Soil, Lithology and Land Use and Land Cover Associations in Rio de Janeiro State, Brazil

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Abstract. *Soil formation and change is controlled by the parent material and land use/land cover dynamics, among other factors. The objective is to identify the main soil-lithology and soil-land use/land cover (LULC) associations in Rio de Janeiro state, Brazil, by preparing raster layers and combining them using map algebra. The primary soil classes include Argisols, Oxisols and Cambisols, occurring across many lithology and LULC classes, followed by Gleisols and Spodosols associated with sandy lithology in the coastal plain. The predominant soil-LULC associations include Argisols and Oxisols on pasture, forest, and agriculture. Soil-lithology and soil-LULC associations in Rio de Janeiro support soil mapping, land conservation and policy making.*

1. Introduction

In the domain of environmental and soil sciences, the importance of an approach centered on soil as an integral part of an ecosystem has been emphasized. Therefore, the transformations that occur in the soil, whether derived from natural- (e.g., geological) or anthropogenic-related processes (e.g., land use/land cover), directly influence ecosystem dynamics and the quality of life on Earth (Grunwald, 2009).

In this context, scientists have developed various methods to map, analyze, and understand the dynamics involved in soil formation and its relationship with landscape transformation, recognizing the influence of these relationships for soil mapping and land use management (Scull et al., 2003; Grunwald, 2009). In recent decades, geotechnologies have facilitated the digital mapping of soils through the use of software that processes environmental data, such as soil data and its covariates in Geographic Information Systems (McBratney et al., 2003).

Grunwald (2009) draws attention to the need to establish appropriate spatial and temporal scales to enhance the applications of digital soil mapping, such as the development of predictive models for soil attribute dynamics. Furthermore, the use of different historical databases should be approached with caution, as they are subject to georeferencing errors and incompatibilities that can lead to inconsistencies and uncertainties in data interpretation. Thus, it is critical to evaluate the relationships among soil and soil-forming factors (i.e., environmental covariates) at regional scales as a first step towards using open-access online databases of legacy soil and environmental data for soil mapping.

2. Objective

The goal is to identify the main soil-lithology and soil-land use/land cover (LULC) associations in Rio de Janeiro state, Brazil, by map algebra of their raster layers. A methodology to prepare and associate soil, lithology and LULC layers is presented.

3. Materials and Methods

3.1. Study area

The Rio de Janeiro state (Figure 1) covers an area of ~43,767 km² and is part of the Southeast region of Brazil, bordered to the south and east by the Atlantic Ocean, to the north, northeast and west by the states of Minas Gerais, Espírito Santo and São Paulo, respectively.

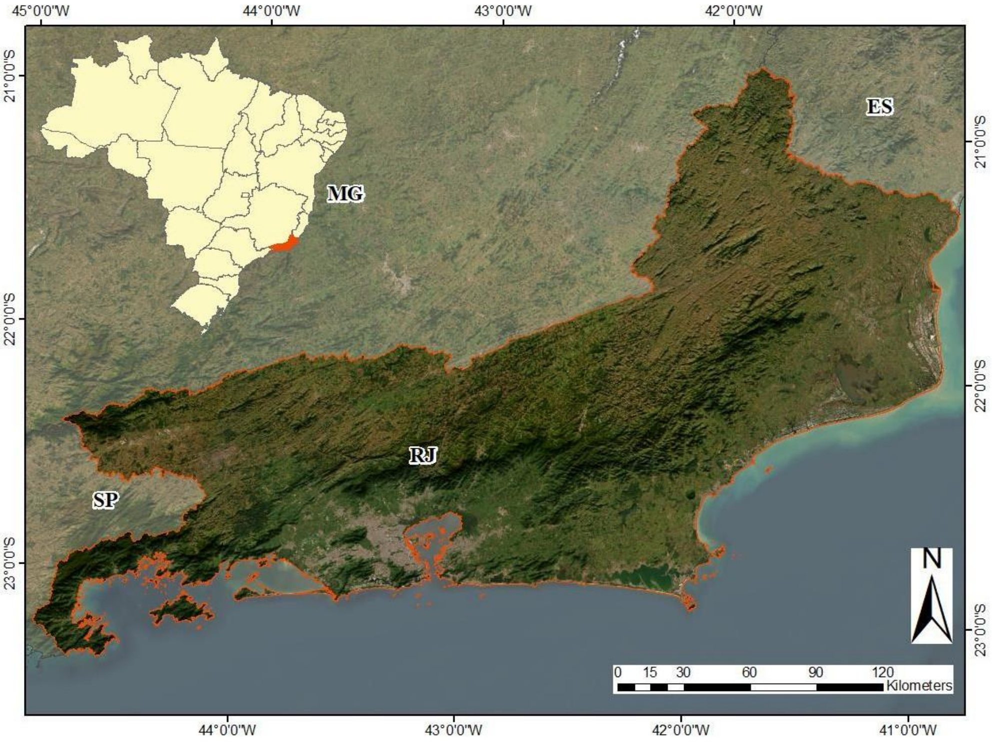

Figure 1. Location of the study area (Rio de Janeiro state, Brazil).

