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"Luiz de Queiroz" College of Agriculture

Restoration of mangrove forests: resilience of pedogenetic processes and soil quality

Laís Coutinho Zayas Jimenez

Dissertation presented to obtain the degree of Master in Science. Area: Soil and Plant Nutrition

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Bachelor In Environmental Management

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SUMMARY

RESUMO

Restauração de manguezais: resiliência de processos pedogenéticos e qualidade do solo

Manguezais são ecossistemas costeiros que provisionam múltiplos serviços ecossistêmicos, por exemplo: (i) seqüestro de carbono; (ii) mitigação das emissões de gases de efeito estufa; (iii) retenção e imobilização de contaminante; (iv) berçário para diversas espécies marinhas. Assim é necessário desenvolver iniciativas de proteção e recuperação de manguezais, uma vez que estão entre os ecossistemas mais impactados e degradados em todo o mundo. Neste sentido, muitos serviços ecossistêmicos estão relacionados a processos pedogenéticos do solo, no entanto, poucos estudos realizaram essa abordagem. Diante disso, este estudo teve como objetivo analisar duas iniciativas de recuperação de manguezais, em diferentes contextos edáficos, visando identificar o restabelecimento de processos pedogenéticos e a restauração da qualidade do solo. Portanto, foram analisados dois manguezais com áreas de replantio em dois compartimentos da costa brasileira: a) um no estado do Ceará (CE) localizado na região nordeste marcada por um material de origem rico em quartzo e clima semiárido; b) outro localizado no estado do Rio de Janeiro (RJ), região Sudeste, que apresenta material de origem rico em ferro e clima tropical úmido. Em ambos os locais estudados foi possível observar em resposta ao desenvolvimento da vegetação, o restabelecimento de processos pedogenéticos como paludização, gleização e sulfidização que estão relacionados à serviços ecossistêmicos como seqüestro de carbono e retenção e imobilização de contaminantes. Nosso estudo também identificou o aumento qualidade do solo utilizando a ferramenta Soil Management Assessment Framework (SMAF), ressalta-se que essa é uma abordagem que nunca foi utilizada em estudos envolvendo manguezais. De fato, as iniciativas de revegetação de manguezais foram capazes aumentar a qualidade do solo a partir de parâmetros como: densidade, conteúdo de carbono, conteúdo de fósforo e pH e o aumento da qualidade do solo afetou positivamente o restabelecimento de funções ecossistêmicas como seqüestro de carbono. Além disso, a ferramenta SMAF mostrou-se ser uma ferramenta útil para estudos de qualidade do solo, no entanto ajustes devem ser considerados, assim como o número de variáveis inseridas. Em geral também identificamos que o restabelecimento de processos de pedogenéticos pode ocorrer em curto período de tempo e que essa abordagem é fundamental para inferir sobre a capacidade de manguezais impactados de desenvolver suas funções ecossistêmicas.

Palavras-chave: Processos Redox, Recuperação ambiental, Sequestro de Carbono, Areas úmidas, Pedologia

ABSTRACT

Restoration of mangrove forests: resilience of pedogenetic processes and soil quality

Mangroves are coastal ecosystems that provide many ecosystem services, for example: (i) carbon sequestration; (ii) mitigation of greenhouse gas emissions; (iii) retention and immobilization of contaminants; (iv) nursery for several marine species; so it is necessary to develop mangrove protection and recovery initiatives, which are among the most impacted and degraded ecosystems in the world. In addition, many ecosystem services are related to pedogenetic soil processes, however, few studies have carried out this approach. Therefore, this study aimed to analyze two mangrove recovery initiatives in different soil contexts, aiming at identifying the restoration of pedogenetic processes and soil quality. Therefore, two mangroves with reforestation areas were analyzed in two compartments of the Brazilian coast: a) one in the state of Ceará (CE) located in the northeast region marked by a source material rich in quartz and semiarid climate; b) another located in the state of Rio de Janeiro (RJ), in the Southeast region, which presents material rich in iron and a humid tropical climate. In both sites, it was possible to observe the reestablishment of pedogenetic processes such as paludization, gleization and sulfidization, which are related to ecosystem services such as carbon sequestration and retention and immobilization of contaminants. Our study also identified the soil quality improvement using the Soil Management Assessment Framework (SMAF) tool, it is emphasized that this approach has never been used in studies involving mangroves. In fact, mangrove revegetation initiatives were able to increase soil quality of parameters such as: bulk density, carbon content, phosphorus content and pH, and the increase in soil quality positively affected the restoration of ecosystem functions such as sequestering carbon. In addition, the SMAF tool proved to be a useful tool for studies of soil quality, however, adjustments should be considered, as well as the number of variables inserted. In general we also identify that the reestablishment of pedogenetic processes may occur in a short period of time and that this approach is fundamental to infer about the capacity of impacted mangroves to develop their ecosystem functions.

Keywords: Redox Processes, Environmental recovery, Carbon sequestration, Wetlands, Pedology

1. INTRODUCTION

The decline in biodiversity and the rates of pollution have never been so high, and these are the effects of antropogenic activities such as: changes in land and sea use, industrial activities, urbanization, and inappropriate disposal of effluents. It was reveled in may of 2019 by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) (Ngo et al., 2019). Such catastrophic revelations about the path taken by environmental resources point to the urgent need for the development of policies and mechanisms aimed at environmental protection and recovery.

Some mechanisms that aim to encourage protection and recover of the environment. One of them is Reducing Emissions from Deforestation and Forest Degradation (REDD +) which seeks to reward developing countries for reducing greenhouse gas emissions of deforestation, and the role of forest conservation, sustainable forest management, and increasing forest carbon stocks (Marked by the "+") (Nantongo and Vatn, 2019). Brazil won, in February of 2019, 96.5 million dollars of in response to the results achieved in 2014 and 2015 (Nações Unidas Brasil, 2019).

In this context of developmnet of payment programs for environmental services, and and with funding for environmental recovery initiatives, is necessary to disseminate and understand the importance of mangroves to the development of ecosystem services.

Several studies have evidenced the potential of mangrove soils to promote high organic carbon accumulation which makes it the largest organic carbon compartments in the terrestrial biosphere in response to the redox conditions that affect the rates of the organic matter decomposition (Donato et al., 2011; Kauffman et al., 2018). Since controlling the greenhouse gases effect is one of the 17 Goals of the 2030 Agenda for Sustainable Development developed by the United Nations ("Home - 2018 - United Nations Sustainable Development," n.d.) and has been the subject of many global agreements such as the Kyoto protocol and Paris agreement (De Santis and Bortone, 2018; Gonzalez-Perez, 2016).

Mangrove ecosystems may have a central role in achieving the proposed goals, which is aggravated as research points to the low efficiency of the Amazon forest, once considered the world's carbon sink, to perform this service (de Sá et al., 2019). Furthermore, mangroves produce several other ecosystem services such as pollutant filtration, biodiversity maintence, coast protection from ocean extreme events, besides the cultural and economic services provided by this ecosystem to coastal population (Costanza et al., 1997; De Wolf and Rashid, 2008; Primavera et al., 2019; Tanner et al., 2019; Uchida et al., 2019). Even though, total losses in mangrove area is estimated in 35%, concerning historical data (Sanderman et al., 2018). Brazil contains the second largest mangrove area, but around 20% of the mangrove forest were degraded or lost in the last sixteen years (Feller et al., 2017; MapBiomas, 2017).

Recently, initiatives for mangrove restoration through re-vegetation have been disseminated as an option to repair the environmental impacts in these ecosystems (Feng et al., 2019). We evaluated the changes occurred in soils of the mangrove of two of this re-vegetation initiatives in order to solidify the theoretical bases to affirm the development and production of ecosystemic services and improvement of the quality of the soil. Such studies may prove to be of great value for land use planning (even to be included in mechanisms of payment for environmental services, for example) .

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Mangrove Ecosystem Services and Poverty Traps as a Coupled Natural-Human System, in: Collaboration Across Boundaries for Social-Ecological Systems Science. Springer International Publishing, Cham, pp. 115–152. https://doi.org/10.1007/978-3-030-13827-1_4

2. REPLANTING MANGROVES: RECOVERING PEDOGENETIC PROCESSES AND ECOSYSTEM SERVICES

Abstract

Undersatand pedogenesis is essential to comprehend Ecosystem Services (E.S.) provided by soils., because it is related to soil properties and functions. Pedogenetic processes in mangroves are considered relatively fast (no longer than 100 years) to complete the development and stabilization of the system, driven by the following processes: paludization, gleization, and sulfidization. These processes are related to some of the most important regulators for E.S. in mangroves. So that, one can ask, how long would take to develop these pedological processes and to produce E.S. by increasing the area of mangrove forests? To answer this question, soil samples were collected from areas of re-vegetated mangroves within two completely different edaphic regions of Brazil.At each area, samples were collected from four different sites: one degraded mangrove, two initial/intermediate developed forest, and one well stablished mature mangrove. At the field, we measured in-situ soil's pH and Eh. Samples were brought to the laboratory, followed by analysis of soil texture, organic carbon content, iron fractionation (which allowed us to calculate the Degree of Pyritization, DOP), X-Ray Diffracton (XRD), X-ray fluorescence (XRF). We found the carbon stock increased by the vegetation evolution on both areas, which indicates enhancement of carbon-sequestration sinks induced by the recovery of mangrove forests. Soil carbon content from Rio de Janeiro's mangroves were lower in Mature Mangroves than in the other areas, which happened because there were plants that forms a dense root carpet and high biomass production before mangrove's estabelishment. The sequential extraction of iron demonstrated similar distribution of Fe in all groups of samples: low content of easily mobile Fe; higher contents bound to oxides; and a increase in the pyritic fraction related to the forest development. The DOP was ascendant by the chronossequence evolution on both cases Ceara and Rio de Janeiro. Gleization and sulfidization increased by the augmentment of mangrove forests on both areas, even with the edaphic contexts limitations. Thus, by the planting mangrove species within favorable conditions, nature may enhance pedogenetic processes and consequently increasing E.S.

Keywords: Carbon sequestration, Paludization, Degree of iron pyritization, Chronossequence

2.1. Introduction

The concept of Ecosystem Services (E.S.) consists in a wide range of goods and services provided by ecosystems to the human life. The E.S were first classified within four categories: Cultural; Provisioning; Regulating and Supporting services, and those classes have been used and amplified since then (Ahmed, 2002; Costanza et al., 2014b). More recently, soil has been recognized as one of the key ecosystem components contributing to the provision of E.S (Adhikari and Hartemink, 2016; Targulian and Krasilnikov, 2007).

Mangroves are amongst the most productive ecosystems in the world and provide many E.S., such as coastal protection (attenuating effects of sea level rise, storms, and floods), provisioning habitat (production and protection of marine species), carbon sequestration, filtration of pollutants, besides the cultural aspects envolving fisheries and coastal population (Adhikari and Hartemink, 2016; Costanza et al., 1997). This variety of E.S. is responsible for the high valuation of the coastal ecosystems (considering mangroves and salt marshes), which are considered to produce more than 24 trillion U.S. dollars per year in E.S. (Costanza et al., 2014a).

Despite being so important, mangrove forests are among the most impacted ecosystems by human activities (total mangrove losses is estimated in 35% in the last 30 years; Sanderman et al., 2018). Brazil detains the second largest mangrove area of the globe, but also one of the worst scenarios of degradation, where a total 20% of these costal forests were already lost in the last sixteen years (Feller et al., 2017; MapBiomas, 2017). Due to the recognition of the essential ES provided by mangrove forests and to the increase in conscience by the governments and society, many mangrove plantation initiatives have taken place in different parts of the world aiming the reestablishment of the lost E.S.(Ellison, 2000; Hieu et al., 2017). However, to our knowledge, there are no studies that directly asses the real capacity of mangroves to reestablish their basic pedogenetic processes and thus, regain some of the lost ES upon degradation.

In fact, some of the main E.S. provided by mangrove forests (e.g. carbon sequestration and water purification) are controlled by the soil biogeochemical characteristics and, therefore, by pedogenic processes (Kelleway et al., 2017). In response to the hydromorphic environment, mangrove soils are marked by a set of singular and specific pedogenetic processes, such as: paludization (accumulation of thick organic horizons); gleization (iron and manganese reduction); sulfidization (the formation of sulfidic materials, in response to sulphate reduction). These processes are fast, taking no longer than 100 years for their complete development and kinetic stabilization, depending on the edaphic potential (Arnold et al., 1990).

In the present study we investigate two areas in the Brazilian coast under mangrove re-vegetation programs in order to evaluate how resilient are the main pedogenetic processes of mangrove soils controlling the ES.

The areas chosen are located inside Conservation Areas within two large cities, containing completely different edaphoclimatic conditions.

We aimed to answer the following questions: (a) How does the pedological processes reestablish due mangroves restoration? (b) How does the related ecosystem services of carbon sequestration and water purification develop?

To answer these questions, we evaluated the mangrove re-vegetation stages by the pedogenetic approach. We also demonstrated how soil changes in response to the vegetation development are determinant to soil ES and soil quality.

We worked with the hypothesis that (i) paludization will be developed due to the vegetation increase, as so the gleization and sulfidization (ii) Pedogenetic development results in the increase of the soil potential to perform two ecosystem services: carbon sequestration and filtering of inorganic pollutants.

2.2. Material and Methods

Soil samples were collected at mangroves from two Brazilian States (Ceará e Rio de Janeiro), containig completely different edaphic characteristics. Both sites are located at urban areas affected by anthropic activities (organic and inorganic pollution) (Cavalcante et al., 2009; Farias et al., 2007).

One of the studied sites is located at the Guanabara Bay (Rio de Janeiro). It's a site marked by the accumulation of pollutants due to the disposal of domestic and industrial effluents from urban centers at the surroundings; residues from a oil spill event in the 2000s (1.3 millions of oil tons); and industrial waste containing high contents of trace elements (Brito et al., 2009; Machado et al., 2002).

The Guanabara mangroves were severily degraded and then dominated by *Acrostichum aureum*, which is a common perennial plant with a rhizome-like stem that prevented forest recovery until the re-vegetation initiatives. The restoration initiatives were organized by the Integrated core management (NGI) from the Conservation Unit (C.U.). It first started with a demand from Ministerio Publico em 2005("ICMBio," n.d.).

