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Ecosystem services supply by the soil of forest fragment in a highland humid enclave

Provisão de serviços ecossistêmicos pelo solo de um fragmento florestal do Brejo Paraibano

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ABSTRACT

The encroachment of agricultural activities on the remnants of the Atlantic Forest in the high altitudes of the Brazilian Northeast led to the formation of forest fragments that need to be better understood. To this end, research was conducted in a forest fragment of Mata do Pau-Ferro in a highland humid enclave, locally known as "*Brejo Paraibano*", to characterize the soil through chemical, physical, mineralogical, and geochemical attributes, to evaluate the potential of the soil in the provision of services environment. Ferralsols samples were collected and analyzed in a layer from 0 to 20 cm deep. The results showed that soil properties have a direct influence on the provision of ecosystem services, especially support, regulation, provision, and cultural services. Among the properties, essential nutrient content, carbon stock, minerals that can provide nutrients in the long term, texture, density, and organic matter content stand out, favoring water storage and adequate development of plant species.
KEYWORDS: essential nutrients; climate regulation; territorial planning; carbon stock.

RESUMO

O avanço das atividades agropecuárias sobre os remanescentes de Mata Atlântica de Altitude do Nordeste acarretou na formação de fragmentos de floresta que precisam ser melhor entendidos. Para tanto, a pesquisa foi realizada em um fragmento florestal da Mata do Pau-Ferro no Brejo Paraibano com o objetivo de caracterizar o solo por meio de atributos químicos, físicos, mineralógicos e geoquímicos a fim de avaliar a potencialidade do solo na prestação de serviços ambientais. Foram coletadas amostras de um Latossolo Amarelo Distrófico húmico na camada de 0 a 20 cm de profundidade e carreadas as análises. Os resultados demonstraram que as propriedades do solo influenciam diretamente a oferta de serviços ecossistêmicos especialmente os de suporte, regulação, provisão e culturais. Dentre as propriedades destacam-se os teores de nutrientes essenciais, estoque de carbono, minerais que podem fornecer nutrientes no longo prazo, textura, densidade e teores de matéria orgânica que favorecem armazenamento de água e adequado desenvolvimento de espécies vegetais.
PALAVRAS-CHAVE: nutrientes essenciais; regulação climática; planejamento territorial; estoque de carbono.

INTRODUCTION

The highland humid enclaves of Paraíba, locally known as "*Brejo Paraibano*" (IBGE 2019), are of great ecological and social interest because they are highland Atlantic Forest remnants that are very different from the surrounding Caatinga. The montane forests they host are considered an ecological separation of the Atlantic Forest isolated by the caatinga vegetation, a circumstance that gives these remnants a high biological diversity. They are associated with the occurrence of plateaus and plateaus between 500 and 1.100 m in altitude and are wetter areas than the semiarid region that surrounds them, due to the orographic effect that increases precipitation and reduces temperature, resulting in microclimates that are detached from the context in which they are inserted (MEDEIROS et al. 2017).

In the regional context, these marshes have privileged conditions in terms of soil and air humidity, temperature, and vegetation that cover these conditions. They are considered very favorable for the development of agriculture and livestock, attracting livestock and farmers, making these areas highly threatened by anthropic interventions. For example, the Atlantic Forest of Paraíba has been severely destroyed by agricultural expansion, leaving only small fragments on private lands and some remnants protected by public authorities (BENEVIDES et al. 2019).

This fragmentation leads to the formation of artificial boundaries between forest formation and other land uses. As a result, the fragments are exposed to external influences that alter the flows of energy, matter, and organisms between adjacent environments, affecting the characteristics and properties of the soil.

Soil characterization is fundamental to understanding its functionality and sustainability, as the soil-plant relationship depends on these properties. Nevertheless, it is crucial for environmental diagnosis to evaluate the impacts caused naturally or by human activities, and thus to technically and scientifically guide actions for conservation, protection, and sustainable management, as well as to preserve the environmental services that the forest provides to the population. Soils are often marginalized as mere surfaces, but they provide a wide range of vital ecosystem services (DROBNIK et al. 2018).

