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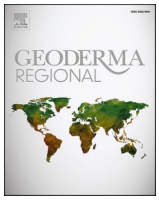

# The Brazilian soil priorities

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## 1. Introduction

Brazil has continental dimension (about 8.5 million km$^2$ area) and includes several biomes (Amazônia, Caatinga, Cerrado, Mata Atlântica, Pampa, and Pantanal) – Fig. 1. To understand the many environments soil surveys started around 1940 and the first soil map of São Paulo State was published in 1943. In 1953, the National Soil Survey Program was approved and in 1958, the first soil survey for the state of Rio de Janeiro was published, followed by the state of São Paulo in 1960 (Anjos et al., 2014). Today, the country plays an important role in global agriculture and its large forest areas are known for influencing global water and climate cycles. Since the Brazilian economy is strongly linked to and dependent on agriculture, environmental resources play an important role in maintaining livelihoods and food security. To support the agronomic knowledge, there are currently 431 undergraduate courses in Agronomy and 76 in Forestry (Fig. 1) in the country, as well as 28 graduate programs in Soil Science.

## 2. Soil types

The diversity of Brazilian soils is proportional to its size, extending for about 4000 km in both N-S and W-E directions, and its different climate regimes contributing to the occurrence of many soil classes. Figure 1 shows that the main soil types (IUSS Working Group WRB, 2015; Santos et al., 2018) in Brazil are Latossolos (Ferralsols), Argissolos (Lixisols and Alisols), Neossolos (Leptosols, Fluvisols, Arenosols and Regosols), Plintossolos (Plinthosols) and Cambissolos (Cambisols). The first two soil types are the most used for agriculture and differ in texture

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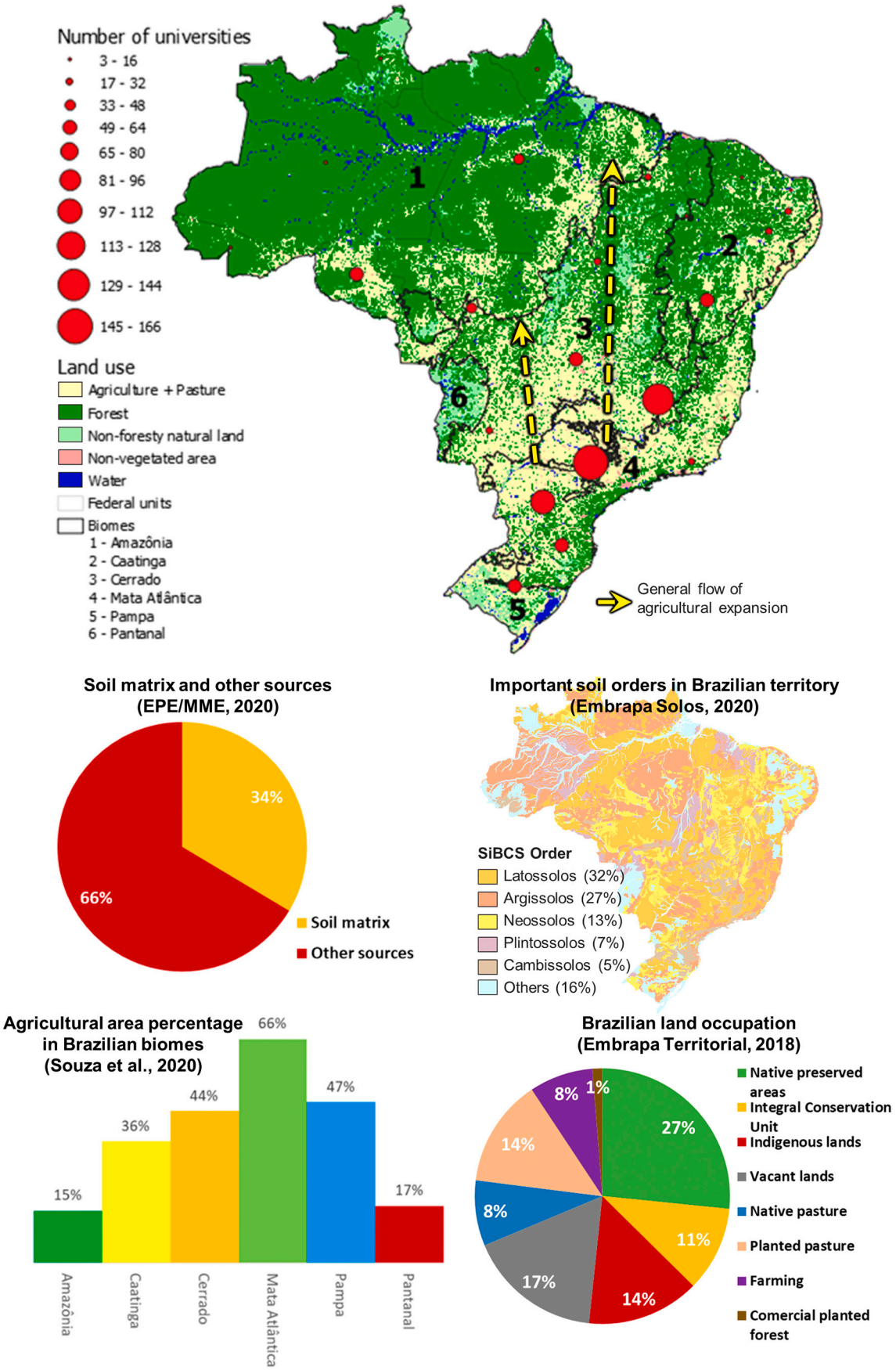