There are two C.U. at the Guanabara Bay, composed mostly by mangroves (covering 6 thousand ha), such as: The APA (Área de Preservação Ambiental) of Guapimirim (created in 1984), which is the first Brazilian mangrove C.U.; and the ESEC (Estação Ecológica) Guanabara (2006). They are both federal units and were managed by Instituto Chico Mendes de Conservação da Biodiversidade (ICMBio) (Atlas dos Manguezais do Brasil, 2018, "ICMBio," n.d.).

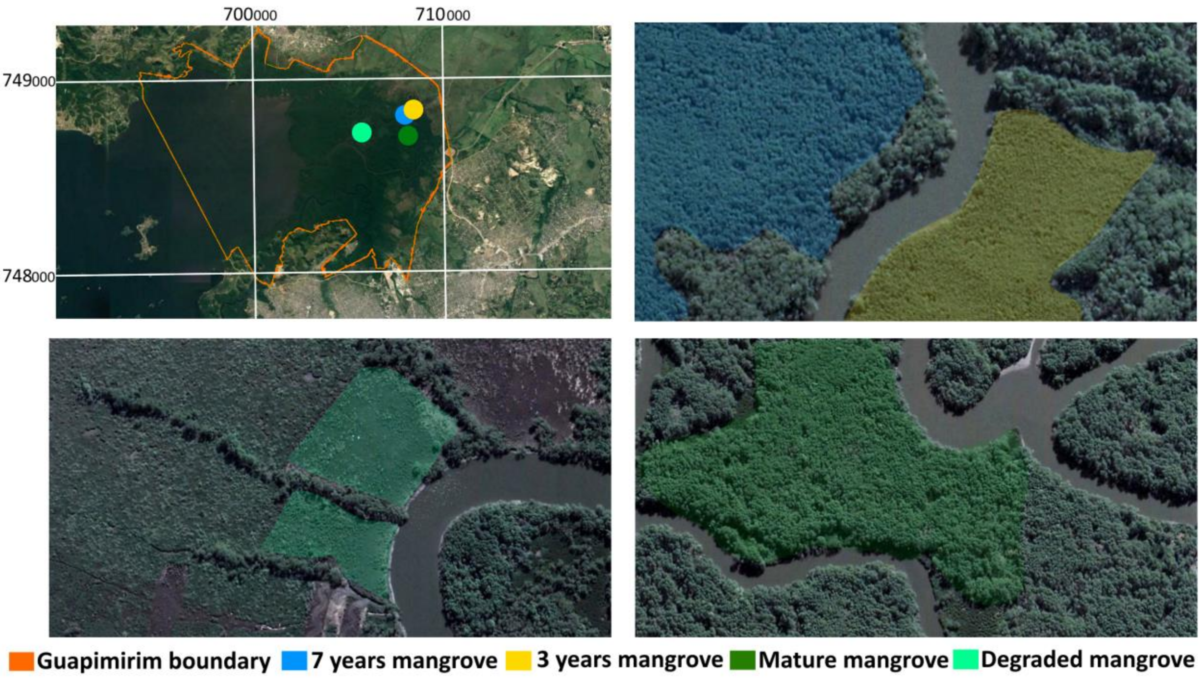

Figure 1: Satelite images of the reforestation in Rio de Janeiro. Identification of Guapimirim APA boundary and identification of reforested forests at different stages of development as well a mature mangrove and a degraded mangrove forest. satellite images obtained with Google Earth Pro

At the Ceará State, the studied mangrove areas included the environmental protection area (APA) of Sabiaguaba (2006) and the Parque Estadual do Cocó (CE) (2017) covering 15,724 km^2, including dunes, lagoons, and mangroves. The Ceara's Environment secretary ("ICMBio, n.d) manages the mangrove forests. There is an ECO-Museum ("EcoMuseu Natural do Mangue") that heads the recovery activities, which include the plantation mangrove seedlings. In Ceara site there are also many sources of impacts, such as the disordered urban occupation (inside the C.U.: in dunes, beaches, mangrove, etc) which is acompained by the disposal of different effluents (FRANÇA et al., 2008).

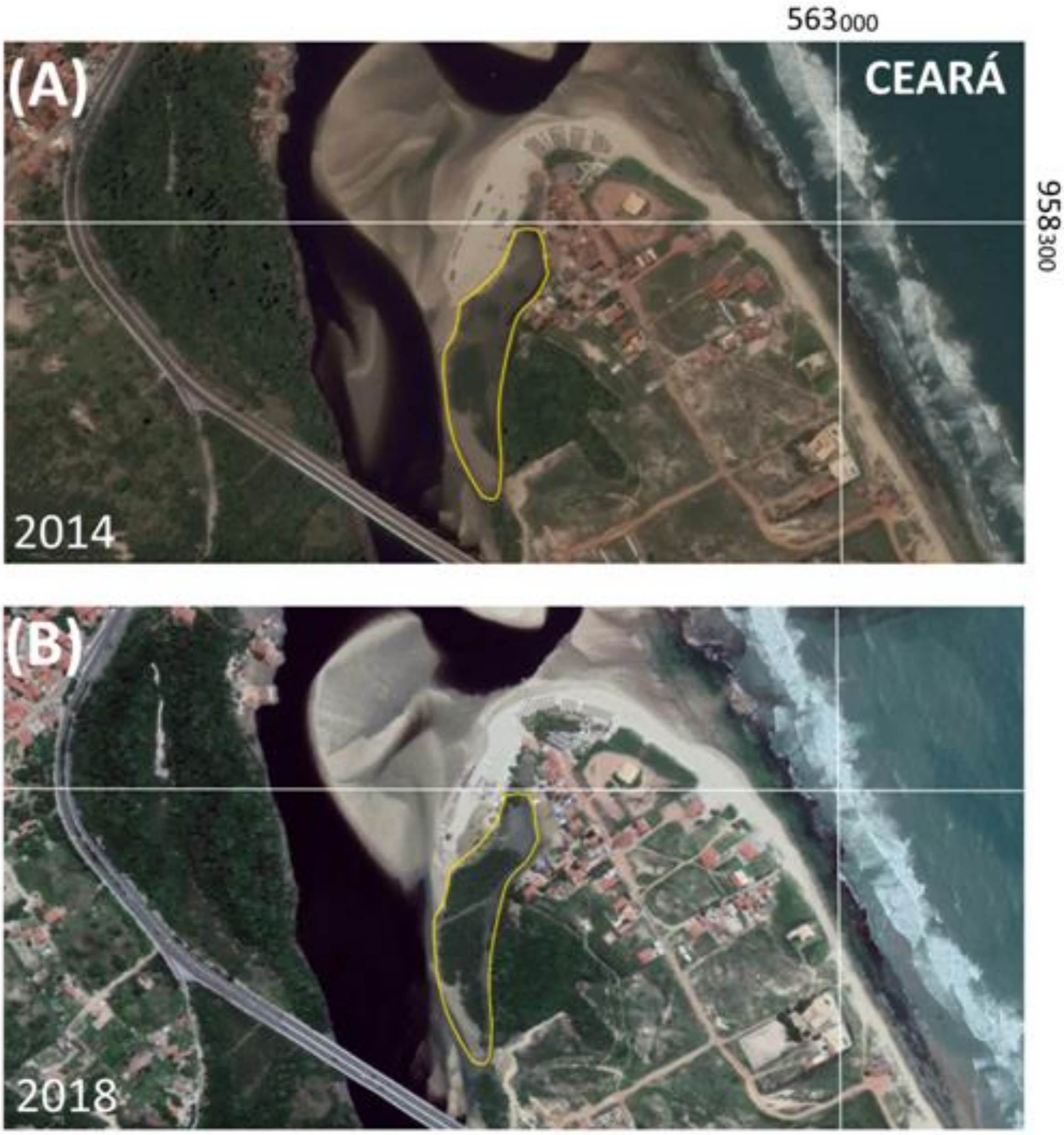

Figure 2: CE - Mangrove forest of Cocó river estuary, State of Ceará, highlighting the development of replanted areas. Satellite images obtained with Google Earth Pro

Both areas differ in the surrounding geology and climate since are located in contrasting Brazilian coastal compartments. The CE sites is located at the NE coast (Mangrove from Cocó river), and the other one at the Southeast Coast (Mangrove from Guanabara Bay) (Figure 1) (Ab'Sáber and Holmquist, 2001; Atlas dos Manguezais do Brasil, 2018).

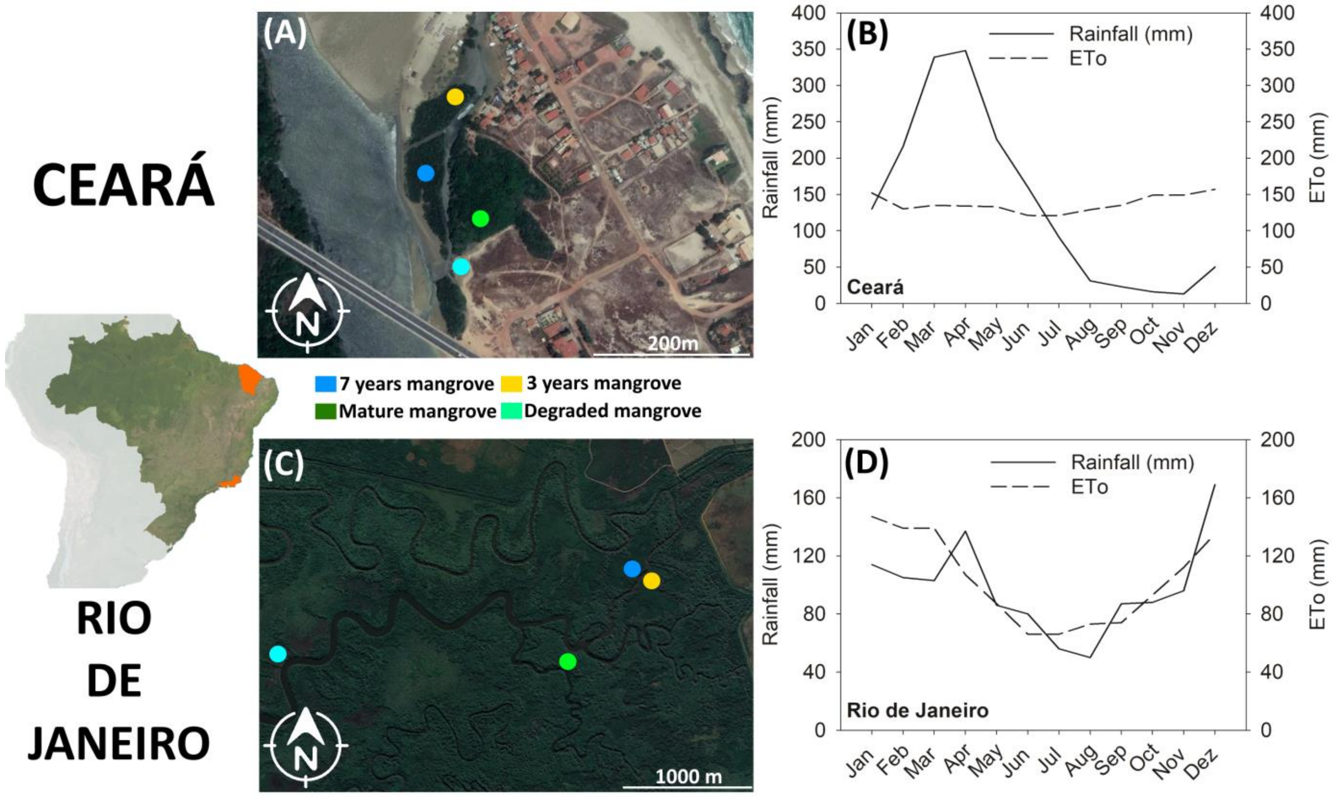

Figure 3: Study sites located in diferent Brazilian coastal compartments, precipitation, and evapotranspiration on each state CE (A, B) and RJ (C,D). Satellite images obtained with Google Earth Pro.

The mangrove at the NE coast is located between the Parque Nacional dos Lençóis Maranhenses (MA) and Natal (RN). In Fortaleza (CE), the climate is semiarid, with a mean annual precipitation under 900 mm and well defined rainy and dry seasons. The geology in Fortaleza's Metropolitan Region E (RMF) is characterized by the Formação Barreiras, which are thick sedimentary deposits of continental, mostly fluvial and lacustrine origin with a predominance of sand-clay texture (Ab'Sáber and Holmquist, 2001; Muehe, 2006[a]). This can also be observed by the proximity of the studied mangrove areas with extensive dune areas.

The Southeast Coast, mangrove ate the Guanabara Bay (RJ), is located between the Doce river (ES) and Guaratuba bay (RJ). The climate is tropical humid, with higher annual rainfall ranging from 1100 to 2100 mm (at the region closed to the Serra do Mar). Granitic rocks, wich are manly composed by quatz, biotite and feldspars, therefore they are rocks that can be a source of iron and clay for the environment more significant than those coming from the Barreiras formation mentioned above.that permeate the coast geologically characterize this area. In the Guanabara Bay there is sedimentation and accumulation of silt-clay particles of alloctone material. (Atlas dos Manguezais do Brasil, 2018; Muehe, 2006b; Soares et al., 2006 Muehe, 2006a, 2006b).

It's also important to highlight the hydrodynamic difference between the RJ and CE areas. Within a bay, there is less influence of the tides and consequently less hydrodynamic than in an area so close to the sea (as is the case of the EC).

2.2.1. Sampling

In both Guanabara Bay and Cocó, we found areas in different phases of vegetative evolution, given the dates in which they were planted. Within each area, soil cores were collected from four sites (0-100cm depth), as follows: one degraded mangrove (DM); one well-established and mature mangrove (MM), one mangrove forest in initial/intermediate development after 3 years and the other after 7 years of planting (sites 3Y and 7Y, respectively).