The value of ecosystem services provided by soil exceeds the value of other parts of an ecosystem, yet the extent and value of ecosystem services provided by soil remain poorly understood (COMERFORD et al. 2013). Assessing the provision of these services using a set of soil attributes allows the diagnosis of soil strengths and weaknesses at the landscape scale. This information, linked to physiographic and climatic aspects, allows the development of decision-making processes at different levels of management regarding land use and management (JÓNSSON & DAVÍÐSDÓTTIR 2016) and nature conservation that mitigate the causes of environmental degradation, preserve ecological functions (PARRON et al. 2015) and avoid indiscriminate and irrational use of natural resources.

The objective of this research was to carry out the chemical, physical, mineralogical, and geochemical characterization of the surface layer of soil with humus horizon in a fragment of a highland Atlantic Forest remnant, in order to prove its potential suitability for providing ecosystem services.

MATERIAL AND METHODS

The study was carried out in a forest fragment of the Mata do Pau Ferro State Ecological Reserve, in the locality of Chã de Jardim, municipality of Areia, "*Brejo Paraibano*" Geographic Microregion, Brazil (6º57'21"S and 35º45'28"W, 595 m), with an area of about 6.500 m² covered by highland Atlantic Forest remnant (secondary vegetation about 50 years old), a disjunction of Floresta Estacional Semidecidual Montana (IBGE 2019). This phytophysiognomy is characterized as a refuge for species of the northeastern Atlantic Forest within the Caatinga domains but also hosts plants with an Amazonian distribution and some species typical of montane forests in southern and southeastern Brazil (TABARELLI & SANTOS 2004) (Figure 1).

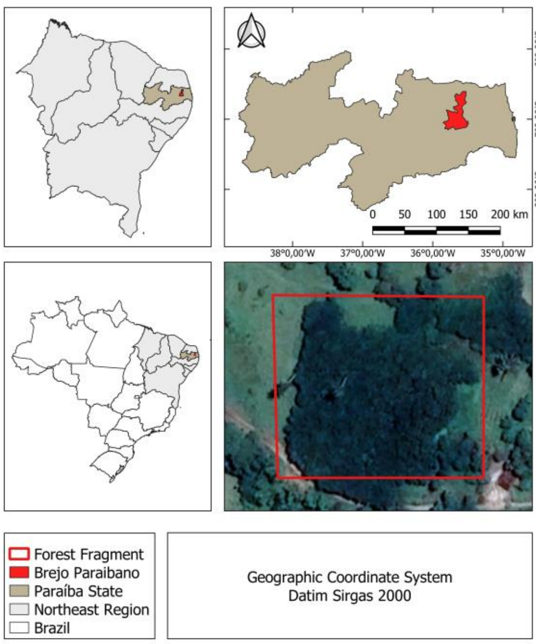


Figure 1. Location of the study area. Mercator projection. Source: The authors.

The climate of the region is classified as As according to Koeppen (ALVARES et al. 2013) and is described as hot and humid tropical. The average annual temperature is 24.0 ºC with highs in January and lows in July. Average annual precipitation is 1.400 mm, with more than 75% of precipitation concentrated in March through August (JACOMINE et al. 1972).

The local relief is flat to gently undulating. The soil in the area is classified as Ferralsol (IUSS WRB 2022). This soil extends over a large area towards the east, forming the so-called Chã de Jardim (HENRIQUES 2012).

Soil collection was carried out in August 2020 according to a completely randomized experimental design. Twenty-five soil samples were collected at a layer of 0-20 cm in a zigzag pattern over the entire area of the forest fragment, excluding marginal areas. Deformed samples were collected for physical, chemical, geochemical, and mineralogical analyzes, and undisturbed samples were collected for soil density determination. Sample preparation and analyzes were performed at the Soil and Mineralogy Laboratory of the Instituto Nacional do Semiárido (INSA).

The physical and chemical analyzes were performed according to the method described in TEIXEIRA et al. (2017).

