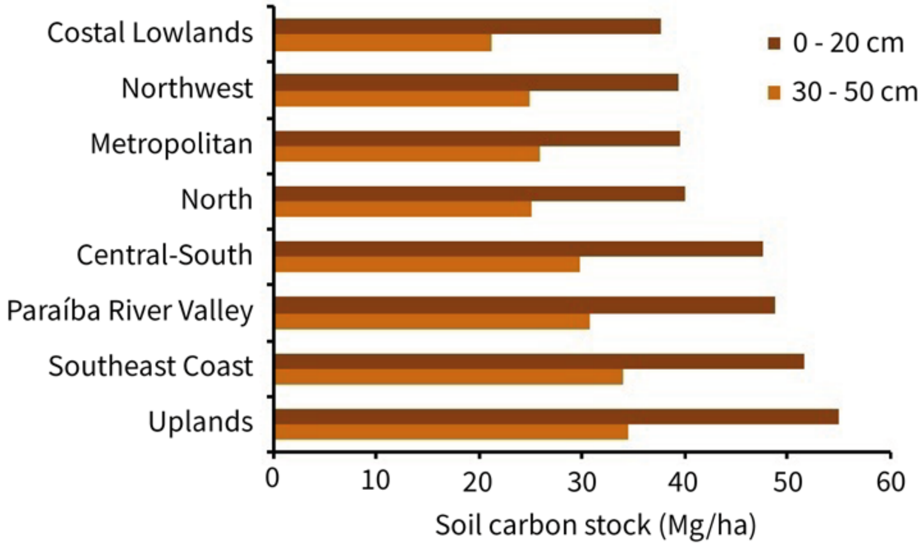
The dots show the field soil carbon stock values at 187 National Forest Inventory sampling sites.

Source: Authors.

The resulting soil carbon stock maps show large soil carbon stocks at the mountainous, high-altitude portion of the state at the Serra do Mar (in the Serrana and Costa Verde regions) and Serra da Mantiqueira (in the Médio Paraíba region) mountain ranges, and at the mangroves close to the coast, mainly at the Paraíba do Sul River delta at the eastern state boundary in the Norte Fluminense region (Figures 1, 2 and Graph 1). Low soil carbon stocks were predicted at most of the coastal lowlands (Baixadas Litorâneas region) at the southeastern portion of the state, at the north-northeast (Noroeste Fluminense region), and at the Metropolitan (Metropolitana) region around the Guanabara Bay.

At high elevations, the lower temperature favors carbon accumulation in soils due to slower biological activity. At the same time, there are many protected areas at high elevations, with pristine vegetation and soils, including deep ones such as Ferralsols, Luvisols, Acrisols and Cambisols. The protected forests have high primary productivity contributing large amounts of plant residues to the soil, which accumulate over time and stabilize as soil organic matter, improving soil carbon stock (Graph 1).

GRAPH 1. Mean soil carbon stocks at 0-20 and 30-50 cm in the mesoregions of Rio de Janeiro state



Source: Authors.

In mangroves and similar landscapes that are temporarily or permanently flooded, where Histosols and Gleysols (Thionic, Histic) predominate, the plant residues are decomposed very slowly due to the lack of oxygen. Like the highland forests, these areas are usually protected, avoiding land degradation and carbon loss. These factors combined favor organic matter accumulation, leading to large soil carbon stocks in these places.

On the other hand, when forests are converted to pasture or crop, soil carbon is lost over time to a greater or lesser degree depending on the land management and conservation, which vary considerably depending on regional soil, landscape and social factors. This explains the low soil carbon stocks found in Rio de Janeiro lowlands, as these lands are mostly occupied by pasture, agriculture and anthropized areas (Projeto MapBiomas, 2023). Alternatives to improve soil carbon stocks in these areas are discussed in Chapter 4 (*Soil Carbon Storage Scenarios Driven by Land Use, Land Cover, and Management Changes in the State of Rio de Janeiro*).

The soil carbon stock maps reflect the spatial patterns of the geospatial covariates used to produce them. The quantile regression forest method allows combining multiple continuous and categorical variables seamlessly to explain the spatial variation of soil carbon stock across the state. It handles non-linear and multifactorial complex relationships, both between the covariates and soil carbon stocks and among the covariates themselves. As such, it allows capturing general soil carbon stock patterns across the state as well as local ones, producing soil carbon stock maps that show consistent trends both statewide and locally. The most important geospatial covariates to predict soil carbon stocks were:

• At 0-20 cm: elevation, precipitation, standardized height, SAGA wetness index, and land use/land cover; and

• At 30-50 cm: standardized height, elevation, Landsat 8 OLI green band, multiresolution index of valley bottom flatness, and SAGA wetness index.

The soil carbon stock maps at 0-20 and 30-50 cm for Rio de Janeiro state provide a first glance of the spatial distribution of soil carbon stocks across the state, showing their general and local spatial patterns that can be linked to land use/land cover dynamics as well as environmental patterns that control or affect soil carbon. The maps portray soil carbon stocks of 2013-2016 and reflect the values observed in the National Forest Inventory during those years. The second edition of National Forest Inventory of Rio de Janeiro is under way and will follow the same sampling and laboratory protocols used in the first inventory. This presents an excellent opportunity to estimate the decadal soil carbon changes across the state.

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QR CODE TO ACCESS AND DOWNLOAD THE SOIL CARBON STOCK MAP FOR RIO DE JANEIRO AT THE 0-20 CM LAYER AT EMBRAPA'S GEOINFO WEBSITE

QR CODE TO ACCESS AND DOWNLOAD THE SOIL CARBON STOCK MAP FOR RIO DE JANEIRO AT THE 30-50 CM LAYER AT EMBRAPA'S GEOINFO WEBSITE

CHAPTER 3

SOIL SPECTRAL LIBRARY AND SOIL CARBON CONTENT ASSESSMENT FOR THE STATE OF RIO DE JANEIRO

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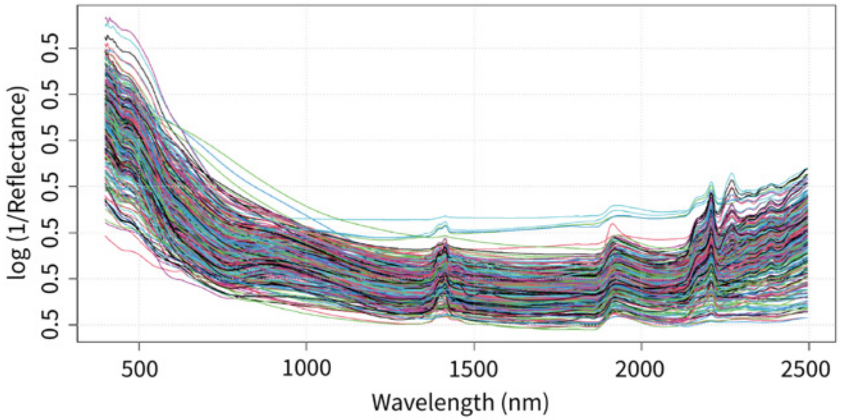
The Brazilian National Forest Inventory (NFI) is a cornerstone program for monitoring the country's forest resources, providing data to support public policies and meet international climate commitments. A key component of the forest functioning and dynamics is soil carbon. To support the NFI, soil spectral libraries (SSL) along with spectroscopy-based models can be developed to rapidly and cost-effectively estimate soil carbon content, allowing to calculate carbon stocks and changes over time.

For this aim, a visible-near infrared (Vis-NIR) SSL was built for the state of Rio de Janeiro, and Vis-NIR spectroscopy model was derived to predict the carbon contents in NFI soil samples across the state. Soil Vis-NIR spectroscopy is non-destructive, rapid, inexpensive, and precise, and has been used to estimate various soil properties, including carbon (Viscarra Rossel *et al.*, 2006; Demattê *et al.*, 2019).

To produce the SSL, soil samples at 0-20 and 30-50 cm depths were used, obtained from the Rio de Janeiro state NFI (SFB, 2018), which took place from 2013 to 2016 and employed a systematic grid sampling of 20 x 20 km, with a total of 251 sampling sites. A total of 355 samples (174 at 0-20 cm, and 181 at 30-50 cm) were used in the study. The NFI soil samples were ground, sieved (2 mm), and dried at room temperature. Then, the soil carbon content was measured by dry combustion in a CHNS 2400 elemental analyzer (Perkin Elmer, Waltham, EUA).

Soil spectral curves at the Vis-NIR range (350-2500 nm) were obtained in the laboratory using an ASD FieldSpec 4 spectroradiometer (Malvern Panalytical, Malvern, United Kingdom), averaging 100 repetitions per sample, and Spectralon® (Labsphere, North Sutton, USA) as a white reference. Before spectral reading, the samples were dried at 45 °C overnight to harmonize the water content. Once collected, the soil spectral curves were transformed to log(1/reflectance) (Figure 1).

FIGURE 1. Soil visible-near infrared spectral curves transformed to log(1/reflectance)



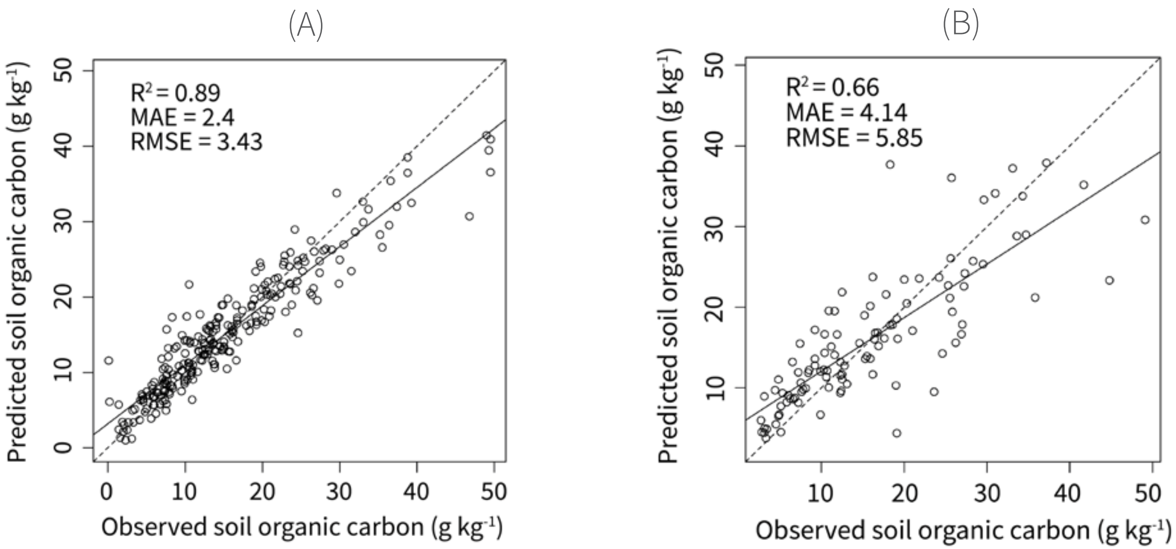
Source: Authors.

The Vis-NIR-based soil carbon content prediction model was derived using cubist (Quinlan, 1993) via the Cubist package (Kuhn and Quinlan, 2024) in R (The Comprehensive R Archive Network, 2024). Cubist is a multivariate method that combines decision tree-based modeling to split the dataset into homogeneous subsets with multiple linear regression to predict the target variable in each subset. This method has been successfully used to predict soil carbon in other regions in Brazil (Demattê *et al.*, 2019; Moura-Bueno *et al.*, 2021).