**Fig. 1.** Overview of the Brazilian soil resources and academic institutions. Adapted from Embrapa Solo (2020), EPE/MME - Empresa de Pesquisa Energética/ Ministério de Minas e Energia (2021), Souza Jr. et al. (2020) and Embrapa Territorial (2018).

of surface layer and fertility, usually having low pH, are nutrient-poor, deep and well to moderately drained, and occur in different landforms. Each region of the country has site-specific soil dynamics that scientists need to understand and register through soil survey. This gigantic variety of combinations of soil forming factors requires extensive field work to model adequately the Brazilian pedoenvironments. Despite the low amount of Histosols and Gleisols, they have a strong impact on several biomes and the environment.

## 3. Mapping and archiving soils

From 1970 to 1986, the RADAMBRASIL Project (IBGE, 2018) executed surveys of soils, geology, climate, vegetation, geomorphology, soil suitability, and other factors in the entire territory. Despite this, the country has currently mainly medium and small-scale soil surveys (1:250,000 to 1:1000, 000) and only a few detailed ones (0.25% of them), produced in the 1970s (Mendonça-Santos and Santos, 2006). Brazil is recognized for its advances in soils and agricultural management systems, but it is still lacking information on soil properties and distribution at a detailed level. To reach this we need to understand soil-landscape relationships in each biome incorporating solid multidisciplinary training (e.g., digital soil mapping and pedometrics) for soil scientists and pedologists. Publicly available national soil profile databases have georeferenced data from nearly 15,000 sites (Cooper and Sparovek, 2005; Samuel-Rosa et al., 2020) that will be augmented and incorporated by the recently launched Brazilian Soil Survey Program – PronaSolos (Polidoro et al., 2016). Other databases, as the Brazilian Soil Spectral Library has data from 45,000 sites (Demattê et al., 2019). Initiatives on geotechnologies to accelerate this process have been developed, including the Brazilian Soil Spectral Service (BraSpecS) that provides a free online soil attributes prediction service (Demattê et al., 2022).

## 4. The complex relationship between food security and environmental quality

Brazil is among the top five food producers in the world, despite 51% of its territory being covered with native, protected vegetation (Fig. 1). Currently, Brazilian agriculture uses 8% of the lands for crops, and there is still a possibility of using another 13% of arable land in vacant regions. Besides, 14% of the Brazilian territory is used for pasture. We need to know what are the types of soils in each biome and ecosystem to perform adequate land and environmental planning.