The pipette method was used for soil particle size analysis to measure the total (Tclay) (dispersed in NaOH) and natural clay (Nclay) (dispersed in water) contents. The sand content was separated by sieving (0.53 mm sieve) and the silt fraction was calculated by difference from the total soil mass. The bulk density of the soil (Db) was determined by the volumetric ring method.

The pH was determined in water (1:2.5 – dry soil:H_2O) and in KCl (1:2.5 - dry soil:KCl 1 mol L^{-1}). The ∆pH was calculated: ΔpH = pH KCl - pH H_2O. Electrical conductivity (EC) was determined using a direct-reading conductivity meter (1:5.0 – dry soil:H_2O). Exchangeable contents of Ca^{2+}, Mg^{2+}, and Al^{3+} were extracted with KCl 1 mol L^{-1}, while P, K^+, and Na^+ were extracted with Mehlich 1 solution (HCl 0.05 mol L^{-1} + H_2SO_4 0.0125 mol L^{-1}). Potential acidity (H + Al) was extracted with $CaC_4H_6O_4.H_2O$ 0.5 mol L^{-1} pH 7.0. Ca^{2+} and Mg^{2+} were determined by complexometry, Al^{3+} and H+Al by titration, K^+ and Na^+ by flame photometry, and P by colorimetry.

Total Organic Carbon (TOC) was determined according to the method proposed by YEOMANS & BREMNER (1988). Organic carbon stock (CS) was calculated according to DON et al. (2010). TOC content was converted to soil organic matter (SOM) by multiplying by the Van factor Bemmelen (1.724). Total carbon (TC), total nitrogen (TN), and total sulfur (TS) were determined by dry combustion in a CHNS elemental analyzer.

The results were used to determine the indices of the degree of flocculation (F), silt/clay ratio, total bases (SB), effective cation exchange capacity (t) and potential (T), base saturation (V%), aluminum saturation (m%), and percent sodium saturation (PST). Texture class was defined by the United States Department of Agriculture (USDA) proposed texture triangle (SOIL SURVEY STAFF 2017).

For mineralogical analyzes, the organic matter of the soils was oxidized with hydrogen peroxide (H_2 O2). The sand fraction of the soils was separated by sieving and the clay and silt fractions were separated by sedimentation (JACKSON 2005). The minerals of the sand and silt fraction were identified on microscope slides. The clay fraction of the soils was mounted on oriented slides and analyzed at room temperature (25ºC). The minerals were subjected to X-ray diffraction in a D-2 phaser diffractometer. Identification of the mineral phases present was performed using the EVA program of the D-2 Phaser.

The contents of major elements (SiO_2, Al_2O_3, CaO, MgO, K_2O, Na_2O, P_2O_5, Fe_2O_3, and TiO_2) of the sand, silt, and clay fractions of the soils were determined by energy dispersion X-ray fluorescence spectrometry (EDXRF).

Sisvar 5.7 software (FERREIRA 2019) was used for descriptive statistical analysis.

RESULTS AND DISCUSSION

Chemical Attributes

Chemical attributes were interpreted according to the criteria defined by SOBRAL et al. (2015). The Ca^{2+} content is considered average (2.6 $cmol_c$ dm^{-3}), while Mg^{2+} (1.3 $cmol_c$ dm^{-3}) and K^+ content (0.7 $cmol_c$ dm^{-3}) are high and Na^+ content is low (1.0 $cmol_c$ dm^{-3}) (Table 1). These slightly elevated values of basic cations at the surface must be due to land use, since secondary vegetation occurs in the study area. Results of this type were also obtained under similar environmental conditions in the state of Pernambuco (ARAUJO et al. 2017).

The contents of these cations reflect high values of effective (7.7 $cmol_c$ dm^{-3}) and potential CEC (18.5 $cmol_c$ dm^{-3}) and a sum of bases of 5.7 $cmol_c$ dm^{-3} (Table 1). Nevertheless, the soil is dystrophic and has a low base saturation (30.5%) because the charges in this soil are occupied by acid components (H^+ and Al^{3+}). This dystrophy is the result of the leaching process of basic cations during soil formation.