The relief of the state consists of mountainous areas and lowlands. The mountainous region comprises the extensive *Serra do Mar* Mountain range, stretching from the coast in the Parati municipality, where it is known as *Serra da Bocaina*, central part of the state in the municipalities of Petrópolis, Teresópolis and Nova Friburgo, where it is named *Serra dos Órgãos* region (Fundação Ceperj, 2010).

The Rio de Janeiro lowlands comprises depressions and plains (IBGE, 2009), including the *Paraíba do Sul* river depression to the north, the *Guanabara* and *Sepetiba* depressions to the south, and the coastal plain, which is more extensive in the northeastern coastal areas of the state.

According to INEA Land Use and Land Cover mapping (2018), fields and/or pastures are widely distributed throughout the state, occupying more than 50% of the territory. Forest formations in various vegetative stages cover around 30% of the state, corresponding mainly to the *Serra do Mar* region, with the largest fragments in protected areas. Agriculture occupies around 7% of the state and urban areas about 6%. Rocky outcrops cover only around 0.5% of the territory, while mangrove areas, sandy ridges and restinga occupy 0.4%, 1.3% and 0.9% respectively.

Based on past studies and mappings, Heilbron et al (2016) proposed the mapping of the Geology and Mineral Resources of the State of Rio de Janeiro. According to the authors, the state's territory is located over a crystalline basement, that belongs to an orogenic belt which extends for approximately 1400 km along the S-SE coast of Brazil, called Ribeira Belt. The basement rocks have been deformed in the Neoproterozoic, during diachronic processes of subduction and continental collision in the Brasilian-Pan African Cycle, and exhibits complex deformation processes. These units cover about 20% of the state, being characterized, by granitic and basic ortho derivative metamorphic rocks, with alkaline tendency (Heilbron et al. 2016).

Neoproterozoic metasedimentary and metavolcanosedimentary sequences of high metamorphic degree occur interspersed with the basement and occupy around 40% of the territory. They are mostly paraderivative gneisses, rich in mica and other aluminous minerals, interspersed with quartz-rich rocks, calcisilicate, carbonate and amphibolite. Heilbron et al (2016) also highlight the presence of intense magmatism associated with the various phases of the amalgamation of the continents. These are mainly granite and granitoid massifs (deformed or not) that stand out in the landscape, such *as Serra dos Órgãos, Maciço de Itatiaia* and *Morro do Pão-de-Açucar*.

During the Mesozoic and Cenozoic, the Ribeira Belt was affected by the rifting process in the separation of the Gondwana continent and the formation of the Atlantic Ocean. This process was called by Almeida (1976) as the Southeast Brazilian Rift System, where there are records of periods of tranquility and stability, favoring sedimentation and periods of intense magmatic activity and reactivation of Brazilian structures, marked by the presence of mafic alkaline dikes or plutonic intrusions of felsic alkaline magma, the uplift of *Serra do Mar* and the and formation of inland and coastal basins in tilted structures in a hemi-graben system (Heilbron, et al. 2016).

Cenozoic (Tertiary and Quaternary) sedimentary coverings, notably occur in the northeastern part of the state, in the region of the *Paraíba do Sul* river delta, where sediments are reworked by the sea. Tertiary basins and Quaternary deposits also occur, represented by river plains and sandy ridges in the metropolitan region, and small inland Tertiary basins with Quaternary deposits along rivers, all associated with the formation of the Southeast Brazilian Rift System duringthe Mesozoic (Carvalho Filho et al., 2003).

3.2. Preparation of soil, lithology and land use/land cover layers

The spatial layers used in this research were: soil, lithology and LULC. The software used was ArcMap v. 10.7.1 (ESRI, Redlands, USA). In order to adjust the spatial reference of the dataset, all maps were reprojected to Lambert Conical and Conformal projection system. With the state of Rio de Janeiro divided into two distinct UTM zones (zone 23S and 24S), due to its east-west extension, the use of Lambert Conical projection system is necessary, aiming to reduce the level of deformation in the studied area, as highlighted in the IBGE cartographic manual (1999).