Prior to modeling, the samples were randomly split into a training (248 samples ~70%) and a testing set (107 samples ~30%). The training samples were exclusively used to calibrate the cubist model, whereas the testing set served to validate the model soil carbon predictions. A committee of five cubist models was used to improve the accuracy of the predictions.

Soil carbon contents in the Rio de Janeiro NFI vary from 0.1 to 49.5 g kg^{-1}, with a mean, median and standard deviation of 15.5, 13.2 and 9.9 g kg^{-1}, respectively. Soil carbon content predictions vary from 1.0 to 41.4 g kg^{-1}, with a mean, median and standard deviation of 15.5, 14.1 and 8.2 g kg^{-1}, respectively. Observed and predicted soil carbon contents were highly correlated in both model training, with a R2 of 0.89 and root mean square error (RMSE) of 3.4 g kg^{-1} (Figure 2A), and validation, with a R2 of 0.66 and RMSE of 4.1 g kg^{-1} (Figure 2B).

FIGURE 2. Predicted versus observed soil carbon content in the of: (A) model training; and (B) external validation



Where: R^2 = Coefficient of determination;
MAE = Mean absolute error;
RMSE = Root mean square error.

Source: Authors.

The cubist models obtained soil carbon content predictions with similar or better accuracy than previous studies in other regions (Moura-Bueno *et al.*, 2021) or nationwide (Demattê *et al.*, 2019). Regionally, Moura-Bueno *et al.* (2021) achieved RMSE of 5.3 to 6.6 g kg^{-1} for soil carbon prediction from Vis-NIR data alone or combining Vis-NIR, spectral classes and environmental covariates, whereas Demattê *et al.* (2019) found a a slightly higher RMSE of 6.9 g kg^{-1}.

The Vis-NIR spectroscopy models for soil carbon content prediction at 0-20 and 30-50 cm for Rio de Janeiro state allow assessing soil carbon contents, stocks and changes, supporting future NFI campaigns across the state. Other statewide soil-related projects may benefit from the model produced here to expedite soil analysis. Accordingly, SSL and Vis-NIR spectroscopy-based prediction models may be extended to other soil properties as well as other states and regions in Brazil.

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CHAPTER 4

SOIL CARBON STORAGE SCENARIOS DRIVEN BY LAND USE, LAND COVER, AND MANAGEMENT CHANGES IN THE STATE OF RIO DE JANEIRO

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1. INTRODUCTION

Soil is a major reservoir of biosphere carbon (FAO, 2018). Forests around the globe store, on average, 45% of carbon in the soil (up to 1 m deep) (Pan *et al.*, 2024). Based on data from the Brazilian National Forest Inventory (NFI), the technical team at Embrapa Soils estimated that forest soils accumulate 136 Tg (million tons) of carbon (Chapter 2 of this book), which means that most of the carbon in these forests is in their soil. This high proportion of carbon in the soil in the Atlantic Forest, when analyzed in conjunction with the study of Lima *et al.* (2020), demonstrates that soil is a resilient carbon reservoir. Despite significant losses of aboveground biomass associated with biodiversity loss in recent decades, the biome's soil still maintains a large carbon reservoir.

Assuming that: At least 1/3 of the pasture lands in the state of Rio de Janeiro are in an intermediate or severe state of degradation (Bolfe *et al.*, 2024); agricultural activities are carried out in rugged terrain; and there is a significant deficit of Legally Protected Areas (~ 111 thousand ha) and Reserves (~ 82 thousand ha) in the state of Rio de Janeiro (Ribeiro *et al.*, 2021), this chapter presents a theoretical exercise to assess the (realistic) potential for carbon sequestration or storage in the soils of Rio de Janeiro, if restoration actions or incentives for reforestation and good agricultural practices were promoted, as well as economic compensation mechanisms implemented, for each administrative region.

2. SOIL CARBON: CURRENT AND REACHABLE STOCKS

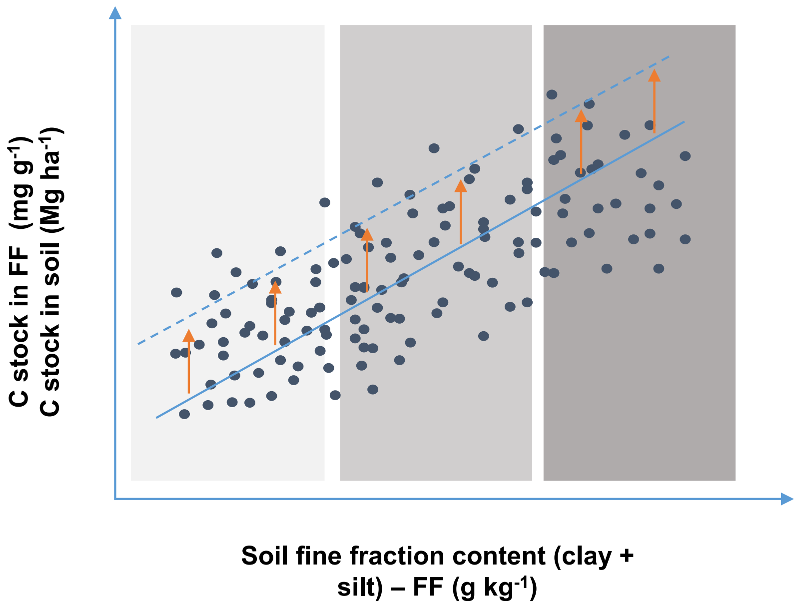
The potential for carbon accumulation or storage in soils in agroecosystems is difficult to estimate, considering that these environments can store more carbon than native vegetation, which is often used as a storage reference in carbon sequestration projects.

The concept of reachable soil carbon (C-att) (Ingram; Fernandes, 2001) has been adopted as the soil's capacity to gain carbon if carbon input is unrestricted, and plant and soil management increases carbon flow and stabilization in the finer soil fractions. In other words, the concept implicitly implies the upper limits that certain soils and land use/land cover (LULC) classes can achieve through the adoption of better management practices. In other words, soils with low carbon stocks, smaller than those considered "reachable", would provide greater opportunities for carbon sequestration.

The term "reachable carbon" is associated with the finest soil fraction (<60 µm or 0.060 mm), also called mineral-associated organic matter (MAOM) (Cambardella; Elliot, 1992; Six *et al.*, 2002; Cotrufo *et al.*, 2019), which is the fraction of soil organic matter where most of the soil carbon stock is found (Feller and Beare, 1997; Cotrufo *et al.*, 2019). Therefore, the same approach by Karunaratne *et al.* (2024) was used in the present study to estimate the reachable carbon deficit in the soils of Rio de Janeiro state.

According to this approach, the difference between the carbon stock (Mg ha^{-1}) in a given land use and its 90^{th} percentile for the state's different administrative regions illustrates the reachable carbon deficit, which indirectly expresses the soil's carbon sequestration potential, and can be used to guide efforts and policies aimed at increasing the stock of this natural asset and fostering markets or other mechanisms for economic compensation (Giorgiou *et al.*, 2022; Karunaratne *et al.*, 2024). Given the limitations of the adapted methodology and the dataset used, it is worth noting that the C-att value defines only a threshold value, not the carbon saturation point for the state's soils. In other words, higher stock values can be achieved in different regions.

FIGURE 1. Theoretical relationship between total organic carbon stock (Mg ha^{-1}) or carbon stock in the fine fraction (FF) of the soil (mg g^{-1}) (y-axis), and the FF (clay + silt) content of the soil (g kg^{-1}) (x-axis)



The solid and dotted lines indicate the overall relationship between the soil FF content and the current organic carbon stock (solid line), and reachable organic carbon stock (dotted line). The reachable carbon stock deficit is indicated by the orange arrows.

Source: Adapted from Karunaratne *et al.* (2024).

The 90th percentile, adopted as a theoretical reference, demonstrates, for each administrative macro-region, the reachable for each LULC class (in this case, pasture and forest formation) representative of the region. Although a recent concept, derived from studies that consider finer fractions of soil organic matter (Karunaratne *et al.*, 2024), it clearly illustrates that soil carbon stocks can be increased to certain real values, in a more viable accumulation scenario, both in time and space. Table 1 summarizes the descriptive statistics of the soil carbon stock (0-50 cm) and provides an estimate of the reachable carbon deficit per hectare and the carbon sequestration potential for each region of the state.

TABLE 1. Average and 90th percentile values of soil carbon stock (Mg ha^{-1}) at 0-50 cm in the main land use/land cover classes from the Brazilian National Forest Inventory in the state of Rio de Janeiro

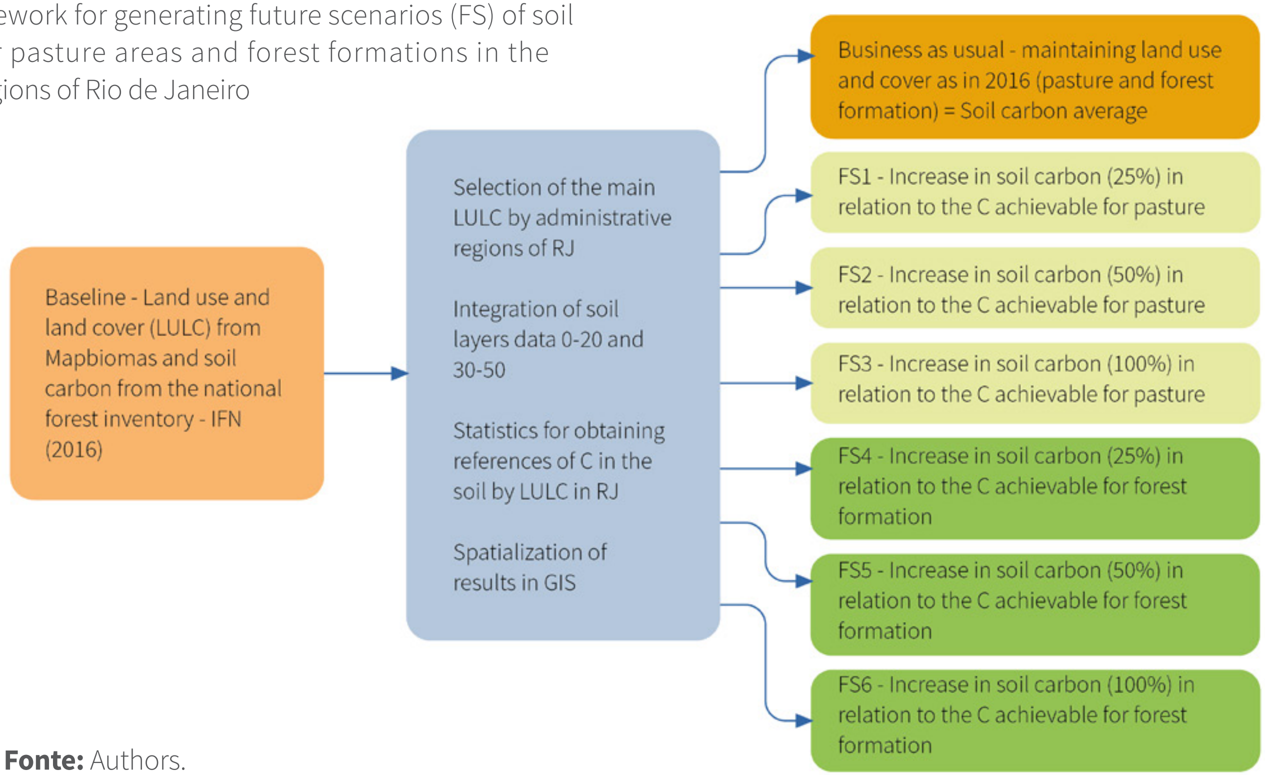
Region	Land use/land cover	Average C (baseline)	C at the 90th percentile (reachable C)	Sample size	Reachable C deficit	C sequestration potencial
Costal Low Lands	Forest formation	83,09	127,76	22	44,57	++
Costal Low Lands	Pasture	67,88	91,32	9	23,44	+
Central-South	Forest formation	91,24	195,25	10	104,01	+++
Southeast Coast	Forest formation	86,44	110,69	4	24,25	++
Metropolitan	Forest formation	87,30	114,46	14	27,16	++
Metropolitan	Pasture	60,13	90,03	4	29,90	++
Paraiba River Valley	Forest formation	103,27	126,85	15	23,58	++
North	Forest formation	99,46	166,56	17	67,10	+++
North	Pasture	84,62	144,81	14	60,19	+++
Northwest	Forest formation	107,01	194,56	7	87,55	+++
Northwest	Pasture	64,67	95,19	16	25,52	++
Uplands	Forest formation	115,61	184,33	19	68,72	+++
Uplands	Pasture	100,02	157,64	5	57,62	++