Table 1. Descriptive statistics of chemical attributes of Ferralsol in a forest fragment of Mata do Pau-Ferro, Chã de Jardim, Areia, Paraíba, Brazil.[(1)]

		X	σ^2	σ	CV	As	c	pr<D
pH_{H2O}	1:2.5	4.9	0.0	0.0	0.9	-1.5	3.3	0.2
pH_{KCl}	1:2.5	3.9	0.0	0.2	4.1	0.0	1.7	1.0
ΔpH	-	-1.0	0.0	0.2	15.8	0.0	-1.2	1.0
EC	μS cm^{-1}	79.1	5.8	2.4	3.0	0.0	1.7	1.0
Ca^{2+}	$cmol_c$ dm^{-3}	2.6	0.9	0.9	35.4	-0.7	2.2	1.0
Mg^{2+}	$cmol_c$ dm^{-3}	1.3	0.0	0.0	1.2	0.0	1.7	1.0
K^+	$cmol_c$ dm^{-3}	0.7	0.0	0.1	7.4	0.4	1.2	0.4
Na^+	$cmol_c$ dm^{-3}	1.0	0.6	0.8	76.8	0.4	1.2	0.5
Al^{3+}	$cmol_c$ dm^{-3}	2.1	0.1	0.2	11.0	-0.2	1.4	0.9
H+Al	$cmol_c$ dm^{-3}	12.8	1.0	1.0	7.6	-0.4	1.4	0.6
P	mg dm^{-3}	2.6	0.1	0.3	12.7	0.1	2.0	1.0
SB	$cmol_c$ dm^{-3}	5.7	1.4	1.2	20.9	-1.4	2.9	0.6
t	$cmol_c$ dm^{-3}	7.7	1.3	1.2	14.9	-0.4	2.4	0.9
T	$cmol_c$ dm^{-3}	18.5	1.6	1.3	6.9	0.6	1.6	0.5
V	%	30.5	28.5	5.3	17.5	-1.3	3.0	0.5
m	%	27,3	1.3	1.1	10.0	1.1	2.7	0.8
PST	%	5.3	15.3	3.9	74.1	0.4	1.2	0.6
TOC	g kg^{-1}	35.1	10.8	3.3	9.4	-0.1	1.3	0.9
CS	Mg ha^{-1}	94.0	78.0	8.8	9.4	-0.1	1.3	0.9
SOM	%	6.0	0.3	0.6	9.6	-0.1	1.3	0.9
TC	g kg^{-1}	55.6	19.0	4.4	7.8	0.3	2.2	1.0
TN	g kg^{-1}	0.6	0.1	0.3	52.5	-0.3	1.5	1.0
TS	g kg^{-1}	0.6	0.1	0.4	57.5	-1.3	3.0	0.4

[(1)] Soil analyses performed according to the methodologies described by Teixeira et al. (2017). X: arithmetic mean; σ^2: variance; σ: standard deviation; CV: coefficient of variation (in %); As: coefficient of asymmetry; c: shorts coefficient; pr<D: Kolmogorov-Smirnov normality test.

The low pH associated with the dystrophy and the low P content (2.6 mg dm^{-3}) would require the application of corrective agents and fertilizers in the soil for the cultivation of agricultural and/or forestry crops, but since this is a nature reserve, no intervention is required.

The TOC content (35.1 g kg^{-1}) corresponds to 63% of TC (55.6 g kg^{-1}) with consequent high SOM content (6.0%) and an CS of 94 Mg ha^{-1}. The carbon stock in this soil is higher than the value estimated by SFB (2019) for Atlantic forest areas in the state of Paraíba, which is 47.93 ± 7.53 Mg ha^{-1}. These values reflect a low degree of degradation of this fragment, making this soil a reservoir of essential nutrients for plants, as well as an important shop of atmospheric carbon, which directly affects the carbon cycle.

