

CHAPTER 2

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

Gustavo M. Vasques, Fabiano C. Balieiro, Telmo B. Silveira Filho, Monise A. F. Magalhães, Ricardo O. Dart, Adinan M. M. Martins, Bárbara C. Andrade, João Pedro N. C. Pedreira, Rachel B. Prado



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 MapBiomass, 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

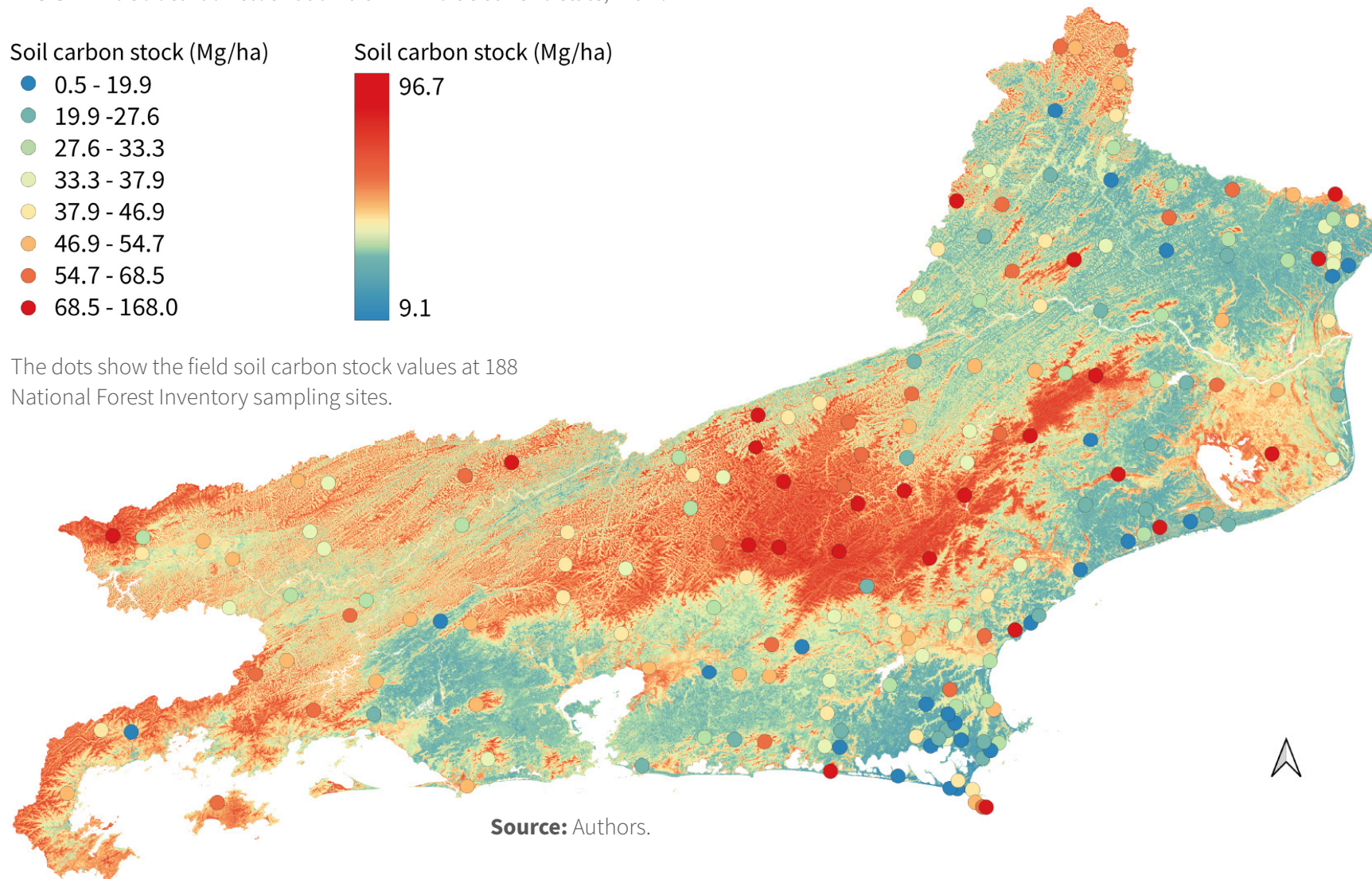
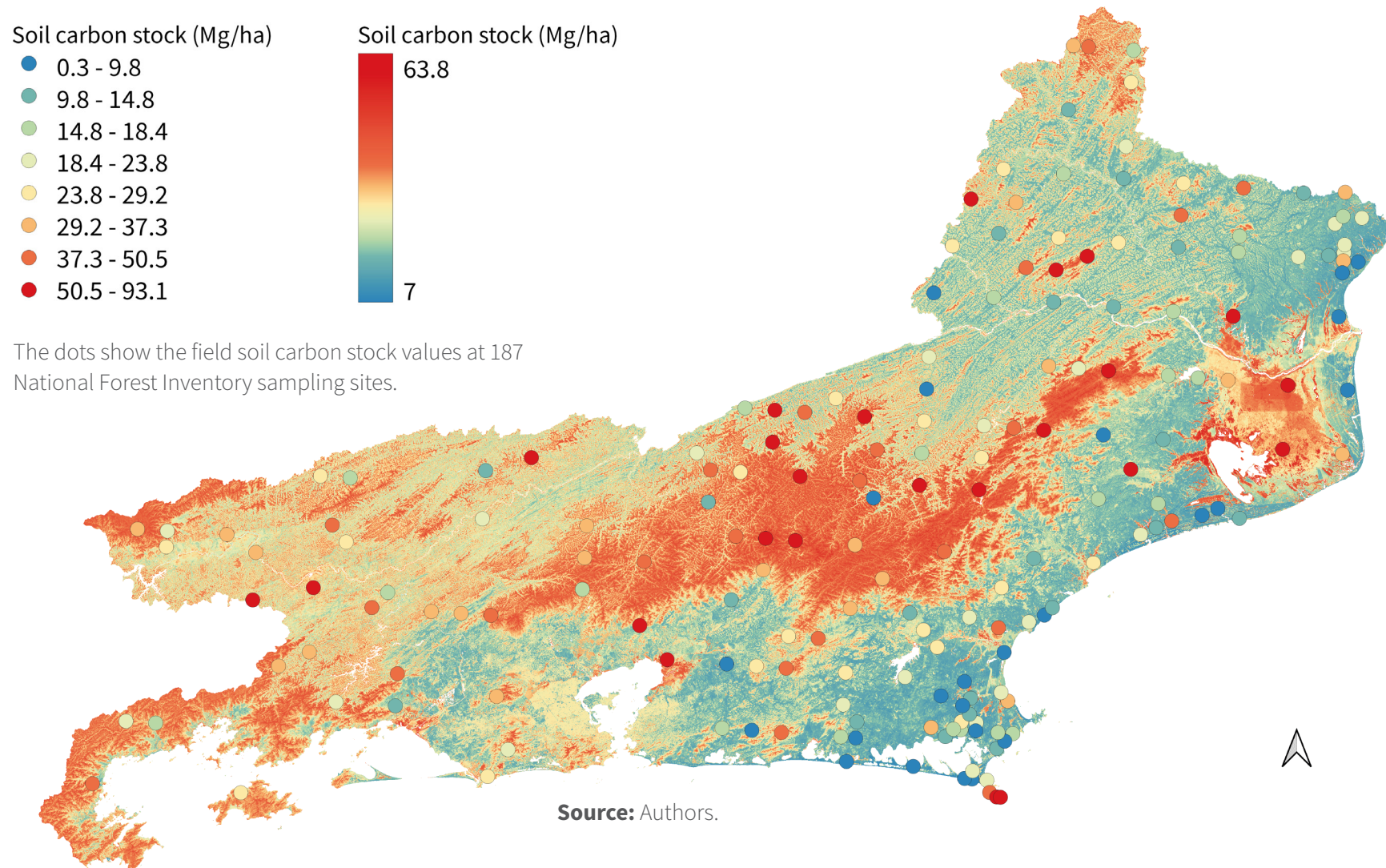