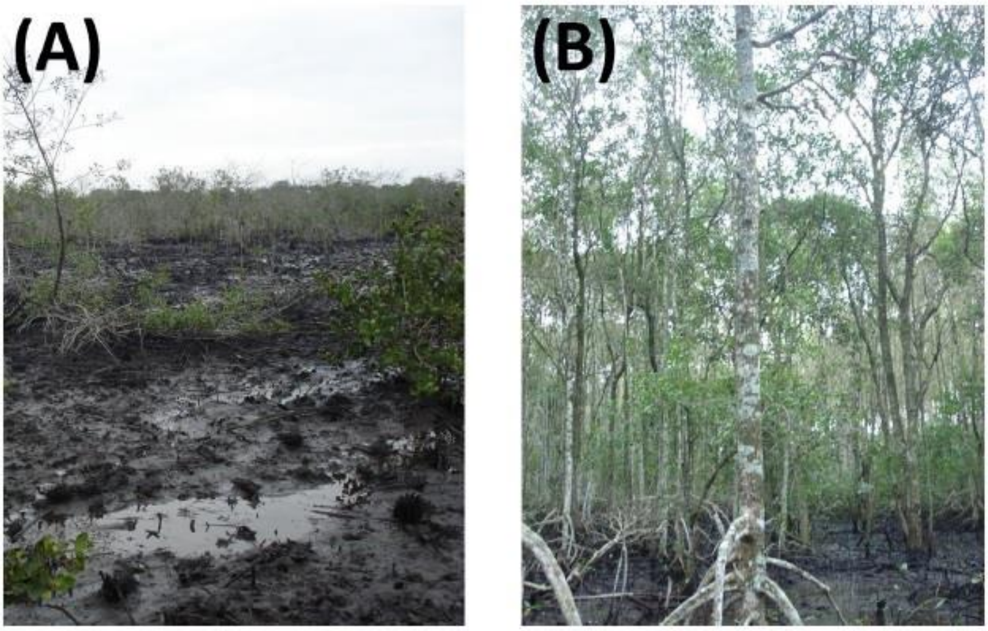

Figure 4: Detail of mangrove ate the Guanabara Bay under two contrasting conditions: Degraded Mangrove (DM)(A) and Mature mangrove (MM)(B).

For each site, during the low tide, PVC tubes were used to collect four undeformed soil cores. The PVC tubes (0.05 m in diameter by 0.6 m in length) were attached to a stainless-steel sampler. After each soil sampling, these tubes were hermetically sealed and transported (vertically) under refrigeration to the laboratory.

During the sampling procedures, we performed field measurement of redox potential (Eh) and pH. To measure Eh, a platinum electrode was used and the final reading were corrected to a calomel reference electrode (+244 mV). All pH values were measured with a glass electrode calibrated with the standards solutions of pH 4.0 e 7.0.

2.2.2. Soil Texture

Soil texture was determined by the densimeter method. Soil samples were dispersed mechanically (agitation for 12 hours) and chemically (using a solution of 0.15M of sodium hexametaphosphate and 1M of sodium hydroxide) prior to analysis (Gee & Bauder,1986).

2.2.3. Fe Sequential extraction

We conducted iron sequential extraction according to previous methods proposed by Tessier Campbell and Bisson (1979), Huerta-Díaz and Morse (1990), and Fortín Leppard and Tessier (1993). This method has been largely used to study mangrove soils (Nóbrega et al., 2013; Otero et al., 2009), allowing to identify iron in six distinct operationally defined fractions:

F1 - exchangeable and soluble Fe, extracted by $MgCl_2$ 1M, pH 7, agitated for 30 minutes;

F2 - Fe associated to carbonates, extracted by a solution of NaOAC 1M, pH 5 (adjusted using acetic acid), agitated for 5 hours;

F3 – Fe in ferrihydrite, extracted by a solution of hydroxylamine 0.04M + acetic acid 25% (v/v), 30°C, agitated for 6 hours;

F4 – Fe in lepidocrocite, extracted by a solution of hydroxylamine 0.04M + acetic acid 25% (v/v), 96°C, agitated for 6 hours;

F5 – Fe in other crystalline oxyhydroxides, extracted by a solution of $Na_3C_6H_5O_7$ (sodium citrate) 0.25M + $NaHCO_3$ (sodium bicarbonate) 0.11M and 3g of $Na_2S_2O_4$ (Sodium dithionite), 75°C, agitated for 30 minutes;

F6 – Fe in pyritic forms, (after previous elimination of the silicates using HF 10 M, for 16 hours agitating; and organic matter elimination using concentrated H_2SO_4, for 2 hours), using a solution of HNO_3 concentrated.

Between each step, samples were centrifuged (6,000 RPM for 30 minutes) for the extract separation, washed with ultrapure water and centrifuged again.

Following the determination of the pyritic-Fe we calculated the Degree of Fe Pyritization. (DOP), characterized by the portion of pyritic iron (F6) over the sum of Fe reactive (F1 to F5), all the iron that can be pyritized, plus the pyritic iron (Berner, 1970; Ferreira et al., 2007).

$$DOP= [Fe\text{-}pyritic/(Fe\text{-}pyritic + Fe\text{-}reactive)] \times 100$$

2.2.4. Organic-C determination and carbon stocks

To perform the organic-C analysis, soil samples were pre-treated with HCl 1M for carbonate elimination, centrifuged (4,000 rpm for 20 minutes) and washed with ultrapure water. soil cores were cut into 0–10, 10-20, 20-30, 30-40 and 40-50 cm sections, then Organic-C was determined in an elemental analyzer of dry combustion (LECO SE-144 DR), on dry samples (45ºC) (Howard et al., 2014).

To calculate carbon stocks, we used the density values*depth*C(%), but in order to compare the areas, we used the first area (degraded mangrove) mass to adjust the correct depth (density of the first area*10cm/density of the second area). Were made it on cores of 10 cm depth until 30cm.

To convert organic-C to CO_2 , we multiplicated C content per 44 (molecular mass of CO_2) and dividedby 12 (Carbon molar mass).

For each observation, the average annual change in soil organic-C pool concentration was calculated as follows (Lunstrum and Chen, 2014):

$$\Delta C=CMM-CDM/\Delta t$$

2.2.5. Total iron and sulfur contents

The Total-Fe and Total-S were determined by a X-ray fluorescence spectrometer (XRF). All samples were dried at 105 °C and finely ground using an agate mill prior to analysis.

2.2.6. Soil mineralogy

Mineralogy characterization was carried out in a X-ray diffractometer (XRD), samples were scanned from 3 to 60 °2θ, with 0.02 °2θ step size and count time of 3s/ step, using a *Rigaku Miniflex II* (CuKα radiation). Soil samples were pre-treated to remove soluble salts and organic matter.

Total samples were carried out for the four vegetation stages (DM 3Y 7Y and MM) on both CE and RJ. The clay mineralogy analysis was only possible in the RJ samples, once there were not enough sample to concentrate clay in CE's ones (very sandy material). Fractions were separated by sifting and decanting (Jackson, 1969).

Clay samples were treated for iron oxides removal and analysed under 5 different conditions: Saturated with Mg2; saturated with Mg2 and solvated with etilenglicol (Mg-E); saturated with K+ on three temperatures 25 ºC, 300 ºC and 550 ºC for 3 hours (Jackson, 1969).

2.2.7. Statistical analysis

Statistical analyses were conducted in SigmaPlot, Excel, and XLSTAT. The relationships among the soil parameters of each area were assessed using by Spearmans's correlation coefficient (r) and using discriminant analysis (DA) which distinguish between degradaded areas and revegetation using a set of discriminating variables that measure characteristics on which the groups to differ. Discriminant analysis do this by forming one or more linear combinations of the discriminating variables (Reimann et al., 2008).

2.3. Results

2.3.1. Soil texture

The two studied sites (states CE and RJ) differed in soil texture (Figure 5). Soils from CE were marked by a sandy-loam texture and thus, are coarser than the RJ soils which presented a silty-clay and silty-clay-loam textures (Figure 5).

2.3.2. Eh and pH

The pH values in the RJ site were close to neutrality for all vegetation stages (ranging from 6.69 to 7.51). In the CE site, there was some difference between areas—the vegetated one showed an alkaline soil reaction (pH = 8), and the well-established area was moderately acid (pH = 6,3).

Eh values varied along the mangrove's chronossequences within each region. In CE, Eh decreased drastically, in the different vegetation stages, with a sub-oxic environment in the mature (MM) mangrove (20.75 ± 162). In the degraded (DM) and intermediate areas (3Y and 7Y), Eh values hardly changed from ± 437mV.

In Rio de Janeiro, Eh values showed an oxidized environment for all vegetation stages, with high Eh values within each plot: +249 ± 25mV (DM); +340 ± 74mV (3Y); +407 ± 147mV (7Y) and +423 ± 197mV (MM), on this latter plot Eh decreased with the depth: from +509mV (0-10cm) to +198mV (20-30cm).

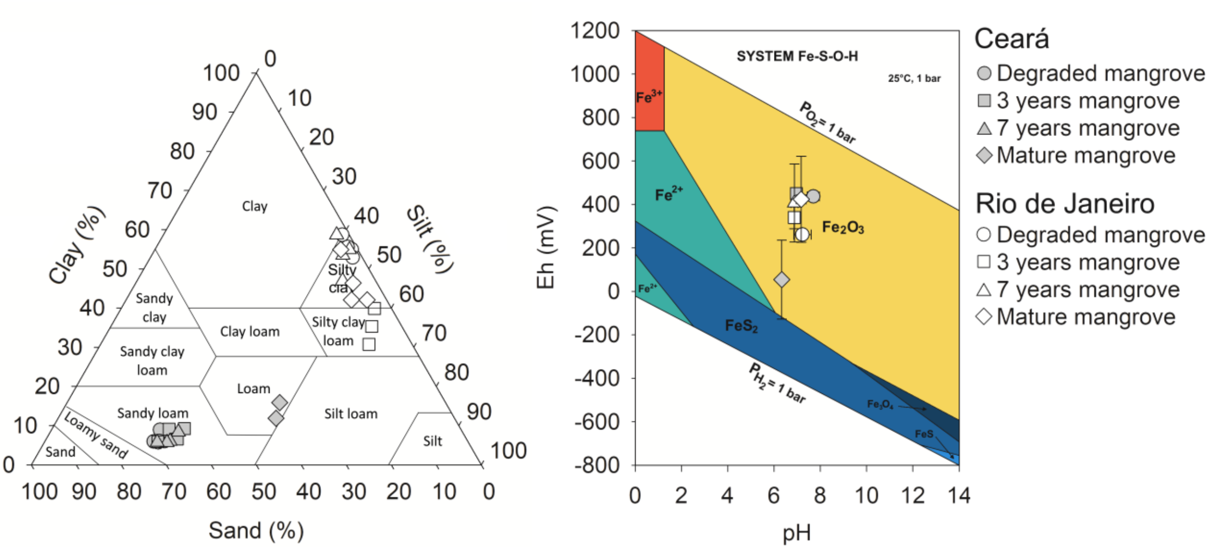

Figure 5: Soil texture triangle and ph-Eh diagram with plots from the four re-vegetation stages at Ceara and Rio de Janeiro

2.3.3. Soil organic-C

Total organic carbon contents in Ceara's mangroves increased accompaning the vegetation evolution: from 0.40% (DM) to 1.88% (MM). However, the carbon content from Rio de Janeiro's mangroves behaved differently, expressing a increase from the degraded area: 12.12% (DM) to the area of 7 years: 17.16% (7Y), and a smaller amout of carbon content on the mature area: 9.99% (MM).

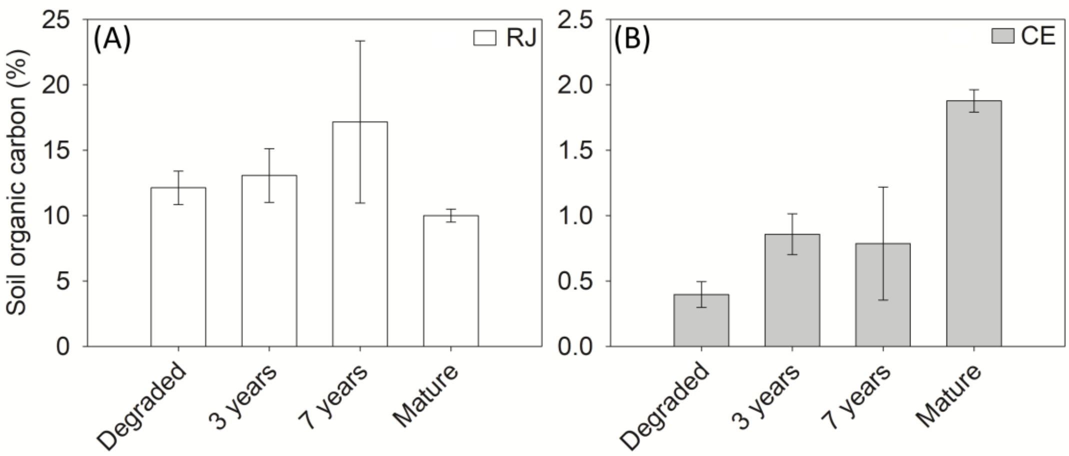

Figure 6: Total organic-C(%) contents in the four stages of mangrove restoration (DM; 3Y; 7Y; MM) at each region RJ (A) and CE (B).

In CE, organic-C contents decreased with depth, as follows: Incipient vegetation values ranged from 1.05% (0-10cm) to 0.52% (40-50cm) in 3Y and from 1.33% (0-10cm) to 0.28% (40-

50cm) in 7Y. In the mature area (MM) the amplitude was smaller from 1.78% (0-10cm) to 1.61% (40-50cm). Inverselly for the Rio de Janeiro sites: in incipient forests, the organic-C (%) increased in depth from 10.8% (0-10cm) to 14.79% (20-30cm) (3Y) and from 10% (0-10cm) to 20.94% (20-30cm) (7Y). And in the mature area (MM) depth didn't influence organic-C (%) contents.

The bulk density of the soil decreased with vegetation development on both cases: ranging on RJ from 0.305 g cm^{-3} (DM) to 0.282 g cm^{-3} (MM), and on CE from 1.308 g cm^{-3} (DM) to 0.599 g cm^{-3} (MM). Carbon equivalent stock were calculated using this values from 0 to 30cm depth.