These values are also higher than those found for the surface horizons of Ferralsols, including those with humus horizons under different morphoclimatic conditions of the Brazilian territory (ANDRADE et al. 2004; MARQUES et al. 2011; ARAUJO et al. 2016; 2017).

The predominance of aliphatic organic compounds indicates low chemical recalcitrance and complex associations of organominerals are not major mechanisms for carbon accumulation in these humic soils (ARAUJO et al. 2017); the lack of correlation between clay fraction and TOC content ($p < 0.05$) in the studied soil confirms these claims.

The contents of TN and TS are the same, similar to those found in near-forest areas in the Vaca Brava microbasin (SOUSA 2013); however, our results are 30 times higher than those of the author mentioned above. The author attributes these values to the location of the areas in relief, which leads to variations in soil fertility due to the leaching and infiltration of nutrients. These results support that the soil of the studied forest plot is an important reservoir of these nutrients.

The TN contents found are similar to those found for humic oxisols exposed to different temperature and precipitation regimes in northeastern Brazil, strongly influenced by the low N content of the soil, which limits microbial activity, leading to low rates of mineralization of organic matter (ARAUJO et al. 2016). The low N torques and high C/N ratio obtained in this study confirm these observations.

Physical Attributes

The sand, silt, and clay contents represent a textural class is sandy clay (Table 2). A fact credited to the action of pedogenetic processes acting on sedimentary material from the Serra dos Martins Formation, in which they contributed to the increase in clay contents from the formation of kaolinite and Fe/Al oxides.

Table 2. Descriptive statistics of physical attributes of Ferralsol in a forest fragment of Mata do Pau-Ferro, Chã de Jardim, Areia, Paraíba, Brazil.[(1)]

		X	σ^2	σ	CV	As	c	pr<D
Sand	g kg^{-1}	609.2	386.2	19.7	3.2	-0.4	1.9	1.0
Silt	g kg^{-1}	15.8	13.7	3.7	23.4	-0.7	2.2	1.0
Tclay	g kg^{-1}	375.0	275.0	16.6	4.4	0.6	2.0	1.0
Nclay	g kg^{-1}	168.0	320,.0	17.9	10.7	-0.8	2.1	0.5
Db	g cm^{-3}	1.3	0.0	0.0	1.2	0.0	1.7	1.0
F	%	55.1	25.5	5.1	9.2	0.3	1.3	0.7

(1) Soil analyses performed according to the methodologies described by Teixeira et al. (2017). X: arithmetic mean; σ^2: variance; σ: standard deviation; CV: coefficient of variation (in %); As: coefficient of asymmetry; c: kurtosis coefficient; pr<D: Kolmogorov-Smirnov normality test.

The low silt/clay ratio (0.04) indicates a high degree of weathering in this surface soil layer, which is confirmed by the occurrence of gibbsite in the clay fraction (Figure 2a), with a strong influence of precipitation on the removal of cations and residual concentration of Al (alitization).

The clay fraction did not show a correlation with the organic constituents of the soil, even being inversely proportional. Evidence points to a chemical protection mechanism from the association of organomineral complexes, probably of lesser importance when compared to what is observed for other humic soils with a more clayey texture (MARQUES et al. 2011).