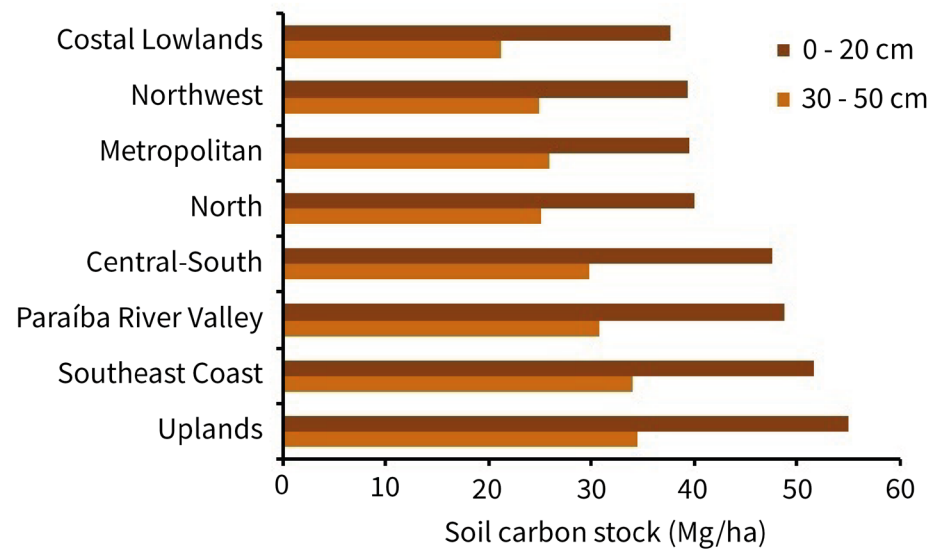
FIGURE 2. Soil carbon stock at 30-50 cm in Rio de Janeiro state, Brazil



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 MapBiomass, 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.