The soil layer used was produced by Embrapa Solos at the 1:250.000 scale (Carvalho Filho et al., 2017), and was downloaded in shapefile format from <https://geoinfo.cnps.embrapa.br/layers/geonode%3Asolos_rj_lat_long_wgs84_1>. The soil layer was dissolved by the soil order (Santos et al., 2018) of the first component of the mapping unit in the legend, resulting in 17 categories, where 10 categories represent soils orders and the other 7 categories represent other non-soil features.

The lithology layer was obtained from the Geological and Mineral Resources Map of Rio de Janeiro State at the 1:400.000 scale (Heilbron et al., 2016), produced by the Brazilian Geological Survey, and was downloaded in shapefile format from <https://rigeo.sgb.gov.br/handle/doc/18458>. A "lithotype" field was created in the lithology layer attribute table to group lithology types by their similarities as related to soil formation (e.g., sandy *vs.* clayey lithology) (Andrade et al., 2023, in these Proceedings). Then, the lithology layer was dissolved by the lithotype field, resulting in 9 lithology categories.

The soil and lithology maps were produced at very different scales, which directly affects the amount of information generated combining them. As de Menezes and Neto (1999) highlight, generalization processes can cause a significant change in analysis, which may result in loss or gain of information. In order to approximate the level of detail of the two maps, only the first categorical level of soil classification was used, as a way of generalizing the mapped information, reducing its scale and making it more compatible with the lithological classification.

The soil and lithology shapefiles were clipped to the Rio de Janeiro state boundaries and converted to raster format, with an output cell size of 30 m. To reduce errors and inconsistencies generated in the combination of soil with lithology and LULC layers, the classes that represent water bodies, rocky outcrops and "other"-type categories were removed from all layers by using a conditional statement in the *Map Algebra* tool of the *Spatial Analyst* extension.

The LULC map was obtained from the MapBiomas project (MapBiomas, 2016), following the instructions at item 5 of the "MapBiomas Collections" page <https://brasil.mapbiomas.org/colecoes-mapbiomas>, using a Toolkit on the Google Earth Engine plataform. The map was downloaded in raster format, with 30 m of pixel resolution. The 22 classes were merged into 12 classes, based on similarities of the environment, such as wetlands, environments with sandy soils, agricultural areas and built-up and barren areas (Andrade et al., 2023, in these Proceedings).

3.3. Combination of soil with lithology and LULC layers

In a raster layer, the "Value" field presents the value of the pixel. In this study, each pixel value represents a specific category in the soil, lithology or LULC raster layers, respectively. The "Count" field shows the number of pixels that belong to each pixel value; therefore, the sum of the Count field corresponds to the number of pixels of the raster.

The soil raster was combined with the lithology and LULC rasters, respectively, by weighted sum. The weights are multiplication factors that are defined to avoid overlapping of category combinations. As such, the first raster was multiplied by a factor of 10, one order higher than the order of the categories of the second raster. Given the value ranges of the soil, lithology and LULC rasters, a multiplication factor of 100 was used for the first raster to derive soil-lithology and soil-LULC combined rasters (Equations 1 and 2, respectively). In the resulting rasters, in the pixel values the hundreds represent the lithology and LULC categories, respectively, and the units represent the soil categories. For instance, a pixel value of 302 means that the lithology (or LULC) class in the pixel is 3 and the soil class is 2.

$$soil\_lithology = 100 \times lithology + soil \tag{1}$$

$$soil\_LULC = 100 \times LULC + soil \tag{2}$$

4. Results and Discussion

4.1. Soil and lithology associations

The most common soil-lithology associations in the state, covering about 77% of the territory, are shown in Figure 2. Argisols are present in the majority of soil-lithology combinations, covering ~35% of the state, and coincide with all types of parent materials. Although Argisols are mainly associated with Quartzofeldspathic rocks (~18%), most Mafic and ultramafic rocks (~6%) and Carbonate and silicate rocks ~5% are associated with Argisols.