C sequestration potential (Reachable C deficit / 30 years): (+) 0.0-1.0 Mg ha^{-1} $year^{-1}$; (++) 1.0-2.0 Mg ha^{-1} $year^{-1}$; and (+++) 2.0 -3.0 Mg ha^{-1} $year^{-1}$.
Source: Authors.

3. SOIL CARBON STOCK SCENARIOS IN RIO DE JANEIRO: METHODOLOGICAL ASPECTS

Carbon stock values were measured via dry combustion in soil samples collected at 0-20 and 30-50 cm during the first phase of the NFI (SFB, 2018) in the Embrapa Soils laboratories. These data, together with a harmonized LULC map (MapBiomas, 2016) and maps of the administrative regions and municipalities of the state of Rio de Janeiro (CEPERJ, 2014), were used to generate soil carbon stock scenarios, as a function of LULC, for each administrative region of the state, considering their suitability and historical agricultural practice, according to the framework presented in Figure 2.

FIGURE 2. Framework for generating future scenarios (FS) of soil carbon stocks for pasture areas and forest formations in the administrative regions of Rio de Janeiro



Fonte: Authors.

Due to the methodology adopted by the Brazilian Forest Service, it was necessary to integrate the carbon stock values at 0-20 and 30-50 cm for the 0-50 cm layer, in Mg ha^{-1}, using the following equation:

C stock (0-50 cm) = [C stock (0-20 cm) + C stock (30-50 cm)] / 40 * 50

Using an Excel spreadsheet, the following were calculated: mean, minimum, 90th percentile and number of points sampled in the NFI for the LULC class in each administrative region (n), based on the carbon stock data (0-50 cm) obtained in the 168 NFI sampling points, for each land use/land cover and administrative region. The result of this analysis supported the generation of the scenarios, as follows:

- Baseline C value for LULC classes and regions: the average carbon stocks (Mg ha^{-1}) for LULC classes and administrative regions, considered real stocks, that is, those that best represent the soil carbon stock values in the LULC classes in that region;

- Reachable C value for LULC classes and regions: the carbon stock values (Mg ha^{-1}) of the 90th percentile of the most representative LULC classes in the NFI (forests and pastures), used as a reference for how much carbon can realistically be stored if good management and conservation practices are adopted; and

- Reachable C deficit for CUCTs and regions: difference between the reachable and the baseline C stock values, by CUCT and administrative region (the greater the difference between the baseline and reachable C stock for a given LULC, the greater the reachable carbon deficit, that is, the greater the soil carbon sequestration potential for that LULC and administrative region).

Using this data, it was possible to estimate scenarios for increasing soil carbon equivalent to 25, 50, and 100% of the carbon deficit up to the reachable C value. Again, these values define only a limit, not the carbon saturation value for the soils of Rio de Janeiro state, and can be considered conservative estimates of the carbon sequestration potential of Rio de Janeiro soils. Based on these estimated values, maps were derived for the following future scenarios (FS) for soil C stock:

- Business as usual: maintaining baseline soil C stock (average C stock) values in forest formations and pastures for 30 years;

- FS1: baseline (average) carbon stock + increase of 25% of the reachable carbon deficit in pastures in 30 years;

- FS2: baseline (average) carbon stock + increase of 50% of the reachable carbon deficit in pastures in 30 years;

- FS3: baseline (average) carbon stock + increase of 100% of the reachable carbon deficit in pastures in 30 years;

- FS4: baseline (average) carbon stock + increase of 25% of the reachable carbon deficit in forest formations in 30 years;

- FS5: baseline (average) carbon stock + increase of 50% of the reachable carbon deficit in pastures in forest formations in 30 years;

- FS6: baseline (average) carbon stock + increase of 100% of the reachable carbon deficit in forest formations in 30 years.

In addition, a complementary theoretical exercise was conducted, focusing on the state's deficit of Legal Reserve areas. To contribute to estimates of the potential for soil carbon accumulation through restoration actions, the difference between the baseline carbon stock values (in Mg ha^{-1}) of forest formations and pastures was calculated for each region, assuming the conversion from pastures with low productivity potential to forest. The potential for soil carbon accumulation in these converted areas, in Mg ha^{-1}, was then calculated for the conversion of 25% and 50% of the pasture areas in each region. The time required to achieve the reference values is approximately 20 to 30 years of restoration.

4. RESULTS AND DISCUSSION

In general, regardless of the administrative region, higher carbon stocks at 0-50 cm were observed in forest soils (~96.7 Mg ha^{-1}) than in

TABLE 2. Total soil carbon stock at 0-50 cm (Mg) by administrative region of the Rio de Janeiro state, in pasture and forest formations, estimated by the different scenarios

Region	LULC	C stock (Mg) - LULC x region (ha)								
		Area (ha)	C Business as usual (C average)	FS1	FS1	FS2	FS2	FS3	FS3	FS4
				Pasture	Pasture	Pasture	Pasture	Pasture	Pasture	Forest formation
				(25% of C achievable deficit)	(C average + 25% of C achievable deficit)	(50% of C achievable deficit)	(C average + 50% of C achievable deficit)	(100% of C achievable deficit)	(C average+ 100% of C achievable deficit)	(25% of C achievable deficit)
Costal Low Lands	Forest formation	85.095,92	5.776.311,19							948.181,31
Costal Low Lands	Pasture	169.837,39	11.528.562,00	995.247,10	12.523.809,10	1.990.494,21	13.519.056,21	3.980.988,41	15.509.550,41	
Central-South	Forest formation	89.829,35	8.196.029,77							2.335.787,63
Southeast Coast	Forest formation	169.216,04	14.627.034,87							1.025.872,27
Metropolitan	Forest formation	211.661,93	18.478.086,15							1.437.184,47
Metropolitan	Pasture	172.053,45	10.345.574,21	1.286.099,57	11.631.673,78	2.572.199,14	12.917.773,35	5.144.398,29	15.489.972,50	
Paraiba River Valley	Forest formation	205.639,64	21.236.406,18							1.212.245,71
North	Forest formation	123.496,55	12.282.967,24							2.071.654,69
North	Pasture	478.299,19	40.473.677,66	7.197.207,09	47.670.884,75	14.394.414,19	54.868.091,85	28.788.828,39	69.262.506,05	
Northwest	Forest formation	66.372,10	7.102.571,31							1.452.738,34
Northwest	Pasture	408.099,30	26.391.781,70	2.603.673,53	28.995.455,23	5.207.347,06	31.599.128,76	10.414.694,13	36.806.475,83	
Uplands	Forest formation	300.763,55	34.771.274,71							5.167.117,89
Uplands	Pasture	240.792,07	24.084.022,80	3.468.609,76	27.552.632,56	6.937.219,53	31.021.242,33	13.874.439,05	37.958.461,85	

pasture soils (~78.9 Mg ha^{-1}), demonstrating the importance of forest preservation and restoration not only for carbon conservation and biodiversity, but also for other ecosystem services provided by forests, including food and fiber production, nutrient cycling, and water regulation. These results are corroborated by other authors (Vieira *et al.*, 2011; Gomes *et al.*, 2014), who demonstrate that typic forested biomes store more carbon in the soil than other land uses.

On the other hand, both pastures and other LULC provide higher carbon sequestration rates if good agricultural and management practices are

Continuation - C stock (Mg) - LULC x region (ha)				
FS4	FS5	FS5	FS6	FS6
Forest formation	Forest formation	Forest formation	Forest formation	Forest formation
(C average + 25% of C achievable deficit)	(50% of C achievable deficit)	(C average + 50% of C achievable deficit)	(100% of C achievable deficit)	(C average + 100% of C achievable deficit)
6.724.492,50	1.896.362,62	7.672.673,81	3.792.725,25	9.569.036,44
10.531.817,40	4.671.575,27	12.867.605,04	9.343.150,55	17.539.180,32
15.652.907,14	2.051.744,54	16.678.779,41	4.103.489,07	18.730.523,94
19.915.270,62	2.874.368,96	21.352.455,11	5.748.737,91	24.226.824,06
22.448.651,89	2.424.491,42	23.660.897,60	4.848.982,84	26.085.389,02
14.354.621,93	4.143.309,38	16.426.276,62	8.286.618,75	20.569.585,99
8.555.309,65	2.905.476,68	10.008.047,99	5.810.953,36	12.913.524,67
39.938.392,60	10.334.235,78	45.105.510,49	20.668.471,57	55.439.746,28

planned in a coordinated manner and properly executed. It is noteworthy that Assad *et al.* (2013) reported, in a meta-analysis carried out on pastures in the Atlantic Forest biome, for the 0-30 cm layer, carbon stocks compatible with those found in the present study of 50 Mg ha^{-1}.

According to the proposed scenarios FS1, FS2 and FS3, of increases of 25, 50 and 100%, respectively, of the reachable C deficit in pastures, the carbon stocks of the state's pastures can be increased by 13.57 to 54.26 Tg (million tons) (or 49.66 to 198.60 Tg CO2eq) through the adoption of good soil management and conservation practices, as well as the integration of livestock systems with crops and forestry components in the regions of Costal Lowlands, Metropolitan, North, Northwest and Uplands, where data were available for the estimates. On the other hand, the soil C increases in forest formations for all regions of the state were estimated from 15.65 Tg (increase of 25% of the C-att deficit) to 62.60 Tg (100% of the C-att deficit), made possible by the adoption of efficient forest restoration techniques, such as active or assisted restoration, resulting in multiple benefits, both for biodiversity conservation and soil carbon sequestration.