REFERENCES

CARVALHO FILHO, A.; LUMBERAS, J. F.; WITTERN, K. P.; LEMOS, A. L.; SANTOS, R. D.; CALDERANO FILHO, B.; CALDERANO, S. B.; OLIVEIRA, R. P.; AGLIO, M. L. D.; SOUZA, J. S.; CHAFFIN, C. E. Mapa de reconhecimento de baixa intensidade dos solos do estado do Rio de Janeiro (RJ) [CNPS]. *In*: GEOINFO. Brasília, DF: EMBRAPA, 2003. Available at: <https://geoinfo.dados.embrapa.br/catalogue/#/dataset/1680>. Accessed: 01 set. 2025.

CONRAD, O.; BECHTEL, B.; BOCK, M.; DIETRICH, H.; FISCHER, E.; GERLITZ, L.; WEHBERG, J.; WICHMANN, V.; BÖHNER, J. System for automated geoscientific analyses (SAGA) v. 2.1.4. **Geoscientific model development**, v. 8, n. 7, p. 1991-2007, 2015. DOI: <https://doi.org/10.5194/gmd-8-1991-2015>. Available at: <https://gmd.copernicus.org/articles/8/1991/2015/>. Accessed: 01 set. 2025.

GEOLOGICAL SURVEY (Estados Unidos). USGS EROS Archive - Landsat Archives - Landsat 8-9 OLI/TIRS Collection 2 Level-2 Science Products. *In*: USGS SCIENCE FOR A CHANGING WORLD. U. S. Geological Survey. [Washington, D. C.: United States Geological Survey], 2020. DOI: <https://doi.org/10.5066/P9O-GBGM6>. Available at: <https://www.usgs.gov/centers/eros/science/usgs-eros-archive-landsat-archives-landsat-8-9-olitirs-collection-2-level-2>. Accessed: 01 set. 2025.

HEILBRON, M.; EIRADO, L. G.; ALMEIDA, J. Mapa geológico e de recursos minerais do estado do Rio de Janeiro. *In*: RIGEO. Repositório Institucional de Geociências. Rio de Janeiro: CPRM, 2016. Available at: <https://rigeo.sgb.gov.br/handle/doc/18458>. Accessed: 01 set. 2025.

HUTCHINSON, M. F. **Anudem version 5.3**: user guide. Canberra: Australian National University, 2011. Available at: https://fennerschool.anu.edu.au/files/usedem53_pdf_16552.pdf. Accessed: 01 set. 2025.

INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA. **Base cartográfica contínua do estado do Rio de Janeiro, escala 1:25.000, versão 2018, na ET-EDGV 3.0**: nota técnica 01/2023. [Rio de Janeiro]: IBGE, 2023. Available at: https://geoftp.ibge.gov.br/cartas_e_mapas/bases_cartograficas_continuas/bc25/rj/versao2018_edgv_3.0/informacoes_tecnicas/NT01_2023_BC_RJ_20230623.pdf. Accessed: 01 set. 2025.

INSTITUTO NACIONAL DE METEOROLOGIA (Brasil). **Normais climatológicas do Brasil**: Período: 1981-2010. Brasília, DF: INMET, 2025. Available at: <https://portal.inmet.gov.br/normais>. Accessed: 01 set. 2025.

MAPBIOMAS. **Coleção 7.1 da série anual de mapas de cobertura e uso da terra do Brasil**. [São Paulo, SP]: MapBiomass, 2023. Available at: <https://brasil.mapbiomas.org/colecoes-mapbiomas>. Accessed: 01 set. 2025.

MCBRATNEY, A. B.; SANTOS, M. L. M.; MINASNY, B. On digital soil mapping. **Geoderma**, v. 117, n. 1-2, p. 3-52, 2003. DOI: [https://doi.org/10.1016/S0016-7061\(03\)00223-4](https://doi.org/10.1016/S0016-7061(03)00223-4). Available at: <https://www.sciencedirect.com/science/article/abs/pii/S0016706103002234>. Accessed: 01 set. 2025.

MEINSHAUSEN, N. Quantile regression forests. **Journal of Machine Learning Research**, v. 7, n. 35, p. 983-999, 2006. Available at: <https://jmlr.org/papers/v7/meinshausen06a.html>. Accessed: 01 set. 2025.