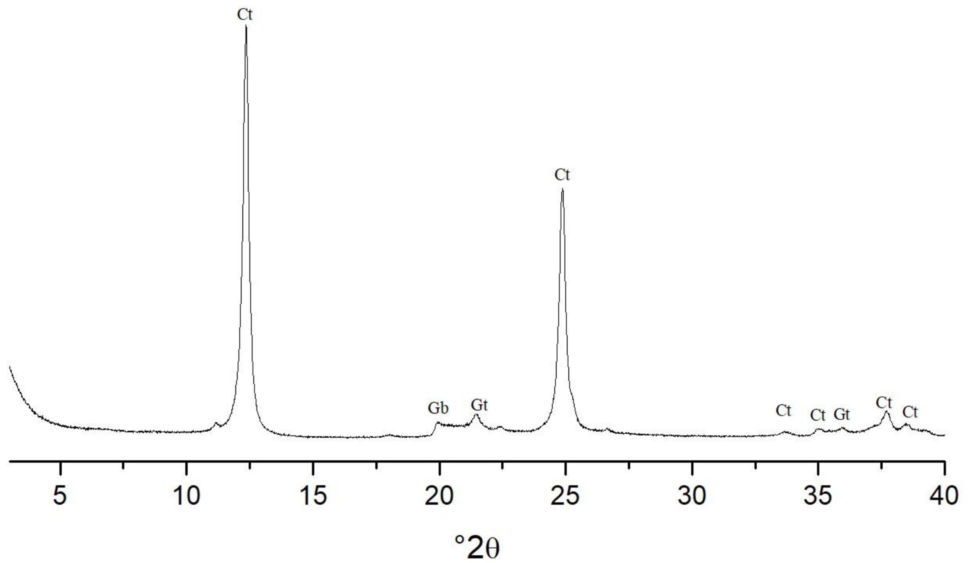
Other humic horizons in the Northeast region have shown low clay contents, similar to those found in this study, indicating that this poorly reactive kaolinitic clay fraction does not explain the accumulation of organic matter in these soils (ARAUJO et al. 2016; 2017).

The Ds values found are similar to those found for other horizons enriched in organic matter from the Barreiras Formation (ARAUJO et al. 2016). In addition, these values also reflect the occurrence of latosolization, whose weathering processes entail significant losses of easily weatherable minerals, and are associated with soil homogenization by bioturbation, allows the formation of medium to large aggregates in subangular formats, which, due to their considerable porosity, contribute to the reduction of soil density.

Mineralogy and Geochemistry

The soil mineralogy (Figures 2a and 2b) is typical of highly weathered soils and soils with a humus horizon in Brazil (ANDRADE et al. 2004). Given the highly weathered nature of the soil, the sand and silt fraction is mainly quartz (0.43, 0.31, and 0.24 nm). Low-intensity reflections at 0.38 and 0.31 nm also confirm the presence of feldspars. Kaolinite is the predominant mineral in the clay fraction of the soil, as confirmed by reflections 0.72 (*d*001), 0.35 (*d*002) and 0.22 nm (*d*003). Gibbsite (0.48 nm) and goethite (0.41 and 0.24 nm) were also identified in the clay fraction.