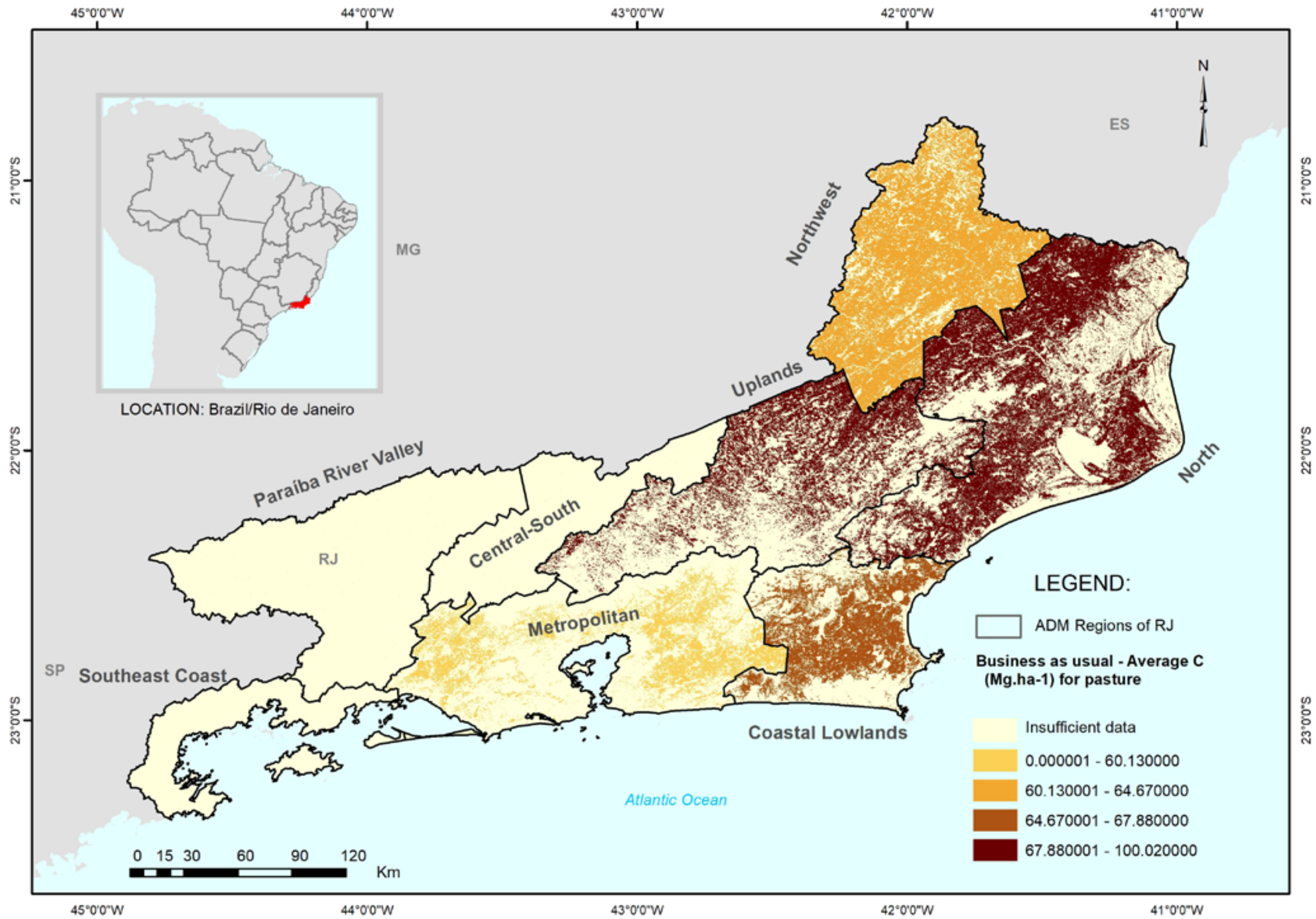
Source: Authors.

The results show that the regions with the largest reachable carbon deficits and, therefore, the greatest potential for carbon accumulation, under pastures, are the North region (with 53% of the state's potential), followed by the Uplands (25%) and Northwest (19%) regions. The regions with the greatest potential for carbon gain in forest formations areas are the Uplands (33% of the estimated total), the Central-South (15%), and the North (13%) regions. These results are consistent with the history of intense land use in these regions. However, the lack of sampling points under pastures in the Paraíba River Valley, Southeast Coast, and Central-South regions limited applying the scenarios of soil C increase in pastures in these regions.

Figure 3 presents the maps of the soil C stock baselines for pasture and forest formations, respectively, and under the six future scenarios (FS1 to FS6), indicating the regions where the greatest and smallest soil carbon gains could occur in pasture and forest formation areas. Such scenarios could come true if good agricultural and livestock practices, soil and water conservation policies, and economic incentives were included as cornerstones in the the state's agro-environmental planning. The color intensities in the different regions highlight what was previously mentioned: the North, Northwest, and Uplands regions have the greatest potential for carbon sequestration in pastures should they be better managed or combined with crops or tree plantations; and the more central regions, such as Uplands and Central-South, have high potential for soil carbon gain in forest formations through assisted or active restoration.

It is important to emphasize that the government has a duty, through its public policies and incentives, to support rural producers in building sustainable rural landscapes throughout the Rio de Janeiro state. In this context, the increase in soil carbon stocks in Rio de Janeiro, as envisioned in this document, will be associated with the provision of multiple ecosystem services by the soil. Carbon sequestration is just one of them, and producers can also benefit from the C credit market if they find it interesting. Undoubtedly, those farmers who already practice regenerative agriculture or livestock farming, and whose farms have soils with high levels of organic matter should receive economic or fiscal incentives for continuing managing their soils sustainably, avoiding the loss of stored carbon, benefiting the society as a whole.

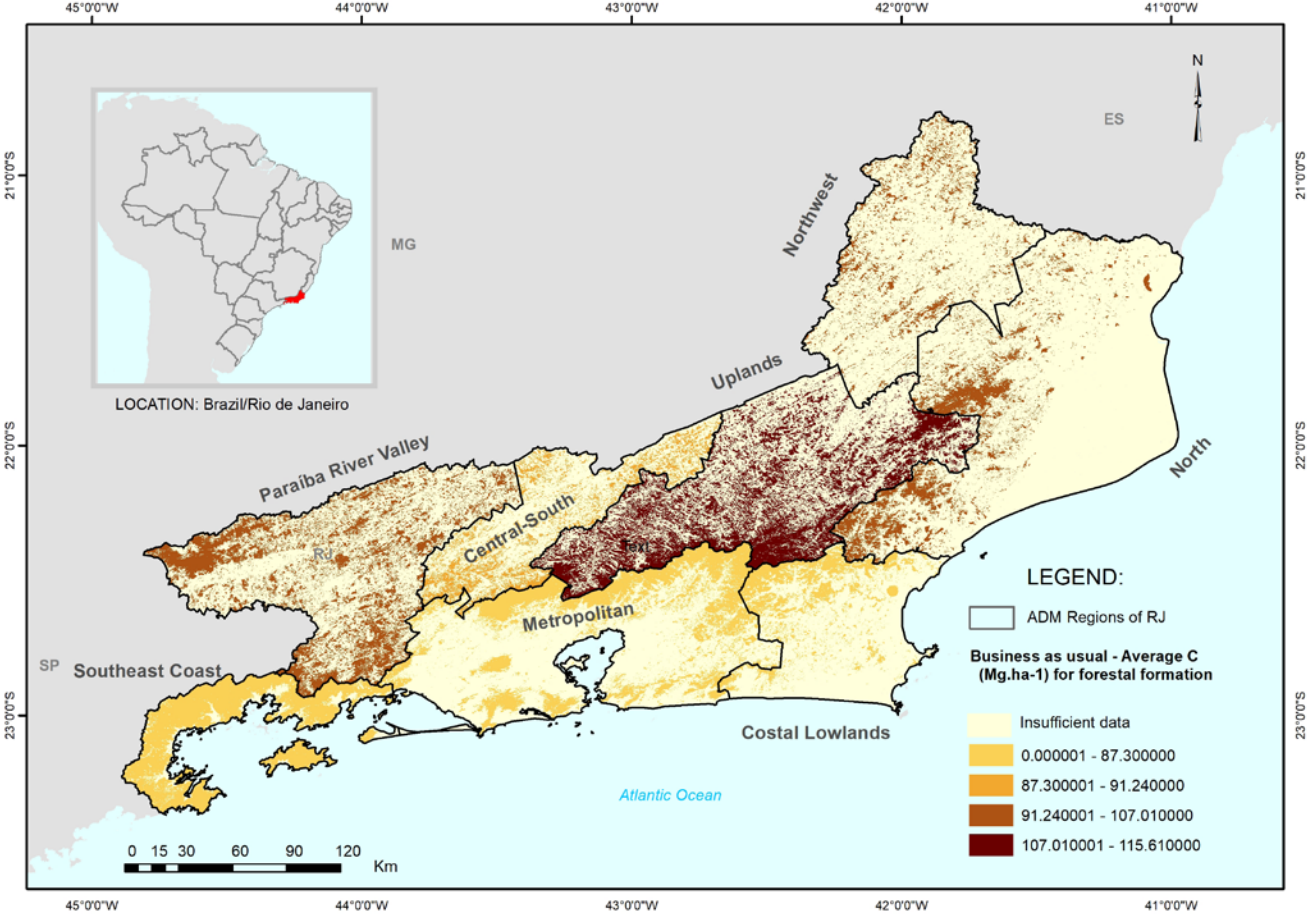
FIGURE 3A. Future soil C stock scenarios for the administrative regions of Rio de Janeiro state: Business as usual (C stock baselines ~ average C stocks) for pastures (A), and forests (B); C stock baselines (average C stocks) + increases of 25 (FS1), 50 (FS2), and 100% (FS3) of the reachable carbon deficit in pastures (C, D, and E, respectively); and C stock baselines (average C stocks) + increases of 25 (FS4), 50 (FS5), and 100% (FS6) of the reachable carbon deficit in forest formations (F, G, and H, respectively)



(A) - BusinessP

Source: Authors.