Despite that, cultivated soils show a great loss of biodiversity, mainly caused by intensive and indiscriminate deforestation and due to degradation of lands by water erosion. The Mata Atlântica biome has been negatively impacted since the first settlers, followed by the Cerrado (Brazilian neo savanna, Fig. 1), and Amazon Forest since the 20th century. To better use and preserve these environments, it is necessary to know and understand their pedodiversity and its values (Botelho and Brilha, 2022) also through an integrated approach (Paula Silva et al., 2021; Garcia et al., 2022).

Nearly 60% of the entire Amazonian biome is located in Brazil, having 25,000 km of navigable rivers and accounting for 67% of the world's tropical forests. These areas are systematically deforested and illegally exploited under the pressure of countless factors, from inappropriate actions by farmers to political intervention in expansion programs. This brings soil degradation, with loss of physical, chemical and biological quality and reduction of soil functions and services to the ecosystems. It is necessary to maintain and secure livelihoods and protect the environment.

The Cerrado biome occupies 23,3% of Brazil's land area (about 2 million $km^2$) and has been under agricultural use since the 1980s. The rise of agriculture in these areas was one of the greatest achievements of Brazilian agronomy science in the 20th century, as the crops are produced on highly weathered soils, with low natural fertility, initially used for extensive beef cattle ranching on unimproved pastures (Lopes and Guimarães, 2016). Currently, the rapid loss of native vegetation combined with intense monocultures without conservation agriculture practices, and the low coverage of the precision agriculture network makes the Cerrado one of the world's most threatened biomes (Strassburg et al., 2017).

The Caatinga in northeastern is a semiarid biome, unique to Brazil, with less developed and shalow soils and low vegetation coverage due to the climate conditions of hydric stress, making these areas vulnerable to desertification. The Pantanal is the largest tropical wetland and one of the most pristine and threatened biome by wildfires in the world. Pantanal soils are dominantly hydromorphic with a great chemical, physical, and mineralogical variability. The soils are, in the majority, originated from sediments and located in a flat relief, a characteristic that leads to seasonal floods. In the Pampa biome, in southern Brazil, the herbaceous native vegetation that was once dominated by natural grasslands, with the advent of agriculture commodities, has been substituted by annual crops, mainly soybeans. This change in land use still lacks environmental impact studies.

## 5. Soil management and conservation

Although Brazilian farmers are reaching yearly higher crop productivities, researchers still do not know what would be the possible maximum productivity to achieve. This situation makes farmers invest heavily in fertilizers, while the real issue could be of a different nature, as on soil dynamic solutions and soil conservation practices. Considering current knowledge, it is hard to say if the best sustainable management is adopted. This creates pressure to expand agriculture to new lands instead of increasing productivity on the areas already in use.

From the north to the south of Brazil, annual crops are growing, largely in a no-till system. Traditional crops, such as sugarcane has been grown for centuries, often on the same soils; while it can supply food and energy needs, depending on crop and harvesting management, it is a good form of soil carbon sequestration. Livestock production, largely extensive, occupies a large area in Brazil from north to south regions. Brazil has one of the largest livestock populations in the world, although some of the pastures and soils are degraded. The historical use of Brazilian pastures demands a global model to study the evolution of grazed tropical and subtropical soils and the good and bad consequences of pastures management on the properties of highly weathered soils. The territorial extent of the country, the extent of protected areas and the diversity of land uses all play an important role in environmental balances.

Southern Brazil has a subtropical climate with relatively more carbon-rich soils than other regions and is an important producer of meat, soybean, rice, and wine. The state of Parana is nearly twice the size of Portugal and produces several crops (rice, sugarcane, soybeans, corn, cotton). In the Southeast, the state of São Paulo was a pioneer in the world, starting a project called Pro-Alcohol in 1978, using sugarcane as biofuel. Since then, the system has evolved, making Brazil the first country where almost 90% of the automobiles are adapted to run on this fuel. Today, 37% of Brazil's energy matrix comes from crops produced in the soil (Fig. 1).