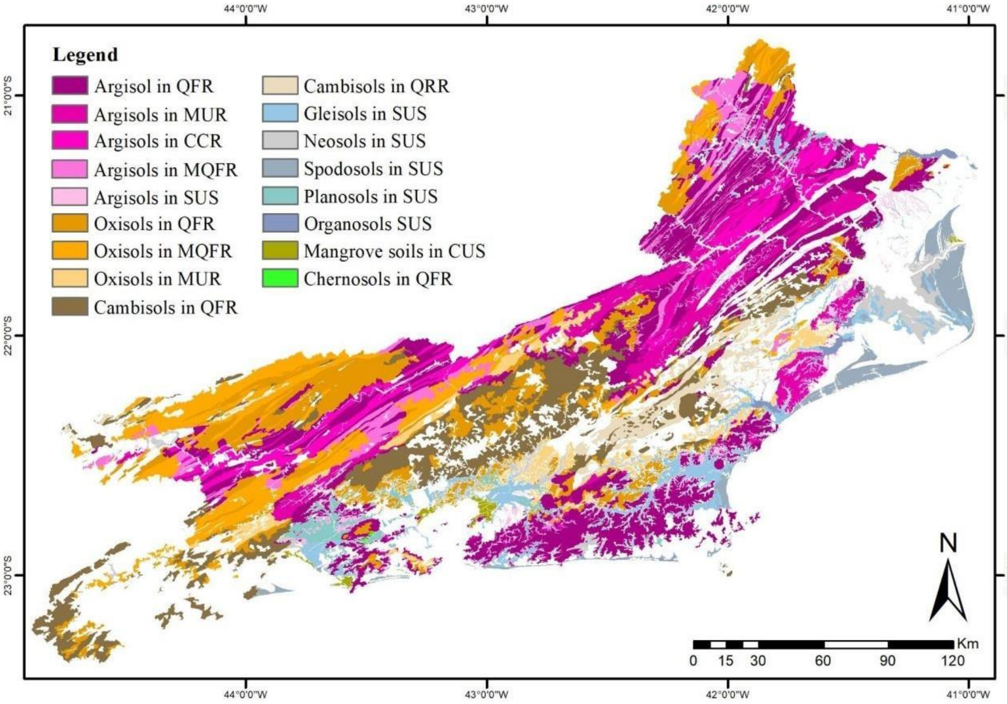

Figure 2. Most common soil and lithology associations in Rio de Janeiro state, Brazil. QFR, Quartzofeldspathic rocks; MUR, Mafic and ultramafic rocks; CCR, Carbonate and calcisilicate rocks; MQFR, Micaceous quartzofeldspathic rocks; SUS, Sandy unconsolidated sediments; QRR, Quartz-rich rocks; CUS, Clayey unconsolidated sediments.

Second in the occurrence area, Oxisols occupy ~21% of state mostly in the central to west and southwest regions (Figure 2), with more than half of the Oxisols associated with Quartzofeldspathic rocks (~11%), followed by Quartzofeldspathic micaceous rocks (~7%) and Mafic and ultramafic rocks (~3%).

Cambisols have the third largest area (~12% of the state) and are located in the central part of the state (Figure 2). They are associated with Quartzofeldspathic rocks (~10% of the state) and Quartz-rich rocks (~2%). Gleisols, Neosols, Spodosols, Planosols and Organosols make up for 11% of the state and are mostly associated with Sandy unconsolidated sediments in the state lowlands and coastal plains. Mangrove soils (0.3% of the state) are associated with Clayey unconsolidated sediments

4.2. Soil and land use/land cover associations

The predominant soil-LULC combinations, covering about 80% of the state, are shown in Figure 3. Soil combinations with Pasture, Forest and Mosaic of pasture and agriculture take up most of the state, followed by Agriculture, Beach, dune and sandbank, and Wetlands and mangrove.

About 55% of the state is occupied by Pasture, and Mosaic of pasture and agriculture. The soils that occur in these LULC classes include Argisols (30% of the state), Oxisols (~16%) and Cambisols or Gleisols (~9%). Native Atlantic Forest (i.e., the “Forest” LULC category) covers about 27% of the state, and is mainly associated with Cambisols (~11%), Oxisols (~9%) and Argisols (~7%).