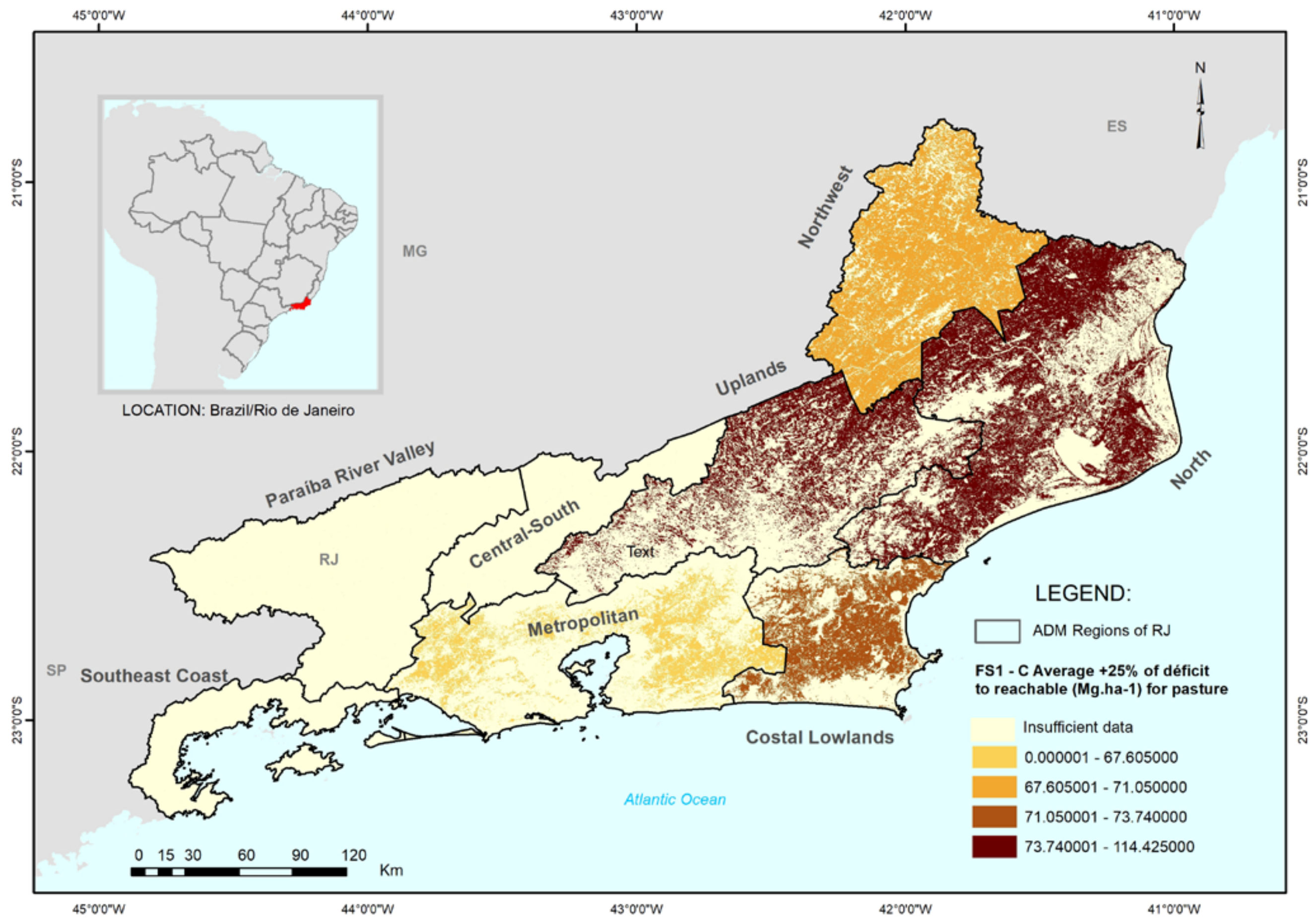
FIGURE 3B. Future soil C stock scenarios for the administrative regions of Rio de Janeiro state: Business as usual (C stock baselines ~ average C stocks) for pastures (A), and forests (B); C stock baselines (average C stocks) + increases of 25 (FS1), 50 (FS2), and 100% (FS3) of the reachable carbon deficit in pastures (C, D, and E, respectively); and C stock baselines (average C stocks) + increases of 25 (FS4), 50 (FS5), and 100% (FS6) of the reachable carbon deficit in forest formations (F, G, and H, respectively)



(B) - BusinessF

Source: Authors.

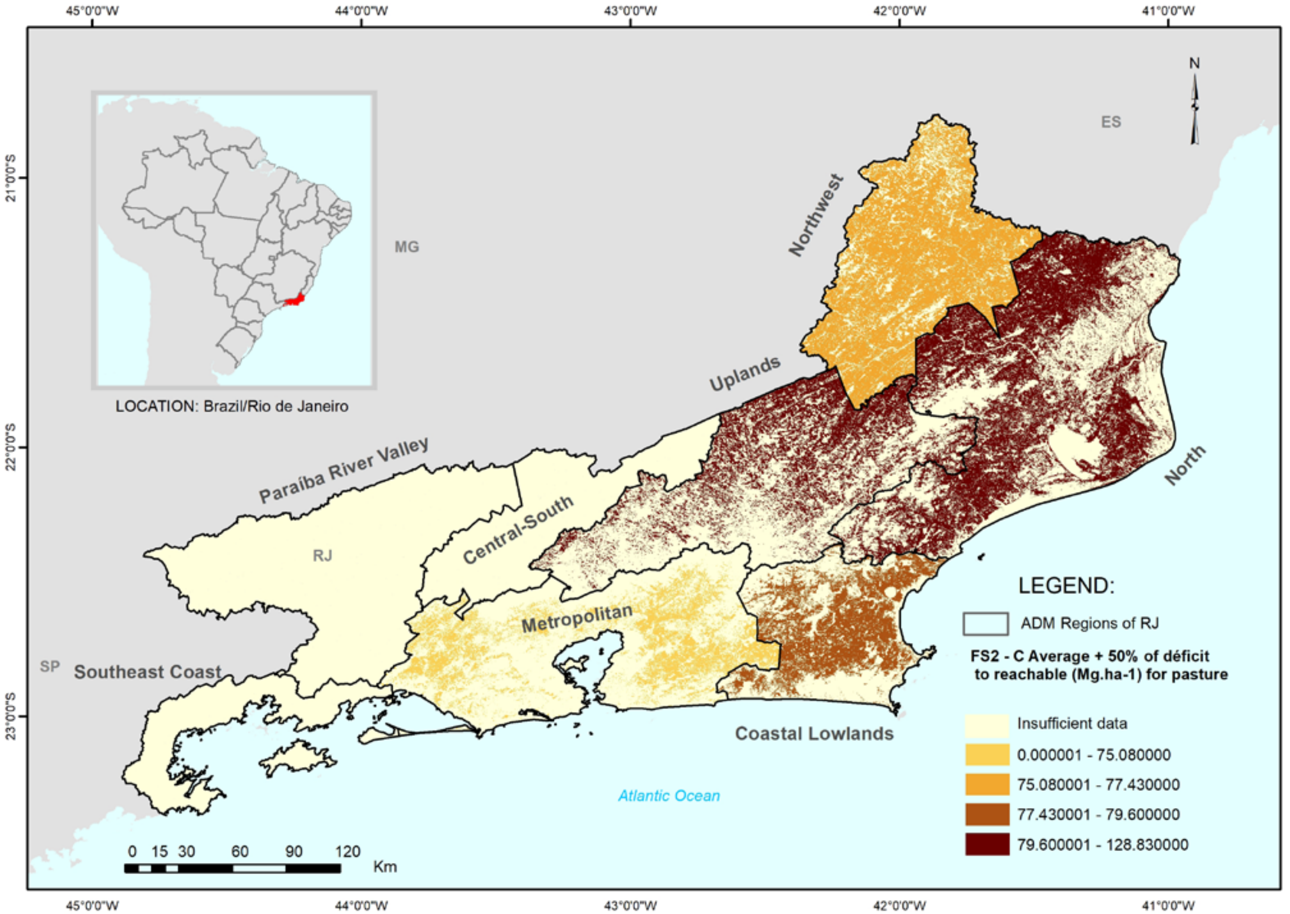
FIGURE 3C. Future soil C stock scenarios for the administrative regions of Rio de Janeiro state: Business as usual (C stock baselines ~ average C stocks) for pastures (A), and forests (B); C stock baselines (average C stocks) + increases of 25 (FS1), 50 (FS2), and 100% (FS3) of the reachable carbon deficit in pastures (C, D, and E, respectively); and C stock baselines (average C stocks) + increases of 25 (FS4), 50 (FS5), and 100% (FS6) of the reachable carbon deficit in forest formations (F, G, and H, respectively)



(C) - FS1

Source: Authors.

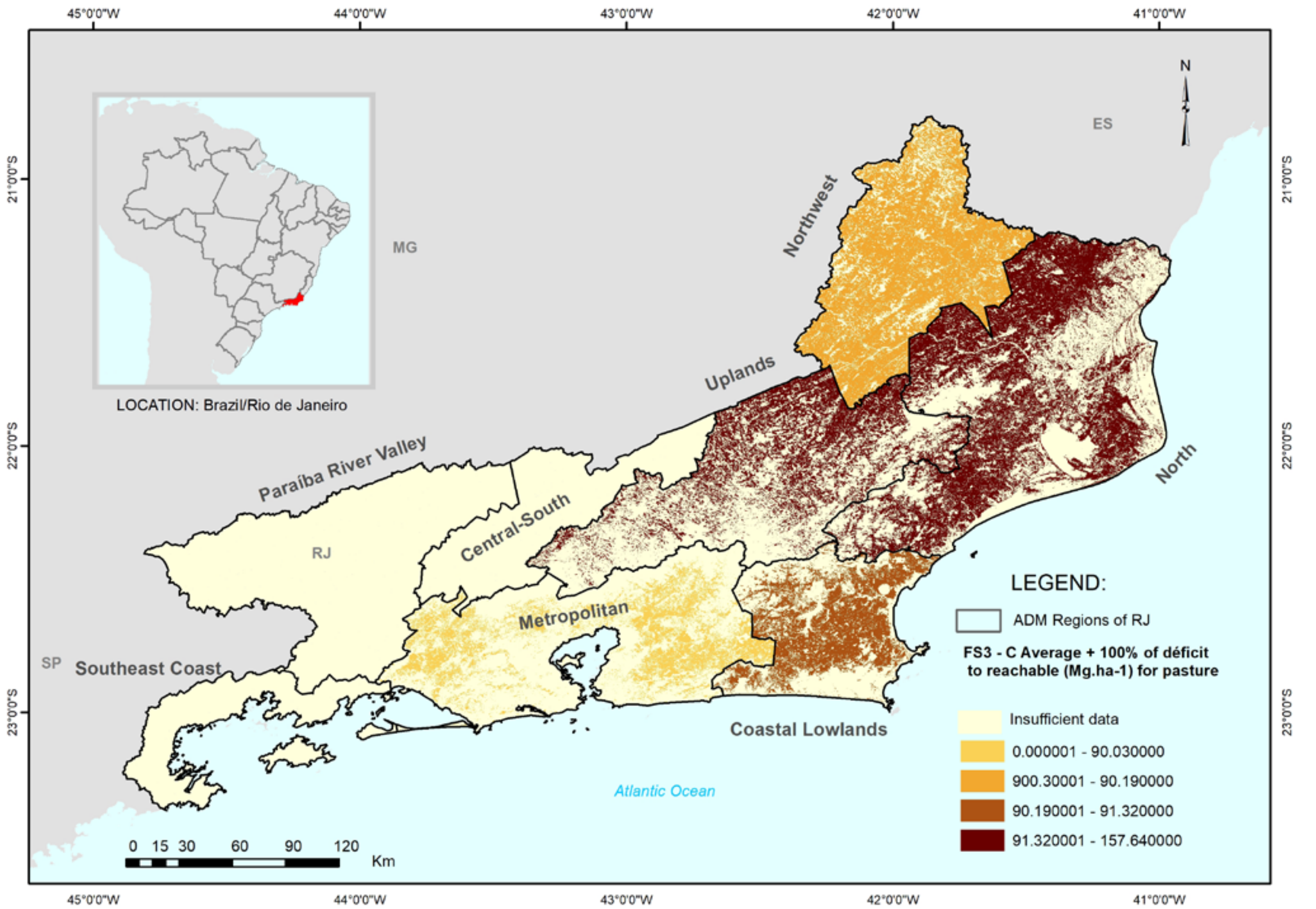
FIGURE 3D. Future soil C stock scenarios for the administrative regions of Rio de Janeiro state: Business as usual (C stock baselines ~ average C stocks) for pastures (A), and forests (B); C stock baselines (average C stocks) + increases of 25 (FS1), 50 (FS2), and 100% (FS3) of the reachable carbon deficit in pastures (C, D, and E, respectively); and C stock baselines (average C stocks) + increases of 25 (FS4), 50 (FS5), and 100% (FS6) of the reachable carbon deficit in forest formations (F, G, and H, respectively)



(D) - FS2

Source: Authors.