As agriculture progressed, the acreage expanded to other states in the north (Fig. 1). States such as Mato Grosso do Sul, Mato Grosso, and Tocantins are now large producers of soybeans, corn, cotton and sugarcane. Nevertheless, agricultural areas expanded to areas surrounding important biomes. Minas Gerais state also grows many crops, including large areas of coffee plantations. Nowadays, agriculture is expanding even more to other states in the north region (Fig. 1), including lands in the Amazon biome. Although these regions have suitable soils for agriculture, there are also significant sandy or rocky areas that are being over exploited. The Northeast Region has some areas with semi-arid climate, but water reserves in the aquifer allow irrigated agricultural systems making them one of the most important exporters of tropical

fruits in the world.

To achieve the overall hihgly relevant status in the global agriculture production, many strategies have been taken by Brazil. One of them is the use of fertilizers, which ranks fourth in the world with about 45 million tons per year. However, it is estimated that Brazil loses about 20 ton/ha of soil every year which makes a national program on soil conservation urgent. An emerging topic, in soil and environment priorities, is related to mining, where Brazil presents today about 11.500 sites, which relates to environmental risks to soil and the ecosystems where they are located.

## 6. Carbon

Important initiatives have been taken, such as the *Integra* project, which deals with the mitigation of eroded lands, and the *Renovabio*, created in the sugarcane agricultural system, promotes carbon emission credits and soil carbon stock. Brazil has taken several measures to increase soil carbon sequestration and/or reduce greenhouse gas ($CO_2$, $CH_4$, and $N_2O$) emissions to the atmosphere. One of them is the ABC Federal Program (Low C emissions in Agriculture). The program ABC aims to implement sustainable technologies, selected to meet the country's commitments (NDCs) to reduce greenhouse gas emissions in the agricultural sector by implementing or improving the following technologies: i) restoration of degraded pastures; ii) crop-livestock-forest integration and agroforestry systems; iii) no-till; iv) biological nitrogen fixation; v) planted forests; vi) animal waste treatment; and vii) climate change. In order to illustrate the outcome of the program, the no-till soil management system is applied in 26 million ha with a weighted average soil C accumulation rate of 0.5 t C $ha^{-1}$ $yr^{-1}$ in the first 10 cm depth (Cerri et al., 2007). This results in an estimated change in total soil C of about 13 million tons per year. In addition, it should be considered the C offset due to the significant decrease in fuel consumption due to reduced use of tilling operations (60 to 70%), as compared to conventional tillage. Results from the ABC program for 2010–2018 showed that management practices have improved on more than 52 million hectares (e.g., 1.5 times the size of Germany), avoiding emission of about 170 million metric tons of $CO_2$ equivalents (MAPA, 2021).

## 7. Conclusion

The Brazilian agricultural business and industry are committed to continue to increase their participation in the global biomass production. The focus on fertilizers, not considering other soil functions, is changing to a new, more holistic paradigm. Therefore, the productivity of Brazilian agriculture can still be increased by improving and adopting appropriate soil management practices for each biome, and encompassing environment protection. We need to develop integrated management systems for land uses and conservation adapted to the variability of soils. The lack of diffusion of information and detailed soil mapping in the country brings about significant differences in the development of these topics. The complexity of the Brazilian biomes leads to a high level of uncertainty regarding soil response to agricultural interventions, and also impacts on carbon and microbiological soil dynamics. Monitoring impacts and conservation of these biomes is crucial, their soils are rich in ecobiosystems and their degradation will have negative impacts on climate, water and soils, local and globally. Despite the importance of all disciplines, at first, to normalize the issues it is absolutely necessary to have detailed soil survey information to make the best decision on all areas, from management and planning of agriculture to the conservation of ecosystems.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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