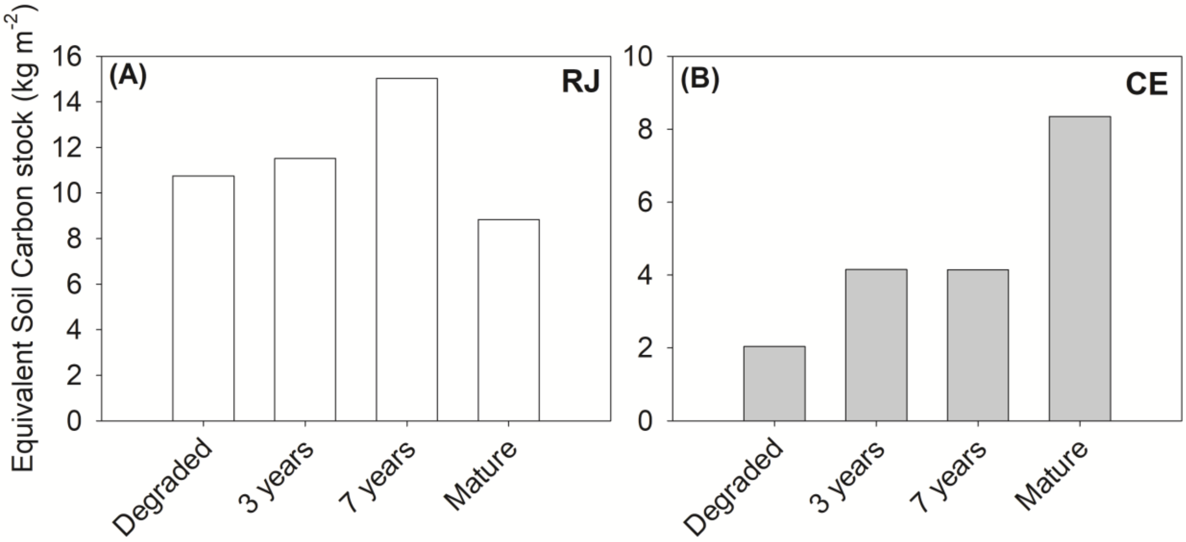

Figure 7: Equivalent Soil Carbon stock contents (Kg m^{-2}) the the four different stages of revegetation (DM; 3Y; 7Y; MM) of RJ (A) and CE (B).

In the CE site, Soil Carbon Stocks (SCS) increased: values were: 2.0381 kg m^{-2} (DM); 4.155 kg m^{-2} (3Y), 4.14 kg m^{-2}(7Y), and 8.350 kg m^{-2}(MM). While results from RJ carbon stocks were: 10.748 kg m^{-2} (DM), 11.507 kg m^{-2} (3Y), 15.02 kg m^{-2} (7Y) and 8.83 kg m^{-2} (MM), Showhing the same behavior of the total organic contents.

2.3.4. Iron sequential extraction

The iron sequential extraction showed a similar distribution of the element across all samples: low contents of labile Fe, (F1 max 1.41% on CE, 0.88% on RJ) and F2 (max 3.60% on CE and 2.07% on RJ) to total iron distribution (Figure 8 A and B). A more representative amount of iron is related to oxides (maximum values of ∑ F3, F4, F5 were: 97.7% on CE and 74.9% on RJ), mainly of them in lepidocrocite (F4 max 51.7% on CE and 27.8% on RJ). We can also see a clear increase of the pyritic Fe in response to the increasing years of forest development (from 0.89% to 49% on CE and from 34.2% to 65.4% on RJ).

In CE, F4 (Fe-lepidocrocite) represented half of total at the first three areas (DM: 51.30%; 3Y: 51.70%; 7Y: 44.75%) and a one-third of the total Fe (31.55%) at the mature mangrove (MM). In RJ, Fe related to lepidocrocite decreased with the restoration stages: DM: 27.78%; 3Y: 21.65%; 7Y: 20.08%; MM: 13.38% respectively. At CE, in the first three areas (DM, 3Y, 7Y) Fe-pyritic (F6) contributed very little to total iron contentscontents: 0.89%; 0.99%; 1.18%, respectively. Contrastingly, at the well-established mangrove, pyritic-Fe contribution increased to 43%. This increase was also observed at the RJ site, where the contents were 34.16%; 39.12%; 51.38%; 65.36%, respectively for DM 3Y and 7Y.

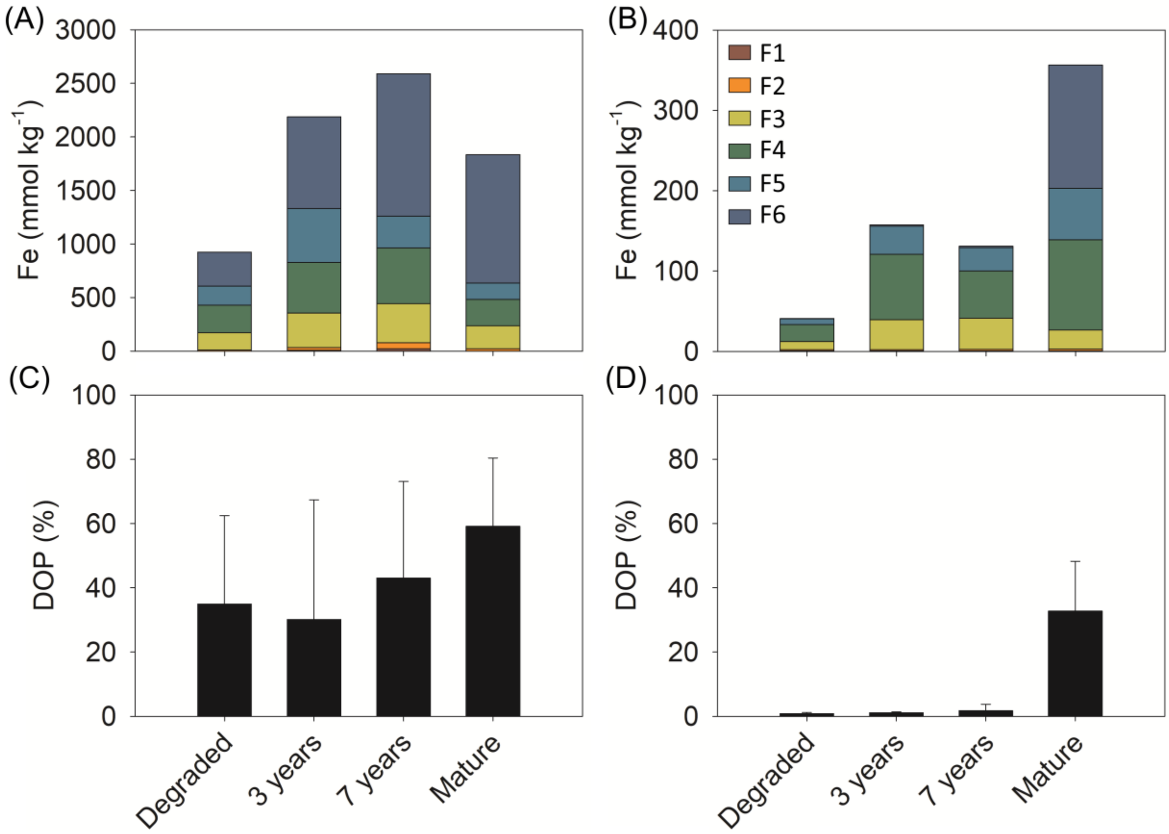

Figure 8: Iron sequential extraction data in RJ (A) and in CE (B) F1: Exchangeable; or F2: associated to carbonates; F3 ferrihydrite ;F4: lepidocrocite; F5: other crystalline oxyhydroxides; F6 pyritic iron. and Degree of Fe Pyritization values in RJ(C) and CE (D).

2.3.5. Degree of Fe pyritization (DOP)

The DOP values followed the same patern of F6 and increased in both sites (Ceara and Rio de Janeiro). The increase in CE was more pronounced contents when compared to the RJ data. The RJ's DOP showed a smaller increment, higher values at the development stages when compared to CE.

2.3.6. Soil mineralogy

Total soil samples from each vegetation phases were analysed in both sites for mineralogy. In CE samples, quartz predominates, according to its parent material. At RJ soils were composed of quartz, kaolinite, and jarosite (in the vegetated samples only).

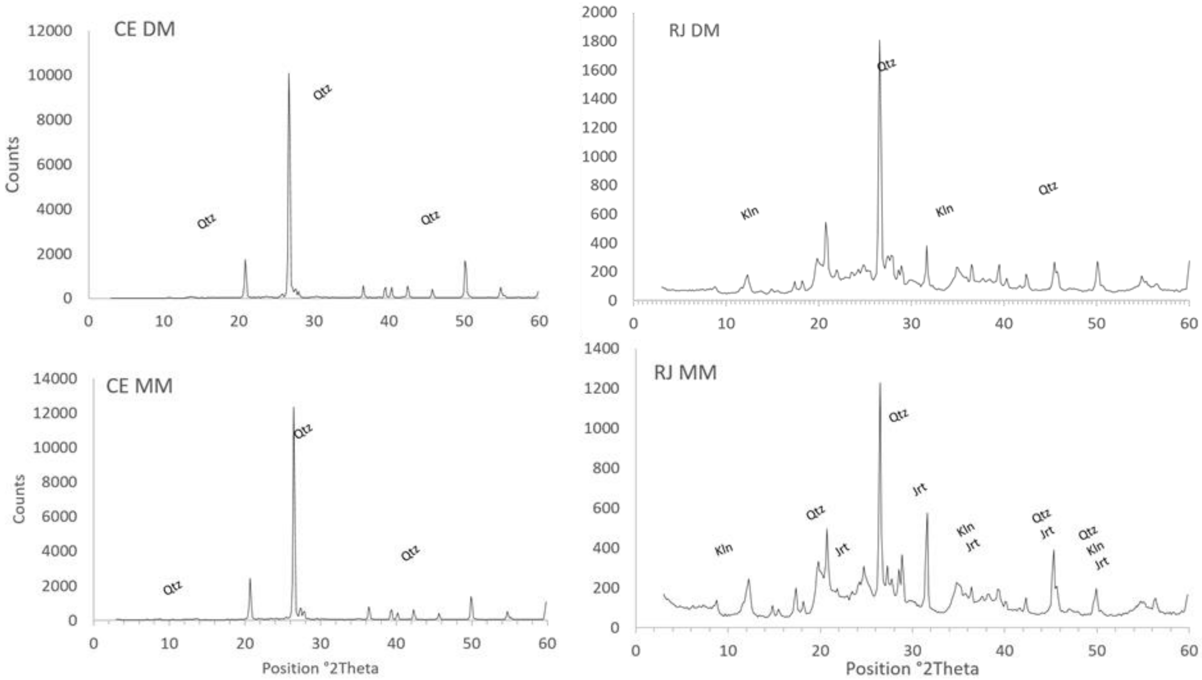

Figure 9: DRX results for total soil samples on both the Degraded and the Mature Mangrove in RJ and CE

Rio de Janeiro's clay analysis had the same diffraction graph for all samples (DM; 3Y; 7Y; MM): XRD showed the presence of Kaolinite (peak at 0.72 and 0.36 nm that disappear after thermal treatment at 500°C) and Illite (peaks at 1.0 and 0.34 nm that is not affected by either treatment).

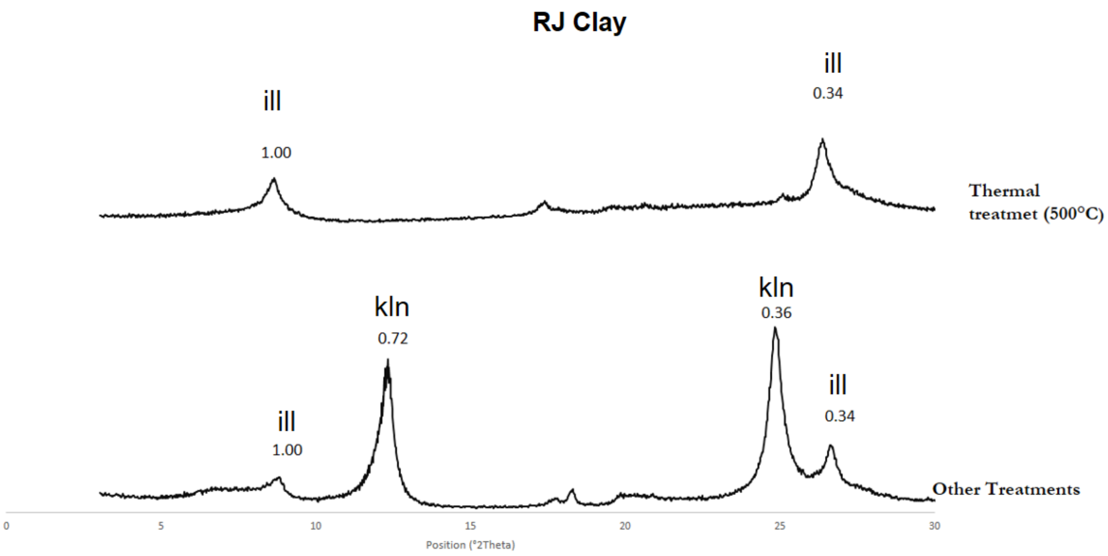

Figure 10: Rio de Janiero's clay DRX showing Kaolinite and Ilite peaks.

2.3.7. Total Fe e S contents

On CE mean Fe concentrations were 2074 (DM); 6426 (3Y); 5416 (7Y); 19687 ppms (MM) and the S contents were 1139 (DM); 1302 (3Y); 1560 (7Y); 9233 ppm (MM).

On RJ mean Fe concentrations were 29857 (DM); 54269 (3Y); 57367 (7Y); 49929ppm (MM) and the S contents were 9955 (DM), 27237 (3Y), 29294 (7Y), 19570ppms (MM).

So, total contens of Fe and S were higher on RJ than on CE. The maximum Fe found on CE samples was 3.42% and the maximus S 1.10%, while on RJ samples maximus values of Fe and S were 7.17% and 6.36% respectively.

In CE samples there was a significant increase in Fe (mean values ranged from 0.21% in DM to 1.97% in MM) and S (mean values raged from DM: 0.11% to MM: 0.93%) as a response to age of restoration. However, in RJ, this increase of Fe and S contents was only true between the degraded area (DM) and the area with seven years of plantation (7Y). In this latter is where we found the maximum values (mean values were 5.74% for Fe and 2.93% for S), although values found in the mature area (MM) were also high (mean values were 4.99% for Fe and 1.96% for S).

Considering data from both CE and RJ we can see that the increase of S contents is related to to the Fe ones, so there is a positive correlation between them (figure 11).