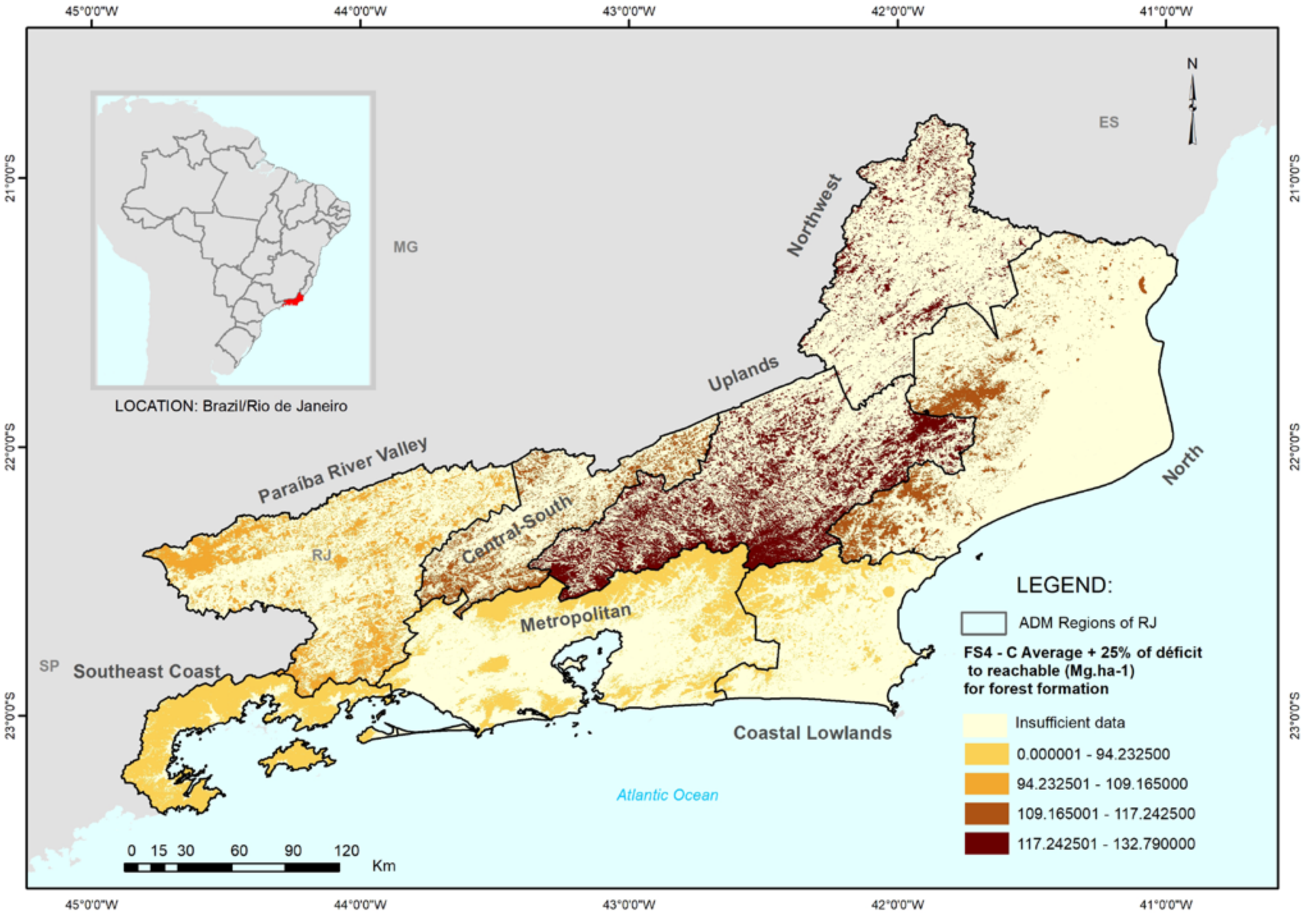
FIGURE 3E. Future soil C stock scenarios for the administrative regions of Rio de Janeiro state: Business as usual (C stock baselines ~ average C stocks) for pastures (A), and forests (B); C stock baselines (average C stocks) + increases of 25 (FS1), 50 (FS2), and 100% (FS3) of the reachable carbon deficit in pastures (C, D, and E, respectively); and C stock baselines (average C stocks) + increases of 25 (FS4), 50 (FS5), and 100% (FS6) of the reachable carbon deficit in forest formations (F, G, and H, respectively)



(E) - FS3

Source: Authors.

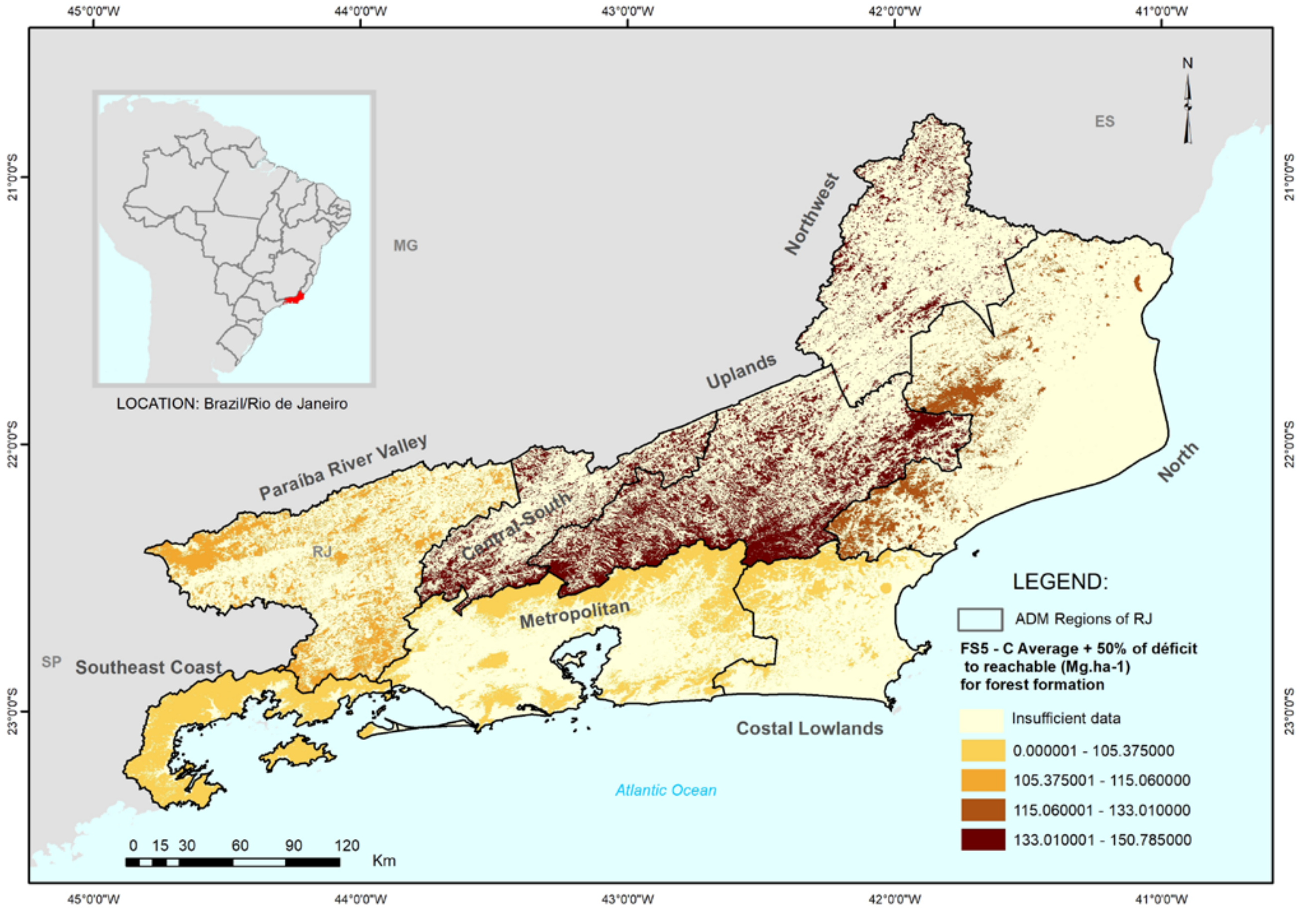
FIGURE 3F. Future soil C stock scenarios for the administrative regions of Rio de Janeiro state: Business as usual (C stock baselines ~ average C stocks) for pastures (A), and forests (B); C stock baselines (average C stocks) + increases of 25 (FS1), 50 (FS2), and 100% (FS3) of the reachable carbon deficit in pastures (C, D, and E, respectively); and C stock baselines (average C stocks) + increases of 25 (FS4), 50 (FS5), and 100% (FS6) of the reachable carbon deficit in forest formations (F, G, and H, respectively)



(F) - FS4

Source: Authors.

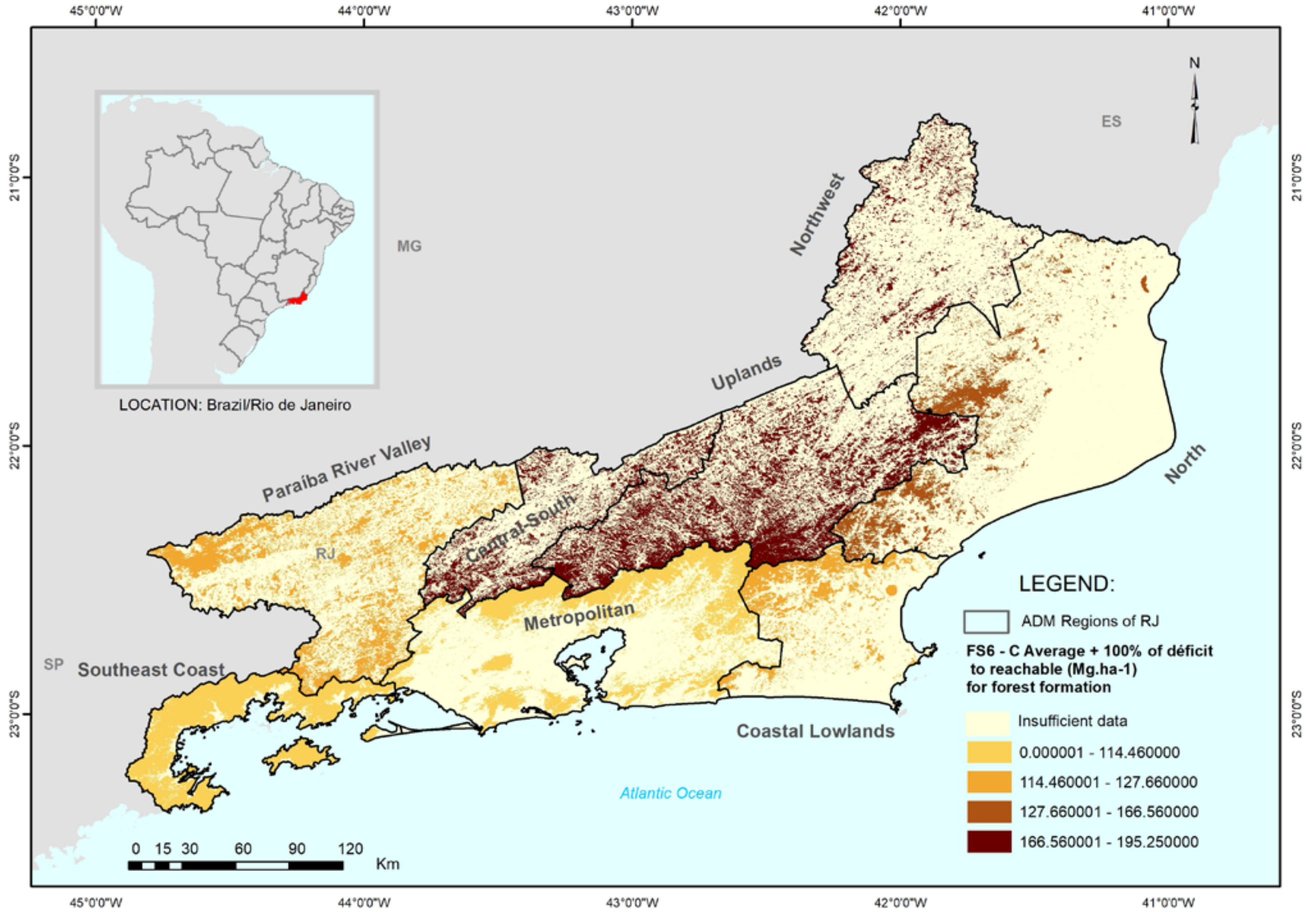
FIGURE 3G. Future soil C stock scenarios for the administrative regions of Rio de Janeiro state: Business as usual (C stock baselines ~ average C stocks) for pastures (A), and forests (B); C stock baselines (average C stocks) + increases of 25 (FS1), 50 (FS2), and 100% (FS3) of the reachable carbon deficit in pastures (C, D, and E, respectively); and C stock baselines (average C stocks) + increases of 25 (FS4), 50 (FS5), and 100% (FS6) of the reachable carbon deficit in forest formations (F, G, and H, respectively)



(G) - FS5

Source: Authors.