MEINSHAUSEN, N. QuantregForest: quantile regression forests. Versão 1.3-7.1. *In*: THE COMPREHENSIVE R ARCHIVE NETWORK. [Viena, Áustria]: CRAN, 2017. Available at: <https://CRAN.R-project.org/package=quantregForest>. Accessed: 01 set. 2025.

THE COMPREHENSIVE R ARCHIVE NETWORK. The R Project for Statistical Computing. *In*: THE COMPREHENSIVE R ARCHIVE NETWORK. [Viena, Áustria]: CRAN, [2024]. Available at: <https://www.R-project.org>. Accessed: 01 set. 2025.

SERVIÇO FLORESTAL BRASILEIRO. **Inventário Florestal Nacional**: Rio de Janeiro: principais resultados. Brasília, DF: MMA, 2018. Available at: <https://www.gov.br/florestal/pt-br/centrais-de-conteudo/publicacoes/relatorios/relatorios-ifn/IFNRJprincipaisresultados.pdf>. Accessed: 01 set. 2025.

AUTHORS BIOGRAPHIES

Gustavo de Mattos Vasques

Is a Forestry Engineer from the Federal University of Viçosa (UFV) and holds a Ph.D. in Soil Science from the University of Florida (UF). He has expertise in data science, geophysics, and geotechnologies applied to soil science. Gustavo has been a researcher at Embrapa Soils since 2011. (gustavo.vasques@embrapa.br).

Fabiano de Carvalho Balieiro

Is an Agronomist, with a Master's in Soil and Plant Nutrition from the Federal University of Viçosa (UFV) and a Ph.D. in Soil Science from the Federal Rural University of Rio de Janeiro (UFRRJ). He has been a

Researcher at Embrapa Soils since 2007 and a permanent professor in the Graduate Program in Environmental and Forest Sciences at UFRRJ since 2019. His research focuses on nutrient cycling and organic matter dynamics in natural and planted forests, as well as other agroecosystems. (fabiano.balieiro@embrapa.br).

Telmo Borges Silveira Filho

Is a Forestry Engineer, with a Master's and a Ph.D. in Environmental and Forest Sciences from the Federal Rural University of Rio de Janeiro (UFRRJ). He has experience in forest management and has served as a public servant since 2006. Telmo is the Superintendent of Climate Change and Forests at the Subsecretariat of Climate Change and Biodiversity Conservation of the State Secretariat for Environment and Sustainability of Rio de Janeiro (SEAS). (telmoborges.florestal@gmail.com).

Monise Aguillar Faria Magalhães

Is a Forestry Engineer with a Master's in Environmental and Forest Sciences from the Federal Rural University of Rio de Janeiro (UFRRJ), specializing in conservation units. She has experience in environmental and forest project management and public policies, with over 15 years of professional experience. She currently works for the Superintendent of Climate Change and Forests at the Subsecretariat of Climate Change and Biodiversity Conservation of the State Secretariat for Environment and Sustainability of Rio de Janeiro (SEAS). (monise.seas@gmail.com).

Ricardo de Oliveira Dart

Is a Geographer from the Pontifical Catholic University of Rio de Janeiro (PUC/RJ) and holds a Master's in Geography from the Federal University of Rio de Janeiro (UFRJ). He has experience in geoprocessing and has worked as an Analyst at Embrapa Soils since 2009. (ricardo.dart@embrapa.br).

Adinan Marzulo Maia Martins

Holds a Bachelor's degree in Mathematical and Earth Sciences from the Federal University of Rio de Janeiro (UFRJ), holds a Master's degree in Geography, and is a Ph.D. candidate in Geography at the same institution. He has experience in geoprocessing and remote sensing and has been a researcher and collaborator at Embrapa Soils/FAPED projects since 2023. (adinanmaia@gmail.com).

Bárbara Coelho de Andrade

Is a Geologist from the Federal Rural University of Rio de Janeiro (UFRRJ) and a Master's student in Environmental and Forest Sciences at the same institution. She has experience in geoprocessing, analysis, and interpretation of environmental data. (barbaraumcoelho@gmail.com).

João Pedro das Neves Cardoso Pedreira

Holds a Bachelor's degree in Mathematical and Earth Sciences from the Federal University of Rio de Janeiro (UFRJ) and is pursuing a Master's in Geography at the State University of Rio de Janeiro (UERJ). He has experience in geoprocessing and environmental indicator production. He has been a collaborating researcher at Embrapa Soils/FINEP since 2023. (neves.jope@gmail.com).

Rachel Bardy Prado

Holds a Ph.D. in Environmental Engineering Sciences and has been a researcher at Embrapa for 22 years. She has experience in national and international projects, focusing on rural landscape sustainability, watershed management, ecosystem services, and related policies. (rachel.prado@embrapa.br).

**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**