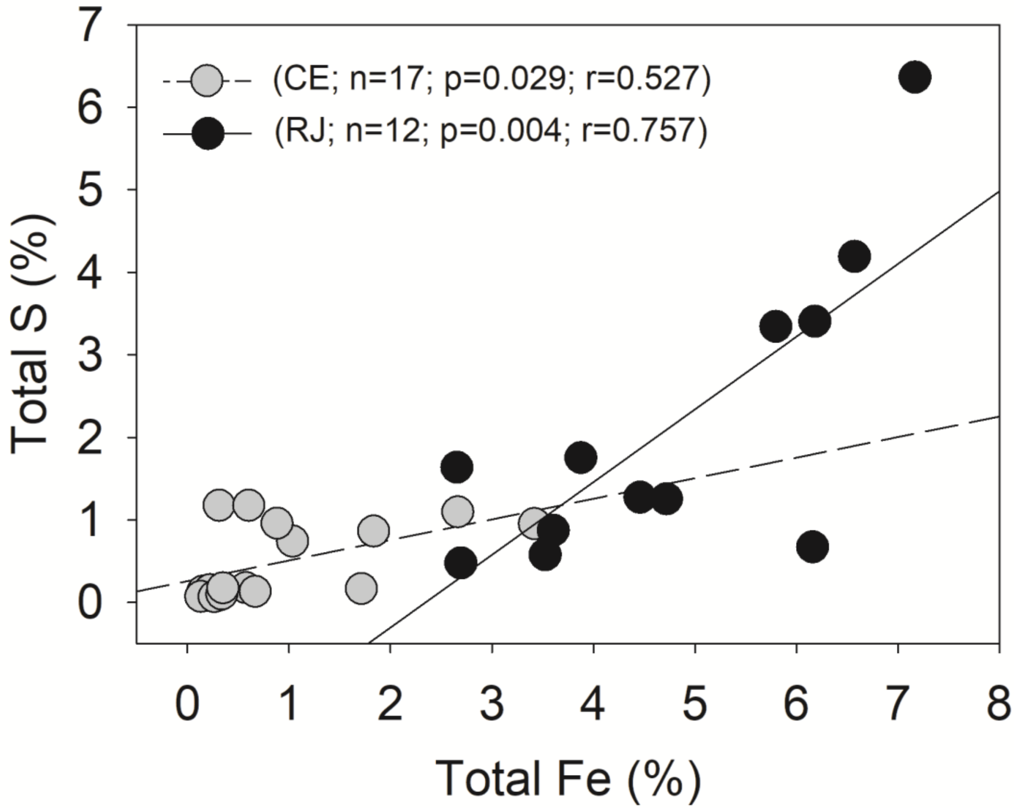

Figure 11: Positive correlation between Fe and S contents (considering data from CE and RJ)

2.4. Discussion

2.4.1. Oganic-C storage

The accumulation index of Ceara's Soil Carbon Stocks SCS is 0.555 tC ha^{-1} $year^{-1}$, which means about one-third of the global average of mangrove capacity to sequester carnon (1.55 tC ha^{-1} $year^{-1}$) (Lunstrum and Chen, 2014) and represents 2,036 tCO_2 ha^{-1} $year^{-1}$. We didn't sample or analyzed above-ground carbon, although soil carbon can represent more than 90% on mangrove areas (Kauffman and Donato, 2012b). On RJ, Soil Carbon Stocks didn't behave in the way we expected: the amouts of DM area were already high, which increased to 3Y and also to 7Y, but values found in MM area did not follow this trend, being similar to those in the DM area (around 10%). Before planting mangrove species there was organic matter on soil from the previous vegetation, so on non-vegetated (DM), 3 years (3Y) and 7 years (7Y) vegetation the organic-C contents are the amount of the sum of the organic matter from mangroves plus the previous vegetation's carbon. The previous vegetation was the *Acrostichum aureum* and which can form a dense root mat, explaining the high contents of organic-C on the first threee areas of the RJ chronossequence (Ferreira et al., 2010; Xin et al., 2018). Considering these three areas influenced by an additional source of carbon we can see the expected increasing behavior: the mean organic-C contents ranged from 12.11% (DM) to 17.16% (7Y) an the accumulation index was 2.035 tC ha^{-1} $year^{-1}$. This accumulation index means a storage of 7.462 tCO_2 ha^{-1} $year^{-1}$, a very high rate, as in the first years of a mangrove forest development the accumulation of C is more relevant than after it reaches maturity (Kristensen et al., 2008a; Marchand, 2017). Besides that, the amount of organic-C on the MM ~10%+- 0.5, is superior to the world's mean (5.4% on 0-10 depth) (Adame et al., 2018; Ha et al., 2018; Lunstrum and Chen, 2014).

It is well established that mangrove soils are highly efficient in sequestering organic C especially in response to the slow decomposition rates promoted by the anoxic conditions (Kauffman et al., 2018; Nóbrega et al., 2016).

Some additional factors affect the organic matter decay, such as moisture, oxygen availability, temperature, pH, clay contents, C/N rates, contents of lignin and polyphenols (FOG, 1988; Kristensen et al., 2008b; Walse et al., 1998). Our results showed that clay contents differed among the studied areas, as soil samples from CE were coarsers textured than RJ's ones (figure 5), and that RJ has kaolinite and Ilite composing the soil mineralogy while CE is predominated by quatz (figures 9 and 10). As a reponse to that, organic matter present in CE area is more vulnerable to mineralization than the RJ ones.

The soil material from RJ showed more than 30% of clay in all samples and, thus, a higher capacity to preserve and accumulate organic matter (Schmidt et al., 2011). Different studies evidenced a positive correlation between turnover time of soil organic-C and abundance of clay minerals (Kleber et al., 2015). The RJ samples containted phyllosilicates in the clay fraction, manly kaolinite and illite, which were reported to stablish a association with organic matter (Kleber et al., 2015). This organomineral interaction configure one of the main factor that gives the organic matter persistence in soils, since the mineral phase protects physically and chemically the organic matter from enzymatic attack and from oxidation process (Baldock and Skjemstad, 2000). The kind of adsorption/complexation varies in relation to the organic molecule structure and to the type of clay mineral (Baldock and Skjemstad, 2000; Dixon and Weed, 1992; Kleber et al., 2015; Schmidt et al., 2011). These protection mechanisms may explain the higher soil organic C contents in RJ mangroves in all vegetation stages (DM; 3Y; 7Y; MM).

However, in the CE plots, the maximum content of organic-C in soil was 2.7% at 0-10 cm depth, and 1.6% at 30-40 cm depth, both on the mature mangrove MM area. These values are under the world's average organic-C contents for mature mangroves, which are: 5,4% (0-10cm) and 2,8% (30-40cm) (Lunstrum and Chen, 2014). For the first depth (0-10cm) of the CE soil samples, the calculated annual totals Oganic- C change is 0.06% year^{-1} , while the the the world's average change for this depth in mangroves is 0.12% year^{-1}(Lunstrum and Chen, 2014). These lower organic C contents in CE may be related to the coarser soils and to the lower clay contents which present low protection to the organic matter, and also related to the climatic conditions that favors orgnic matter oxidation and also corresponds to lowes rates of vegetation development.

At the CE mangrove, the restablishment of mangrove vegetation clearly increased the participation of clay in the particle size distribution, and so the organic-C contents of the CE got less susceptible to mineralization as the vegetation progressed. It is well known that clay contents in soils usually correlate positively organic soil organic-C, by adsorption on the organic molecules surfaces or by the formation of organo-mineral complexes(Kleber et al., 2015). The positive and highly significant correlation between clay and organic-C (Figure 12) in soil of CE's mangroves. This increase happened because the mangrove roots systems act in the retention of finer particles; both the pneumatophores of *Avicennia* and the stilt roots of *Rhizophora* (see Zhou et al., 2010). This high capacity to retain sedments coming from the continent is also an important ecosystem service which is developed in synergy with the carbon accumulation.

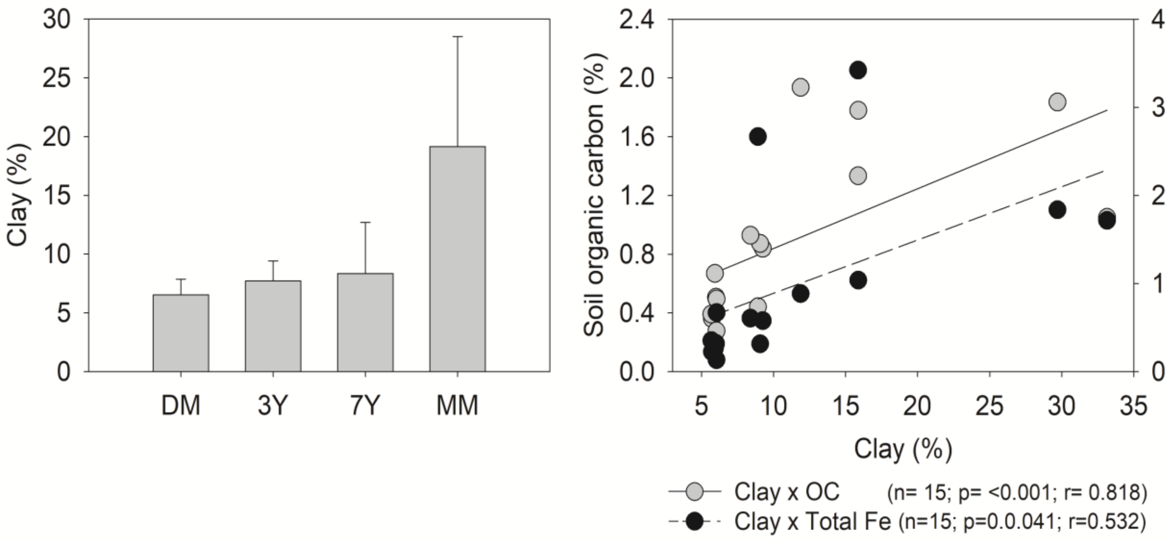

Figure 12: Increase in clay content and positive correlation between clay contents and C-oganic (%) and total Fe in the CE mangrove.

As iron oxides are found in the clay fraction of the soil, there is positive correlation between total Fe and Clay contents (Goldberg, 1989). In CE's mangroves they are both increasing within the forest development (figure 12). The higher iron oxides amounts affect the pedogenetic processes of gleization and sulfidization (Araújo et al., 2012; Nóbrega et al., 2013a). The advancement of the iron reduction enhaces the sulfate-reduction, which is (analytically) considered the subsequent processas, as it is less spontaneous on the absence of oxygen (Fitzpatrick et al., 2017; Otero et al., 2006). In this case, increasing amonts of total Fe will be linked to a increase on the gleization process, as Eh on the mature area MM is sub-oxic (20.75 mV ± 162 mV) and consequently will induce the development of the subsequent pedogenetic processes.

2.4.2. Capacity to retain inorganic pollutants

In order to assess the soil capability to retain metals, we focused on iron and sulfur dynamics. Several work have reported the potential of mangrove soils to act as sinks for metals, specially by the precipitation of metal sulfides (Bayen, 2012; Machado et al., 2014) in response to sulfate reduction.

Results from the iron sequential extraction pointed that in both studied states the less clystaline oxides contributions for iron distributions (reveled by F3 and F4 contents) has fallen by the forest development. In CE the sum of F3 and F4 contributions ranged from 74.81% (DM) to 38.45 % (MM) and in RJ it ranged from 50.00% (DM) to 28.00% (MM). Which means that during the re-vegetation development the soil redox capcities were potentialized and, consequently, iron oxides of low crystallinity were gradually reduced. In fact with the stablishment of the mangrove forest the soil redox capabilities are developed (Gleason et al., 2003; Nóbrega et al., 2013b; Sherman et al., n.d.).

At the same time, and proportionally, F6 contributions to iron distribution has increased on both areas CE (from 0.89% in DM to 42.82% in MM) and RJ (from 36.76% in DM to 60.99% in MM).

This is suggesting that during the ecosystem ripening Fe is released from oxides and combined to sulfides (also released by sulfate reduction) and precipitating as pyrite. The Figure 13 well illustrate this, by showing the negative correlation between Fe in the Pyritic portion and Fe in the low-crystaline oxides (ferrihydrite and lepidocrocite).

In response to the high cristalinity, the amount of oxides reveled by F5 did not vary much with the vegetative growth of the mangrove, since it was weakly affected by changes in soil redox conditions. In CE it 19.15% (DM) to 17.91% (MM) and in RJ from 18.78% (DM) to 11.27% (MM).

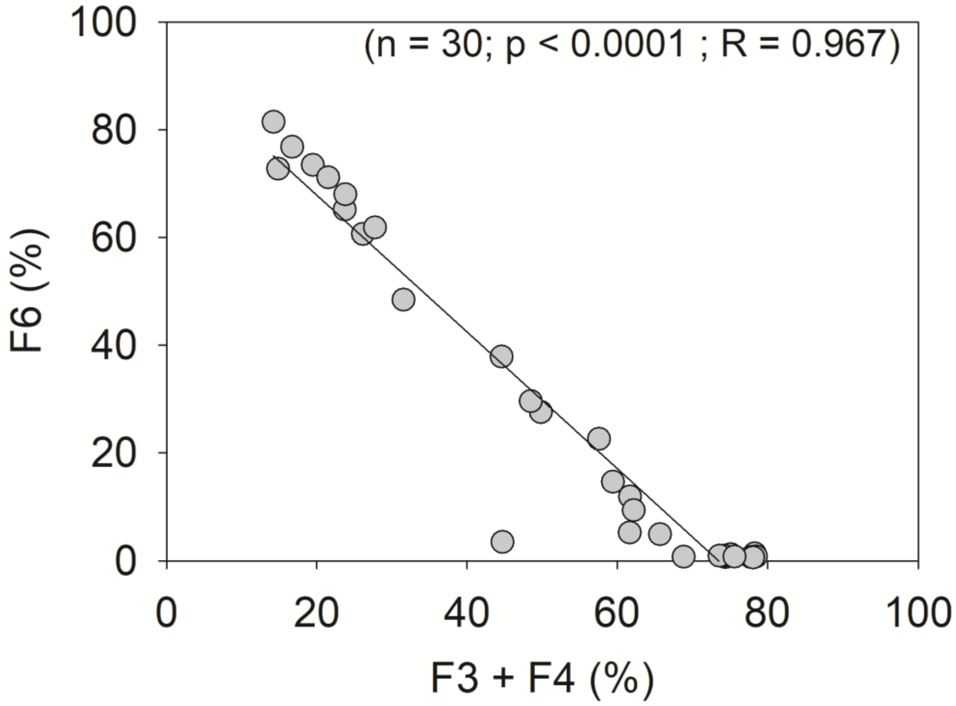

Figure 13: Negative correlation between the contributions from Fe-pyritic (F6) and Fe- ferrihydrite plus Fe-lepidocrocite (F3, F4) to the iron sequential extraction.