FIGURE 3H. Future soil C stock scenarios for the administrative regions of Rio de Janeiro state: Business as usual (C stock baselines ~ average C stocks) for pastures (A), and forests (B); C stock baselines (average C stocks) + increases of 25 (FS1), 50 (FS2), and 100% (FS3) of the reachable carbon deficit in pastures (C, D, and E, respectively); and C stock baselines (average C stocks) + increases of 25 (FS4), 50 (FS5), and 100% (FS6) of the reachable carbon deficit in forest formations (F, G, and H, respectively)



(H) - FS6

Source: Authors.

5. EFFORTS TO INCREASE SOIL CARBON STOCKS IN RIO DE JANEIRO STATE

Rural property planning is the foundation for building sustainable landscapes, increasing soil organic matter levels, and, consequently, increasing the supply of soil ecosystem services. The principles of sustainable, conservation, agroecological, or regenerative agriculture are widely known and should form the foundation for building healthy soils with high levels of organic matter. Practices such as contour planting, crop rotation or intercropping, no-till farming, green manuring, and integrated pest and waste management should be incorporated into Rio de Janeiro's production systems, regardless of the region.

Establishing a relationship of trust with farmers and local and state governments is essential to establishing and consolidating compensation mechanisms for sustainable land use in Rio de Janeiro, including C offset markets. Some challenges to consolidating soil carbon-based offset markets include: i) the lack of regulations at different levels; ii) scattered and contradictory information in the academic and non-academic literature, which often hinder rather than contribute to the discussion on carbon market regulation; iii) inadequate project timelines, which inspire distrust in both sellers and buyers; iv) the lack of information and training on the topic; v) inefficient communication among stakeholders; and vi) the difficulty of operationalization, and the high cost of monitoring and certifying soil carbon gains.

Furthermore, the production decline in rural areas, resulting from the low level of productivity, the difficulty in accessing technical assistance and rural extension, and the limited financial and marketing support, will require joint efforts in various spheres in favor of establishing a new development model for these areas (Vidal *et al.*, 2020).

Multi-activity, with incentives for developing specific niches (such as housing for leisure, rest, and rural tourism), the production of value-added goods (organic and artisanal), and traditional productive activities (community- and family-based), can also benefit from the different compensation mechanisms for the conservationist use of soil, forests and biodiversity, with gains that extend to the entire society, going beyond the limits of the rural landscape.

Public policies, such as the Brazilian Low Carbon Agriculture Plan (Plano de Agricultura de Baixo Carbono), Organic Agriculture Program (Programa de Agricultura Orgânica), and National Water Resources Policy (Política Nacional de Recursos Hídricos), as well as environmental (or economic) compensation mechanisms that support farmers who adopt sustainable production practices, with favorable credit conditions or in the form of compensatory incentives, must be aligned with social demands and conducted with the least political interference.

To this end, and to overcome these challenges, the State Secretariat for Environment and Sustainability (Secretaria de Estado de Ambiente e Sustentabilidade), the State Secretariat for Agriculture, Fisheries, and Supply (Secretaria de Estado de Agricultura, Pesca e Abastecimento), and the Technical Assistance and Rural Extension Company of Rio de Janeiro (Empresa de Assistência Técnica e Extensão Rural do Rio de Janeiro) are working collaboratively to develop the Agroecological Transition Assessment Instrument (Instrumento de Avaliação da Transição Agroecológica). This instrument brings together a set of methodological tools to characterize and classify the different phases of the agroecological transition of agroecosystems in the Rio de Janeiro state, enabling the development of a participatory transition plan, developed by the Social Nucleus for Agroecosystem Management

(Núcleo Social de Gestão do Agroecossistema) and the team of extension workers responsible for monitoring the transition (SEAS, 2025). These actions are supported by the following legal instruments:

1) Technical Note SEAS/SEAPPA/EMATER-RIO n. 01/2024, instrument for assessing the agroecological transition (IATA) and preparing the agroecological transition plan in agroecosystems within the state of Rio de Janeiro (Rio de Janeiro, 2024);

2) Joint Resolution SEAPPA/SEAS/EMATER-RIO/INEA n. 16, of November 26, 2024, which establishes criteria and procedures for recognizing agroecological transition in the production unit, and establishes a methodology for classifying the transition phases of agroecological production in agroecosystems within the state of Rio de Janeiro (Rio de Janeiro, 2024).

Along these lines, SEAPPA and the ILPF Network (Crop-Livestock-Forest Integration Network), a public-private entity, signed a Memorandum of Understanding in May 2025 to strengthen sustainable agriculture in the state of Rio de Janeiro through the implementation of integrated, low-carbon production systems. The work plan outlined in the Technical Cooperation Agreement will involve several teaching, research and extension institutions in the state, as well as state decision-makers, and include technical training, technical dissemination events, territorial assessments, and scientific research focused on the state's needs.

Finally, the capacity and potential of conservation agriculture for improving soil health and, consequently, productivity, including enabling the delivery of multiple ecosystem services, are noteworthy. Rio de Janeiro's soil has the capacity to store significant amounts of carbon, as demonstrated by robust estimates generated from real data collected using a consistent sampling and carbon analysis methodology.

Embrapa Solos will continue working with the NFI samples to obtain more accurate estimates of reachable carbon in the different regions of the state. The data from the first NFI phase obtained so far already provide a regional overview of the potential of agriculture and the forestry sector to sequester carbon in the soil in the context of the farmers' adaptation to climate change, recognizing the externalities generated in the field by the adoption of conservation and sustainable practices. The carbon stored in the soil, resulting from good production and soil conservation practices, will certainly increase the farmers' resilience in the face of ongoing climate change, and benefit the both rural and urban populations through the multiple goods and services generated on their farms.

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CHAPTER 5

TOWARD A JURISDICTIONAL SOIL CARBON STRATEGY IN THE STATE TERRITORY: EXPANDING THE BASKET OF SUSTAINABLE PRODUCTS IN RURAL PROPERTIES IN RIO DE JANEIRO

Telmo B. Silveira Filho, Monise A. F. Magalhães, Fabiano C. Balieiro, Aldair S. Medeiros

1. INTRODUCTION

Soil carbon credits emerge not as a silver bullet for addressing the need to mitigate emissions resulting from climate change, but rather as one more product within the basket of options available to rural producers committed to conservation or regenerative agriculture. These practices foster agricultural systems that interconnect environmental, animal, and human health — the principle of "One Health."

Although methodological divergences and different protocols still exist regarding the general principles of carbon credit accounting, it is necessary to collect data, build information systems, and establish measurable pathways to assess the contribution of soil management to carbon sequestration and climate mitigation.

Without integrity of information and robust data collection, the market cannot consolidate or gain credibility to provide effective responses to emission mitigation. In this sense, this contribution from the state of Rio de Janeiro, in partnership with Embrapa Soils, aims to clarify possible approaches for estimating the initial stock of soil organic carbon, as well as for modeling and measuring changes in this stock over time, always grounded in science.

The content presented here is a foundation for building public policies that focus on the potential of rural areas — beyond food and commodity production — to materialize emerging ecosystem services derived from soil and associated with sustainable agricultural practices.

The era of climate consequences reinforces the need for solutions that generate multiple outcomes and engage various economic sectors. Reducing fossil fuel consumption is crucial; transforming energy generation chains toward using renewable sources is essential; expanding and conserving forest areas is central; and producing food while conserving soil and biodiversity is an integral part of this solution set.

Part of the solution literally lies beneath our feet. Over the past century, the conversion of natural ecosystems into agricultural ones, combined with harmful practices — such as deep and repetitive plowing, extensive monocultures, excessive chemical fertilization, overgrazing, and the absence of mechanical and vegetative soil conservation measures — has caused a reduction of 25% to 75% in the global stock of soil organic matter (Lal, 2011; Sanderman; Hengl; Fiske, 2017).

Public policies that promote sustainable agricultural practices can reverse this trend. Among these practices are the use of cover crops and green manures, reduced soil disturbance, control of overgrazing, efficient nutrient management, and diversification of production systems (Balieiro *et al.*, 2024). These methods have shown potential for restoring soil organic matter stocks (Dupla *et al.*, 2024).

2. QUANTIFICATION OF SOIL ORGANIC CARBON

One of the incentives for adopting these practices is the agricultural soil carbon credit (SCC). SCCs are tradable certificates that allow farmers who implement carbon sequestration practices to sell their emission reductions to organizations interested in offsetting their CO_2 footprint — a mechanism still little disseminated or discussed in Brazil.

These transactions currently take place in voluntary carbon markets, regulated by public or private entities. In 2022, the total global volume of SCC transactions reached 5.1 $MtCO_2e$ (CO_2 equivalent), generating about US$ 50.1 million in value (Mikolajczyk; Bravo, 2023). Experts project that this market could reach between US$ 10 and 40 billion by 2030 (The Voluntary Carbon Market Is Thriving, 2022).

Following the enactment of Federal Law nº 15.042 of December 11, 2024, which establishes the Brazilian Greenhouse Gas Emissions Trading System (SBCE, in portuguese), it becomes necessary to develop measurement, reporting, and verification (MRV) protocols that consider the country's ecological characteristics and agricultural management practices. Additionally, maintaining a matrix of permanence and additionality indicators is required for the future generation and comparison of carbon credits.

The lack of standardization, combined with the diversity of agricultural practices, makes it difficult to ensure reliable monitoring and assessment of real and net climate benefits. A national or subnational MRV system — established through clear regulations accessible to the public, incorporating quality control guarantees, and based on institutional and international agreements — would facilitate accountability consistent with the national context (FAO, 2013).