a) Clay



b) Silt and sand

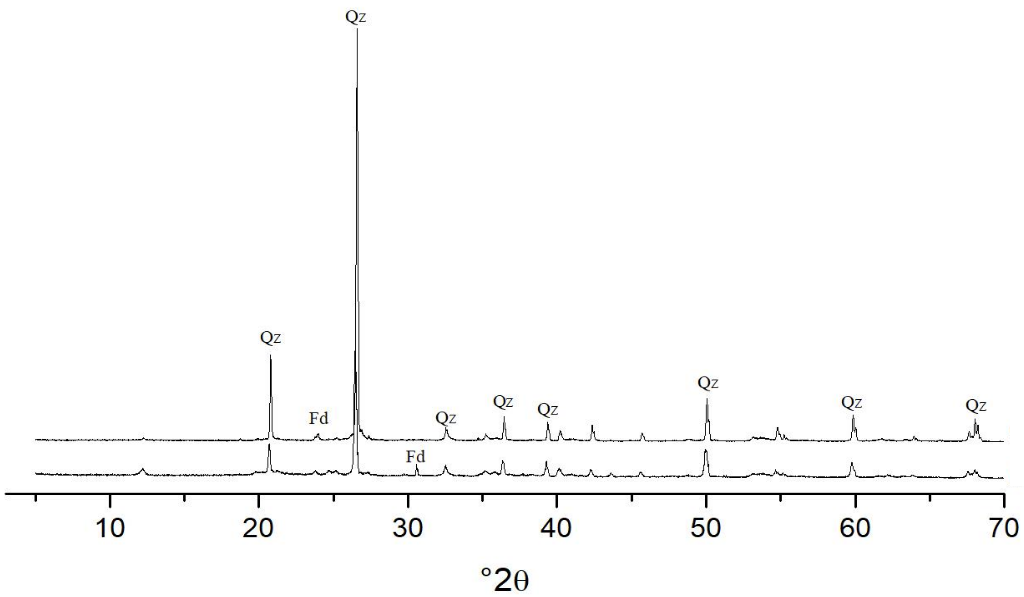


Figure 2. XRD of clay (a), silt, and sand (b) fractions of a Ferralsol from a forest fragment of Mata do Pau-Ferro, Chã de Jardim locality, Areia, Paraíba, Brazil. Ct: kaolinite; Fd: feldspar; Gb: Gibbsite; Gt: goethite; and Qz: quartz.

Leaching of basic cations during soil formation also results in partial removal of Si (desillication) and enrichment of Fe and Al oxides (ferralitization), which can be confirmed by the predominance of kaolinite, goethite, and gibbsite in the clay fraction (Figure 2a). This ferralitization also contributes to the strong predominance of SiO_2 , Al_2O_3, and Fe_2O_3 in the clay fraction of the soils (Figure 3), while the other oxides are present only in minor amounts, reflecting the lower abundance of easily weatherable minerals due to the gradual weathering of these components during soil formation.

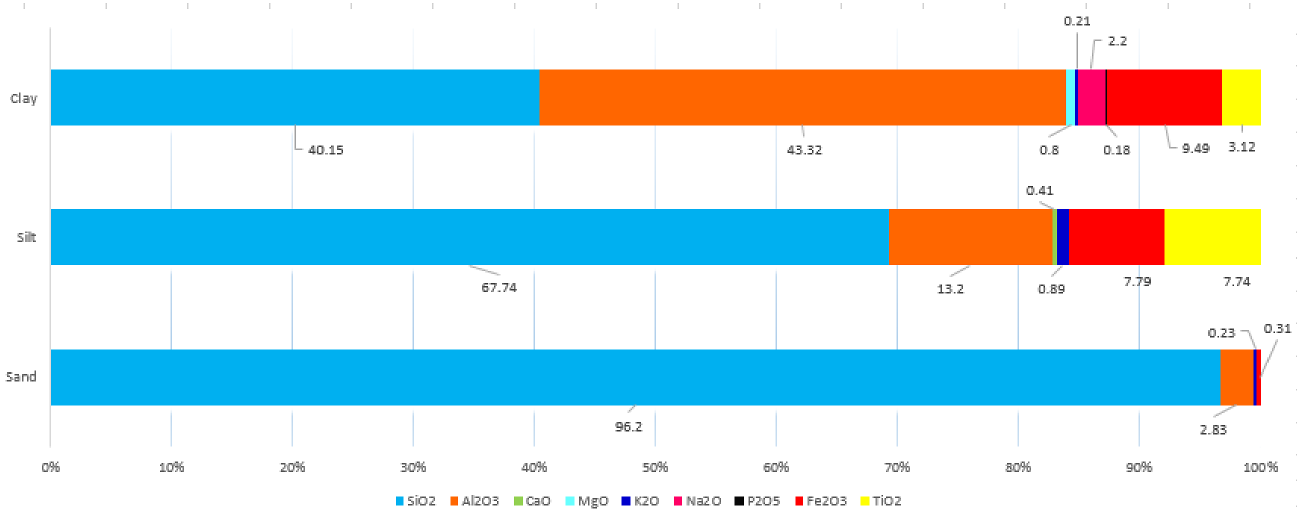


Figure 3. The total composition of major elements and traces of Ferralsol in a forest fragment of Mata do Pau-Ferro, Chã de Jardim locality, Areia, Paraíba, Brazil.

The presence of kaolinite and gibbsite reflects the intense desilication of the soil, while the slightly acidic conditions, high humidity, considerable organic matter content, and low Fe oxide content of the sedimentary parent material contribute to the nucleation of goethite. It is noteworthy that the crystallization of gibbsite is inhibited in soils at low pH and high carbon content, which could indicate a formation that is not contemporaneous with the humification process that culminated in the formation of the humic horizon, already detected in the Brazilian Northeast region (ARAUJO et al. 2017).