In both mature (MM) areas (CE and RJ), Eh values had an abrupt drop below 20 cm depth, this may be explained by the root system from mangrove vegetal species that can be responsible for the local oxidation effects, which are generally highly dense on this depth (McKee, 1993; Otero et al., 2009; Thibodeau and Nickerson, 1986). On our samples Eh values at 0-10cm showed oxic conditions on both cases (CE: +266mV and RJ: +509mV) falling significantly with depth (CE: -79mV (30-40cm) and RJ: 198mV (20-30cm)).

Besides the Eh values and the iron sequential extraction, we use sulfidization rates to perceive the soil's capability to reduce sulfates and generate iron pyritic fractions. The Degree of Piritization (DOP) demonstrates this. Indeed, DOP is strongly and positively correlated to the Degree of Trace Metal Pyritization (DTMP) (Huerta-Diaz and Morse, 1990; Machado et al., 2014; Otero et al., 2009). And as it is shown in figure 8, the DOP has significantly increased in both (CE and RJ) areas by the development of mangrove forest and so Fe and S contents are related, as shown results from XRF, because they are in the piritic portion in both CE and RJ (Figure 11).

The Accumulation of organic C (paludization) in the soil represents an energy input on the environment, affecting the physic-chemical conditions (e.g acting as an electron source to the system)(Weber et al., 2006). Consequently it triggers the subsequent processes (e.g. gleyzation and sufidization). Thereat, there is positive correlation between DOP and organic-C showing a the relationship between sulfidization (represented by DOP) and paludization (represented by organic-C) (figure 14). Summarizing the pedogenetic processes pathways we say that by the development of mangrove re-vegetation, organic C is accumulated (paludization) wich leads to the Iron (gleization) and Sulphate reduction, thus the pyrite is formed (sulfidization). Electrons coming from the organic matter trigger the mechanism that leads soil to provide the ecosystem service of water purification by metal precipitation. So, mangroves with high organic-C are likely to carry out this service (figure 14).

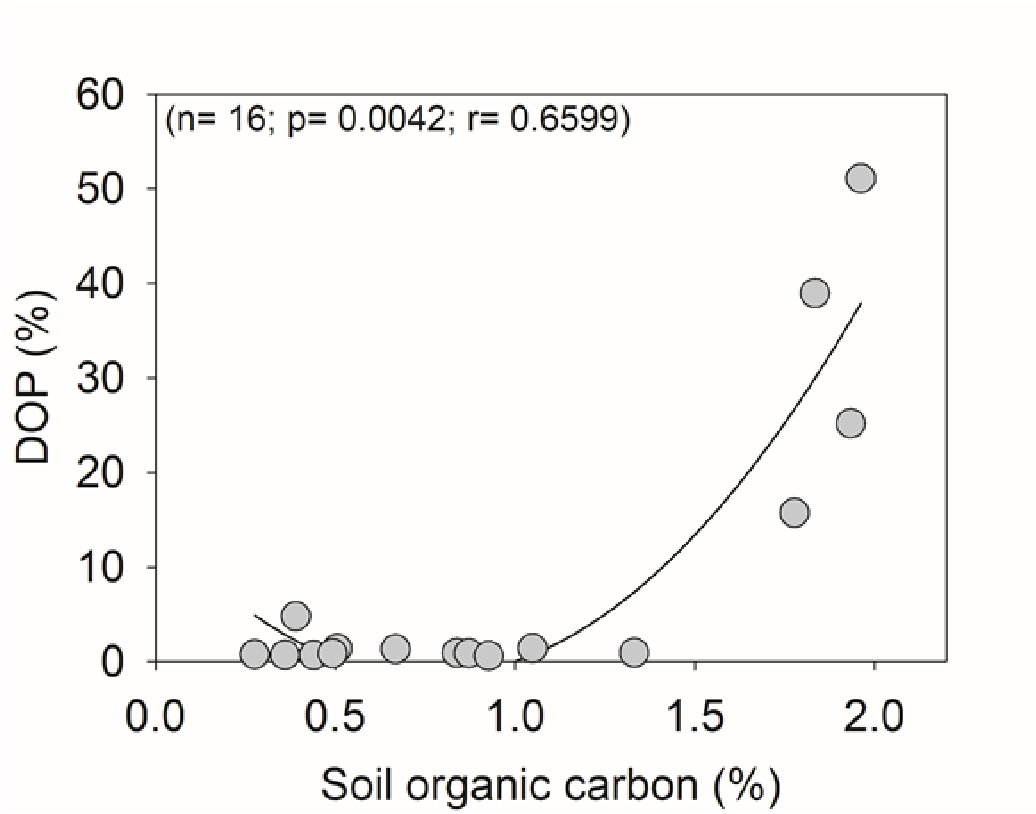

Figure 14: Significant positive relationship between Degree of iron Pyritization and Soil organic carbon, graph made with CE data

2.4.3. Pedogenesis and Ecosystem Services

The pedogenetic processes studied occurred in different intensities and velocities in each study site, as so the recovery of the mangrove E. S.. Integrating data from F6; organic-C (%), Fe Reative; DOP; total Fe and total S we had the following analysis of principal components (APC):

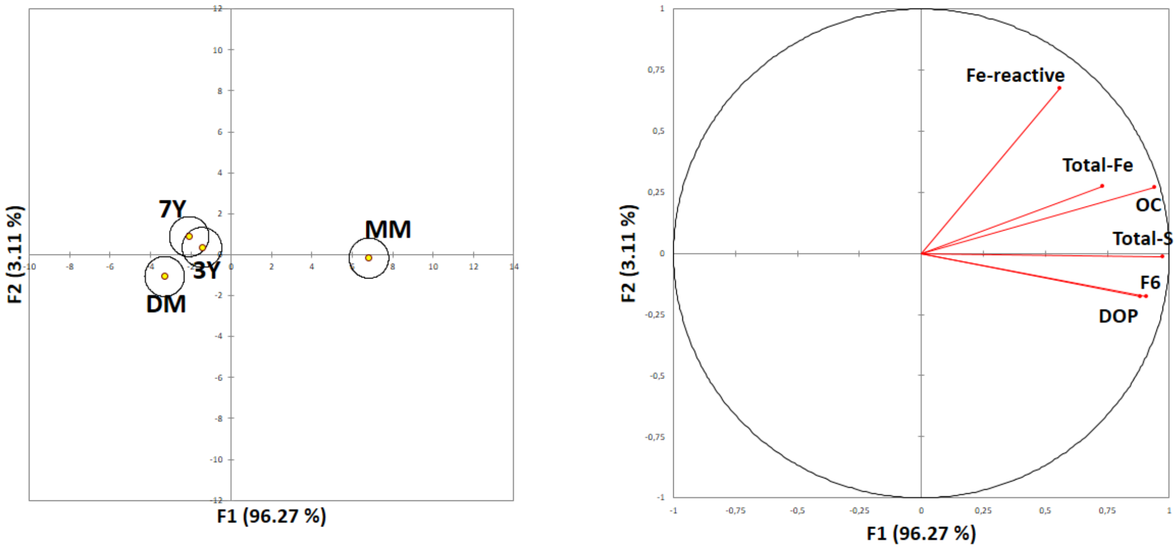

Figure 15: Principal Component Analysis of CE mangrove soil. Integratin data from organic-C, DOP, Fe-reactive, Total S, Total Fe and F6

The discriminant analyses from CE samples shows a clear difference from the areas in relation to parameters (F1 and F2): The F1 envolves total S; F6; DOP, so it to the role of mangroves as sinks for trace metals. Whereas, the F2 could (Fe-reactive; Fe total; organic-C) is related to the C sequestration.

The MM area at CE presented high values for all variables as it is a mature well established mangrove with well stablished pedogenetic processes (e.g. high sulfidization: high DOP; Total S; high gleization: high total Fe; high paludization: high organic C).

The organic-C estorage and the piritization on the first three areas were too incipient since the paludization and sulfidization processes were not sufficiently established in 3Y and 7Y. This slow rates of pedological evolution (in terms of paludization, gleization and sufidization) are manly related to the climatic limitations on CE (related to an evapatranspiration rate higher than precipitation), and parent material limitations (which leads to low amonts of iron and coarse textured soil).

The APC from RJ demonstrates the opposite pattern of development of pedogenesis:

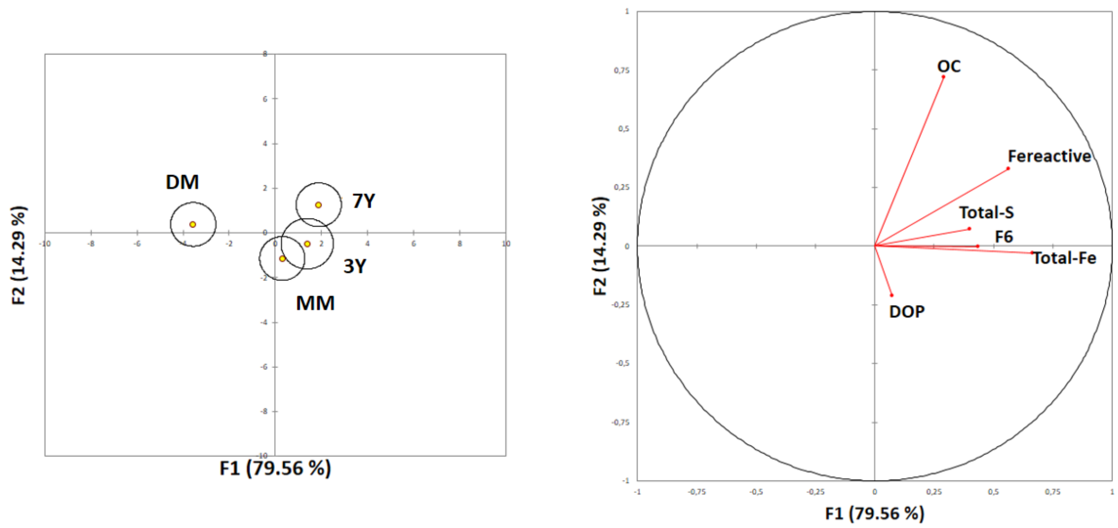

Figure 16: Principal Component Analysis of RJ mangrove soil. Integratin data from organic-C, DOP, Fe-reactive, Total S, Total Fe and F6

In the RJ site DM clearly differed, from the others manly because of lower contents of organic-C and reactive Fe. All the re-vegetated areas (3Y; 7Y; MM) showed the more intense processes related to Fe an S. It happens manly because of the finer texture and the favourable climatic conditions, that in the initial re-vagetation stages the pedologic processes studied were already stablished, and mangrove soils already producing the mentioned ES.

In the fine textured, iron rich soil material, under a tropical humid climate (RJ), 3 years of mangrove re-vegetation was enough to re-trigger paludization and sulfidization. On the other hand, at the semiarid coarse textured mangroves, the ecosystem needs a higher degree of forest development to reestablish these pedogenetic processes. The rapid mangrove development in RJ reflects on the E.S. provision (from the third year).

Even though soil behavior varies on each (RJ and CE) chronossequence, the main diferrence between them is the time that it takes to start playing the whole package of a mature ecosystem, at least by the pedological point of view, and the intensity of that (limited by climate and parent material). The provision of the two E.S. studied is consequences of this pedological maturity. So in fact, the development of mangrove forests on mangrove areas is going to release series of geochemical processes in the soil and it is going to characterize paludization, gleization, and sulfidization.

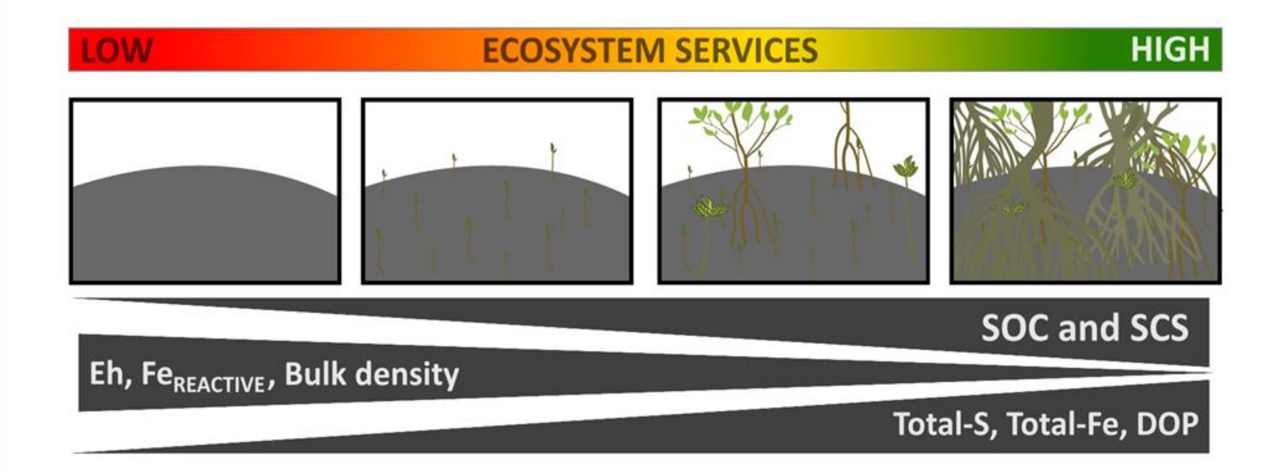

Figure 17: Mangrove development enhaces Soil Organic Carbon (SOC), Soil Carbon Stock (SCS) (paludization), and Total-S, Total-Fe, Degree Of Fe Pyritization (gleization and sulfidization).

By the paludization evaluation, re-establishment of soil carbon pool was measured as so as organic-C storage. This service is related to paludization and occur on mangrove because of their high inputs of organic-C and low decay, in response to the hydromorphic conditions (Harbison, 1986; Kristensen et al., 2008a). Paludization also provides a good representation of oganic-C dynamics in mangroves, given that soil stocks represent up to 90% of total mangrove carbon budget (Kauffman et al., 2018; Kauffman and Donato, 2012a). So we understand that in both cases (fine and coarse textured mangroves) there was the restablishment of paludization and of the mangrove capacity to sequestrate carbon, as a response to re-vegetation iniciatives, although it happened in different velocities.