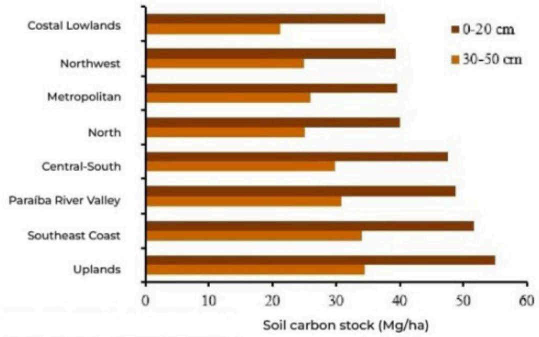
The approach presented in this publication for quantifying soil organic carbon is grounded in current soil science practices. It ranges from soil sampling within a regional grid — following standards of the National Forest Inventory of the state of Rio de Janeiro (IFN/RJ) — to the integration of process-based modeling and remote sensing. This demonstrates that it is possible, on a national scale, to develop and implement robust methods for generating data and information on soil carbon stocks.

Agricultural practices aimed at increasing soil organic carbon can deliver several co-benefits, such as improved water quality, higher productivity, and greater crop resilience (Chaer *et al.*, 2023; Balieiro *et al.*, 2024; Cavalieri-Polizeli *et al.*, 2024). Therefore, even though uncertainties remain regarding their potential for climate mitigation, efforts to build soil carbon remain highly valuable.

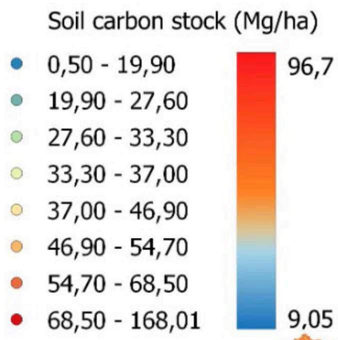
In an innovative way, the conceptual model presented in this study allows for the use of jurisdictional monitoring units and facilitates regional carbon accounting, minimizing monitoring costs for farmers and promoting large-scale implementation of agricultural practices that reduce emissions and store carbon (Figure 1).

FIGURE 1. Soil Carbon Stock across the Territory of the State of Rio de Janeiro
Source: Authors (more information available in Chapter 2).

Soil carbon stock in the state of Rio de Janeiro

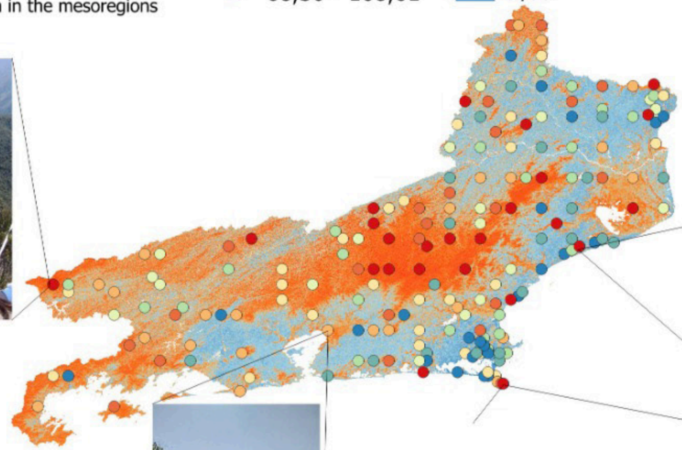


Mean soil carbon stocks at 0-20 and 30-50 cm in the mesoregions of Rio de Janeiro state.



Soil carbon stocks in Rio de Janeiro state add up to ~189 million tons (189 Tg; 1 Tg = 1012 g) at 0-20 cm, and ~119 million tons (119 Tg) at 30-50 cm, respectively.

The largest soil carbon stocks in Rio de Janeiro State are at the mountainous, high-altitude portion of the state at the Serra do Mar (in the Serrana and Costa Verde regions) and Serra da Mantiqueira (in the Médio Paraíba region) mountain ranges, and at the mangroves close to the coast, mainly at the Paraíba do Sul River delta at the eastern state boundary in the Norte Fluminense region.



Montane grassland.

Coastal sandy vegetation

Mangrove vegetation

Submontane Dense Ombrophilous Forest.

QR Code for depth of 0 - 20 cm

QR Code for depth of 30 - 50 cm

3. JURISDICTIONAL PROJECT FOR INCREASING SOIL CARBON

This regional model for soil carbon assessment, linked to policies that promote sustainable agri-food systems, broadens the opportunities for increasing the income of rural producers. Through the State Policy for Sustainable Rural Development, Agroecology, and Organic Production in the State of Rio de Janeiro (State Law nº 8.625/2019), aligned with the National Policy on Payments for Environmental Services (Federal Law nº 14.119/2021), and applied jointly with the Agroecological Transition Assessment Tool (IATA)[1] for agroecosystems and the consolidation of the SBCE, Brazil strengthens its position not only as a major food producer but also as a key player in generating carbon credits derived from forests and soils, thus creating a new environmental commodity.

However, MRV tools, as well as contract and payment models, must take into account the productive and social dynamics of small and medium-sized farmers. Without consistent public policies, direct economic incentives accessible to farmers, technical assistance, rural extension, and continuous monitoring, little progress will be made toward an effective carbon credit market.

The central goal for a future Jurisdictional Project for Increasing Soil Carbon should be to establish technical and financial guidelines and instruments that enable the recognition of soil carbon as both an environmental and economic asset. This includes generating credits for the carbon market but especially supporting Payments for Environmental Services (PES), thereby contributing to carbon removal from the atmosphere, environmental regeneration, and sustainable development of rural properties in Rio de Janeiro.

Technical studies have shown that practices such as reforestation and agroforestry systems (AFS) are effective in increasing soil organic carbon (SOC). Results indicate gains of up to 49% in SOC stock in reforested areas (Macedo *et al.*, 2008) and up to 24% in AFS, when compared to conventional pasture areas (Matos *et al.*, 2022). These data demonstrate both the environmental feasibility and economic potential of these strategies.

The state of Rio de Janeiro, with established initiatives such as the Projeto Conexão Mata Atlântica[2], is well positioned to expand its role in the emerging carbon credit market, generating environmental, social, and economic benefits. The development of technological infrastructure for soil carbon monitoring is one of the strategic recommendations of this Jurisdictional Project.

It can be concluded that the creation of a soil carbon market is desirable and viable, provided there is coordination among public policies, financial resources, technical training, and certification systems based on national metrics with international recognition.

[1] State regulation: Resolução Conjunta SEAPPA/SEAS/EMATER-RIO/INEA nº 16/2024 and Nota Técnica SEAS/SEAPPA/EMATER-RIO nº 01/2024.

[2] Conexão Mata Atlântica Project, learn more at: https://mataatlantica.inea.rj.gov.br/inicio and https://conexaomataatlantica.mctic.gov.br/cma/portal/.

Nature-based Solutions (NbS) encompass a variety of approaches that use ecosystems as the foundation for addressing socio-environmental challenges. These solutions hold great potential to restore, preserve, and enhance ecosystems, while significantly contributing to climate change mitigation (Maia *et al.*, 2022). Among NbS-related mitigation actions, soil plays a crucial role as the largest carbon reservoir in the Earth's surface (see Chapter 2 – *Soil Carbon Stock Maps for the State of Rio de Janeiro: inputs for carbon market opportunities*) (Paustian *et al.*, 2016), making it a key element in building resilient landscapes within the state.

The development of a Jurisdictional Project focused on generating soil carbon credits in the state of Rio de Janeiro seeks to define principles and guidelines that establish its potential as an economic asset connected to the carbon market. This proposal integrates agricultural management with other activities such as crop-livestock-forest systems and ecological restoration. The process aims to make carbon credit commercialization viable while strengthening the state's agricultural sector through the empowerment of farmers and rural landowners across Rio de Janeiro.

4. SOIL CARBON AS AN ENVIRONMENTAL ASSET

The commercialization of carbon credits and Payments for Environmental Services (PES) are financial mechanisms designed to recognize the economic value of environmental conservation, but they differ fundamentally in their structure and objectives (Munhoz; Vargas, 2022).

The commercialization of carbon credits refers to the generation and sale of certificates that represent the reduction or removal of greenhouse gases (GHGs) from the atmosphere — a market-oriented approach to emission offsetting (Souza, 2022). These credits can be voluntarily acquired by companies and individuals seeking to offset their emissions, or they can be used in regulated markets to meet targets established under climate policies (Brazil, 2024). The certification process for carbon credits follows international standards and requires validation by independent auditors to ensure the environmental integrity of the GHG reductions or removals (Souza, 2022).

PES, on the other hand, is a financial mechanism aimed at compensating rural producers, family farmers, settlers, as well as traditional communities and indigenous peoples, for the environmental services they provide, which generate benefits for society as a whole (WRI Brasil, 2021). These services may include conserving native vegetation, restoring degraded areas and forests, improving water quality, removing carbon, or conserving biodiversity, which, for instance, benefits agricultural production through pollination (Prado *et al.*, 2016; WRI Brasil, 2021).

Soil carbon sequestration represents a valuable ecosystem service that can be compensated through PES programs, regardless of its commercialization in the carbon credit market. Therefore, it is essential to adopt an approach that incorporates both pathways — the generation of carbon credits and the recognition of soil carbon as an economic asset under PES — ensuring multiple incentives for soil conservation and sustainable management, particularly benefiting rural producers (Prado *et al.*, 2022).

Unlike carbon credit trading, which focuses on emission offsetting in relatively "closed" markets and on climate change mitigation, PES can encompass various positive environmental externalities, with payments that may take the form of money, goods, or services (Prado *et al.*, 2016, 2022; Souza, 2022). Moreover, PES may be financed by either the private sector or public policies, aiming to encourage sustainable practices and secure long-term environmental benefits.

In other words, carbon credit trading takes place within a structured market in which certified credits are sold to offset emissions, either through regulated or voluntary mechanisms. PES, when considering soil carbon as an environmental asset, does not necessarily depend on a formal market. It is often implemented through public policy or private incentives for environmental conservation. While the carbon market focuses on emission compensation, PES seeks to foster sustainable practices through direct payments, generating externalities that are tangible and socially recognized (Munhoz; Vargas, 2022; Souza, 2022).

Regenerative or conservation agriculture, when linked to a jurisdictional carbon strategy, requires coordinated action with farmers as the central actors. Large-scale restoration across the state of Rio de Janeiro will only be possible through the participation of farmers and rural landowners, who are the main land managers and stewards of ecosystems, bearing the inherent risks of such activities. This means that mechanisms must be developed to finance regeneration and restoration of the Atlantic Forest at multiple scales within the state, promoting sound soil management practices while aligning with broader state ecological goals related to biodiversity conservation and water security.

Ensuring that farmers in Rio de Janeiro are recognized as providers of goods and services for both rural and urban society is a key objective of the State Secretariat for Environment and Sustainability (SEAS) and other state institutions. The first steps have been taken through shared agendas and collaboratively developed solutions — as demonstrated in this publication.

The Agroecological Transition Assessment Tool (IATA), currently under implementation, will allow the state to monitor production systems across different macro-regions and assess the evolution of their soils. A carbon analysis laboratory — using green chemistry-based methods — and a database for storing this information will support the interpretation of carbon accumulation or loss trends in Rio de Janeiro's agroecosystems, providing the foundation for PES policies targeting farmers.

Initial steps have been taken toward building a public policy framework that aims to conserve the Atlantic Forest and strengthen regenerative agriculture, thereby improving the quality of life in rural, forested, and urban areas throughout the state.

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