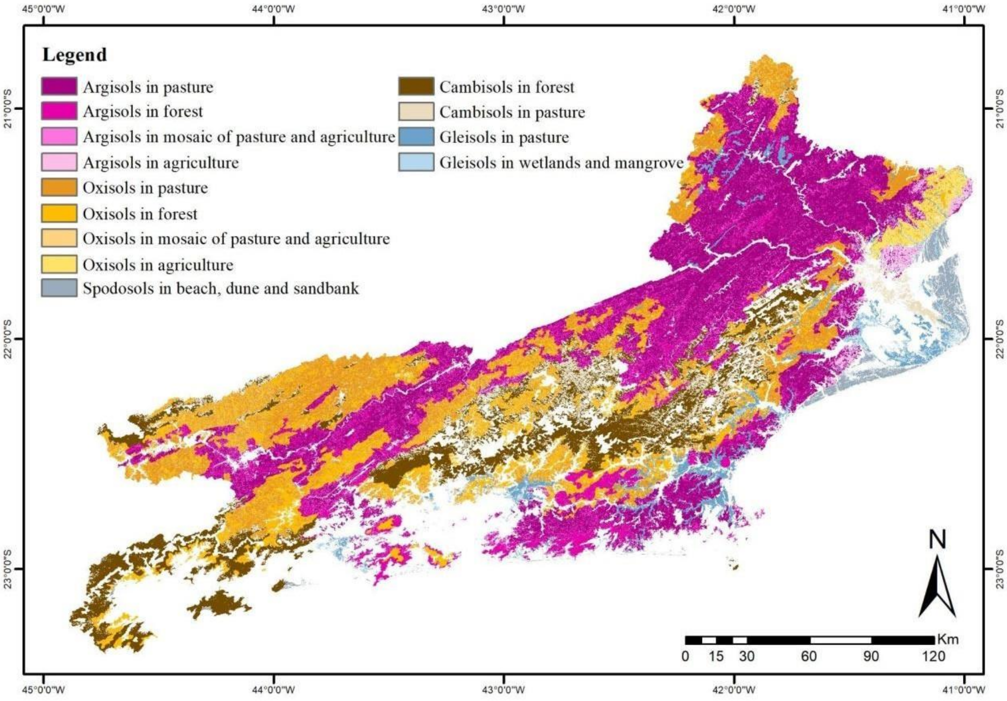

Figure 3. Most common soil and land use/land cover associations in Rio de Janeiro state, Brazil.

Argisols and Oxisols are primarily located in the depressions of the *Paraíba do Sul* River, and *Guanabara* and *Sepetiba* lowlands, and are likely derived from the weathering of the abundant granitic/tonalitic rocks in the state, resulting in acidic, clayey soils with low natural fertility. They are the most widely used soils for pasture and agriculture in the state, and thus, require an adequate management including liming and fertilization to increase their natural pH and improve their natural fertility, as well as conservation measures to avoid erosion, especially in Argisols that are more prone to erosion.

On the other hand, Cambisols are more associated with higher-altitude regions with steeper slopes, where Forest and Pasture LULC, and Quartz-feldspathic rocks lithology prevail. Gleisols and Spodosols derive mainly from Sandy unconsolidated sediments located in the state lowlands and coastal plains. Gleisols are commonly found under Pasture and Wetlands and mangrove LULC, which makes sense, since, by definition, Gleisols are formed in areas that are regularly flooded. Accordingly, Spodosols are soils with sandy texture along the vertical profile that have organic matter and/or iron accumulated in deeper soil layers. Beach, dune and sandbank areas, with which Spodosols are associated, are the ideal environments for their formation. Neosols, Planosols, Organosols, and Chernosols did not exhibit any striking combinations with either lithology or LULC as they occur in small areas in the state.

Soils under Agriculture include mostly Oxisols and Argisols, and account for ~3% of the state. They are concentrated in the northern portion of the state, in the Campos dos Goytacazes and São Francisco do Itabapoana municipalities. Although most agricultural activities occur on Oxisols and Argisols, they also occur on other less representative soil classes; however, some soils classes are less suitable for agriculture due to restricted drainage conditions and high susceptibility to loss of nutrients and biodiversity, as is the case of Gleisols, Organosols, Mangrove Soils and Spodosols.

5. Conclusions

The soil-lithology associations indicate from which parent materials the soils were formed, assisting in the definition of procedures that use lithology information to infer on soil classes, and vice-versa. For instance, lithology layers are commonly used as covariates to predict the occurrence of soil types and to map soil properties by digital soil mapping. Moreover, the soil-lithology associations provide insights on soil and environmental fragility, sustainability, and diversity, e.g. by highlighting simultaneously areas with rare soils and rare geology that deserve tailored preservation and conservation measures and policy.

Along the same lines, soil-LULC associations indicate which land uses are adopted on which soil types. They can be used to guide decisions on soil conservation and management at the local scale, since different soil types require different management strategies depending on the land use; and on land use planning, biodiversity protection, and urban and rural development at the regional scale, by matching soil types and land uses according to their mutual suitability minimizing environmental, social and economic impacts and improving the soil and land quality and sustainability.

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