We also to correlate the sulfidization rates to the evaluation to soil capacity to retain metal, by the use of DOP as an index. We made it because this attribute also relates to the DTMP that points out the ability of the soil to act as a sink of metals and so to regulate water and environmental quality (Harbison, 1986; Huerta-Diaz and Morse, 1990; Machado et al., 2014). We also saw that on both cases (CE and RJ) the re-vegetation lead to the provision of this Ecosystem Service by the development of sulfidization.

By the pedogenesis embasement we can affirm that this Ecosystem Servises are being developed in these mangroves under re-vegetation.

2.5. Conclusion

The three pedogenetic processes studied were developed in soil from both areas (CE and RJ), as so as the correlated Ecosystem Services, as a response to the re-vegetaytion initiatives. Although, it happened on different velocities and intensities in response of the variation of two of the soil formation factors: climate and parent material.

In the region with large contents of total iron, fine textured soil and no water deficit, the pedogenetic processes occurred on high rates. In the region Ecosystem services was reestablished on high rates since the third year of plantation.

The finer textured soil showed a major resilience under alterations on the vegetation in terms of carbon dynamic. Besides, the clayey mangroves showed a major capacity to develop paludization and storage carbon. The accumulation of organic matter lead to the high potential to precipitate metal sulphides and immobilize metals from the environment. Corroborating the fast effect of mangrove planting for the development of these Ecosystem Services.

Besides the edaphic limitations, the coarser textured mangrove, also developed the pedogenetic processes of paludization, gleization and sulphidization. Although, it took longer to stablish the Ecosystem Services. The soil capacity of filtering innorganic pollutants and to sequestrate carbon in a considerable rate, were only reached in mature mangrove. The need to encourage these replanting initiatives is evidenced by the fact that effective environmental returns will in fact not be rapid and by the fact that this area is under an intense and agressive urban occupation. So the advance of mangrove forests represents an important environmental safeguard for the region.

Then, in the place where the paludization occurred faster, a faster rate of gleization and sulfidization was evidenced, showing the interdependence of these processes. However, despite the difference in rates of speed and intensity, now it is known that all of these processes will occur when there are initiatives of revegetation of mangroves. Consequently, the ecosystem services of carbon sequestration and retention of inorganic pollutants will also inevitably occur by the soils of these recovered mangroves.

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3. APPLYING SOIL MANAGEMENT ASSESSMENT FRAMEWORK (SMAF) TO ASSESS SOIL QUALITY ON MANGROVES

Abstract

A soil quality evaluation tool (SMAF) was used for mangrove soils under an forest in a regeneration process. The soil quality was tested according to the parameters of the SMAF dataset (pH, organic-Carbon (%), available P (mg kg-1), Bulk Density (gcm-3)). We have found that the SMAF tool can be used for mangroves. However, the use of the minimum dataset results in high organic-C influence, which leads to a susceptibility to disturbances. Therefore, additional parameters to of the biological and chemical component are necessary for future research. On the other hand, the use of the minimum dataset indicates a correlation between the values of the integrated scores provided by the SMAF tool and the mangrove capacity to sequester carbon. So this soil quality index can be used to point out mangrove capacity of developing this ecosystem service.

Keywords: Environmental recovery, Ecosystem Services, Soil Quality Index, Carbon dynamics

3.1. Introduction

Mangroves are flooded environments, located in the intersection between the water coming from the continent and the ocean (Food and Agriculture Organization of the United Nations., 2007; Hatje and Barros, 2012) For this reason mangrove soils are completle different than soil from terrestrial forests (Huerta-Diaz and Morse, 1990; Machado et al., 2014). The saline environment and redox conditions influenced by tidal, leads to a serie of geochemical processes which are essential for the production of some Ecosystem Services, such as carbon retention and water filtering (Feng et al., 2019; Grellier et al., 2017; Marchand, 2017). Besides that, mangrove forests are also key ecosystem for the ocean and terrestrial biodiversity, while it also play an important role on human protection from catatrophic events, by the attenuation the effects of ocean and wind disturbances (Costanza et al., 1997).

Despite the recognition of mangrove forests as a key component to provide these and other many Ecosystem Services (ES), these forests area declined by 30–50% over the past half century affecting the maintenance of several ecosystem services in many cases due to a loss of soil quality (Donato et al., 2011; Giri et al., 2011). Soil quality is pivotal to assure the ecosystem services maintenance, and the use of a soil quality indices may be a strategic tool in providing information for land managers to make decisions that promote sustainability.

The soil quality aproach has been currently used in mangrove forests in order to understand the magnitude of the land use change effects on these ecosystems, e.g. change of the mangrove forests for rice cultivation (Tripathi et al., 2016) or the clearing of mangrove vegetation

(Grellier et al., 2017). These studies compared pristine forests and impacted areas based on biological, chemical and physical parameters in order to quantify the role of the environmental impacts. Since this type of study has been growing, we have seen a need to standardize soil quality studies for comparison purposes.

In this sense, The Soil Management Assessment Framework (SMAF) is a usefull tool to acess Soil Quality (SQ) that has been well accepted by the scientific community in the last years (Bünemann et al., 2018; Cherubin et al., 2017; Lisboa et al., 2019). It gives a score from zero to one, to each biological, physical and chemical factor and allows calculating an integrated score considering all parameters (Andrews et al., 2004; Bünemann et al., 2018; Lisboa et al., 2019). Although SMAF has been successfully applied in many different ecosystems, it has never been tested in mangrove ecosystems.

We proposed to apply the SMAF tool to investigate mangroves' soil quality. Additionally, we also aimed to correlate SMAF results to the ecosystem service of carbon sequestration.

SMAF scores were applied in two mangrove forests under contrasting edaphoclimatic conditions under a re-vegetation program (Rio de Janeiro and Ceará). Thus, by this investigation, we tested the following hypothesis: i) the development of mangrove forest increases the SQ score from SMAF; ii) high scores on SMAF indicate high potential for Carbon sequestration.

3.2. Material and Methods

The area studied in Rio de Janeiro is inside a Conservation Unit in Guanabara Bay, there are dozens km^2 of mangroves, known to be largely degraded and polluted un the last century (Borges et al., 2009; Farias et al., 2007). The soil of this area is fine textured and, as Rio de Janeiro is located on Brazil's southeast coast, has a high precipitation water regime (figure 14).

Figure 18: Satalite picture of Guanabara Bay, Rio de Janeiro. Satelite imagens obtained by Google Earth Pro

In CE, the mangrove areas studied were also inside a Conservation unit and were also affected by anthropogenic activities, such as human occupation inside the ecosystem, and sewage disposal (Barcellos et al., 2019; Cavalcante et al., 2009). The the soil of this region is characterized by large amounts of sand (which can be confirmed by the presence of dunes surrounding the studied mangrove) and by a water deficit, determined by the marked distribution of rain in the seasons of the year.

Figure 19: Satalite picture of Cocó, Ceará. Satelite imagens obtained by Google Eart Pro.

In both areas, soil samples were collected in mangroves over different vegetation stages: degraded mangrove (DM), three years after replanting (3Y), seven years after replanting (7Y) and, mature mangrove (MM).

The SMAF was used to evaluate effect on soil quality in mangroves under different recovery stages and, in order to do so, we used a minimum dataset to develop SMAF including four soil indicators: pH, bulk density, Soil Organic Carbon (SOC), available P. The Soil Quality Index (SQI) was then calculated by the weighted average, by giving a 33.3% of the score to each mentioned factors: Chemical (by pH and P), Physical (Bulk Density), Biological (SOC).

Undisturbed soil samples were taken with PVC tubes (0.05 m in diameter and 0.6 m in length), during the low tide, these tubes were hermetically sealed and transported (vertically) under refrigeration to the laboratory. Analysis were performed in superficial soil samples (0-30 cm depth) in triplicate. Bulk Density was calculated by using the volume parameters from the soil corer (considering 30cm depth and using the measured soil mass). pH measurements were performed in the field with a glass electrode calibrated with the standard solutions of pH 4.0 e 7.0. Soil Organic Carbon (SOC) contents were determined by dry combustion using an elemental analyzer of dry combustion (LECO SE-144 DR). Total organic C contents were obtained after the pre-treatment of soil samples with HCl 1M (to eliminate carbonates) (Howard et al., 2014). Available P was extracted with Mehlich-1 and determined by colorimetry (Mehlich, 1973).

The soil carbon stock (SCS) calculated by is the SOC contents in the soil and its Bulk Density on the studied depth (Kauffman and Donato, 2012). The SCS was calculated in order to check relationshop between the SMAF score and the carbon dynamic in response to the forest development. pH and P were chosen as components of the chemical indicator, as they evince soil acidity and chemical potential, since P is an important nutrient for mangrove species (Cheeseman and Lovelock, 2004; Feller et al., 2003; Koch, 1997). SOC was used to indicate biological activity, once carbon plays a key factor on the soil biological role, and bulk density brings information on soil physical characteristics (Cherubin et al., 2017; Zornoza et al., 2015).

The scores were calculated from previously defined and published scoring curves based on several aspects (e.g. soil texture, climate, slope, the expected organic carbon content, the mineralogy and the crop). Then, the SMAF spreadsheet has the capability envince the relationship between the score given and and the soil, even considering local specificities that vary among areas. These factors are categorized within the SMAF spreadsheet: there are not many options for categorizing these aspects: the user must include his data in a class defined by the SMAF table (ranging from 1 to 5 or 3, depending on the aspect being classified). The classification guidelines are contained in the table and are the result of previously stipulated algorithm adjustments.

As we applied SMAF on diffent on areas within varied edafoclimatic contexts (CE and RJ), consequently the values determined for the classes of each factor varied between them. Values are presented in Table 1.

Table 1: Values of the classes chosen in the SMAF spreadsheet for each factor in the mangrove areas in Ceará (CE) and Rio de Janeiro (RJ)

	CE	**RJ**	**Indicator scoring curve**
Soil type	3 (medium-low O.M.)	2 (medium-high O.M.)	SOC
Texture	1 (low clay content)	4 high clay content	SOC, BD, P
Soil mineralogy	3 (other)	3 (other)	BD
Weathering class	3 (other)	3 (other)	P
Slope of the field	1 (Flat)	1 (Flat)	P
Climate	2 (high temperature and low rainfalls)	1 (high temperature and high rainfalls)	SOC, P
Crop	Mangrove 117	Mangrove 116	pH, P
P method	Mehlich 1	Mehlich 1	P

When a new Crop class is created, there is the need to inform the ideal pH values and available P contents for the "crop". For both siteswe used 7 as the ideal pH, since mangrove soils usualy present a high capacity for buffering acidity. As regards to P, we considered as ideal contents those registered in the mature mangroves (MM) of each site. (Ponnamperuma, 1972; Smith, 1992).

3.3. Results

In the CE mangrove, the mean Soil Quality Index (SQI) obtained from the integrated SMAF scores of chemical, physical, and biological factors increased with the years after re-vegetation, as follows: DM:0.60; 3Y:0.66; 7Y:0.74; MM: 0.96 (Figure 20).

The SMAF score attributed to the SOC on CE samples ranged from 0.13 (DM) to 0.99 (MM) (Table 2). Furthermore, the Bulk Density (BD) decreased within the forest development: from 0.79 (DM) to 0.99 (MM) (Table 2). P score did not have the same behavior as that of SOC and BD: the higher values were found in DM area (score 0.95) (Figure 22). Values related to pH values, were high in all studied sites (DM 3Y, 7Y, MM) as is kept around neutrality (Osland et al., 2012).

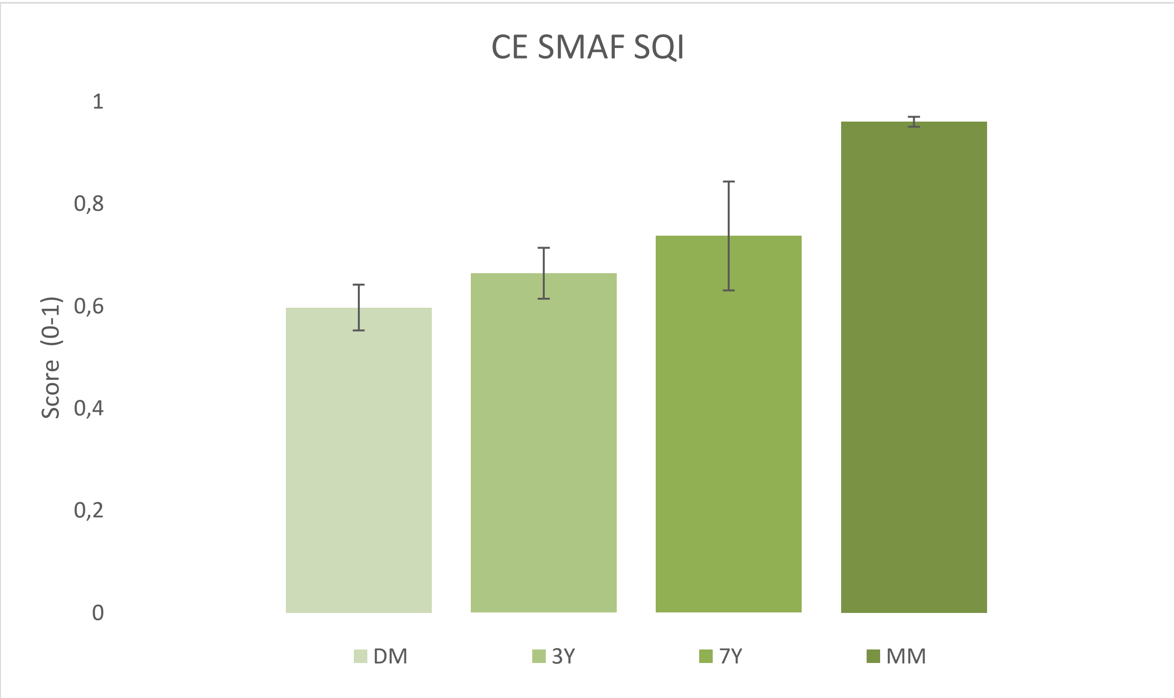

Figure 20: Mean Soil Quality Index SQI for each stage of mangrove development at Ceará: Degraded Mangrove (DM); 3 and 7 years of plantation (3Y e 7Y); and Mature Magroves (MM).