This mineralogical assemblage is directly reflected in the geochemistry of the soils (Figure 3), whose higher Si and Al contents are due to the presence of quartz, kaolinite, and Al oxides, while the considerable Fe_2O_3 contents are due to the presence of goethite. The higher TiO_2 contents in the clay fraction reflect the presence of rutile and/or anatase from the parent material, which, being resistant to weathering, remain as accessory minerals in the smaller soil particles. The low CaO values, consistent with the process of ferritization, indicate that the feldspars serve as a reserve for this element.

Provision of Ecosystem Services

Our results show that the studied forest fragment, even if it is only a small part of the Atlantic forest (highland forest enclave), makes a remarkable contribution to the provision of environmental, regulatory, provisioning, and cultural services. Humic horizons occur in the studied area, the origin of which is attributed to paleoclimate in which plants with the C3 photosynthetic cycle exposed to natural fires predominated (MARQUES 2019).

The high carbon stocks found in these areas, likely due to past climatic conditions that differ from those of today, confirm that these soils act as an important carbon reservoir and are a key component of the global cycling of this element. Considering that the organic matter of these soils consists mainly of a humic fraction with low chemical recalcitrance (ARAUJO et al. 2016). It should be noted that the agricultural use of these areas can contribute to the increase in CO_2 emissions, which directly affects regional climate regulation.

The sandy clay texture, the low values of soil density, and the high content of organic matter (combined with intense biological activity) give the soils a strong and granular structure that allows high hydraulic conductivity and rapid air diffusion. These characteristics are directly related to the ability of these areas to support forest vegetation, resulting in a significant increase in the provision of primary biomass, water quality regulation, aquifer recharge, and the provision of water for vegetation maintenance.

This fact helps maintain an adequate hydrologic cycle, which is important for the health of the watershed through infiltration processes, surface and subsurface runoff, drainage, and water storage. Finally, the correlation between sand content and TOC (0.6; $p < 0.05$) should also indicate the maintenance of SOM in these soils through physical protection in macro- and micro-aggregates (BAYER et al. 2006).

Indirectly, soil properties contribute to the maintenance of utility and cultural services. A balanced and fertile soil allows for the development of plants that produce food, natural fibers, wood for fuel, water, and genetic material, among other things. In addition, the fragment has the potential to contribute to the well-being of society by providing an environment for spiritual and cultural enrichment, cognitive development, reflection on natural processes, recreational opportunities, ecotourism, and recreation.

In general, the population still has a predominantly extractive view of forest resources but is gradually becoming aware of the importance and direct and indirect benefits. In a survey conducted by SFB (2019), most respondents in rural Paraíba (69%) indicated that they use the benefits provided by forests, with utility services being the most frequently cited: cattle and goat rearing (81%), wildlife rearing (5%), and Water harvesting (16%); a significant proportion mentioned regulatory services: soil conservation (22%), protection of springs (10%), legal reserve quotas (5%), and wind protection (1%); the only support service mentioned was health care (15%); and a minority mentioned cultural services: tourism (1%), recreation and leisure (1%), research and teaching (1%), environmental education (0.3%), religious rituals (0.3%).

Therefore, it's important to carry out and disseminate work that makes it possible to increase knowledge about the importance of the environmental services provided by forests, because by recognizing these services, society becomes more aware of environmental issues and the improvement of environmental quality.

In the following phases, techniques that allow accurate measurement of benefits should be promoted, as well as the development of appropriate mechanisms for the economic, social, and environmental valuation of ecosystem services.

CONCLUSION

The presence of soil characteristics reflecting the importance of forest fragments of the highland Atlantic Forest remnant in the Brazilian semiarid region was demonstrated.

The chemical, physical, mineralogical, and geochemical characteristics of the forest fragment soil have a direct influence on the provision of environmental services, and regulation and indirectly on the provision of cultural services.

Due to the regional importance of this phytophysiognomy, protective measures must be taken, aiming at sustainable territorial planning.

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