Table 2: Partial SMAF scores for each indicator used (organic Carbon (%); pH; available P; Bulk Density) in the four studied stages of mangrove development at Ceará: Degraded Mangrove (DM); 3 and 7 years of plantation (3Y e 7Y); and Mature Magroves (MM).

CE	C(%)	pH	P (mgkg-1)	BD (gcm^{-3})
			Means	
DM	0.44	7.70	19.53	1.51
3Y	0.92	7.00	4.47	1.33
7Y	0.92	6.97	8.44	1.35
MM	1.85	6.33	30.37	1.08
			Scores	
DM	0.13	0.77	0.95	0.79
3Y	0.41	0.99	0.19	0.99
7Y	0.44	1.00	0.60	0.97
MM	0.99	0.80	1.00	0.99

Contrastingly, the SQI for RJ was close to 1 in all evaluated mangroves: DM: 0.96; 3Y:1; 7Y:0.96; MM: 1 (Figure 21).

In RJ, the biological SMAF scores (which were based on SOC contents) were the maximum possible (1) in all areas, since they all showed SOC values > 8% (Table 3). pH values were close to neutrality and so the scores related to that were close to 1 in all studied sites (DM, 3Y, 7Y, MM). Overall, the BD values were low (DM: 0.29; 3y: 0.23; 7y: 0.23; MM: 0.27), when compared to well aerated soils, thus the SMAF related to that was high in all areas (Table 3). Since SOC, pH and BD values did not differ significantly between areas; the main differences were related to P variations, still with little influence on the SQI.

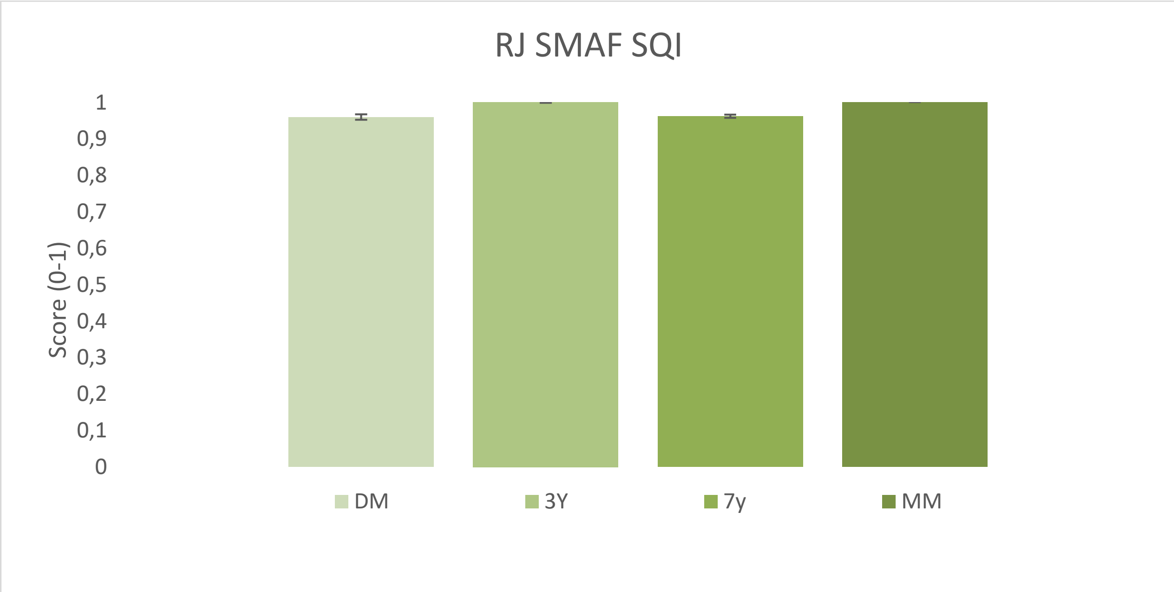

Figure 21: Mean Soil Quality Index SQI for each stage of mangrove development at Rio de Janeiro: Degraded Mangrove (DM); 3 and 7 years of plantation (3Y e 7Y); and Mature Magroves (MM).

Table 3: Partial SMAF scores for each indicator used in the four studied stages of mangrove development at Rio de Janeiro: Degraded Mangrove (DM); 3 and 7 years of plantation (3Y e 7Y); and Mature Magroves (MM)..

RJ	C (%)	pH	P ($mgkg^{-1}$)	BD (gcm^{-3})
		Means		
DM	12.12	7.23	19.37	0.29
3Y	13.06	6.87	39.09	0.23
7Y	17.16	6.88	18.29	0.23
MM	9.99	7.17	64.73	0.27
		Scores		
DM	1	0.93	0.76	0.99
3Y	1	0.98	0.96	0.99
7Y	1	0.99	0.72	0.99
MM	1	0.97	1.00	0.99

3.4. Discussion

3.4.1. Soil quality assessment

We studied the soil from two mangrove's forest under re-vegetation programs. Sites ranged from degraded areas (DM) to mature mangrove forests (MM). We expected that the Soil Quality Index (SQI) scores given from SMAF would reflect the recovery of soil quality upon revegetation (Ha et al., 2018; Marchand, 2017; Osland et al., 2012).

SMAF scores at CE mangroves indicated an increment on soil quality, evidencing that the reestablishment of the vegetation caused the improvement of physical, chemical and biological characteristics of soils. This soil quality has increased in response to forest development especially due to the recovery of SOC dynamics, and despite the unfavorable soil conditions such as the coarse soil texture and local water deficiency (Kelleway et al., 2017; Kleber et al., 2015).

In RJ, SMAF scores increased very little from DM to MM (from 0.96 to 1), and the SQI of DM was close to those registered at the 7Y and 3Y. These results are related to the high Soil Organic Carbon (SOC) contents in all areas (DM, 3Y, 7Y, MM).

This SOC contents are not correlated to the forest development, once it is a response to the previous vegetation on the field of study. Before planting, areas were dominated by *Acrostichum aureum*, whose carbon content is included in the the first three areas of study (DM, 3Y, 7Y).

High scores related to SOC contents are going to reflect on high scores related to BD (Figure 22) (usually soils with high SOC have low BD), and organic matter can also be an important source of P on the soil (Feng et al., 2019; Kristensen et al., 2008). In this case, BD is the only parameter of physical evaluation and SOC the only biological, thus 66.6% of the SQI is directly related to SOC contents, without acounting for the effect of P. In fact, Carbon plays a key role on soil processes, increasing its cation-exchange capacity (CEC), soil porosity, aggregation, nutrient contents and biological activity (Carter, 2002). However, soil response to SOC presence also depends on the quality of this carbon (Grellier et al., 2017; Hieu et al., 2017; Kristensen et al., 2008; Marchand, 2017).

We used a little dataset to generate a SMAF score, however, the use of so little information may cause some disturbance on this Soil Quality Index (SQI).

The biological parameter was based only on SOC contents whereas, other indicators such as microbial activity, enzymatic activities, probably would decrease the influennce of SOC contents on the RJ scores.

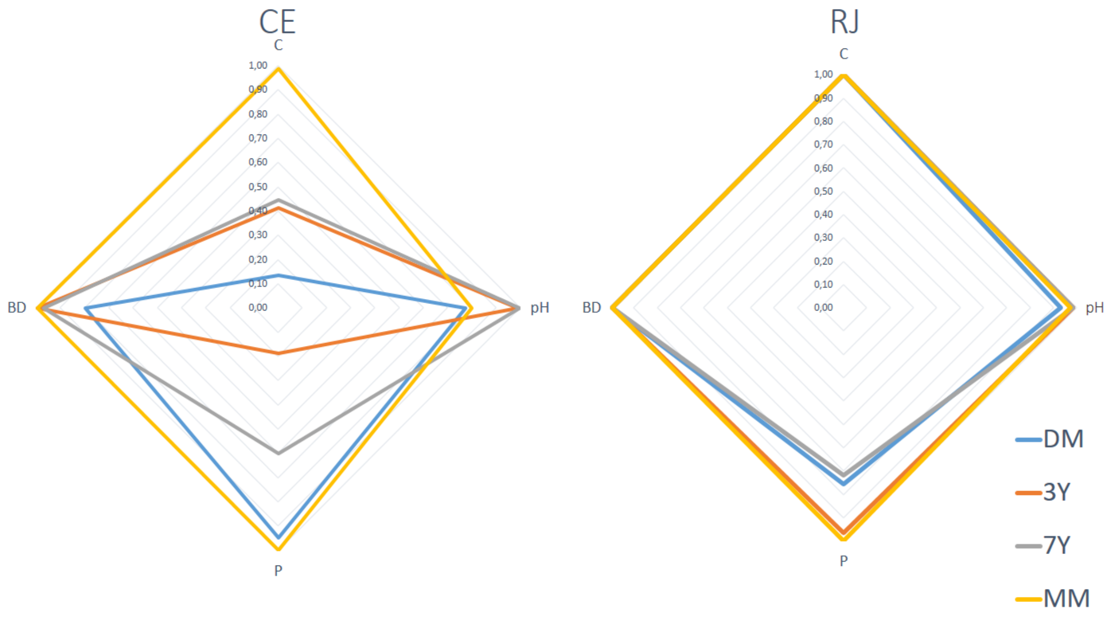

Figure 22: SMAF partial scores based on the information provided by the chosen parameters: C%; pH; P(gkg-1);Bulk Density (gcm-3)

Available-P and pH values were used as the chemical factor for SQI representing the "nutrient quality" of the soils. Although it is important to support the mangrove species demand for nutrients (mangrove plants are usually limited by N or P; Feller et al., 2003; Koch, 1997), on the other hand these values can be related to the sewage disposal or other anthropogenic effluents (Jiménez-Cárceles and Álvarez-Rogel, 2008). In mangrove forests receiving the impacts of P from effluents, the SMAF score must use additional chemical parameters. We do not suggest the substitution of the P as indicator, as there is a demand of P by mangrove species, (P deficiency is usually reported in the literature for Rhizophora; see Feller, 1995; Feller et al., 2003) but that the soil quality analysis include anthropogenic effects. This is also justified since most of the mangroves in the world are somehow affected by anthropic activities (Donato et al., 2011; Keuskamp et al., 2015; Koch and Snedaker, 1997).

3.4.2. Soil quality index and Carbon dynamic

The increase of soil carbon stocks (SCS) in mangrove environments is due to an unbalance between inputs of carbon and the low organic matter decomposition rates, promoted by the reducing conditions (Ferreira et al., 2010; Kristensen et al., 2008; Marchand, 2017).

We found a positive correlation between SQI scores by SMAF and Soil Carbon Stocks (SCS) from both areas (Figure 23). . The result evidence that SMAF scores based on these four parameters (pH, BD, SOC, exchangeable P) may be related to carbon storage.

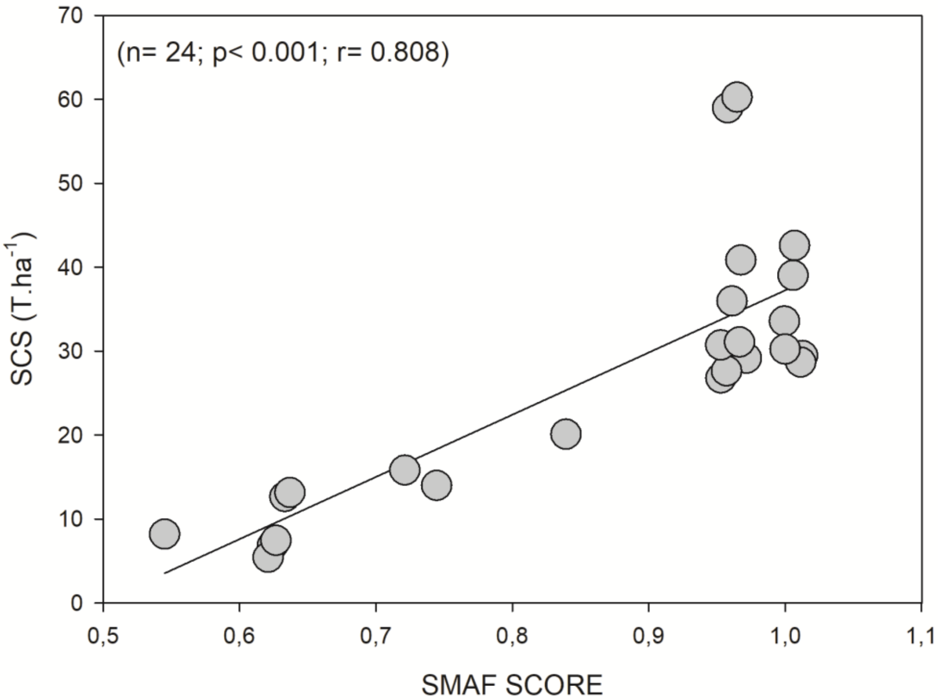

Figure 23: Positive correlation between SMAF score and SCS, considering both data from CE and RJ.

However a high score by SMAF in a single isolated area does not necessarily represent a potential for carbon sequestration. For example, the degraded plot (DM) from RJ showed high SQI scores although the "carbon sequestration" is not active. In fact, since the previous vegetation were removed and there is no more carbon input, the tendency is to lose the organic carbon via mineralization (Ha et al., 2018; Kristensen et al., 2008; Marchand, 2017).

Besides, if there were other indicators besides SOC and Bulk Density, the relative importance of these two parameters would decrease in the integrated score and the correlation with SCS could also decrease, attenuating the possibility of using SMAF scores as an indicator of Carbon sequestration.

3.5. Conclusion

Our results showed an increase in mangrove soil quality by the plantation of mangrove forests. So SMAF can be used for mangrove soils in order to assess changes in soil quality. However, we suggest the inclusion of additional biological (e.g. microbiological enzymes) and chemical parameters for further analyses in order to attenuate disturbances. We also suggest that the SMAF score evaluation used for soil quality to be accompanied by field observations.

The present study used the SMAF tool for assessing the effect on mangrove soils under re-plantation programs. Our pioneering results evidence the potential of the SMAF to monitoring

Soil Quality in mangrove soils, which are the object of many initiatives of protection and recovery.

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